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Improved Coordinated Automatic Voltage Control in Power Grids through Complex Network Analysis

A Thesis presented for the degree of Doctor of Philosophy

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Abstract

Automatic and *Co-ordinated Voltage Regulation* (CVR) contributes significantly to economy and security of transmission grids. The role of CVR will become more critical as systems are operated closer to their capacity limits due to technical, economic and environmental reasons. CVR has 1 min resolution and owing to the inherent complexity of the task, CVR is enabled through zoning-based *Reduced Control Models (RCM)* i.e. simplified models of the network suitable for Voltage Control. RCM not only enables CVR bus also affects its performance and robustness. This thesis contributes towards improved CVR through thorough investigation of the RCM.

As a starting point, with current power systems structure in mind, this work investigates static RCM schemes (i.e. fixed Reduced Control Model for all network configurations). To that end this thesis develops: (1) a novel generic framework for CVR modelling and evaluation and (2) new zoning-based RCM approaches using Complex Network Analysis. The evaluation of CVR in conjunction with both static and adaptive RCM schemes are based on a novel framework for CVR modelling and evaluation. This framework is generic and can be used to facilitate the selection and design of any of the CVR components.

As a next step, due to the fact that a single RCM cannot be optimal for all network configurations, adaptive RCM (i.e. RCM determined in an online event driven fashion) is investigated using the proposed framework. This concerns future transmission grids where RCM is driven by the need for reliability rather than economy of measurement points at a planning phase.

Lastly, this thesis examines zone division in an interconnected system ranging from EHV down to MV, and assesses the required degree of co-ordination for the voltage control of these zones. Essentially, this last item extends the scope of this work's contributions beyond a single transmission-level Independent System Operator (ISO).

Declaration

I hereby declare that this thesis is a record of work undertaken by myself, that it has not been the subject of any previous application for a degree, and that all sources of information have been duly acknowledged.

To Kamilaki

Acknowledgments

I already feel very nostalgic as I am writing this last page of my PhD thesis. I am going to miss the people I have worked with and my research problem itself. I am very thankful for my whole PhD experience, without a doubt the last 3 years and 9 months have been the most intellectually stimulating years of my life so far.

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List of Publications

Journals (peer reviewed)

[1] **V.Alimisis** and P.C.Taylor, "Zoning Evaluation for Improved Coordinated Automatic Voltage Control," in *Power Systems, IEEE Transactions on* , vol.30, no.5, pp.2736-2746, Sept. 2015, doi: 10.1109/TPWRS.2014.2369428

[2] C. Piacentini, **V. Alimisis**, M. Fox and D. Long, “An extension of metric temporal planning with application to AC voltage control,” *Artificial Intelligence Journal*, September 2015, doi:10.1016/j.artint.2015.08.010

Conferences (peer reviewed)

[3] **V.Alimisis**, C.Piacentini and P.C.Taylor, "*Zoning reconfiguration for Coordinated Voltage Regulation in future transmission grids,*" 6th ISGT North America Conference, Washington, February 2015

[4] C.Piacentini, **V.Alimisis**, M. Fox and D.Long, "Combining a Temporal Planner with an Exteranal Solver for the Power Balancing Problem in an Electricity Network". *International Conference on Automated Planning and Scheduling*, June 2013.(best student paper award)

[5] **V.Alimisis**, C.Piacentini, J.E. King, and P.C.Taylor, "Operation and Control Zones for Future Complex Power Systems," *Green Technologies Conference, IEEE* , pp.259-265, April 2013

[6] S.D.J. McArthur, P.C. Taylor, G.W. Ault, J.E. King, D. Athanasiadis, **V.Alimisis** and M.Czaplewski, "The Autonomic Power System - Network operation and control beyond smart grids," *Innovative Smart Grid Technologies (ISGT Europe), 3rd IEEE PES International Conference and Exhibition on* , pp.1-7, Oct. 2012

Books

[7] C.Adams, S.Bell, P.C.Taylor, **V.Alimisis**, G.Hutchinson, A.Kumar and B.R.Turner, “Equity across borders: A whole systems approach to micro-generation,” in Energy Justice in Changing Climate: Social equity and low-carbon energy. London: Zed Books Ltd, pp. 91-115, 2013

List of Acronyms

Acronym	Definition
AGC	Automatic Generation Control
AVC	Automatic Voltage Control
AVR	Automatic Voltage Regulator
ARRF	Average Ratio of Reactive Flows
CNA	Complex Network Analysis
CVR	Coordinated Voltage Regulation
DSO	Distribution System Operator
DG	Distributed Generation
EHV	Extra High Voltage
EMS	Energy Management System
FACTS	Flexible Alternating Current Transmission Systems
FCM	Fuzzy C-Means
HAVC	Hierarchically structured Automatic Voltage Control architecture
HCSD	Hierarchical Clustering with Single Distance
HCVS	Hierarchical Clustering in VAR Space
HSVC	High Side Voltage Control
ISO	Independent System Operator
LV	Low Voltage
MV	Medium Voltage
OLTC	On Load Tap Changer
OPF	Optimal Power Flow
OPI	Overall Performance Index
PDDL	Planning Domain Definition Language
PI	Proportional Integral controller

PMU	Phasor Measurement Unit
PSVR	Power System Voltage Regulator
PVR	Primary Voltage Regulation
QSS	Quasi Steady State
RCM	Reduction of the Control Model / Reduced Control Model
RRC	Ratio of Reactive Charging
ROPF	Reactive Optimal Power Flow
SCADA	Supervisory Control and Data Acquisition
SE	State Estimation
SKC	Spectral K-way Clustering
STATCOM	STATic synchronous COMpensator
SVC	Static VAR Compensator
SVR	Secondary Voltage Regulation
TSO	Transmission System Operator
TVR	Tertiary Voltage Regulation
VCI	Voltage Criticality Index
VPNC	Variation of Pilot Node Centrality

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Chapter 1

Introduction & Background

This Chapter presents a brief overview to the problem of Voltage Control and specifies the particular control problem that this thesis tackles and aims to contribute to, i.e. Automatic and Co-ordinated mid-term Voltage Regulation (CVR) of transmission grids considered as part of the Hierarchical Automatic Voltage Control (HAVC) architecture. To that end, HAVC architecture is presented along with examples of implementation and achieved system benefits. Additionally, this Chapter discusses what affects the CVR performance. Lastly, it presents the main Research Objectives and the outline of this thesis.

1.1 Overview & Motivation

This section provides a brief overview of Voltage Control. It further specifies the particular control task this thesis tackles and motivation towards the automation and co-ordination of the task. It should be noted that, "Voltage Regulation" refers to maintaining a stable output voltage that has small variance over a range of conditions. "Voltage Control" refers to monitoring and modifying the state of a dynamical system and may or may not include "Regulation". This distinction is followed in the rest of this thesis.

The effective control of the transmission network voltage profile contributes significantly to *quality of supply*, *operating economy* and *overall system security* [1, 2].

These desired deliverables correspond to the following list of control objectives;

- Quality of supply: Voltage values must lie within ranges compatible with equipment specifications (constraint satisfaction problem).
- Operating economy: The cost of production including losses (static optimization problem) and the cost of generation operated according to security constraints (dynamic optimization problem) should be optimized.
- Power system security: Voltage control efforts must be evenly distributed among available resources so that the loss of one infeed or line does not endanger the network.

Overall Voltage Control is a problem of dynamic optimization with security constraints. It contains several different timescales, ranging from milliseconds for the compensation of transient fluctuations to several hours for load following. Voltage control actions must therefore be structured over several time scales. Furthermore, voltage control requires various forecast studies (daily, weekly, monthly), whose aim is to define the best equipment arrangement for real-time control and the optimized voltage plan to be implemented [3].

Voltage Control is likely to become very critical in the next decades, as power systems are increasingly operated closer to their capacity limits. This is mainly due to technical, economic and environmental drivers that are summarized below;

- Technical: The electricity demands of industry and residents have increased greatly over the past decades. Residential demand in particular could possibly grow even faster in the future, with the anticipated electrification of transport and heating.
- Economic: Due to the economic pressure on the electricity market, the trend in power system planning utilizes tight operating margins, with less redundancy.

- Environmental: The alarming impacts of global energy consumption have led internationally to the adoption of ambitious environmental targets [4]. The UK for instance has committed to reduce its greenhouse gas emissions by at least 80% by 2050, relative to 1990 levels [5]. This would lead to the proliferation of stochastic sources of renewable energy.

At the same time, monitoring, communications and control equipment are undergoing sea changes which present opportunities for Improved Voltage Control;

- New and more diverse control equipment is introduced at substation level which is microprocessor based, enabling digital monitoring and control [6].
- The communication protocol will be standardized with the 61850 standard [7]. Most of the substation real-time information is used for local control within the substation but some of it can be used for wide-area control.
- Communications are also evolving, ensuring high-quality of real-time data transmission [8] .

Thus future transmission grids are likely to be characterized by increased operational uncertainty and due to that they will be more prone to disturbances. At the same time future transmission grids will be characterized by increased operational complexity due to the inclusion of a wide range of control points with sensing and communication capabilities. Mid-term Voltage Regulation is a steady state control with 1 minute resolution [9] which aims to maintain stable output voltage over a range of conditions. The increased uncertainty being also mid-term (i.e. minute by minute basis) brings mid-term Voltage Regulation in the line of fire. To that end, this thesis tackles and aims to contribute to Mid-term Voltage Regulation in transmission grids of increased operational uncertainty and complexity.

The aforementioned drivers are global; consequently there is an international trend for *improved* Mid-term Voltage Regulation in transmission grids, and more particularly towards (a) *Automation* of the control task and (b) *Coordination* among the reactive power resources and controllers [10, 11].

a) Regarding the need for *automation*: “Manual” grid voltage control is still currently used by most system operators worldwide. This typically involves dispatching the generating units’ forecasted reactive powers, scheduling the power plants’ high side voltages, switching shunt capacitor or reactor banks for power factor correction [3]. Manual control would be quite unsatisfactory in future networks that would include more stochastic sources/loads; hence operating conditions would be much different to the forecasted ones. At the same time, most of the operation manoeuvers aimed for mid-term voltage Regulation at the substation level are also performed manually. In the presence of a voltage alarm, most of the time the Operator waits in the order of minutes to activate a device, with the "hope" that the voltage may return to normal bounds [12]. This is however clearly neither a reliable way to Control Voltage in a stressed system of increased operational uncertainty nor a feasible one in a system of increased operational complexity.

b) Regarding the need for *Coordination*: Voltage set-point co-ordination is often done today according to written operator instructions or requested by the system operator when strongly needed [13]. This is sub-optimal if not completely inefficient. At the same time as monitoring and communications concurrently evolve particularly for the transmission grids, they provide opportunities to harness the available control resources and network margins. Coordination can ensure a more efficient use of reactive power resources, as well as more secure, e.g. the various resources can be evenly deployed so that the loss of an infeed would not reduce substantially the remaining reactive reserves in the system.

The adoption of an Automatic Voltage Control (AVC) strategy is tailored to the transmission grid to be controlled, i.e., network features, available control equipment, and market operation, hence different approaches have been exercised and have been debated in the literature [14]. Automatic Voltage Control systems of hierarchical structure (HAVC) have originated in Europe and enable automatic *closed-loop Coordinated Voltage Regulation* (CVR) [15]. HAVC is elaborated in the next Section, as the examined CVR in this thesis is considered as part of the HAVC architecture.

The focus of this thesis is on Automatic and Co-ordinated mid-term Voltage Regulation of transmission grids. This is a steady-state control problem with resolution of 1 minute. In the rest of the thesis this is simply referred to as Coordinated Voltage Regulation and termed as CVR and is considered as part of the Hierarchically Structured Automatic Voltage Control (HAVC) architecture.

1.2 Hierarchical Automatic Voltage Control (HAVC)

This section is organized as follows; Sub-section 1.2.1 provides an overview of the HAVC architecture. Sub-section 1.2.2 presents examples of implementation. Lastly, Sub-section 1.2.3 presents main alternative approaches to HAVC practiced by different

System Operators worldwide.

1.2.1 Overview of HAVC: concept & terminology

Towards achieving automatic real time voltage control, ideally one would optimize system-wide all control variables running a full AC optimal power flow. However, this is unrealistic and not compatible with real time requirements. Owing to the inherent complexity of the task and the localized nature of voltage and reactive power, reliable albeit suboptimal real time automatic control is delivered through a *zoning* based *Reduced Control Model* (RCM) [16].

A generic hierarchically structured AVC architecture is shown in figure 1.1 below, with the right side presenting an illustration of zoning based RCM on an abstract transmission network. *Zones* are network subdivisions that demonstrate coherence for voltage control and are derived using the Jacobian matrix of the system. Within a *zone*, voltage is controlled on a *pilot bus*, i.e. a central EHV load bus whose voltage magnitude variation is representative of the zonal voltage profile. The control resource is based primarily on the largest synchronous generators within the *zone* that have the maximum regulating sensitivity on the pilot bus. Effectively, the reduced control model is an approximation of the reactive power flow sub-problem of a zone.

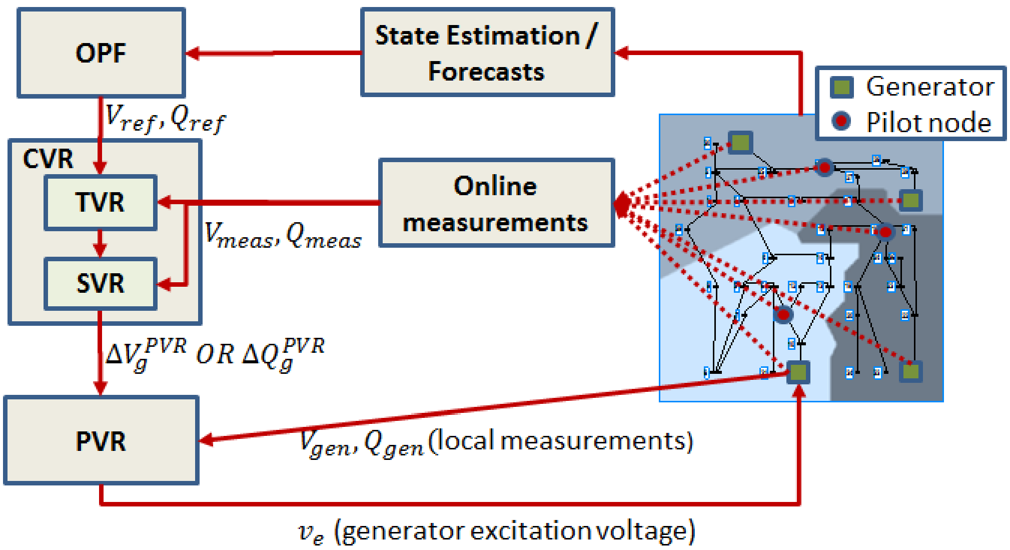


Fig. 1.1 A generic hierarchically structured AVC architecture

As shown on figure 1.1 the HAVC architecture is organized in three different control layers, which are temporally and spatially independent. Temporal independence means that the three control mechanisms do not significantly interact with each other, operating in three adjacent time-scales and maintaining robust performance and stability, when facing system changes; if the control laws were more complex there would always be the risk of oscillation and instability. These three layers constitute the hierarchical structure of grid voltage control and are elaborated below:

- *Primary Voltage Regulation (PVR)* is performed by the generator's Automatic Voltage Regulator (AVR). The AVR regulates the voltage by controlling the excitation system. This performs partial automatic correction, within a few seconds, to compensate against rapid random variation in the EHV voltage. The other controllable devices like synchronous condenser and SVC can also be used for PVR.
- *Secondary Voltage Regulation* (SVR) is a steady state mechanism that counteracts voltage deviations occurring within a *control zone* by adjusting the set-points of Primary Voltage Regulators (PVR) according to a PI law. The control resource is essentially based on the largest synchronous generators within the zone that have the maximum regulating sensitivity on the pilot node. For systems with very long transmission lines and remote generation, the possible zones without generation could have a conceptually similar SVR with a Static VAR compensator coordinating the switching of reactive shunt banks. The SVR ensures a more rational and efficient use of the available reactive power resources, compared to the case of un-coordinated Voltage Regulation. Additionally, SVR is automatic; hence it effectively relieves the System Operator from manual intervention. For optimization, emergency boosting and to avoid conflicting inter-zone control efforts, SVR set-points come from a tertiary loop, the *Tertiary Voltage Regulation (TVR)* which coordinates the decentralized SVRs. TVR minimizes the differences between the actual field measurements and the reference values provided by a reactive OPF. The definition and the implementation of the SVR and the TVR vary from one System Operator to another. However, in principle, in all implementations TVR together with SVR deliver the Coordinated Voltage Regulation (CVR). *CVR is a steady-state control with 1 min resolution.*
- A Reactive Optimal Power Flow (ROPF) guides the CVR. A ROPF is a full AC OPF that minimizes losses with security constraints. Essentially, the ROPF can be regarded as a system-wide "management level". ROPF deploys state estimation and forecasts and issues optimal targets to CVR. This is an offline optimization and it typically runs every 15 mins-1 hour, depending on the implementation.

Hierarchically structured AVC architecture contains three control layers, that are spatially and temporally independent, i.e. (a) an ROPF based management

layer, (b) a mid-term control layer that contains the SVR and TVR and lastly (c) the common-place PVR that acts against rapid fluctuations. TVR together with SVR deliver the Coordinated Voltage Regulation (CVR) which is the focus of this thesis. Reliable albeit suboptimal real time CVR is delivered through a *zoning* based Reduced Control Model (RCM) in a hierarchically structured AVC architecture, owing to the inherent complexity of the task.

1.2.2 Examples of implementation

This subsection elaborates on the main implementations of HAVC, i.e. (a) the French, (b) the Italian and (c) the Chinese cases. Additionally, it briefly refers to system benefits that have been reported from all three implementations.

The first implementation took place in France in the early eighties [17]. The work was sponsored by Electricité de France (EDF) in collaboration with the Massachusetts Institute of Technology (MIT). Today, the French transmission grid is divided into 35 control zones including approximately 100 thermal generators (conventional fuel and nuclear) and 150 hydraulic generators. The annual peak demand is 86 GW and the overall reactive capability is 20 GVAR. In the initial implementation, fixed electrically independent control zones were defined with no inter-zone co-ordination. This was due to the assumption that the interaction among those zones was negligible. However, as the network grew and became more meshed, this assumption was not valid. Hence, in 1989 an improved approach replaced the initial design which involved co-ordination among the individual SVR controllers and is referred to as Coordinated Secondary Voltage Regulation and termed CSVR (this is equivalent to CVR) [15]. Since then, all hierarchical AVC architectures included co-ordination of the SVR controllers.

The Italian system operator (TERNA) also employed a hierarchical AVC. Unlike [15] in the Italian implementation CVR is delivered through Regional Voltage Regulators (RVRs) and Reactive Power Regulators (REPORTs) [13, 18]. RVRs close the control loops of the pilot node voltages, providing each SVR controller with a specific reactive power level. In turn, REPORT closes the reactive power control loops of the plant units, directly operating on the set-points of the Automatic Voltage Regulators (AVRs). RVR also operates the control of capacitor banks, shunt reactors, On Load Tap Changers (OLTCs) and Static VAR Compensators (SVCs) for avoiding saturation of zonal generators. Today this architecture is extended nation-wide and includes 18 control zones, and 35 voltage and reactive-power regulators (REPORTs) installed in power plants. The annual peak demand is 75 GW and the overall reactive capability is 20 GVAR. It is also noteworthy that TERNA at the same time renewed its grid code in order to recognize participation in CVR as ancillary service and also introduced a mandatory framework for billing consumers and DSOs for excessive reactive energy demands [19, 20].

A similar hierarchically structured AVC architecture has been deployed in China. The first implementation was deployed for the Jiangsu provincial power system in 2002 [21] and has been extended to more than 20 control centres in China over the past decade and keeps expanding its coverage. The Chinese implementation presents three novel modifications compared to the European practices.

1) Firstly, there is no hardware based control centre for SVR. SVR and TVR (i.e. the Co-ordination of the SVRs) are implemented at the same Control Centre (CVR) using software modules.
2) Secondly, CVR zone division is no longer fixed but is adapted to the operational conditions and the rapidly evolving Chinese power grid.
3) Similarly to the Italian REPORTs, controlling elements are equipped with a Secondary High-Side Voltage Control (HSVC). In the Chinese implementation however an HSVC is not aware of the specific control zone to which it has been assigned by the RCM (re)configuration module. It simply sends data upwards and receives commands from the Supervisory Control Centre for CVR. This last modification reduces the communication requirements for the CVR with adaptive zone division [22].

The accumulated experience from all three HAVC implementations has reported significant benefits in both aspects of security and economy [23, 24].

1) Flatter voltage profile and fewer voltage violations.
2) Reduced losses with subsequent energy and monetary savings.
3) Effective spinning reactive reserves through co-ordination, which may prove essential during transients following large disturbances.
4) Increased power transfer capability under security constraints.

Research and pilot demonstration projects have also been carried out in many other power grids, including those of Belgium [25], Brazil [23], Spain [26], South Africa [27], Malaysia [28], Romania [29] and North America (PJM) [30].

1.2.3 Alternative approaches

Different approaches to Automatic Voltage Control (AVC) are used due to networks having different features, control equipment and market operation and regulation. This *section presents the main alternative approaches to HAVC practiced by different System Operators worldwide.*

It is noteworthy that beyond the Primary Voltage Regulation (AVRs), the various power system utilities use different approaches to mid-term Voltage and Reactive power control. Hierarchically structured Automatic Voltage Control (HAVC) architecture has been discussed in Sub-Section 1.2.1 and enables sensitive coordinated reactive power dispatch of several plants in a *voltage control zone*, by regulating a *pilot node* i.e. a central to the zone EHV load bus.

An alternative to HAVC is control of the power plant high side bus. In principle, adding a secondary high side voltage bus set-point control loop to the primary generator terminal voltage regulation is a recommended and advanced approach [31]. This can be achieved through AVR line drop compensation. This technology increases grid voltage support but on the negative side at times it may introduce destabilizing interactions between the PVRs. Modern digital schemes achieve the intended objective with minimum adverse interactions. As an example, PSVRs deployed by the Japanese TEPCO achieve this local high-side voltage control and coordinate the reactive power units of a power plant based on direct high-side measurement and have reported positive results [28, 31].

Another common approach is Voltage control at load centres primarily by coordinated switching of capacitor/reactor banks [32]. In North America for instance this practice has been used in conjunction with local automatic high side voltage control at power plants to a relatively fixed and flat schedule [33].The effort is towards reducing generators participation in voltage control, in order to have increased reserves for contingencies and is particularly preferable in networks with long feeders.

Lastly, FACTS controllers, primarily SVCs and STATCOMs are also deployed and enable improved voltage and angle stability. However, the acquisition cost is usually high and frequent switching reduces their lifetime. At the same time, their extended deployment requires a co-ordination system beyond the single substation [3]. An important reason for the use of these power electronic devices is their fast response during dynamic conditions compared to capacitor/reactor banks.

Transmission grid voltage control in UK employs both manual (e.g. switched shunt elements) and automatic actions (e.g. over/under excitation of synchronous generators and SVCs). There are established mechanisms for Obligatory Reactive Power Support from units that are above 50 MW and for Enhanced Reactive Power Provision and respective market mechanisms for the remuneration of their contribution. However, there is no significant evidence towards coordinated use of the Volt-VAR control resources, which could be beneficial for both efficiency and security.

1.3 What affects the CVR performance?

This section identifies and discusses the main component elements of CVR that affect the CVR performance and as such constitute the main design choices for the engineer and researcher.

In a high-level description, CVR is guided by a Reactive Optimal Power Flow (ROPF) that can be regarded as a system-wide “management level”; ROPF deploys state estimation or forecasts and issues optimal targets to CVR.

When assessing the CVR performance what is of interest is the extent to which the optimal targets specified by the ROPF have been reached by CVR. The targets themselves are not of interest, rather the guarantee that the issued targets are pragmatic and in principle achievable, given the global state of the network.

They are predominantly three component elements that affect the CVR performance and they are elaborated below:

- **Definition of the Reduced Control Model (RCM):** This is the selection of controlling buses (i.e. pilot nodes) and control elements (i.e. synchronous generators and condensers). RCM in actual implementations and in this work is based on *zone* division (i.e. coherent areas of the network suitable for voltage control). One might deploy a static (i.e. single) or adaptive (i.e. event driven) zone definition.
- **The control law**: This is the formulation of CVR as an optimization problem, i.e. selection of objective function and set of constraints as well as selection of optimization solvers and test of real-time applicability (i.e. <10 sec for large scale networks).
- **Online awareness**: Awareness refers to knowledge of a current state. Sensors and telecoms allow online data acquisition. When failures or delays occur, libraries of historic responses and forecasts can be deployed.

CVR should not only be characterized by advanced performance but it should also be effective in all or most situations and conditions. As such, interest in CVR evaluation comprises both assessing the **performance** and the **robustness** of the scheme.

Figure 1.2 below schematically presents the various modules CVR consists of or interacts with. In red boxes are the ones that affect its performance and robustness and hence constitute the main design choices for the engineer and researcher.

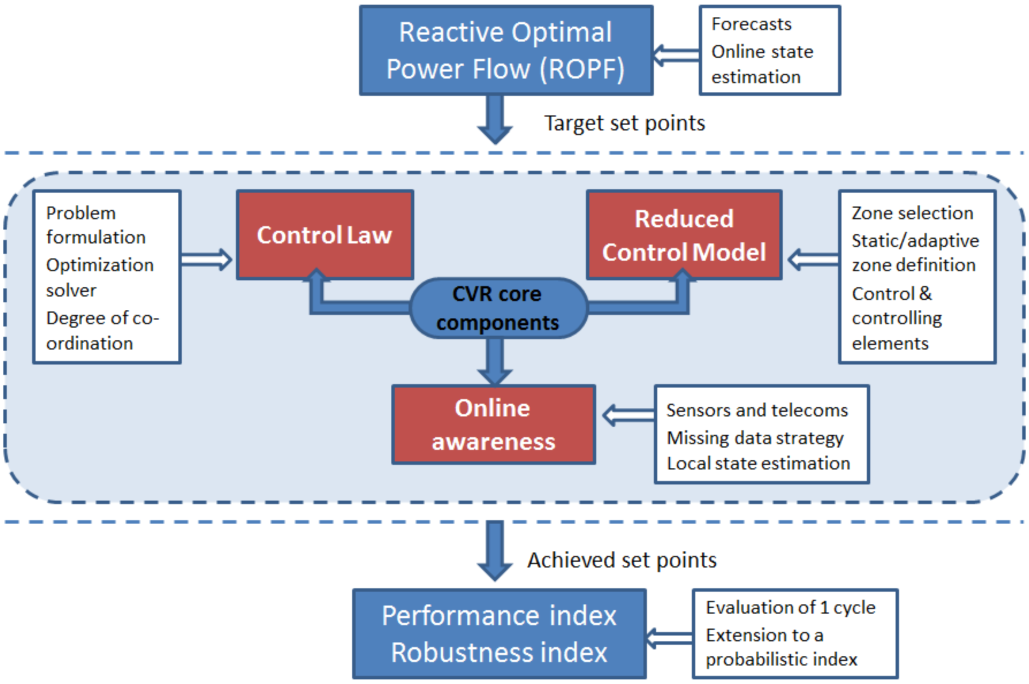


Fig. 1.2 CVR: Core components and other interacting modules

1.4 Research Objectives

This thesis contributes towards improved Automatic & Coordinated Voltage Regulation (CVR) in transmission grids through thorough investigation of the zoning based Reduction of the Control Model (RCM):

1) Zoning is a mixed integer optimization problem and various heuristics have been proposed to perform the classification task. The first objective of this thesis is to develop new zoning based RCM approaches for the CVR application and formulate them as Clustering Optimization Problems using Complex Network representation of the transmission grid.

2) The second research objective is to evaluate how different zoning based RCM approaches serve the CVR control objective. The focus is on both the performance and the robustness that CVR controller achieves in conjunction with a zoning based RCM approach. This item is first investigated in conjunction with a static zone definition, hence the resulting answers are also useful in today's transmission networks of limited observability and communication capabilities.

3) The third research objective is to examine adaptive zoning based RCM in CVR and more particularly to answer: (a) is adaptive RCM feasible from a computational perspective on realistic size networks? (b) What should trigger the adaptive RCM? (c) What is the value of adaptive RCM from a control perspective? And (d) which is the major implementation challenges? This item targets future transmission grids where RCM is driven by the need for reliability, engineering simplicity and guarantee of CVR convergence rather than economy of measurement points at a planning phase.
4) The last research objective is to examine zone division in an interconnected system ranging from EHV down to MV, and to assess the required degree of co-ordination for the voltage control of these zones. Essentially, this last item extends the scope of (1)-(3) beyond a single transmission level Independent System Operator (ISO).

1.5 Thesis Outline

The rest of this thesis is organized as follows;

- **Chapter 2** introduces zoning based Reduction of the Control Model (RCM) as a problem of Complex Network Analysis (CNA). It presents background theory and terminology in a generic fashion on a) power system representation through CNA and b) zoning as a clustering optimization problem. Following these, *it reviews the State of the Art* on a) main zoning methodologies for CVR and b) RCM approaches that can be carried out posterior to zoning identification.
- **Chapter 3** provides an overview of *state of the art frameworks for CVR evaluation* and it further refers to industry best practices with regards to modelling. Following this, it proposes a novel generic framework to model and evaluate Coordinated Voltage Regulation (CVR). The modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the CVR solution. This modelling is extended to a Monte-Carlo framework that can be used to evaluate CVR in conjunction with any configuration of its component elements. The proposed framework constitutes a novel addition to Power Systems literature and forms the backbone of this thesis in evaluating Zoning based Reduced Control Model (RCM) in both static and adaptive schemes.
- **Chapter 4** develops two novel zoning methodologies, termed SKC and FCM and formulates as clustering optimization problems two more approaches that have been adopted by industry, termed HCSD and HCVS. Those four zoning methodologies are representative of the whole spectrum of clustering algorithms as most appropriate

candidates for Hierarchical, Exclusive and Overlapping Clustering. All four zoning methodologies are evaluated with regards to performance and robustness they allow to the CVR controller on various standard test networks. Results are derived using the framework presented in Chapter 3 in conjunction with static zone definition.

- **Chapter 5** investigates Reduced Control Models determined in an online event-driven fashion (adaptive RCM) in pursuit of improved Coordinated Voltage Regulation (CVR). Adaptive RCM is a relatively new concept in CVR literature and largely unexplored. Initially *the few existing references on adaptive RCM are reviewed*. The next two Sections examine the feasibility of adaptive RCM from a computational perspective on realistic size networks and also what should trigger the adaptive RCM. Following this, the Value of adaptive RCM from a control perspective is investigated using the framework proposed in Chapter 3. The chapter concludes by identifying the major implementation challenges in the consideration of adaptive RCM in CVR.

- **Chapter 6** investigates CVR from a whole system perspective, hence beyond the determination and control of CVR zones within an individual ISO. To that end, (a) a horizontal and vertical zone division is presented ranging from EHV down to MV and multiple ISO areas, CVR zones and CVR sub-zones are defined. Additionally, (b) the required degree of co-ordination is investigated for the voltage regulation of both horizontal and vertical zones.

- **Chapter 7** concludes this thesis. It summarizes the main contributions and key findings, as well as the broader implications of this work. Lastly, it points out interesting research questions that could effectively extend this work.

1.6 Definition & Classification of Networks under study

This thesis targets primarily networks belonging to transmission and sub-transmission level, with the exception of Chapter 6 that includes the study of a distribution network. It is important to mention that the boundaries between the various voltage levels and the corresponding network classification as transmission, sub-transmission and distribution may be different for different countries. The classification followed in this thesis is given below.

This thesis uses the following terms for system voltages, similar to [34]:

– Low Voltage (LV) refers to $U_n < 1$ kV

– Medium Voltage (MV) refers to 1 kV < U_n < 35 kV

– High Voltage (HV) refers to 35 kV < U_n < 230 kV

– Extra High Voltage (EHV) refers to 230 kV < U_n

Transmission networks contain EHV and HV buses and distribution networks contain MV and LV buses. There is no fixed cut-off between sub-transmission and transmission. Voltages of 69 kV, 115 kV and 138 kV are used for sub-transmission. This is mainly due to the fact that as power systems evolved, voltages formerly used for transmission were used for sub-transmission.

Chapter 2

Zoning based RCM using Complex Network Analysis (CNA)

Abstract: This Chapter introduces zoning based Reduction of the Control Model (RCM) as a problem of Complex Network Analysis (CNA). Initially, background theory and terminology is presented in a generic fashion on a) power system representation through CNA and b) zoning as a clustering optimization problem. The rest of the chapter is specific to zoning based RCM for Coordinated Voltage Regulation (CVR) and presents a) main zoning methodologies for CVR proposed in the technical literature and b) RCM approaches posterior to zoning.

2.1 Complex Network Analysis (CNA) of Power Grids

The material in this section is organized into three sub-sections. Sub-section 2.1.1 presents an introduction to Complex Network Analysis. Sub-section 2.1.2 explains main concepts and notations of relevance to this thesis. Lastly, Sub-section 2.1.3 discusses Power Systems representation using CNA.

2.1.1 The science of complex networks

Network Analysis is the study of *interacting particle systems* [35]. It is concerned with the study of both tangible objects in the Euclidean space, such as electric power grids, the Internet, highways or subway systems, as well as entities defined in an abstract space, such as networks of acquaintances or collaborations between individuals. Historically, the study of networks has been mainly the domain of a branch of discrete mathematics known as *graph theory*. Since its birth in 1736, graph theory has achieved many exciting developments and has provided answers to a series of practical questions.

During the last two decades network science has witnessed the birth of a new movement of interest and research in the study of *Complex Networks*, i.e. networks whose structure is irregular, complex and dynamically evolving in time [36, 37]. *Complex Network Analysis* (CNA) studies systems with thousands or millions of components with a *renewed attention to the properties of networks of dynamical units*. It has been shown that the coupling architecture has important consequences on the network performance and functional robustness to external perturbations, such as random failures or targeted attacks [38]. Additionally, community structures i.e. tightly connected groups of elements in a network are an important property of complex networks. Finding the communities within a network is a powerful tool for understanding the functioning of the network. Another relevant problem is how to optimize a searching or functional procedure based only on some local information of the network topology.

Recently, the study of complex networks has been expanded to networks of networks [39, 40]. If those networks are interdependent, they become significantly more vulnerable to random failures and targeted attacks and exhibit cascading failures and first-order percolation transitions. Power grids have been of particular interest to the Complex Network Society since its very beginning as they include continuous, discrete, and social dynamics. They have been, though, comparatively less investigated than other networks such as ecological or social ones, mostly due to the difficulties involved in finding suitable data.

2.1.2 Definitions and notations

Graph theory is the natural framework for the exact mathematical treatment of complex networks and, formally, a complex network can be represented as a graph.

An undirected (directed) graph $G = (N, L)$ consists of two sets N and L, such that $N \neq \emptyset$ and L is a set of unordered (ordered) pairs of elements of N.

The elements of $N = \{n_1, n_2, \ldots, n_M\}$ are the nodes (or vertices, or points) of the graph G, while M indicates the size of the graph.

The elements of $L = \{l_1, l_2, \ldots, l_K\}$ are the edges (or links, or ties) of the graph.

A node is usually referred to by its order i in the set N. In an undirected graph, each of the edges is defined by a couple of nodes i and j, and is denoted as (i, j) or l_{ij} .

- The edge is said to be incident in nodes i and j, or to join the two nodes;
- The two nodes i and j are referred to as the end-nodes of edge (i, j).
- Two nodes joined by an edge are referred to as adjacent or neighbouring.

In a directed graph, the order of the two nodes is important: l_{ij} stands for an edge from i to j, and in the general case $l_{ij} \neq l_{ji}$.

For a graph G of size M, the number of edges K is at least 0 and at most $M \cdot (M - 1)/2$ (when all the nodes are pairwise adjacent).
G is said to be sparse if $K \ll M^2$ and dense if $K = O(M^2)$.

Another useful concept is this of average degree of a graph. Average degree $< k_G >$is defined as in eq. 2.1 and is a measure of graph density.

$$< k_G >= \frac{2 \cdot K}{M} \qquad (2.1)$$

There is usually some information, data or energy being transferred from one node to another through a network via the connecting edges. If the transmitting edges have a capacity or weight associated with them, they are denoted as w_{ij} and they indicate a capacitated or weighted network [35].

The centrality of a node CI in a capacitated network is defined as:

$$CI_i = \sum_{j \in G} w_{ij} \qquad (2.2)$$

A central concept in graph theory is that of reachability of two different nodes of a graph. In fact, two nodes that are not adjacent may nevertheless be reachable from one to the other. A *walk* from node i to node j is an alternating sequence of nodes and edges (a sequence of adjacent nodes) that begins with i and ends with j. A *path* is a walk in which no node is visited more than once. A graph is said to be *connected* if, for every pair of distinct nodes i and j, there is a path from i to j, otherwise it is said to be *unconnected* or *disconnected*.

And the following nomenclature:

G	Graph of a network
N	Set of nodes
M	Size of the graph
L	Set of edges
l_{ij}	Edge connecting nodes i, j
$< k_G >$	Average degree of the graph
w_{ij}	Weighted edge connecting nodes i, j
CI_i	Centrality of node i

The usual way to picture a graph is by drawing a dot for each node and joining two dots by a line if the two corresponding nodes are connected by an edge. How these dots and lines are drawn is irrelevant, and the only thing that matters is which pairs of nodes form an edge and which ones do not. Figure 2.1 presents a graphical representation of a network with K = 5 nodes and M = 7 edges, when G (5, 7) is (a) an undirected graph, (b) a directed graph and lastly (c) a weighted undirected graph. In the directed graph, adjacent nodes are connected by arrows, indicating the direction of each link. In the weighted graph, the values w_{ij} reported on each link indicate the weights of the edges and are assumed symmetrical for this example

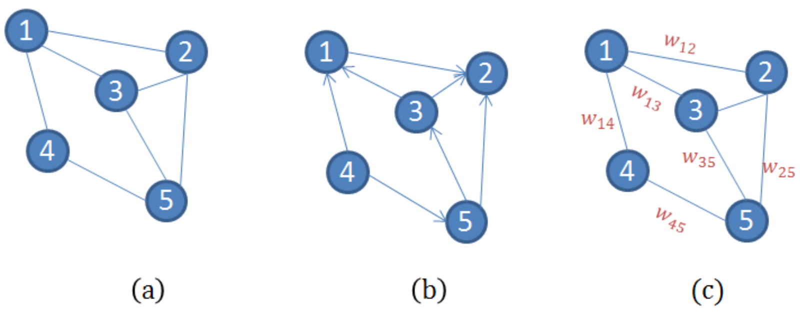


Figure 2.1 Graphical representation of a graph G (5,7) drawn as (a) undirected, (b) directed, (c) weighted undirected

The visual representation of the graph, as in figure 2.1, is helpful for simple calculations and for formulating and understanding abstract arguments. When working with very large graphs, however, the calculations must be left to computers, for which the visual representation is irrelevant. A common representation in this case is the adjacency (or connectivity) matrix A. Essentially, studying the properties of a graph is equivalent to studying the properties of its adjacency matrix.

The adjacency matrix A of a graph G is denoted as $A(G)$ and it is a $N \times N$ square matrix whose entry $a_{ij}(i, j = 1, \dots, N)$ is equal to 1 when the edge l_{ij} exists and zero otherwise. It has the following properties:

- It does not contain self-loops, hence the diagonal is a zero vector:

$$w_{ij} = 0 \;\; if \;\; i = j \tag{2.3}$$

- It indicates whether the graph is directed or not:

$$w_{ij} = w_{ji} \text{ for } G \text{ undirected} \tag{2.4}$$

- The dimensions of the adjacency matrix indicate whether the graph is a multi-graph. A multi-graph is a graph in which more than one edge joins a pair of nodes (see also figure 2.2).

$$MD(G) = \langle A_{ij}^1, A_{ij}^2, \dots, A_{ij}^D \rangle \tag{2.5}$$

And the following nomenclature:

$A(G)$	Adjacency matrix of graph G
$MD(G)$	Multiplicity of the graph

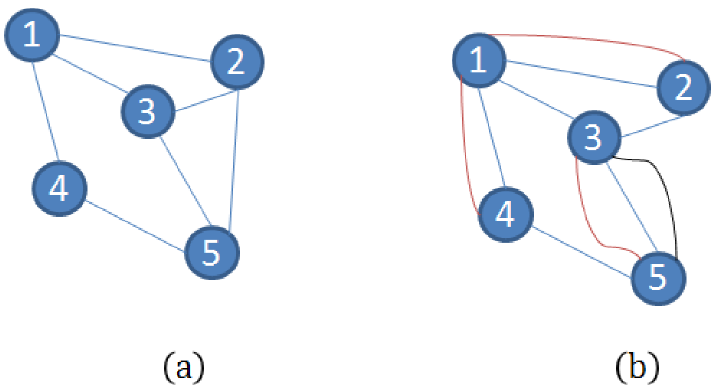


Figure 2.2 Graphical representation of (a) simple graph G (5,7) and (b) multi-graph with multiplicity 3.

2.1.3 Power System representation using CNA

In its most simplified and original form, a power grid graph considers all transmission lines to be single, un-weighted and undirected, as in Figure 2.1.a. above. Although this is an oversimplified description of the grid and it clearly reduces the graph's utility for studying its dynamical properties or for any engineering purpose, it has been useful in order to unravel some universalities, regardless of sizes (i.e. number of nodes or edges) or historical origins, such as in the problem of producing synthetic power grids [41].

However, in describing the performance of power grids, topological analysis is not sufficient, as the connections between components depend not only on its topology, but also on the physical properties that govern voltages and currents [42]. *Power Grids are best described as weighted graphs*, owing to the fact that flow is governed by Kirchhoff's Law and not by decisions made by individual actors at individual nodes. Power injections propagate through the network following a path of least resistance, apportioned by the relative complex impedance of each equivalent path.

Despite the fact that authors of [43] have discussed that in any steady state the direction of power flow in a power network can be measured and will be fixed, *power grids are best described as un-directed networks.* This is due to the highly non-linear and generally non-convex nature of the equations that govern power flow in AC electrical systems, it is possible, and in some cases quite likely, that small changes in the state of the network can reverse the direction of power flow along a particular path.

Addressing fragility and resilience has been the main driver for applying Complex Network Analysis on Power Grids. In fact many studies were performed after major black-outs occurred, e.g. [44, 45, 46]. Indicatively, the vast majority of CNA applications in Power Systems literature refer to the High Voltage end of the Power Grid. Complex Network Analysis is also used to study robustness of a Power Grid, i.e. the ability of a network to avoid malfunctioning when a fraction of its constituents is damaged, as in [47, 48].

2.2 The task of zoning

The task of zoning is mathematically referred to as clustering. This section contains an introduction to Cluster Analysis in CNA (Sub-section 2.2.1). It further provides a basic classification of clustering algorithms (Sub-section 2.2.2) and lastly discusses what constitutes a good clustering (Sub-section 2.2.3).

2.2.1 Cluster Analysis in CNA

The notion of "zone", and the first network formalizations of the concept, was first proposed in the social sciences. A zone, that is a network community in social networks, would be referred as a cluster or cohesive subgraph in CNA. Given a graph G (N, L), a zone (or community, or cluster) is a subgraph G (N', L'), whose nodes are tightly connected i.e. cohesive. Subsequently zoning would be referred to as clustering or more formally Cluster Analysis in CNA [49].

A broad definition of Clustering could be "the process of organizing objects into groups whose members are similar in some way". A cluster is therefore a collection of objects which are "similar" to each other and are "dissimilar" to the objects belonging to other clusters. Clustering can be regarded as a form of *unsupervised classification* in that it creates a labelling of objects (nodes) with class (cluster) labels.

In Power Systems literature, Cluster Analysis has been deployed in various applications, including Transient Stability Assessment [50], Islanding [51, 52], Contingency Screening [53], Load Forecasting [54], Decentralized Voltage Control [55, 56], Real Time Network Simulation [57], Decentralized OPF formulations [58], Congestion Management [59, 60], Microgrids and Multi-microgrids investigations [61, 62, 63].

Although the intuitive idea behind cluster analysis is simple, the successful completion of the task presumes a large number of correct decisions and choices from several alternatives [64]. There are three major blocks of decisions in the formulation of the clustering optimization problem, before the final results can be obtained, as figure 2.3 suggests.

- **Block A**: contains the formulations of the proximity metric, i.e. the specification of a distance that represents the degree of (dis)similarity for any two nodes, following proper data presentation, choice of objects and variables and possibly normalization for the latter [65].
- **Block B**: accounts for the formation of clusters, utilizing the proximity metric defined by Block A. Algorithms and computer implementation needs to be determined, taking into account the reliability of each of the candidate implementations features, e.g. convergence. Other than the optimization algorithm, one needs to define a clustering criteria (or objective function of the optimization process), as well as to decide how to deal with possible missing/corrupted data [66, 67].

- **Block C:** contains the cluster validation i.e. a way to assess the relative appropriateness of clustering solutions proposed by an algorithm from Block B [68, 69, 70]. Especially in multi-dimensional spaces the result of the clustering algorithm (that in many cases can be arbitrary itself) can be interpreted in different ways.

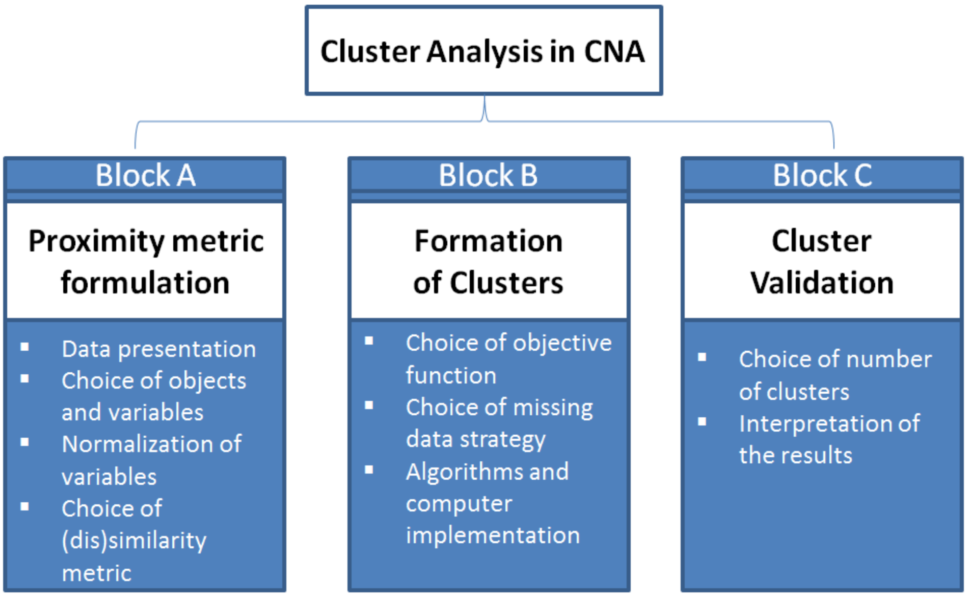


Fig. 2.3 Graphical representation of the three major decision blocks when formulating clustering as an optimization problem

2.2.2 Classification of Clustering Algorithms

Clustering is a mixed integer optimization problem and no global optimum solution exists when moving beyond a handful of nodes. Hence, several heuristics have been developed to perform clustering. Though many different classifications of clustering algorithms have been proposed, a useful one is the following:

- ***Hierarchical Clustering***: Hierarchical clustering is a method of cluster analysis which seeks to build a hierarchy of clusters called dendrogram. Strategies for hierarchical clustering generally fall into two types: *agglomerative* and *divisive*. Agglomerative clustering is essentially a bottom up approach; initially every node is a cluster. At each iteration, the two closest clusters are merged according to some similarity metric. The method converges when a termination criteria is met (e.g. desired number of clusters reached). Divisive clustering is a top-down approach; initially all nodes belong to the same cluster. At each iteration, clusters are successively split into smaller clusters according to some dissimilarity until a termination condition is met [71] .

- ***Exclusive Clustering***: In exclusive clustering, as the name suggests and stipulates, each node belongs to only one cluster. K-means clustering is such an example [72] . Spectral clustering is a variant on K-means clustering that employs the Laplacian L of the network graph and also delivers Exclusive Clustering. Spectral clustering proceeds by choosing the matrix of eigenvectors associated with the K top eigenvalues of L, and performing K-means clustering on that matrix of eigenvectors [73].
- ***Overlapping Clustering***: In overlapping clustering a node can belong simultaneously to more than one cluster. Fuzzy clustering is an example of overlapping clustering, where clusters are treated as fuzzy sets [74]. Every node belongs to every cluster with a membership weight that is between 0 (absolutely does not belong) and 1 (absolutely belongs). Similarly, probabilistic clustering techniques compute the probability with which each node belongs to each cluster. In practice the outcome of an overlapping clustering can be converted to exclusive clusters by using crisp threshold values, once Overlapping clustering algorithm has converged. Overlapping clustering has advantages over crisp clustering, as it can avoid some local minima.

Figure 2.4 presents Clustering outcomes for each of the four classes described above, indicating their different approach to the task.

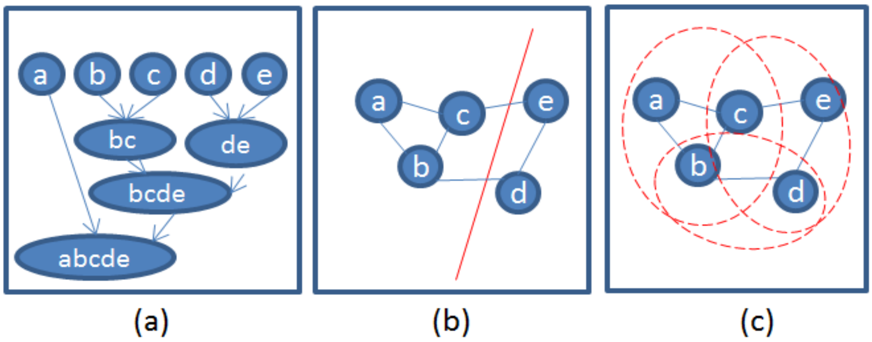


Fig. 2.4 Outcomes for (a) Hierarchical agglomerative Clustering, (b) Exclusive Clustering, (c) Overlapping Clustering

2.2.3 What constitutes a "good clustering"

But how to decide what constitutes a good clustering? There is no absolute "best" criterion which would be independent of the final aim of the clustering. Consequently, it is the user (engineer/researcher) who must make appropriate decisions, in such a way that the result of the clustering will suit their application and needs.

To start with decisions made in Block A of 2.2.1: the effectiveness of the Cluster Analysis depends on the definition of the proximity metric. If an "*obvious*" proximity metric doesn't exist the user must "define" it, which is not always easy. According to [75], choice of the most appropriate (dis)similarity metric is even more important than the choice of clustering algorithms. Multi-dimensional distance metrics may well account for multiple attributes, however one must be cautious when using distances in high dimensions. For instance, when a measure such as a Euclidean distance is defined using many co-ordinates, there might be little difference in the distances between different pairs of samples which may cause the distance function to lose its usefulness [76].

Forming clusters, i.e. Block B of 2.2.1, requires the definition of an objective function. Typical objective functions in clustering formalize the goal of attaining high intra-cluster similarity (nodes within a cluster are similar) and low inter-cluster similarity (nodes from different clusters are dissimilar). This is an *internal criterion* for the quality of a clustering. It is the application and data sets that determine further attributes of interest, such as scalability need, replicability (e.g. deterministic clustering vs stochastic), computational requirements or required ability to deal with noisy data sets. To that end, the choice of algorithms and computer implementation are also of significant importance. Due to the fact that a universally best clustering algorithm does not exist, work in [64] suggests trying several clustering algorithms in order to obtain the best possible outcome.

Special caution is also needed when clustering with multi-criteria, coming for instance from multiple objectives represented through different parallel edges on a multi-graph. The main difficulty in performing multi-objective clustering is that no single optimal solution exists. Instead, an optimal solution exists for each objective in the solution space. Ultimately, finding an optimal clustering for one objective may require accepting a poor solution for the others.

A clustering algorithm can produce various clustering decisions, for different number of clusters and configurations of the algorithm tuning parameters. Cluster Validation, as in Block C of 2.2.1, contains the estimation of the number of clusters and the result interpretation and according to [77] it is as important as the clustering strategy itself. Exclusive clustering algorithms are usually of form K-estimates, and require the specification of a fixed number K of clusters, to which they would ultimately allocate each of the nodes. On the contrary, Hierarchical Clustering algorithms produce a set of solutions with different numbers of clusters, which are then presented by a hierarchical graphical structure called a dendrogram.

Besides cluster definitions being an application dependent concept, all clusters can be compared with respect to an expression of certain properties: density, variance, dimension, shape, and separation [78]. The cluster should be a tight and compact high-density region of points when compared to the other areas of space. From compactness and tightness, it follows that the degree of dispersion (variance) of the cluster is small. The shape of the cluster is not known *a priori*. It is determined by the used algorithm and clustering criteria. Separation defines the degree of possible cluster overlap and the distance to each other. The above are used to form validation criteria, which are however *internal criteria* for the quality of the clustering. Irrefutably, the ultimate validation is direct evaluation in the application of interest. This is however particularly expensive, when a big number of samples needs to be clustered and studied. In that case, internal criteria can be used to come down to a few clustering outcomes [79] and then those can be evaluated directly with performance metrics in the application of interest.

2.3 Zoning based RCM for CVR: Definition

This section defines the scope, drivers and functionality of zoning based Reduction of the Control Model (RCM) for the application of Coordinated Voltage Regulation (CVR).

Towards achieving automatic real time voltage control, ideally one would optimize system-wide all control variables running a full AC optimal power flow. However, this is unrealistic and not compatible with real time requirements (i.e. collect data from an increased number of active points, process them and send back commands in a reliable manner within 1 min) [3]. Owing to the inherent complexity of the task, reliable albeit suboptimal real time automatic control is delivered through a *zoning* based *Reduced Control Model (RCM)*. *Zones* are network sub-graphs/ sub-divisions that demonstrate coherence to voltage control and are derived using the Jacobian matrix of the system [16].

Within a *zone*, voltage is controlled on a sub-graph centroid that is called a pilot bus. Essentially, a pilot bus is a central EHV load bus whose voltage magnitude variation is representative of the zonal voltage profile. The control resource is based on the largest synchronous generators within the zone that have the maximum regulating sensitivity on the pilot bus. Local switching resources might also be deployed, only when needed, in accordance with the available margin of the generators reactive resources. Figure 2.5 presents the zoning based RCM outcome on a typical transmission network.

Please note, in this thesis RCM is always zoning based. An alternative to this is the research direction followed by authors in [80, 81, 82] where heuristics and artificial intelligence techniques are used to identify the most suitable pilot nodes by minimizing, in a system wide fashion, the linearized version of a particular CVR control objective function. This latter research direction has attracted increased interest in academic literature. However, compared to zoning based RCM a) it has not been used in hierarchical AVC field implementations, b) it does not always guarantee coherent zones for CVR, c) it can be applied only on a single/few network states due to scalability issues and this will be a limiting factor when considering future power networks, d) it is tied to a particular formulation of the control problem and, lastly, e) if application in an online fashion is of interest, like in this thesis, the second research direction bears a significant computational cost that prohibits online application.

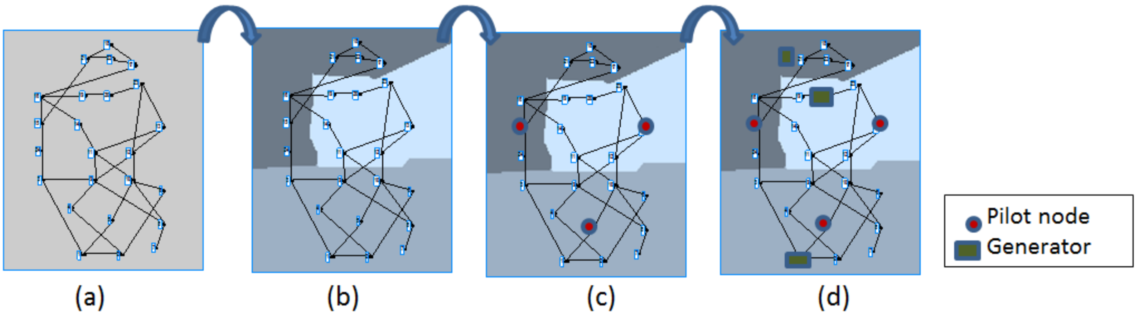


Figure 2.5 Identification of the zoning based Reduced Control Model (a) Study Case Network, (b) Zoning determination, (c) Pilot node centroid identification and (d) Control resources identification

2.4 Zoning methodologies for CVR: Literature Review

This section reviews existing literature on zoning methodologies for CVR. The literature review follows the classification of Sub-section 2.2.2; hence Zoning using Hierarchical Clustering is presented first, then Zoning using Exclusive Clustering follows and lastly Zoning using Overlapping clustering.

- ***Zoning for CVR using Hierarchical Clustering***

The earliest study on zoning for CVR is presented in [17]. The authors proposed a distance metric based on the logarithmic voltage magnitude sensitivities, termed electrical distance, and in particular they showed that this metric can qualify as a formal distance under certain conditions. The proposed distance has been deployed in order to group the buses, using hierarchical agglomerative clustering. The clustering outcomes are validated using relative diameter criteria. This approach has been deployed in the French hierarchical AVC implementation and has proved particularly effective. Other than that, it is a seminal work in that it introduced the concept of electrical distance and further unravelled its close relationship with the theory of information.

Work described in [83, 84] can be thought of as variations of [17]. Authors of [84] considered full Jacobian sensitivities and changes in network topology for the formation of the voltage control zones. The resulting zones are quite robust however this comes with a substantially increased computational cost. Research presented in [83] adds a pre-clustering stage to normalize the electrical distance in order to reduce the computational cost. This design decision however possibly calls for meta-heuristics in cases where ranges of classification are not adequately narrow. This variation of [17] is also met in [55, 85].

A more intuitive hierarchical clustering method has been proposed in [86], aiming to deliver zones that can dynamically adjust to topological and operational changes. Despite its motivation it uses geographical shortest paths as a distance metric between load nodes and generation. Geographical shortest paths are computed using Dijkstra's algorithm which is known to have a polynomial complexity. Other than that, geographical shortest paths at times contradict Kirchhoff's law; hence approach in proposed in [86] is not particularly promising.

The problem of Zoning for CVR is transformed into a clustering-analysis problem in a higher dimensional Euclidean space in [22]. Unlike [17], the authors introduced the concept of "VAR control space" to quantify the distance between the buses which considers the quasi-steady zonal control characteristics. This multi-dimensional metric has been deployed within hierarchical agglomerative clustering. The latter uses average zonal distance as criteria for clustering validation. This approach has been used in the Chinese AVC commercial implementation and is further followed in studies in [30, 87].

Essentially, there exist two well established zoning methodologies based on Hierarchical Clustering, i.e. [17, 22]**. No comparison has been drawn among them in academic literature. Owing to the fact that they have been used in actual AVC implementations they can be regarded as the most suitable benchmark for any new proposed approach.**

- ***Zoning for CVR using Exclusive Clustering***

Authors of [88] demonstrated that k-means clustering based method is also a well-deserved approach for zoning for CVR and it can compete with conventional hierarchical clustering approach. In this work, k-means divides the network into a fixed number of zones. It deploys the normalized electrical distance to account for node proximities, as in

[83] hence it might call for metaheuristics to deal with a number of singletons (i.e. zones containing only one node).

Reference [89] applies spectral k-means clustering in order to identify zones for CVR application. Posterior to the identification of a fixed number of zones, it uses disturbance propagation metrics to verify the weak coupling between the zones that is an advanced investigation. The weight matrix is calculated based on the apparent power between nodes, despite the fact that voltage sensitivities would have been a more motivated choice. Furthermore, the authors do not present a systematic approach for selecting an appropriate number of zones.

Spectral clustering is an attractive approach to zoning for CVR for the following reasons: a) it does not make strong assumptions for the statistics of the clusters and allows for arbitrarily connected non-convex geometries (e.g. exclusive clustering approaches that use k-means without pre-clustering stage in eigen-space assume that the variance of the distribution of each variable is spherical and favour balanced clusters in terms of number of elements, which might not be the most appropriate clustering outcome for CVR), b) it achieves dimensionality reduction through a pre-clustering stage in eigen-space (e.g. classifies iteratively a matrix N x k instead of a matrix N x N and for the CVR application k is typically less than 30% of N), and c) is semi-convex compared to exclusive clustering approaches that use k-means (i.e. avoids some local optima). On the negative side, spectral clustering may be sensitive to the choice of parameters (e.g. selection of initial centroids and hence is stochastic) and also computationally expensive for large node sets.

Essentially, there is a research gap for a novel formulation of spectral clustering for CVR which will have the following key attributes: a) proximity metrics tailored to the control problem, b) reproducible output, and c) inexpensive clustering validation.

- ***Zoning for CVR using Overlapping Clustering***

Fuzzy logic has also been used to identify zones for the CVR application. In Fuzzy logic each node of the network has a degree of belonging rather than belonging completely to one zone. This results in Overlapping Clusters which however can be transformed into exclusive clusters with the use of crisp thresholds.

Reference [90] uses normalized voltage sensitivities to construct a fuzzy similarity matrix that accounts for nodes proximities. Following that, nodes are clustered using transitive closure method based on fuzzy equivalent relation. Validation though is rather intuitive, i.e. the authors assign to the fuzzifier various crisp values and ultimately stop once a reasonable number of clusters have emerged. In that process simple heuristic rules are deployed in cases where crisp values result in singletons.

An approach using fuzzy C-means is introduced in [91] and demonstrated robustness for various operating conditions in the network. The use of fuzzy C-means is commendable as it avoids a number of local optima (compared to exclusive clustering approaches). However, the clustering problem formulation in [91] presents some limitations: a) Proximity between nodes is calculated using phase angle sensitivity, despite the fact that the choice of voltage sensitivities would have been a more motivated choice. And b), the validation stage is rather empirical, similar to [90].

Essentially, none of the above fuzzy clustering approaches appears to have a complete clustering formulation, indicating there is a research gap for a novel formulation.

2.5 RCM identification -posterior to zoning

This section reviews existing literature on identification of the Reduced Control Model (RCM) posterior to zoning.

Once a zoning division has been reached, the Reduced Control Model (RCM) for Coordinated Voltage Regulation (CVR) can be built. This includes identification of Controlling Points (Pilot nodes) and Control Elements (e.g. Generators).

- ***Pilot node identification***

With regards to the identification of Pilot nodes (posterior to zoning), there are mainly three approaches in literature:

(a) The zonal centroid has been used as a pilot node in the French AVC implementation [17, 15], due to the fact that such measurement points provide a good image of the changes in the voltages taking place within the zones. The index L_m denotes the proximity of node m to all other nodes belonging in the same zone C in terms of electrical distance and is defined as:

$$L_m = \sum_{m,n \in C} D_{mn} \qquad (2.6)$$

Where D_{mn} accounts for the electrical distance between nodes m and n. The load bus that minimizes the L_m norm is selected as pilot node. Such centroids are normally well connected buses and strong with respect to load perturbations within the zone they belong. Hence, this allows system operators to monitor the system load perturbations more accurately and maintain the voltage deviations within a reasonable range.

(b) Pilot node identification in the Italian CVR scheme [13] selects the strongest buses of the coherent zones, that is, the buses with the largest three-phase short circuit current. This is motivated by the fact that associated voltages exhibit the smallest deviations following a disturbance. In this respect they are the strongest buses in the system.

(c) The last direction proposes to use the heaviest loaded buses as pilot nodes [89]. A possible argument in favour of such a choice is that the power changes at the largest load will experience the largest perturbations, which in turn will have the greatest influence on the voltage magnitudes within a zone.

As discussed in [92] and proved by simulations, the first two criteria i.e. approaches (a) and (b) are nearly equivalent. This means that the load bus situated at the centre of a region is also the strongest bus with respect to load perturbations, and has the largest three-phase short circuit current and is generally a well-connected bus. The last approach, i.e. (c), has not been followed in practice and can result in pilot node sets different to those of approaches (a), (b). A weakness of this last approach comes from the fact that controlling the voltages of the most heavily loaded bus does not guarantee the effective and due voltage support at the stronger busses around them.

- ***Control element identification***

With regards to the identification of the control elements, the vast majority of CVR investigations in literature consider all synchronous generators or a subset of them as control elements [3]. More specifically, the synchronous generators that have control capability above a threshold are selected in each zone, as in (2.7):

$$QR_g \cdot C_{pg} \geq a_c \qquad (2.7)$$

Where QR_g is the reactive capability of the generator, C_{pg} is the sensitivity of the zone's pilot node to the control generator and a_c is the allowed minimum control capability in the examined zone. A smaller value for the a_c threshold results in the inclusion of more control elements in the CVR problem and ultimately in higher performance (with regards to achieving optimal targets). However, a_c threshold should be kept in a conservative value in order to discourage the participation of control elements with insignificant reactive reserves.

Alternatively, FACTS connected to pilot nodes have been considered as control elements. This approach is investigated in [91] and is better suited to networks with long transmission lines. CVR implementations under the hierarchical AVC paradigm, however, consider primarily synchronous generators as control elements.

While various approaches have been presented in academic literature and in practice to do the zoning, Reduction of the Control Model, carried out posterior to zoning, presents very little ambiguity. Predominantly, zonal centroids are selected as pilot nodes and synchronous generators with the maximum regulating sensitivity are selected as control elements.

2.6 Concluding Remarks

This Chapter introduced zoning based Reduction of the Control Model (RCM) as a problem of Complex Network Analysis (CNA). Mathematically, zoning is the task of clustering i.e. identification of communities in a complex network representation. Complex networks can be naturally represented as graphs, *and particularly for the case of the transmission grid weighted undirected graphs are to be preferred*. Clustering algorithms can be classified as Hierarchical, Exclusive and Overlapping and clusters may need to satisfy a single or multiple objectives. For the case of multi-objective clustering special caution is needed, since finding an optimal clustering for one objective may require accepting a poor solution for the others.

It is noteworthy that posterior to zoning identification RCM is defined in practice and in academic literature with very little ambiguity. On the contrary, literature review on zoning for CVR, revealed a wealth of approaches in all classes of clustering algorithms. Two well established hierarchical clustering based approaches, i.e. [17, 22] have been identified as suitable benchmarks owing to the fact that they have been used in actual AVC implementations. With regards to Exclusive Clustering and Overlapping Clustering, literature review revealed that none of the existing approaches has a complete formulation; hence there is a research gap for novel formulations. Lastly, all the aforementioned Zoning approaches satisfy a single control objective (i.e. CVR) hence no compromise is needed as it would have been the case in multi-objective clustering.

Chapter 3

A generic framework for CVR modelling & evaluation

This chapter presents a novel generic framework to model and evaluate Coordinated Voltage Regulation (CVR). The modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the CVR solution. This modelling is extended to a Monte-Carlo framework that can be used to evaluate CVR in conjunction with any configuration of its component elements. The proposed framework constitutes a novel addition to Power Systems literature and forms the backbone of this thesis in evaluating Zoning based Reduction of the Control Model (RCM) in both static and adaptive schemes.

3.1 Literature review & Motivation

This section provides an overview of existing frameworks for evaluation of Coordinated Voltage Regulation (CVR) and it further refers to industry best practices with regards to CVR modelling. It further provides the motivation for developing a novel generic framework for CVR modelling and evaluation.

With regards to CVR evaluation; Work in [80] by Iowa State University is well established and proposes a methodology to assess the performance of Coordinated Voltage Regulation as a function of a Reduced Control Model decision. The emphasis of this work is on the selection of the Reduced Control Model, thus it deploys a linearized formulation of the power flow equations so that the latter can be used as the objective function of a heuristic search. However, the interest of Coordinated Voltage Regulation is most apparent when the system is working close to its transmission capacity limit. In such a situation the linearized model may be far from optimal.

To that end, framework presented in [93] takes into account the system non-linearity, so that full power flow equations can be used. The computation time is much increased in this work; however, the framework is used for offline study of RCM selection in CVR performance. The main limitation of this work is that it is tied to a particular formulation of the Control Module.

PMU based Coordinated Voltage Regulation has been studied in [94]. This work evaluates the CVR performance in conjunction with PMU deployment at a number of buses, using the mean and standard square error of the voltage deviations all across the load buses. This work indeed demonstrates the benefits improved sensing technologies brings to CVR. However, the approach ignores the role of RCM and CVR control module selection which also determine the performance CVR achieves (see Chapter 1, Section 1.3).

With regards to modelling; A Quasi-Steady State (QSS) simulator for the design of a knowledge-based system for supervision and control of regional voltage profile was developed in Federal University of Rio de Janeiro [95]. Slow acting voltage instability mechanisms, such as, OLTC actuation and over-excitation limiters are thoroughly modelled. This effort focuses on assessment of long-term regional voltage control by power plants and synchronous condensers. Among its limitations, this simulator neglects the electromechanical transients. The simulator was equipped with fuzzy logic routines to allow studying of a supervisory knowledge-based system for monitoring and control of regional voltage profile using Fuzzy Logic. Despite of this being a novel attribute, the above modelling has not been adopted in actual practice.

Contrary to QSS, ASTRE and CRESO discussed below have been adopted in actual practice and are state-of-the art tools used in Power System industry.

University of Liege, Belgium, has developed ASTRE [96] that is a voltage stability and security analysis software presently used by Transmission System Operators (TSO) in France, Canada, Belgium and Greece. The application of ASTRE to the French system required the ability to model the various secondary voltage controllers in operation in this system. This included a representation of the “standard” proportional-integral (PI) controllers as well as the sensitivity matrix-based controller in operation in the Western regional control centre of RTE, the French TSO. ASTRE is incorporated to GAMME, the real-time security analysis software used in RTE control centres.

Centro Electtrotecnico Sperimentale Italiano (CESI) performed studies on the Coordinated Voltage Regulation on transmission grids and has developed state of the art computer tools. Among those, CRESO (Network Calculation for Security and Optimization from CESI) [3] is an integrated software system that allows the simulation and analysis of a power network under steady-state conditions, as well as the optimization of the reactive power generation. Conventional power flow calculation and advanced functions for network studies are available, such as state estimation, reactive power re-dispatch and computation of pilot node voltage references.

The above items are significant work in the area of CVR modelling and evaluation. However, recent literature on Coordinated Voltage Regulation (CVR) has presented:

(a) New zoning methodologies to deliver the desired Reduction of the Control Model (e.g. Hierarchical clustering in VAR control space [21])

(b) Alternative control modules (e.g. various degrees of co-ordination [97])

(c) Advanced data filtering techniques and deployment of improved sensor technologies (e.g. PMU based CVR [94])

(d) CVR with adaptive zoning division (e.g. the Chinese hierarchical AVC implementation [22]).

Despite the fact that (a), (b), (c) and (d) all try to deliver improved CVR currently there is no generic framework to simulate and evaluate CVR performance with respect to all the above aspects. In light of the above, this chapter contributes a novel generic framework to simulate and assess the performance of CVR with respect to all the aforementioned aspects.

The proposed framework has the following novel key attributes:

(a) It is not tied to any specific RCM module.

(b) It is not tied to any specific control module, unlike [93].

(c) It is the first to the author's knowledge to consider and enable the investigation of robustness against erroneous data in CVR, while again it is not tied to any particular data acquisition technique.

(d) It is the first to incorporate the possibility of adaptive zone division in CVR.

At the same time, the selection of component elements from a planning perspective requires the evaluation of CVR for several different scenarios and without linear approximations. Hence,

e) In its Monte-Carlo extension this framework deploys full AC load flow equations (unlike work in [82]) and can facilitate the selection and design of CVR components.

Ultimately, this framework allows the first thorough CVR evaluation in conjunction with any possible configuration of its component elements. At the same time, the modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the CVR solutions adopted by industry. The entire coding has been developed in MATLAB and is the sole work of this author. The implementation is both efficient and easy to integrate with other Power System tools.

3.2 Proposed framework for CVR modelling & evaluation

The material in this section is organized in two sub-sections; Sub-section 3.2.1 presents the framework with an emphasis on the modelling of the main functions, which essentially can be used for online applications. Lastly, Sub-section 3.2.2 extends the above modelling to a Monte-Carlo framework that can be used to evaluate design choices for CVR in an offline/planning fashion.

3.2.1 Proposed framework: modelling and functions for online application

Inarguably, a detailed evaluation of the Coordinated Voltage Regulation (CVR) performance requires a quite complex mathematical modelling in order to capture the main system requirements and features, as actually implemented in the CVR solution.

The proposed framework contains four main Blocks, as presented in Figure 3.1 below. Blocks A, B, C and D present the core functions in boxes of grey colour. The enabling library modules are in dashed boxes, main functions are in cylinders of white font and auxiliary ones in boxes of blue font.

The four main Blocks are detailed in Figure 3.1.

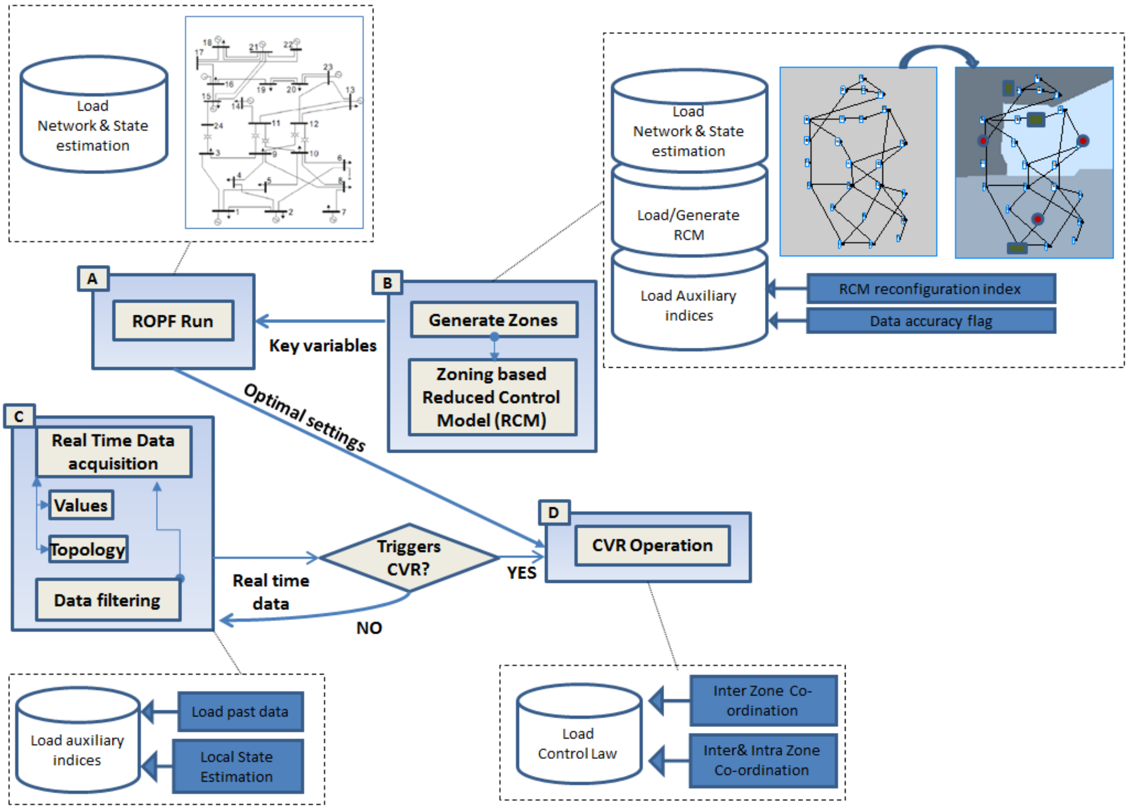


Fig. 3.1 Proposed framework: modelling and functions for online application

-Block A: This Block solves a system-wide AC Optimal Power Flow (OPF) which minimizes system losses while considering security constraints. This formulation is referred to as Reactive Optimal Power Flow (ROPF) in literature. This block requires as input a model of the network and the latest state estimation/forecasts, as shown on figure 3.1. It receives information of the most appropriate Reduced Control Model and provides reference voltage and reactive power level values (V_{ref}, Q_{ref}) and respective control limits ($V_{max}, V_{min}, Q_{max}, Q_{min}$) to block D for the corresponding key variables.

The optimal references values are computed by the ROPF in order to attain global goals for economy and security. The Objective Function most commonly refers to real losses minimization, while alternative formulations are also possible (e.g. [98]).

ROPF is essentially the optimization problem formulated below:

$$minf = P_{loss} = \sum_{(i,j)\in NL} (P_{ij} + P_{ji}) \qquad (3.1)$$

With the constraints:

$$h(x) = \begin{cases} P_{G_i} - P_{D_i} = V_i \cdot \sum_{j\in I} V_j \cdot (G_{ij} \cdot cos\theta_{ij} + B_{ij} \cdot sin\theta_{ij}) \\ Q_{G_i} - Q_{D_i} = V_i \cdot \sum_{j\in I} V_j \cdot (G_{ij} \cdot sin\theta_{ij} - B_{ij} \cdot cos\theta_{ij}) \\ \qquad i = 1, \dots, NB \qquad \theta_s = 0 \end{cases} \qquad (3.2)$$

$$Q_{G_i}{}^{\min} \leq Q_{G_i} \leq Q_{G_i}{}^{\max} \qquad i = 1, \dots, NQG \qquad (3.3)$$

$$V_i{}^{\min} \leq V_i \leq V_i{}^{\max} \qquad i = 1, \dots, NB \qquad (3.4)$$

$$t_k{}^{\min} \leq t_k \leq t_k{}^{\max} \qquad k = 1, \dots, NT \qquad (3.5)$$

And the following nomenclature:

NL	Set of branches
P_{ij}	Active power of the branch i -j.
$j \in I$	All nodes j connected to node i, including j=i
θ_s	Phase angle of the slack bus
NB	Number of buses
NQG	Number of control generators
NT	Number of transformer tap changers*
P_{G_i}, Q_{G_i}	Active and reactive power of the generator on bus i
P_{D_i}, Q_{D_i}	Active and reactive power of the load on bus i
V_i, θ_i	Voltage magnitude and phase angle of bus i
G_{ij}, B_{ij}	Real and imaginary part of bus admittance matrix (note that these are functions of tap position)

t_k	Tap ratio of the transformer k
${t_k}^{\min}, {t_k}^{\max}$	Tap ratio limits for the transformer k
${V_i}^{\min}, {V_i}^{\max}$	Voltage magnitude limits for bus i
${Q_{G_i}}^{\min}, {Q_{G_i}}^{\max}$	Reactive power limits for the generator on bus i

In (3.1) terminal voltage of generators is the decision variable. The inclusion of equation (3.5) is optional and depends on the network strategy. If included, tap ratio of transformers is an additional decision variable. It is considered continuous and is ultimately rounded to the nearest integral tap position.

-Block B: This Block loads the Reduced Control Model (RCM) or updates the Reduced Control Model in case a significant event occurs. A zoning based RCM consists of a zoning algorithm that divides the network into weakly coupled control zones, and an algorithm for pilot node selection and control element selection within the zones. This block requires as input a model of the network and the latest state estimation, as shown on figure 3.1. Block B provides to the CVR of *Block D* pilot nodes to base the control on and the set of available reactive resources to regulate a zone's voltage profile. Research into the *Reduction of the Control Model (RCM)* is developing in two directions. The first deploys heuristics to divide the system into weakly coupled zones and then identifies with exhaustive search pilot nodes and controlling elements to base the control on. This approach is referred to as *zoning based RCM*. The second direction uses heuristics and artificial intelligence techniques to identify the most suitable pilot nodes by minimizing, in a system wide fashion, the linearized version of a particular CVR control objective function [81]. In this case, weak coupling requirement constitutes a static constraint of the optimization task.

In this framework one might load an RCM derived with any of the two basic approaches. When a new RCM needs to be generated (e.g. following a significant event), this thesis deliberately deploys *zoning based* RCM. This is because *zoning based RCM* complies with online requirements and is not tied to any particular control module, contrary to the second research approach. Various formulations of zoning based RCM are detailed in Chapter 4. Here a generic zoning based approach for RCM is presented.

❖ Zoning based Reduction of the Control Model (RCM)

In principle, zoning based RCM contains two stages; a) definition of zones and b) definition of RCM based on the selected zones.

a) Definition of zones refers to the division of the network into a judiciously selected number of zones. This employs;

- Distance metric among the buses.
- Objective function to base the formation of zones on.
- Clustering criteria to select number of zones.

b) Definition of RCM includes the selection of pilot nodes (3.6) and controlling elements (3.7) with exhaustive search within each zone. Contrary to stage-a, stage-b derived posterior to zone definition presents very little ambiguity.

Selection of pilot nodes:

$$min\{L_m\} = \sum_{m,n \in C} D_{mn} \tag{3.6}$$

Selection of controlling elements:

$$QR_g \cdot C_{pg} \geq a_c \tag{3.7}$$

And the following nomenclature:

D_{mn}	Electrical distance between buses m, n
L_m	Electrical centrality of bus m
QR_g	Reactive capability of the generator g
C_{pg}	Sensitivity of the zone's pilot node p to the control generator g
a_c	Allowed minimum control capability in the c zone

-Block C: This Block specifies the voltage deviation vector-target upon which CVR controller acts. In an online CVR application, this Block stands for the Real time data acquisition and filtering. Essentially the CVR is measurement based and the PI controller acts only if the measured values lie above the controller's threshold (as in the conditional block of figure 3.1). The CVR controller has knowledge of the voltage deviation vector only at the pilot nodes ΔV_P as well as of the reactive power Q_g and receives reference values from the ROPF. Measurements are filtered to promote accuracy.

In theory the ΔV $[N \times 1]$ voltage deviation vector all across the N load buses can be estimated as the difference between the voltage magnitude from Block A, V_{ref}, and the voltage magnitude after disturbance V_{ad} as in (3.8):

$$\Delta V = V_{ref} - V_{ad} \tag{3.8}$$

In an online fashion V_{ad} is based on measurements and is known only on the pilot nodes. In practice CVR includes filters to promote accuracy (or comparison to local state estimator output). In the general case, CVR controller is considered to act based on the information $\{\hat{x}\}$ = $\{ \widehat{\Delta V}_P , \hat{Q}_g \}$.

One kind of filter focuses on each individual frame, taking into account the electrical constraints of different measurements. This is a local state estimator for a single substation or control zone, used to evaluate measurement quality rather than directly providing input data. Another kind of filter focuses on a single measurement carried out over several continuous samples (for instance the last five data-acquisition periods [99]).

And the following nomenclature:

ΔV	Voltage deviation vector
V_{ref}	Voltage set-points specified by the ROPF
V_{ad}	Measured voltage magnitude after a disturbance
x, $\hat{x}$	Measured value and refined measurement

-**Block D**: This Block contains the CVR control law. Simply stated, the effect of CVR within a zone is to keep the voltage of a pilot bus at its specified set point value, while sharing the total reactive power generation over the various participating generators according to participating factors. Typically, each participation factor is proportional to the reactive capability of the corresponding generator [3].Similar to ASTRE [100] the formulation of the control law as optimization problem considers distributed zones that feature both inter and intra Zone Co-ordination. This is also similar to the Western France and Chinese CVR implementation, e.g. [15, 21]. Please note however, that any other control law can be integrated in this approach.

❖ Formulation of the CVR optimization problem

CVR with inter and intra zone co-ordination regulates the voltage at a pilot buses set PN_{set} instead of single pilot bus regulation. This is done through the coordinated control of the synchronous resources that participate in CVR in each zone and the inter-zone coordination accounts for the effect of neighboring compensation, ensuring individual zones do not over-react.

- A standard power flow computation is first performed until convergence is reached. At the obtained solution, C_{pg} and C_{vg} sensitivities are computed from the inverse Jacobian.
- A quadratic programming model, similar to [15, 21] is then solved. The primary goal of CVR is to control the voltages at the pilot buses PN_{set} to follow the optimal forecasted reference values as updated by the ROPF of Block A. The secondary goal (with lower priority) is to align the MVAR distribution among the participating generators in each control zone to enhance security of supply. For the latter a reference value for the reactive power level is specified for each area, e.g. for the *J*-th area:

$$Q_{ref_J} = \frac{\sum_{g \in SVR_J} Q_g}{\sum_{g \in SVR_J} Q_{g,max}} \tag{3.9}$$

Where SVR_J is the set of generators participating in SVR for area *J*.

The quadratic programming problem solved is given in equations (3.10)-(3.13):

$$min\left\{\sum_{i \in PN_{set}} (\Delta V_P)^2 + \mu \cdot \sum_{J \in k}\left(\sum_{g \in SVR_J}\left(Q_{ref_J} - \frac{Q_g + \Delta Q_g}{Q_{g,max}}\right)^2\right)\right\} \tag{3.10}$$

Subject to the following inequality constraints:

$$V_{P,min} \leq V_P + C_{pg} \cdot \Delta Q_g \leq V_{P,max} \tag{3.11}$$

$$V_{G,min} \leq V_G + C_{vg} \cdot \Delta Q_g \leq V_{G,max} \tag{3.12}$$

$$Q_{g,min} \leq Q_g + \Delta Q_g \leq Q_{g,max} \tag{3.13}$$

Equations (3.11) and (3.12) are the voltage operation limits. Equation (3.13) shows the reactive power operation limits of the controlled generators, which are dependent variables with respect to the active power output.

And the following nomenclature:

μ	Weighting factors of the two objectives
$Q_g, Q_{g,min}, Q_{g,max}$	Current reactive output and limits for generator g
ΔQ_g	Regulation amount for generator g
$V_p, V_{p,min}, V_{p,max}$	Current voltage magnitude and limits for pilot bus p
$V_g, V_{g,min}, V_{g,max}$	Current voltage magnitude and limits for generator g
C_{pg}	Voltage Sensitivity for pilot bus p to reactive output of generator g
C_{vg}	Voltage Sensitivity for generator g to reactive output of g

3.2.2 Proposed framework: extension to MC formulation for offline studies

This Sub-section presents a novel generic probabilistic framework that can be used offline to evaluate CVR performance in conjunction with any configuration of its component elements. The framework uses the modelling of main functions detailed in paragraph 3.2.1 and adds some extensions to account for a) tasks performed offline and b) the probabilistic assessment of the performance/robustness of CVR.

A flow-chart of the proposed probabilistic framework is shown in figure 3.2 below and extensions/modifications to that of figure 3.1 are indicated in red font. At each iteration, blocks A and C effectively generate a system state, blocks B, D and the newly added block E solve and evaluate the performance for that state. Overall, a great number of iterations are executed for a probabilistic assessment of CVR performance and robustness. More specifically:

- **Block A:** First a random system state is generated by sampling the yearly load duration curve, then similarly to Sub-section 3.2.1. Block A solves a system-wide Reactive Optimal Power Flow which minimizes system losses while considering security constraints and provides system state information and respective control limits to blocks

B,C and D.

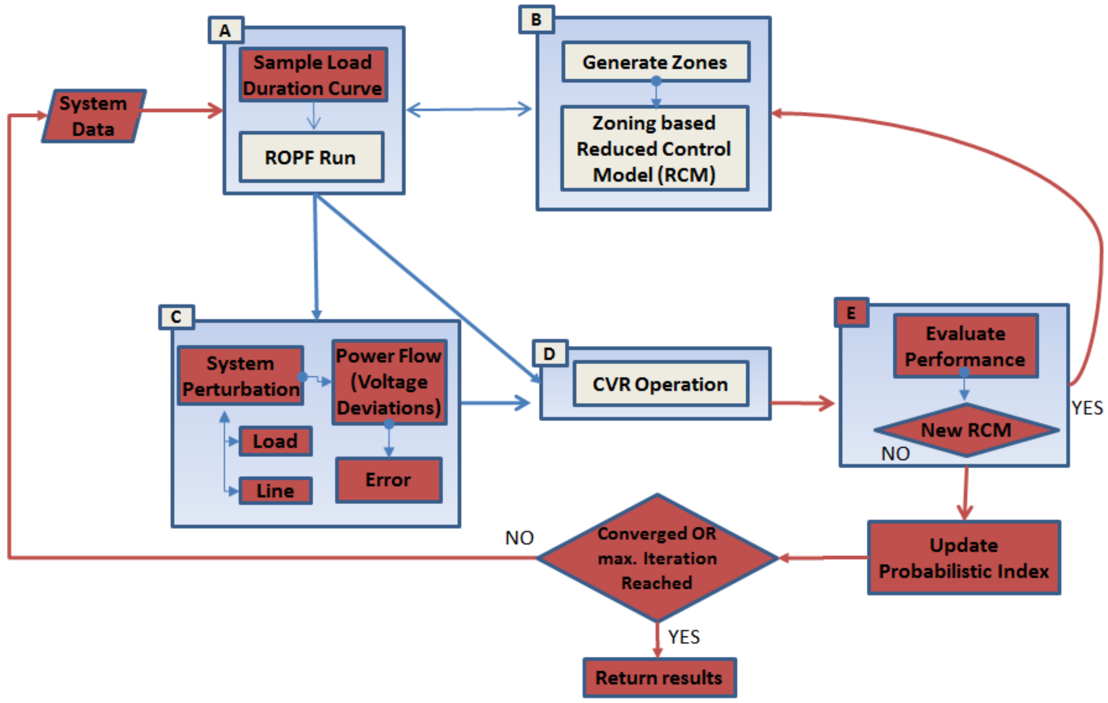


Fig.3.2 Flow-chart of the proposed probabilistic framework

- **Block B**: This is identical to Block B of Sub-section 3.2.1 and in general any Reduced Control Model methodology can be deployed.
- **Block C**: This block creates voltage deviations and provides the CVR with the voltage deviation vector-target to act upon. Unlike Block C of Sub-section 3.2.1, data acquisition is an offline task here and is formulated as below.

This block creates voltage deviations and provides the CVR with the voltage deviation vector-target to act upon. This vector is generated as follows:

- Reactive load is perturbed around its nominal value by sampling a probability distribution. Perturbations are assumed to be instantaneous. Randomly selected line trips are also considered. This system perturbation approach could be extended to account for any possible system contingency.
- Owing to the hierarchical control loops being time dynamically decoupled, the transient response of generators is assumed to have reached steady state when CVR acts. Thus steady-state AC load flow equations are used to derive mid-term voltage values. This gives the values of the ΔV $[N \times 1]$ voltage deviation vector all across the network of N buses, as the difference between the voltage

magnitude from Block A, V_{ref}, and the voltage magnitude after disturbance V_{ad} as in (3.14):

$$\Delta V = V_{ref} - V_{ad} \qquad (3.14)$$

- The CVR controller has knowledge of the voltage deviation vector only at the pilot nodes ΔV_P as well as of the reactive power Q_g produced by those control resources that participate in the CVR.
- To account for erroneous data, the controller is considered to act in the general case based on the information $\{ \widehat{\Delta V_P}, \widehat{Q}_g \}$ and any probability distribution function can be deployed to introduce uncertainty. The source of uncertainty can be any of the following: noisy measurements; imperfect predictions or corrupted data.

And the following nomenclature:

V_{ad}	Voltage after disturbance calculated by full AC load flow equations
$\Delta V_P, Q_g$	CVR knowledge of pilot node deviations and reactive output of generators
$\widehat{\Delta V_P}, \widehat{Q}_g$	CVR imperfect knowledge of pilot node deviations and reactive output of generators

- **Block D**: This is identical to Block D of Sub-section 3.2.1. In general any Control Module can be integrated in the framework.
- **Block E**: This block evaluates the CVR performance with a metric particular to this layer of the hierarchical control.

- The performance PI_i of one iteration of the CVR is assessed based on the average absolute relative error for the N load buses, as in (3.15).

$$PI_i = \frac{1}{N} \cdot \sum_{i=1}^{N} \left| 1 - \frac{V_{ac}(i) - V_{ad}(i)}{\Delta V(i)} \right| \qquad (3.15)$$

ΔV values are computed as in (3.23). The *ac* index signifies the voltage value after control and *ad* the voltage value after a disturbance. All values are computed by full AC load flow which incorporates the ΔQ_g correction vector that is computed from Block D.

- The performance PI_i is compared to a threshold PI_{thres}. The latter can be customized according to Operator's experience or based on a library of past responses. A performance PI_i lying below the desired threshold calls for reconfiguration of the zones and pilot nodes. In order to proceed with that, two conditions must be satisfied:

  a) The examined RCM must be zoning based and its zoning module must be compatible with adaptive RCM schemes' requirements

  b) Ensure that PI_i performance does not drop due to the introduction of erroneous data

  If both conditions are satisfied, the analysis returns to Block B and the PI_i value of performance for this cycle is updated.

```
if (PI_i < PI_thres) && (RCM==Adaptive)&&( {ΔV̂_P , Q̂_g} == {ΔV_P, Q_g})
then
  goto Block B
  update PI_i
end
```

- As a probabilistic performance measure the expected value of the PI is used, i.e.:

$$OPI = 1 - E\,\{PI\} \qquad (3.16)$$

  This is updated at the end of each iteration. Effectively this approach is equivalent to a non-sequential Monte-Carlo method [101]. To evaluate CVR robustness with regards to a feature of interest (e.g. effect of erroneous data, tuning of the control law or fixed RCM) the OPI absolute variation $\Delta(\mathrm{OPI})$ and the angle of OPI variation $\Delta(\mathrm{OPI})/\Delta x$ are also of interest.

  And the following nomenclature:

$\mathrm{PI_i}, \mathrm{PI_{thres}}$	Voltage deviation vector
OPI	Index of probabilistic performance

The proposed metric PI and its Monte-Carlo extension OPI get normalized values within the range 0-100%. Regarding their interpretation; Both PI and OPI indicate the extent to which CVR follows some pre-specified targets and it is the ROPF that guarantees that the issued targets are pragmatic and in principle achievable, given the global state of the network.

In case of a significant contingency, posterior to the ROPF solution, it might be that CVR cannot deliver the desired voltage security. Hence, an additional index is examined for voltage security, termed *Voltage Criticality Index* and denoted as VCI. This is elaborated below.

For the *i-th* PQ bus, its proximity to voltage limits can be quantified by equation in (3.17).

$$J_i = \frac{|V_{ac} - V_{ref}|}{|V_{lim} - V_{ref}|} \tag{3.17}$$

As a minor variation of [102], we formulate the Voltage Criticality Index as in (3.18).

$$VCI = \sum_{i=1}^{N_{bus}} \gamma_i \cdot J_i.^2 \tag{3.18}$$

Where γ_i is a logic variable such that :

$$\gamma_i = \begin{cases} 1 & if\ voltage\ outside\ limits \\ 0 & otherwise \end{cases} \tag{3.19}$$

Hence, VCI will be zero if voltage on all buses is within limits. A non-zero value of the VCI will indicate one or multiple voltage contingencies.

And the following nomenclature:

V_{lim}	Voltage magnitude limit
J_i	Proximity to voltage limits for bus i
VCI	Voltage Critical Index for a given state

3.3 Concluding Remarks

This Chapter proposed a novel framework to model and evaluate CVR performance and robustness. This framework is generic in that it is not tied to any specific control module, Reduction of the Control Model (RCM), Reactive Optimal Power Flow (ROPF) implementation or a specific filtering technique.

The modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the CVR solution. This modelling has been extended to a Monte-Carlo framework that can be used to evaluate CVR in conjunction with any configuration of its component elements. The author developed the entire coding in MATLAB and delivered the proposed framework structured as in the Blocks of Sub-section 3.2.

It should be noted that in the modelling voltage dynamics have been neglected, based on the assumption that the associated control loops are dynamically decoupled in time, i.e. the time constant of the power plant reactive power control loop is chosen to be sufficiently longer than that of the primary voltage control loops and sufficiently shorter than that of the Secondary Voltage Regulation. For the interested reader adequate justification of the above can be found in [9].

Essentially, the proposed framework can be used to select and design a CVR control module, assess robustness of different filtering techniques and sensor technologies (e.g. PMU based CVR as proposed in [94]), assess vulnerability to malicious attacks or select an RCM approach and determine the value of adaptive RCM.

Chapter 4

Development & Evaluation of zoning based RCM in CVR

Reduction of the Control Model (RCM) enables Co-ordinated Voltage Regulation (CVR) in transmission grids and is based in this thesis on zoning. Zoning is a mixed integer optimization problem and different heuristics have been proposed to perform the task. This Chapter develops two novel zoning methodologies, Spectral K-way Clustering (SKC) and Fuzzy C-Means (FCM). It further formulates as clustering optimization problems two approaches that have been adopted by industry, Hierarchical Clustering with Single Distance (HCSD) and Hierarchical Clustering in VAR Space (HCVS). All four zoning methodologies are evaluated with regards to performance and robustness they allow to the CVR controller. Results are derived using the framework presented in Chapter 3.

4.1 Motivation

Reduction of the Control Model (RCM) enables Co-ordinated Voltage Regulation (CVR) in transmission grids and furthermore affects CVR performance, as discussed in Chapter 1, Section 1.3. In this thesis RCM is zoning based for the following two reasons; a) its low computational cost favours online application, and b) it constitutes the only research direction adopted in actual AVC implementations. To that end, *the first goal of this Chapter is to evaluate how different zoning based RCM approaches serve the CVR control objective*. In this investigation, the focus is on both performance and robustness that CVR controller achieves in conjunction with a zoning based RCM approach.

Zoning is a mixed integer optimization problem and no exact solution exists when moving beyond a handful of nodes. Hence different heuristics have been deployed to perform the classification task. Multiple Zoning approaches have been deployed both in academic literature and actual practice. It is noteworthy though that once a zoning is derived, RCM is defined in practice and in academic literature with very little ambiguity. *Effectively, proposing a novel zoning based RCM methodology for CVR is equivalent to introducing a new formulation of the zoning optimization problem.*

The second goal of this Chapter is to develop new zoning based RCM approaches, i.e. as explained in the previous paragraph this is equivalent to developing new zoning methodologies that allow the CVR controller satisfying performance and robustness. As discussed in Chapter 2, mathematically zoning is the task of clustering and clustering algorithms are heuristics that can be classified as *Hierarchical, Exclusive* and *Overlapping*. Literature review on zoning methodologies for CVR of Chapter 2, Section 2.4 has been particularly useful in identifying the research gaps.

References [17, 22, 88, 83, 86] all present zoning methodologies for CVR that deploy Hierarchical Clustering. Each individual reference is critically discussed in Chapter 2, Section 2.4. Here it is noteworthy to remind the reader that essentially; two well established zoning methodologies exist within this class of clustering algorithms, i.e. *Hierarchical Clustering with Single electrical distance* [17] and *Hierarchical Clustering in VAR control space* [22]. No comparison has been drawn between them in academic literature. Owing to the fact that they have been used in actual AVC implementations they can be regarded as the most representative of the Hierarchical Clustering approaches and a suitable benchmark for any new proposed zoning methodology.

References [89, 88] both present zoning methodologies for CVR that deploy Exclusive Clustering. Again, each individual reference is critically discussed in Chapter 2, Section

2.4. Here it is noteworthy that Spectral clustering has been identified as a promising approach compared to other exclusive clustering algorithms. And essentially, there is a research gap for a fresh formulation of spectral clustering for CVR which needs to meet the following objectives; a) proximity metrics tailored to the control problem, b) reproducible output, c) inexpensive clustering validation d) combination of internal validation with validation in the application of interest (external validation).

References [90, 91] both present zoning methodologies for CVR that deploy Fuzzy Clustering, which is an example of Overlapping Clustering algorithms. Again, each individual reference is critically discussed in Chapter 2, Section 2.4. Here it is noteworthy that essentially none of the referenced fuzzy clustering methodologies appears to have a complete clustering formulation. Hence, there is a research gap for a new methodology that needs to meet the exact objectives specified in the above paragraph, i.e. (a)-(d).

4.2 Zoning methodologies adopted by industry

This section formulates as clustering optimization problems two Hierarchical Agglomerative Clustering approaches that have been deployed in actual AVC implementations, i.e. Hierarchical Clustering with Single Distance (Sub-section 4.2.1) and Hierarchical Clustering in VAR control space (Sub-section 4.2.2). The formulation of the optimization problem follows the three-stages' structure of Cluster Analysis discussed in Chapter 2, Section 2.2.1; 1) Proximity metric formulation, i.e. formulation of an "electrical distance" that represents the degree of similarity for any two nodes; 2) formation of clusters, i.e. a cost function or some other type of rule to form a number of zones utilizing the proximity metric; and 3) cluster validation, i.e. a way to assess the relative appropriateness of clustering solutions proposed by an algorithm.

4.2.1 Hierarchical Clustering with Single Distance (HCSD)

This approach along with the concept of *electrical distance* was first introduced in [17] and has been deployed in the French AVC implementation.

- **Proximity metric formulation:** The transmission grid under study can be represented as a weighted undirected graph. Buses are the nodes of the graph and are the objects to be clustered.

The weighted edges represent the degree of coupling in terms of voltage between two nodes, *m* and *n*. The coupling can be quantified by the attenuation of voltage variations, defined as:

$$a_{mn} = [\frac{\vartheta V_m}{\vartheta Q_n}] \Big/ [\frac{\vartheta V_n}{\vartheta Q_m}] \qquad (4.1)$$

Equation (4.1) requires as input the latest Jacobian calculation and in the general case it is not reflexive, i.e. $a_{mn} \neq a_{nm}$. For a_{mn} to be deployed in an undirected graph, the normalization of equation (4.2) is considered in order to obtain symmetrical distances.

$$b_{mn} = a_{mn} \cdot a_{nm} \qquad (4.2)$$

Owing to the fact that the graph under study is dense, the proximity metric is ultimately formulated as in Eq. (4.3).

$$D_{mn} = -\log(b_{mn}) \qquad (4.3)$$

Eq. (4.3) allows us to move from a product to a sum and D_{mn} would always be a non-negative weight.

And the following nomenclature:

$\frac{\vartheta V}{\vartheta Q}$	Sensitivity of voltage magnitude to reactive power
a_{mn}	Attenuation of voltage variations of nodes *m*, *n*
D_{mn}	Electrical distance of nodes *m*, *n*

❖ **Formation of clusters:** Agglomerative clustering (bottom-up) is used to merge nodes into clusters using the *complete linkage criterion*. In complete linkage criterion, the similarity of two clusters is the similarity of their most dissimilar members. This is equivalent to choosing the cluster pair whose merge has the smallest diameter. This complete-linkage merge criterion is non-local; the entire structure of the clustering can influence merge decisions. This results in a preference for compact clusters with small diameters over long, straggly clusters, but also causes sensitivity to outliers.

At each iteration, the *complete linkage criterion* defines the proximity of any two clusters C_I, C_J:

$$ICD_{I,J} = max\{D_{mn}: m\epsilon C_I \;\; and \; n\epsilon C_J\} \qquad (4.4)$$

Then clusters are merged, based on (5.5):

$$C_I \cup C_J \ :/ min\{ICD_{I,J}\} \qquad (4.5)$$

The result of the iterative algorithm is a tree of clusters, called dendrogram, which shows how the clusters are related.

And the following nomenclature:

C_I, C_J	Distinct clusters *I*, *J* at the end of an iteration
$ICD_{I,J}$	Proximity of two clusters *I*, *J*

❖ **Cluster validation**: To obtain the most appropriate k number disjoint groups the dendrogram is cut at a desired level, based on the *relative diameter criterion*. The selection of this cluster validation index is motivated by the design decision to use the complete-linkage criterion and is formulated below.

The diameter of a cluster diam_C in (4.6) is the maximum distance between any two points in the cluster, while the relative diameter of k clusters is obtained from (4.7).

$$diam_C = max\{D_{mn} : m, n \epsilon C\} \qquad (4.6)$$

$$RD = \frac{\sum_{i=1}^{k} diam_{C_i}}{k} \qquad (4.7)$$

The changes in the slope of the relative diameter curve *RD* correspond to a deterioration of the quality of the groupings. Ultimately, the most appropriate number of zones *k* within [*1*,k_{max}] is derived from the following equation:

$$k: max\{|RD_2 - RD_1|, \dots, |RD_{k_{max}} - RD_{k_{max}-1}|\} \qquad (4.8)$$

The validation criterion in Eq. (4.8) is not expensive computationally and the needed input can be calculated along the iterative agglomerative process.

And the following nomenclature:

$diam_C$	Diameter of a single cluster C
RD	Relative diameter of a clustering outcome
k	Most appropriate number of clusters

4.2.2 Hierarchical Clustering in VAR control space (HCVS)

This approach along with the concept of *VAR control space* was first introduced in [22] and has been deployed in the Chinese commercial AVC implementation.

❖ ***Proximity metric formulation***: Similarly to HCSD of Sub-section 4.2.1, the transmission grid under study is represented as a weighted undirected graph. Load Buses are the nodes of the graph and are the objects to be clustered.

Nodes are linked by edges and the weight the edges bear utilizes the VAR control space concept; For a network with g reactive power sources and l nodes to be classified and S_{ij}, the sensitivity of the *i-th* node's voltage with respect to the *j-th* reactive power source's VAR output, the "VAR control space" is defined as a *g*-dimensional Euclidean space where each load node can be described by a coordination vector $\{x_{i1}, x_{i2} \dots x_{ig}\}$. Variable x_{ij} is defined as in Eq. (4.9) below:

$$x_{ij} = -log(|S_{ij}|) \qquad (4.9)$$

Based on the above definition, each component of a node's coordination vector represents how much the node is coupled with a specified reactive power source.

The proximity metric for two load nodes $m\,\{x_{m1}, x_{m2} \dots x_{mg}\}$ and $n\,\{x_{n1}, x_{n2} \dots x_{ng}\}$ is defined by (4.10):

$$D_{mn} = \sqrt{|x_{m1} - x_{n1}|^2 + \cdots + |x_{mg} - x_{ng}|^2} \qquad (4.10)$$

The electrical distance D_{mn} is thus symmetric and non-negative. Unlike the proximity metric in HCSD, Eq. (4.3), expression in Eq. (4.10) does not qualify as a formal distance it considers however the quasi-steady zonal control characteristics.

And the following nomenclature:

S_{ij}	Voltage sensitivity of PQ node i to PV node j
$\{x_{m1}, x_{m2} \dots x_{mg}\}$	Vector sensitivity of PQ node m to all PV nodes *1..g*
D_{mn}	Electrical distance of PQ nodes *m*, *n*

❖ ***Formation of clusters***: Similarly to the HCSD approach, agglomerative clustering is used, however singletons are merged iteratively to construct the *dendrogram*, based on the *average linkage criterion* which is formulated below:

Average linkage criterion, as in Eq. (4.11) looks for the average similarity between the nodes in different clusters. In principle it creates clusters of somewhat more similar variances.

$$ICD_{IJ} = \frac{1}{\sum memb(C_I) \cdot \sum memb(C_J)} \sum_{m \epsilon C_I} \sum_{n \epsilon C_J} (D_{mn}) \qquad (4.11)$$

It follows that nodes strongly coupled with the same set of reactive resources would be placed in the same cluster.

And the following nomenclature:

C_I, C_J	Distinct clusters *I*,*J* at the end of an iteration
$ICD_{I,J}$	Proximity of two clusters *I*, *J*

❖ ***Cluster validation**:* The average inter-cluster distance *(AD)* is used to determine the most appropriate number of clusters k, within the examined range [1,k_{max}]:

The average inter-cluster distance (AD) is formulated as in Eq. (4.12)

$$AD = \sqrt{\frac{\sum ICD_{IJ}^2}{k}} \quad I = 1, \ldots, k; \;\; J = I + 1, \ldots, k \qquad (4.12)$$

It follows that the greater the AD, the weaker the coupling between the clusters. Thus, k is determined as follows:

$$k\text{: } \max\{AD\} \qquad (4.13)$$

And the following nomenclature:

AD	Average Distance of a clustering outcome
k	Most appropriate number of clusters

The selection of this validation index is motivated by the design choice to use the average linkage criterion in the merging stage. AD index in Eq. (4.12) is not expensive computationally and can be calculated along the iterations.

4.3 Development of two novel zoning methodologies

This section presents a) a Spectral K-way Clustering approach for Zoning for Coordinated Voltage Regulation (CVR), termed SKC, (Sub-section 4.3.1) and b) a Fuzzy

C-Means Clustering approach for Zoning for CVR, termed FCM, (Sub-section 4.3.2). The formulation of the optimization problems follows the three-stages' structure of Cluster Analysis discussed in Chapter 2, Section 2.2.1; 1) Proximity metric formulation, 2) formation of clusters and 3) cluster validation. SKC and FCM formulations for CVR Zoning are effectively extending the state of the art and are aimed contributions of this thesis.

4.3.1 Spectral k-way Clustering (SKC) for CVR zoning

This Sub-section formulates as optimization problem a novel zoning methodology for Coordinated Voltage Regulation (CVR) which deploys Spectral k-way Clustering.

Overall, Spectral Clustering is preferred among other Exclusive Clustering algorithms, for the following reasons; a) It can be solved efficiently by standard linear algebra software, b) very often it has been found to outperform traditional exclusive clustering algorithms such as the K-Means [103], c) It does not make strong assumptions for the statistics of the clusters, d) it achieves dimensionality reduction through a pre-clustering stage in eigen-space and furthermore this pre-clustering is non-linear and allows for arbitrarily connected non-convex geometries [104].

On the negative side, spectral clustering presents a number of challenges a) its output is generally non-deterministic as it is sensitive to the choice of internal parameters and b) it can be computationally expensive for large node sets. SKC is formulated below with special emphasis put on making adjustments to overcome the aforementioned limitations.

❖ **Proximity metric formulation:** Similarly to the approaches discussed in Section 4.2, the transmission grid under study can be represented as a weighted undirected graph. Buses are the nodes of the graph and are the objects to be clustered. The proximity metric is formulated below:

The weighted edges represent the degree of coupling in terms of voltage between two nodes, *i* and *j* and is quantified by equations (4.14)-(4.16)

The coupling can be quantified by the attenuation of voltage variations, defined as:

$$a_{mn} = [\frac{\vartheta V_m}{\vartheta Q_n}] \Big/ [\frac{\vartheta V_n}{\vartheta Q_m}] \qquad (4.14)$$

Equation (4.14) requires as input the latest Jacobian calculation and in the general case it is not reflexive, i.e. $a_{mn} \neq a_{nm}$. For a_{mn} to be deployed in an undirected graph, the normalization of equation (4.15) is considered in order to obtain symmetrical distances and to move from a product to a sum.

$$D_{mn} = -log(a_{mn} \cdot a_{nm}) \qquad (4.15)$$

Due to the fact that Spectral Clustering is more efficient and reliable on sparse graphs the proximity metric is finally formulated as in (4.16):

$$w_{mn} = D_{mn} \cdot A(G)_{mn} \qquad (4.16)$$

Hence proximities are expressed based on Lagonotte formal electrical distance $W = [w_{mn}]$, however a sparse formulation is used, i.e. w_{mn} is zero if nodes *m, n* are not topologically adjacent in graph *G*.

And the following nomenclature:

$A(G)$	Topological adjacency matrix of graph G
$W = [w_{mn}]$	Sparse matrix of electrical distance

❖ **Formation of Clusters:** Spectral clustering works by first transforming the data from Cartesian space into similarity space and then clustering in similarity space. The original nodes are projected into the new coordinate space which encodes information regarding nodes proximities. The similarity transformation reduces the dimensionality of space and, effectively, *pre-clusters* the nodes into orthogonal dimensions. Towards the formation of clusters, this pre-clustering stage is an essential 1st step and is formulated below:

The mapping from Cartesian space to similarity space is facilitated by the creation and diagonalization of the degree matrix;

For a graph G of size N, the degree matrix of the graph is notated as

$D(G) = [d_{mn}]$ and is defined as:

$$d_{mn} = \begin{cases} 0 & if\ m \neq n \\ \sum_{k=1}^{N} w_{mk} & if\ m = n \end{cases} \qquad (4.17)$$

The Laplacian of graph *G* is a $N \times N$ symmetric matrix defines as

$$L(G) = D(G) - A(G) \qquad (4.18)$$

Here, the normalized Laplacian is preferred due to the fact that its eigenvalues are scale independent which is more advantageous for clustering purposes [73]. The latter is also a $N \times N$ symmetric matrix defined as:

$$L_n = D^{-\frac{1}{2}} \cdot L \cdot D^{-\frac{1}{2}} \qquad (4.19)$$

The Normalized Laplacian is singular, it has rank at most *n-1* and it has 0 as eigenvalue. The rest of the eigenvalues are positive. The multiplicity of zeroes represents the number of connected sub-graphs.

For a spectral k-way classification the k top eigenvalues are used to assign coordinates to the nodes of the graph in R^k: $\{x_1, \dots, x_N\} \in R^k$. Note that X is the $N \times k$ matrix whose columns are the top k eigenvectors and x_i is the i-th row of X. The rows of X are normalized to have length 1 in R^k:

$$U_i = \frac{x_i}{\|x_i\|} \quad 1 \leq i \leq N \qquad (4.20)$$

Effectively, when one stacks the lowest k-eigenvectors of this matrix as columns in a new matrix and normalize them (Eq.4.20), the rows of the matrix are the new coordinates for each node in the new space.

And the following nomenclature:

D(G)	Degree matrix
A(G)	Topological adjacency matrix of graph G
$L(G)$	Laplacian matrix of graph G
$L_n(G)$	Normalized Laplacian of graph G
U	Matrix of Eigen-vectors of graph G

The eigenvectors span the linear space defined by the clusters. At this stage k-means is used to derive the final Clustering, since the focus is on exclusive Clustering algorithms. The K-means part is run because the eigenvectors can be degenerated. Overall, the clusters could sit at any coordinates in the space as long as they are rotated 90 degrees from each other relative to the origin. This second stage of clusters formation is formulated below:

K-means iteratively minimizes the following objective function:

$$J = \sum_{j=1}^{k} \sum_{i=1}^{N} \left\| U_i^j - C_j \right\|^2 \tag{4.21}$$

This optimization iterates until the movement of the k-centroid points falls below some minimum threshold or a maximum number of iterations is reached.

And the following nomenclature:

C_j	Centroid of cluster j
U	Matrix of eigen-vectors of graph G
N	Number of nodes
k	Pre-specified number of clusters

SKC is heuristic and partially probabilistic, hence it possibly converges in local minima and it may even provide non replicable outcome. The randomized component is the selection of the initial centroids. To overcome the problem of non-replicability, an initial set of centroids is specified through a preliminary clustering on a random 10% subsample of the node-set. Alternatively one could specify a particular probability distribution function for the initial centroids or come up with a different heuristic rule. In the CVR control problem though there is no evidence towards the preference of a particular probability distribution function that can be suggested as a good fit.

After this selection, a large number of Replicates are deployed to ensure a somewhat deterministic behaviour of the heuristic. Replicates refer to the number of times the clustering is repeated, each with different starting conditions. In each Replicate the algorithm moves nodes between clusters until the sum of the distances (or square distances) $sumd$ cannot be decreased further. K-means returns the solution with the lowest value of $sumd$ among all of the examined Replicates. The drawback of this design decision is that SKC takes more time to converge. However, this delivers a replicable outcome which is essential when considering adaptive zoning based RCM in CVR.

❖ **Clustering validation:** Eigengap analysis is used in the proposed SKC formulation in order to identify the most appropriate clustering decision. This validation index is formulated below:

Eigen gap is the difference between two consecutive eigenvalues.

The eigenvalues of L_n are sorted in an ascending order and the relative eigengap γ is examined:

$$\gamma = \frac{v_{k+1} - v_k}{v_k} \qquad (4.22)$$

A number of clusters k within the range $[1, k_{max}]$ which maximizes γ indicates that the network admits a good decomposition in k-clusters and this is revealed by the spectral embedding in dimension k.

And the following nomenclature:

v_k	k-th sorted eigen-value
γ	Relative eigen gap
k	Selected number of Clusters

It is noteworthy, that the relative eigengap criterion can identify the most appropriate number of clusters before one proceeds to k-means optimization. This significantly reduces the computational cost of the SKC methodology and allows online application of SKC on large scale graphs. The latter statement is demonstrated and further discussed in Chapter 5, section 5.2.

4.3.2 Fuzzy C-means (FCM) for CVR zoning

Fuzzy clustering extends crisp clustering in the sense that nodes can belong to various clusters with different degrees of membership at the same time, whereas crisp or deterministic clustering assigns each node to a unique cluster. The main driver towards developing a fuzzy clustering methodology for CVR zoning is that *fuzzy clustering can reduce the number of local minima compared to crisp clustering* [105]. This is mainly due to the fact that the non-zero membership degree property of fuzzy clustering has a smoothing effect on local minima. Fuzzy C-means is an effective way to establish fuzzy inference rules, hence it has been popular among other fuzzy clustering algorithms. On the negative side, the algorithm suffers heavy computational burden. Additionally, it is strongly sensitive to the initialization treatment, which usually requires a priori knowledge of the cluster numbers to form the initial cluster centres.

A FCM zoning methodology for CVR zoning is formulated below:

- **Proximity metric formulation**: Similarly to the approaches discussed in Section 4.2, the transmission grid under study can be represented as a weighted undirected graph. Buses are the nodes of the graph and are the objects to be clustered. The proximity metric is identical to HCSD. Hence proximities are expressed based on formal electrical distance.

The weighted edges represent the degree of coupling in terms of voltage between two nodes, *m* and *n*. The coupling can be quantified by the attenuation of voltage variations, defined as:

$$a_{mn} = [\frac{\vartheta V_m}{\vartheta Q_n}] \Big/ [\frac{\vartheta V_n}{\vartheta Q_m}] \quad (4.23)$$

The proximity metric is ultimately formulated as in Eq. (5.24).

$$D_{mn} = -log(a_{mn} \cdot a_{nm}) \quad (4.24)$$

The proximity metric matrix in here is dense, semi-positive and has zeros only on the diagonal. Work in [91] has reported that the adoption of electrical distance in zoning for CVR with fuzzy k-means is responsible for non-connected clusters. This short coming has not been an issue here and any discontinuities witnessed have been adequately tackled through simple membership degree tuning with sufficient results in all examined scenarios.

- ***Formation of Clusters*:** Fuzzy k-means is used to assign the N nodes into k clusters. This is formulated below:

FCM is based on the minimization of the following objective function:

$$J_m = \sum_{i=1}^{N} \sum_{j=1}^{k} u_{ij}^m \cdot \left\| d_i - C_j \right\|^2 \quad \text{with} \quad 1 \leq m < \infty \quad (4.25)$$

In Eq. (4.25) d_i is the i-th row of the D (N×N) electrical distance matrix, u_{ij} is the degree of membership of d_i in the cluster *j* and the norm ||*|| is expressing the similarity between the measured data and the centre.

The variable *m* is the fuzzifier and determines the level of cluster fuzziness. A large m results in smaller memberships and hence fuzzier clusters. In the limit m = 1, the memberships u_{ij} converge to 0 or 1, which is the simple k-means.

Fuzzy clustering is carried out through an iterative optimization of the objective function in equation (4.25) with the update of (a) membership u_{ij} and (b) cluster centroids C_j .

$$u_{ij} = \frac{1}{\sum_{t=1}^{k} \left(\frac{\|d_i - C_j\|}{\|d_i - C_t\|} \right)^{\frac{2}{m-1}}} \qquad (4.26)$$

$$C_j = \frac{\sum_{i=1}^{N} u_{ij}^{m} \cdot d_i}{\sum_{i=1}^{N} u_{ij}^{m}} \qquad (4.27)$$

This procedure converges to a local minimum or a saddle point of J_m when:

$$\left\{ \left| u_{ij}^{(iter+1)} - u_{ij}^{(iter)} \right| \right\} < \varepsilon \text{ or} \qquad (4.28)$$

$$max\{iterations\}$$

And the following nomenclature:

u_{ij}	Membership degree of node i in cluster j
m	Fuzzifier within $[1..\infty]$
ε	Termination criteria between [0…1]

When Fuzzy c-means terminates it returns a matrix of centroids. These centroids are theoretical and they do not map directly onto an actual node. It also returns a matrix $N \times k$ which indicates the degree of membership for each of the N nodes to each of the k clusters. This is a fuzzy classification and this outcome cannot be deployed in CVR application. To that end, one more stage is added which does the crisp clustering; each node is assigned to the cluster that has the maximum membership degree.

FCM is heuristic and partially probabilistic, hence it possibly gets stuck in local minima and it may even provide non replicable outcome. The randomized component is the selection of the initial centres. To overcome the problem of non-replicability, similarly to SKC (Sub-section 4.3.1), an initial set of centroids is specified through a preliminary clustering on a random 10% subsample of the node-set and a larger number of Replicates is used.

❖ ***Clustering validation*:** The last stage involves clustering validation, i.e. an assessment of the relative appropriateness of clustering solutions proposed by various runs of the

FCM algorithm for different k number of clusters. The validation index used is formulated below:

The appropriateness of a clustering decision based on a value k is validated using Xie and Beni index [106]:

$$V_{XB}(k) = \frac{\sum_{j=1}^{k}\sum_{i=1}^{N} u_{ij}^{m} \cdot \left\|d_i - C_j\right\|^2}{N \cdot \min\limits_{i\,j}\left\|C_i - C_j\right\|} \tag{4.29}$$

Where d_i is the i-th row of the D (N×N) and the norm ||*|| is expressing the similarity between the measured data and the centre C_j. A smaller value for the V_{XB} index signifies a more appropriate clustering decision that provides compact clusters that are adequately separated.

And the following nomenclature:

$V_{XB}(k)$	Xie and Beni index for k-clusters
C	Cluster centroid

It is desirable to select a validation index that can be calculated fast once Fuzzy k-means converges. Besides Xie and Beni index, suitable candidates examined were the partition coefficient [107] and partition entropy [108]. Xie and Beni index is preferred in here due to the fact that it accounts both for compactness and separation, unlike [108, 107] and at the same time it is not overly complex. On the negative side, Xie and Beni index may become unreliable when number of clusters are close to number of nodes, however this drawback does not affect its suitability in zoning for Coordinated Voltage Regulation (CVR) where maximum number of clusters is conservative and cannot exceed the number of synchronous control elements.

4.4 Results & Discussion

This section presents and discusses the most informative Results taken from broad experiments. It is organized into three Sub-sections. Sub-section 4.4.1 tests and discusses some generalities of interest which are common in all zoning methodologies. Sub-section 4.4.2 introduces the case study networks and summarizes the different zoning based RCM approaches under study. Sub-section 4.4.3 evaluates the various zoning based RCM approaches on the CVR control of these case study networks.

4.4.1 Zoning methodologies: Basic properties

Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) methodologies all use proximity metrics that require as input only the Jacobian matrix of the system, which is readily available and is updated periodically as the conditions vary. Due to this input, it follows that all zoning methodologies are structure and state dependent. Under a number of trials it became evident that (a) Zoning methodologies based on hierarchical agglomerative clustering, i.e. HCSD, HCVS are deterministic and thus replicable even if suboptimal, *under the assumption that proximity distances selected and number of zones prevent the formation of ties*. And (b) zoning methodologies deploying k-means or a variant of it, i.e. SKC, FCM, can achieve a replicable output through the proposed sampling of initial centroids and the deployment of a large number of Replicates (i.e. iterations).

As all zoning methodologies are heuristic algorithms, they provide no guarantee that they will converge to the global optimum solution. A well designed zoning methodology is expected, though, to have *the ability to identify obvious boundaries*. To prove the latter, similar to [109] the IEEE-96 system [110] is used. This is an atypical system and is framed by replicating the IEEE RTS-24 network [111] three times and with few interconnections. A 72-mile 230 kV line connects area 2 to area 3 and a 67-mile 230 kV line connects area 1 to area 3. The grouping results for this system are presented in figure 4.1 and are identical to all zoning methodologies when three clusters are requested. The above outcome validates their basic ability to identify obvious boundaries.

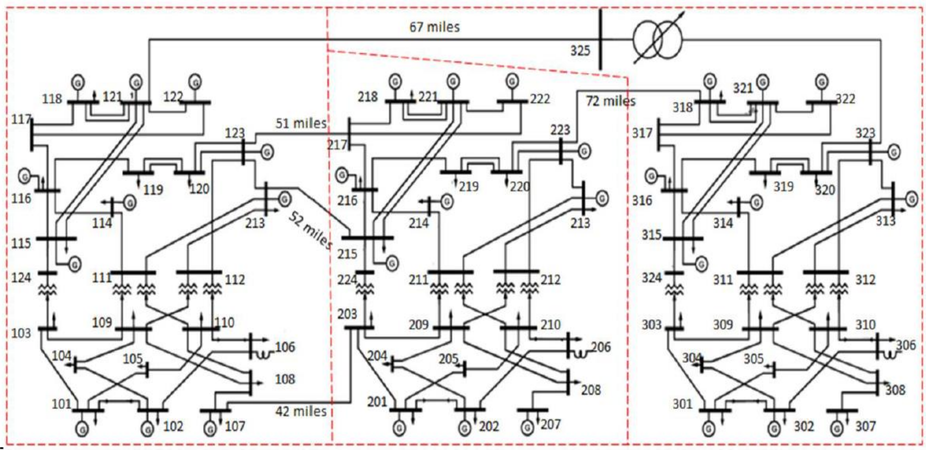


Fig.4.1 Topology of the 3-area system [110]. Note that all zoning methodologies produce the same zoning result as illustrated in this figure.

4.4.2 Zoning based RCM approaches and Case study networks

This Sub-section contains a summary of the examined zoning approaches to Reduction of the Control Model (RCM) and a brief description of three typical transmission networks that are used as case studies.

Sections 4.2 and 4.3 formulated four zoning methodologies as clustering optimization problems, i.e. Hierarchical Clustering with Single Distance (HCSD), Hiearchichal Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM). Section 4.1 discussed that once a zoning is derived, RCM is defined in practice and in academic literature with very little ambiguity. Hence, the extension of each formulated zoning methodology to zoning based RCM is straight-forward, as figure 4.2 indicates.

Hence, a single RCM definition is deployed in conjunction with all zoning methodologies; Zonal centroids are assigned as pilot nodes, similar to [17]. Control is based on synchronous generators, similar to [13, 15, 21]. In addition to generators, synchronous condensers in some cases are also considered, if explicitly stated. This selection reflects the industrial practice.

The question of interest is how HCSD based RCM, HCVS based RCM, SKC based RCM and FCM based RCM affect the performance and robustness of Coordinated Voltage Regulation (CVR). This question is examined in Sub-section 4.4.3 on three typical transmission networks: (a) 30 bus test network (b) 39 bus test network and (c) 118 bus test network.

These test networks are presented here and they have been selected for the following reasons; (a) they cover the range of both transmission and sub-transmission voltage levels, (b) they are characterized by different degrees of controllability and variety of control resources and (c) the last two networks are the most commonly used in CVR studies.

- **IEEE 30-Bus test network**

The IEEE 30-Bus test network represents a portion of the American Electric Power System in the Midwestern USA and is presented in figure 4.3 below. Data for the steady-state analysis can be found in reference IEEE Common Data Format by [111, 112]. This electrical network contains 132 kV-33 kV voltage levels. It has 30 Buses and 41 branches, hence it is meshed with average degree $<k>=2.73$. It contains 21 loads served by 6 synchronous generators. The ratio of controllable buses to overall buses is ~20%.

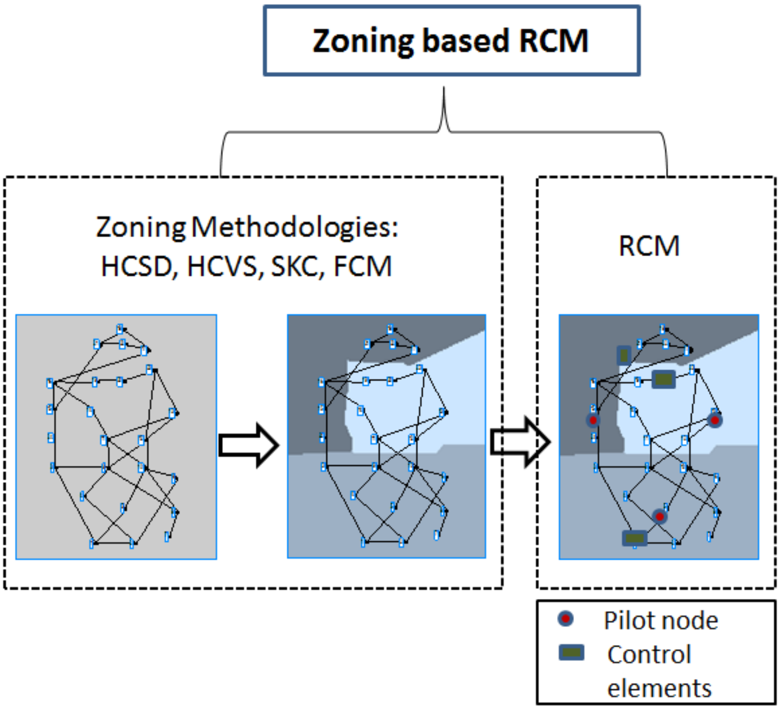


Figure 4.2 Summary of zoning-based RCM approaches under study

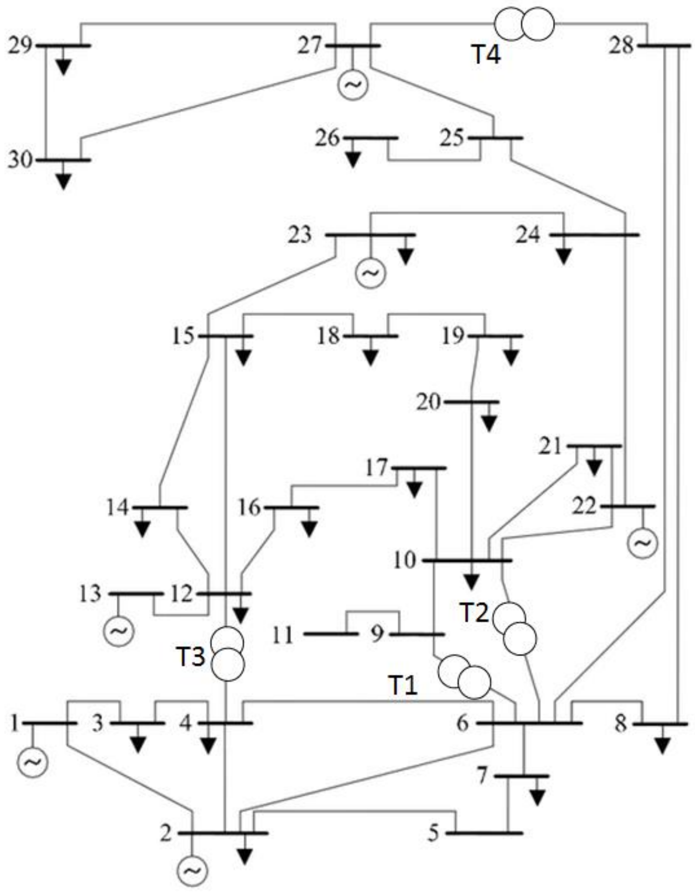


Fig. 4.3 One line diagram- IEEE 30 Bus system [111]

- **The 39-bus test network**

The 39 bus test network represents the New England ISO and belongs to transmission level. This network is often used in CVR studies and is presented in figure 4.4 below. It features 9 synchronous generators and one interconnection to the New York power system. It has 39 Buses and 46 branches, hence it is meshed with average degree <k>=2.36. The ratio of controllable buses to overall buses is ~25%. Data for the steady-state analysis can be found in [111].

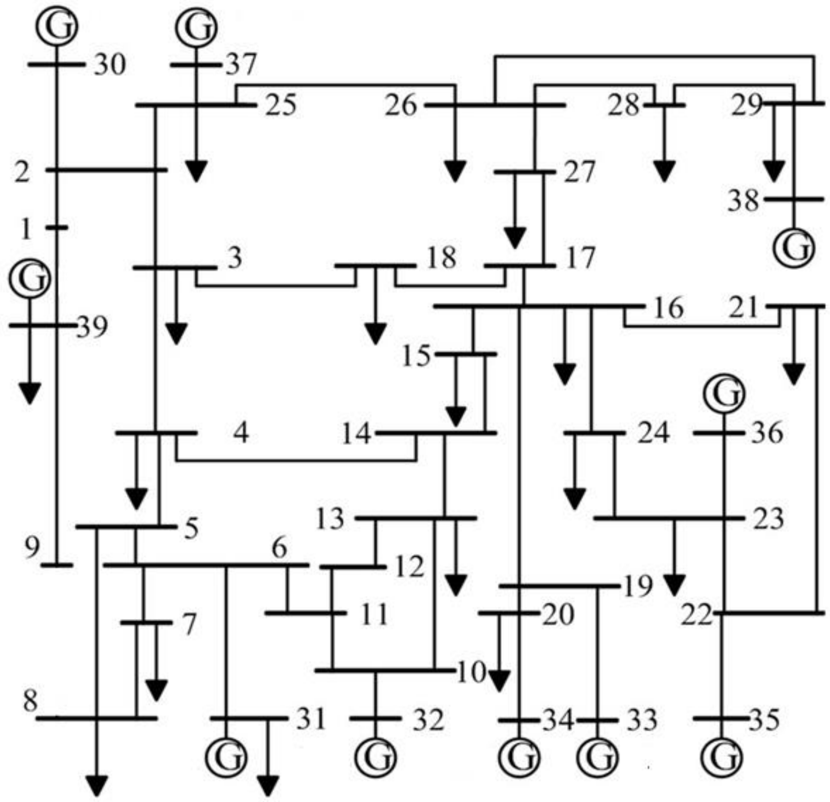


Fig. 4.4 One line diagram- 39 buses test network [111]

- **The 118-bus test network**

The 118 bus test network represents the American Midwest ISO and belongs to transmission level. This network is often used in CVR studies and is presented in figure 4.5 below. It has 118 Buses and 186 branches, hence it is highly meshed with average degree <k>=3.15. It features 19 synchronous generators and 35 synchronous condensers. It is particularly rich in controllability, i.e. the ratio of controllable buses to overall buses is ~45%. Data for the steady-state analysis can be found in [111].

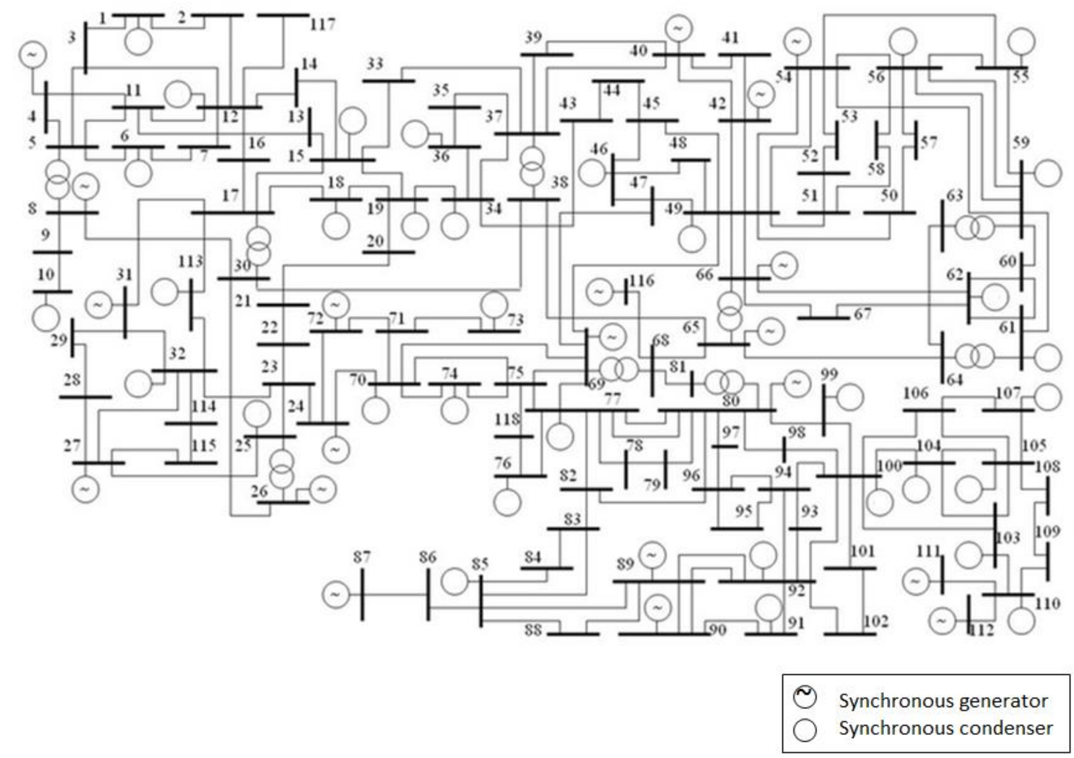


Fig.4.5 One line diagram- 118 bus test network [111]

4.4.3 Evaluation of Zoning based RCM in CVR

This Sub-section presents how the four zoning based RCM approaches (i.e. HCSD, HCVS, SKC and FCM based RCM) affect the performance and robustness of the CVR controller in three representative standard test networks. (i.e. 30 bus, 39 bus and 118 bus test network).

- **Results on the 30 bus test network**

Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) based RCM approaches are applied to suggest the most appropriate Reduction of the Control Model (RCM) for a single network state (maximum loading conditions and no topological changes). Each of them searches for a solution within the range {2..6} number of zones. The lower bound of this range comes from the fact that central Coordinated Voltage Regulation (CVR) is not feasible or reliable in the general case. The higher bound of this range is specified by the number of synchronous generators, which are 6 for the 30 bus test network.

Each of the zoning methodologies is represented by the zoning outcome that optimizes its validation index. The parameters that optimize the clustering validation are listed in Table 3.1. As can be seen, HCSD, HCVS and SKC methodologies all suggest 3 zones, based on the maximization of the Relative Diameter (RD), Average Zonal Distance (AD) and Relative Eigen-gap (γ) respectively. FCM also suggests 3 zones, based on the minimization of Xie and Beni Index V_{XB}.

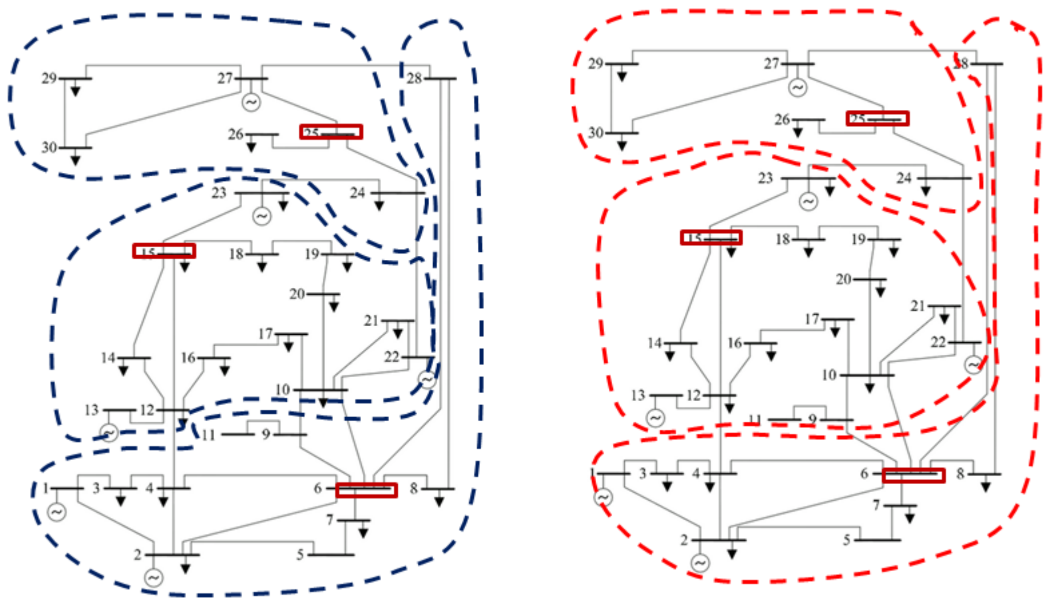
TABLE 3.1

FEATURES OF CLUSTERING VALIDATION

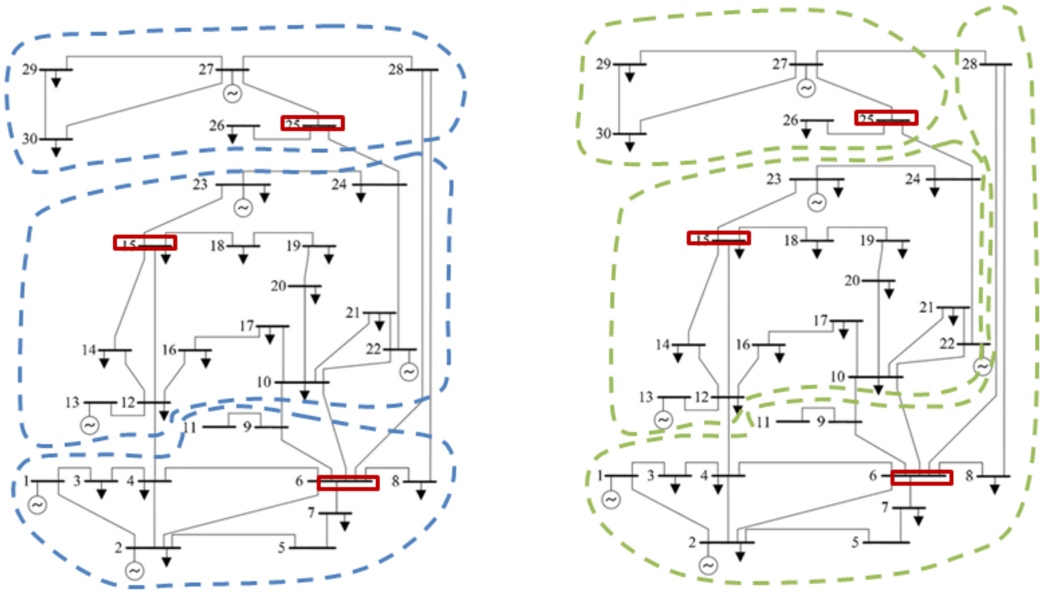
-30 BUSES TEST NETWORK

Zoning methodologies	***Validation criteria –f(x)***	***optimum{f}***	***x:/f optimum***
HCSD	$\mathbf{max\{\Delta \boldsymbol{RD}(\boldsymbol{k})\}}$	0.231	3
HCVS	$\mathbf{max\{A\boldsymbol{D}(\boldsymbol{k})\}}$	2.369	3
SKC	$\mathbf{max\ \{\boldsymbol{\gamma}\ (\boldsymbol{k})\}}$	0.512	3
FCM	$\mathbf{min\ \{\boldsymbol{V_{XB}}(\boldsymbol{k})\}}$	2.678	3

Figure 4.6 presents the zoning decisions made by each of the zoning methodologies and the resulting Reduction of the Control Model (RCM).



(a) HCSD based RCM (b) HCVS based RCM



(c) SKC based RCM　　　　(d) FCM based RCM

Figure 4.6 RCM for the 30 bus test network based on
(a) HCSD, (b) HCVS, (c) SKC and (d) FCM

As can be seen from Fig. 4.6 all zoning methodologies suggest different zoning boundaries, however the differences are minor. Any differences in bus classification (e.g. buses 9, 11, 24 and 28) come from the fact that each of the zoning methodologies uses a different proximity metric (e.g. SKC uses a sparse variation of proximity deployed in HCSD, FCM) and all deploy different clustering algorithms (e.g. Spectral k-means in SKC vs Fuzzy C-Means in FCM) or different variations of the same clustering algorithm (e.g. HCSD builds a dendrogram deploying complete linkage criterion, while HCSD builds a dendrogram deploying average linkage criterion). In this particular network the differences are minor, hence the Reduction of the Control Model is identical no matter which zoning methodology has been deployed to derive it. This is quite an exceptional case and indicates that while in principle zoning definitions determine the nature of the corresponding RCMs, similar zoning outcomes (coming from different zoning definitions) could result in the same RCM being selected. Owing to the fact that RCM is identical to all approaches, the performance and robustness of CVR would be obviously identical for all cases.

- **Results on the 39 bus test network**

HCSD, HCVS, SKC and FCM based RCM approaches are deployed to suggest the most appropriate Reduction of the Control Model (RCM) for a single network state (maximum loading conditions and no topological changes). Each of them searches for a solution within the range {2...10} number of zones. The lower bound of this range comes from the fact that central CVR control is not feasible or reliable in the general case. The higher bound of this range is specified by the number of the synchronous generators, which are 10 for the 39 bus test network.

Each of the zoning methodologies is represented by the zoning outcome that optimizes its validation index. The parameters that optimize the clustering validation are listed in Table 4.2. As can be seen, HCSD, HCVS, and SKC methodologies all suggest 4 zones, based on the maximization of the Relative Diameter (RD), Average Zonal Distance (AD) and Relative Eigen-gap (γ) respectively. FCM suggests 5 zones, based on the minimization of Xie and Beni Index V_{XB}.

TABLE 4.2

FEATURES OF CLUSTERING VALIDATION

-39 BUS TEST NETWORK

Zoning methodologies	***Validation criteria –f(x)***	***optimum{f}***	***x:/f optimum***
HCSD	**max{$\boldsymbol{\Delta RD(k)}$}**	0.026	4
HCVS	**max{A$\boldsymbol{D(k)}$}**	7.061	4
SKC	**max {$\boldsymbol{\gamma}$ ($\boldsymbol{k}$)}**	0.449	4
FCM	**min {$\boldsymbol{V_{XB}(k)}$}**	0.096	5

Figure 4.7 presents the zoning decisions made by each of the zoning methodologies and the resulting Reduction of the Control Model. The selected pilot nodes within the zones are also identified and highlighted: {HCSD:[4,20,21,28]}, {HCVS:[1,6,16,26]}, {SKC:[6,20,21,26]} and {FCM:[1,6,16,20,28]}.

As can be seen, different zoning methodologies, sharing the same control objective and network, make different decisions and a natural question is which is the most appropriate for CVR. Internal validation criteria provided the most appropriate outcome for each zoning methodology, they are however specific to each approach and may produce contradicting decisions if combined, as reference [113] points out. Due to that, this thesis proceeds by comparing the optimized through validation zoning outcomes directly on the application of interest, using the framework which has been presented in Chapter 3.

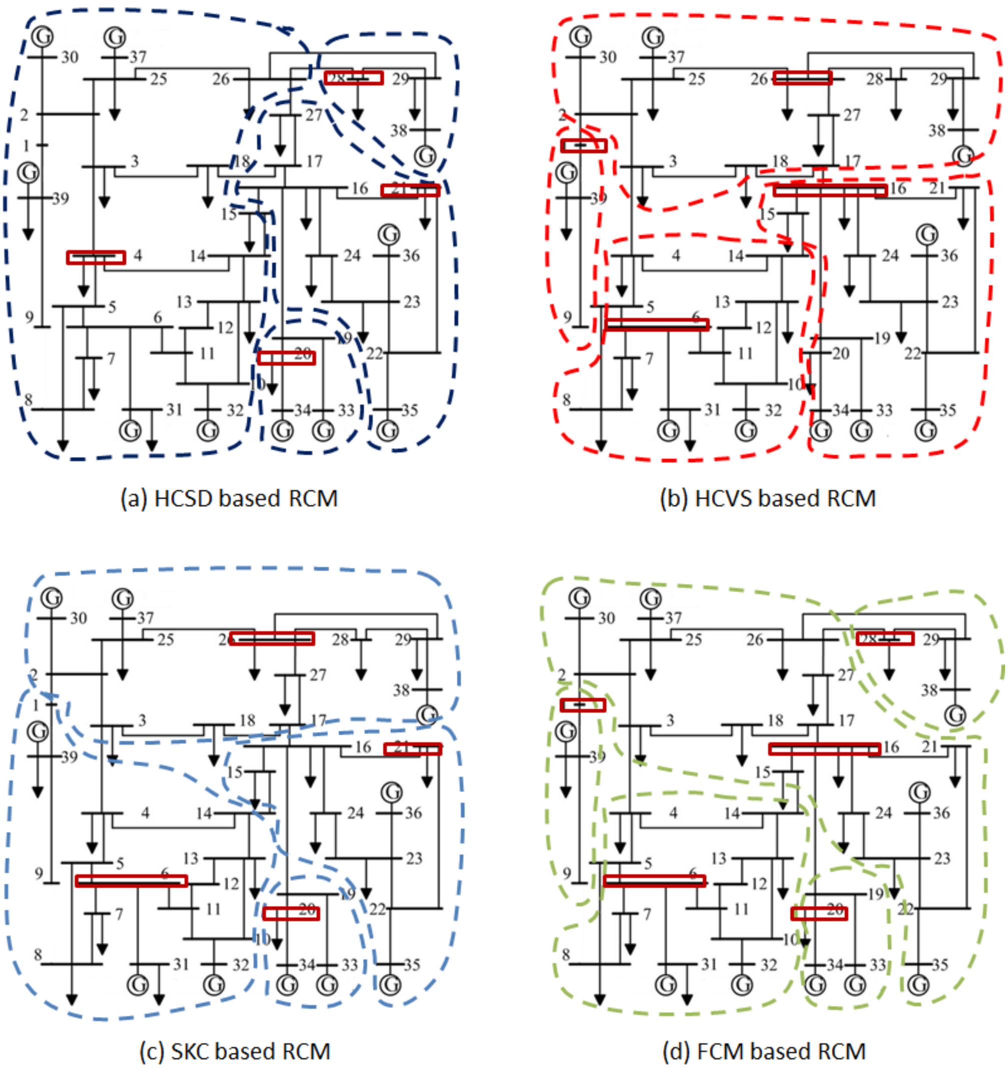


Fig.4.7 RCM for the 39 bus test network based on
(a) HCSD, (b) HCVS, (c) SKC and (d) FCM

❖ *Evaluation –Static RCM and accurate measurement*

The performance CVR achieves with respect to the four zoning methodologies is now compared. Static Reduction of the Control Model (RCM) is considered and accurate measurements; $\{ \widehat{\Delta V_P}, \widehat{Q}_g \} = \{ \Delta V_P, Q_g \}$ in block C of the framework. The probabilities associated with the system load level and load deviation are expected to be obtained from available system data. In absence of such data for the test system, the different load levels (as percentage of maximum) are assumed to follow the cumulative probability distribution of figure 4.8, similar to [114]. Deviation cases over base-case load are assumed to follow the cumulative probability distribution of figure 4.9, similar to [82].

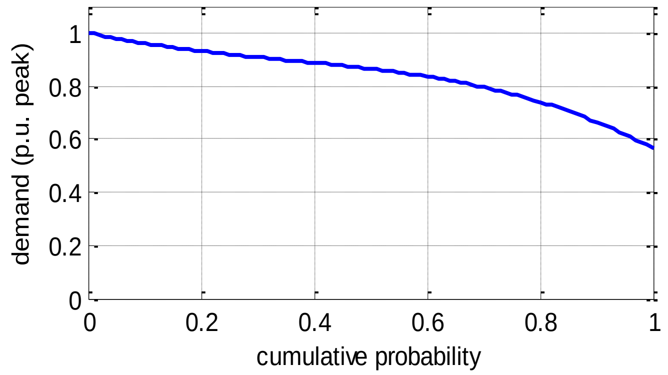


Fig. 4.8 Load duration curve [114]

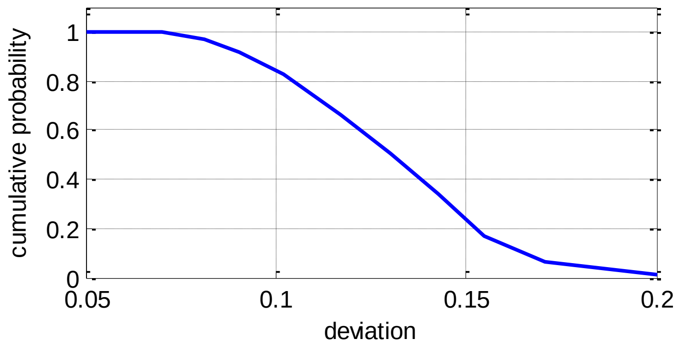


Fig. 4.9 Cumulative probability distribution for load deviations [82]

Simulation results for the case of accurate measurement are presented in table 4.3. The CVR algorithm is common to all zoning methodologies and the measurements introduce no uncertainty to the problem. However, results reveal that the selection of the zoning methodology affects the performance the voltage control algorithm achieves.

TABLE 4.3
ZONING METHODOLOGY EVALUATION
-39 BUS TEST SYSTEM

Zoning Methodology	**HCSD**	**HCVS**	**SKC**	**FCM**
OPI (%)	86.91	92.09	91.23	89.88

As can be seen in table 4.3, HCVS and SKC methodologies achieve the highest performance for this case study. This can be explained from the fact that HCVS uses a distance metric that accounts for the quasi steady state characteristic of CVR law and SKC optimizes the Normalized Cut and not the Ratio Cut. Overall, a higher performance is very much desirable as it signifies reduced losses and enhanced voltage profile.

❖ *Evaluation –Static RCM and noisy pilot bus measurements*

This paragraph is concerned with the robustness of a zoning methodology to measurement errors. The analysis described above is repeated (exact network and probabilistic modelling). However, this time CVR acts upon a voltage deviation vector which bears an error ε, as in:

$$\widehat{\Delta V_P} = |1 - \varepsilon| \cdot \Delta V_P \qquad (4.30)$$

In the general case ε can follow any distribution. In this example, error ε follows uniform distribution with same magnitude for all pilot node measurements. This error is initially set at 2% and gradually increased to 10%. Figure 4.10 presents the OPI performance of each zoning methodology with respect to the measurement error. Obviously, increasing the level of measurement errors deteriorates the zoning methodologies OPI performance. The final OPI curves are quite linear for the error range examined. A smaller curve slope indicates a more robust zoning methodology. Zoning methodologies demonstrate different degrees of robustness to measurement errors. Based on the slope of their corresponding OPI curves, HCSD appears to be the most robust to measurement errors, while FCM the least robust. It is noteworthy that for increasing errors SKC methodology outperforms the HCVS. The above indicate that a zoning methodology should be selected in accordance with the expected accuracy of the voltage measurements CVR receives.

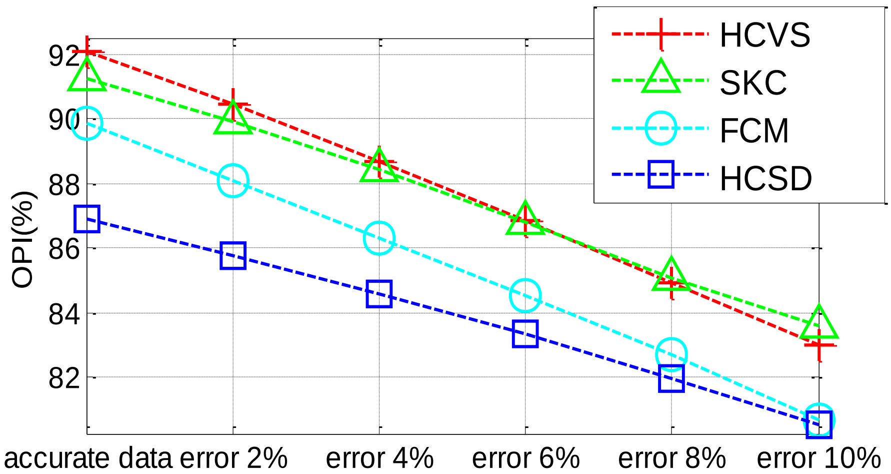


Fig. 4.10 Zoning methodologies comparison under various measurement errors -39 bus test network

- **Results on the 118 bus test network**

Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) approaches are deployed to suggest the most appropriate Reduction of the Control Model

(RCM) for a single network state (maximum loading conditions and no topological changes). The 118 bus test network is an interesting case due to having such high ratio of controllable buses (~45%). Each of the zoning methodologies searches for a solution within the range {2...54} number of zones. The lower bound of this range comes from the fact that central CVR control is not feasible or reliable in the general case. The higher bound of this range is specified by the number of the synchronous control elements; 19 synchronous generators and 35 synchronous condensers.

Each of the zoning methodologies is represented by the zoning outcome that optimizes its validation index. The parameters that optimize the clustering validation are listed in Table 4.4. As can be seen, number of most appropriate zones varies for most of the zoning methodologies.

TABLE 4.4
FEATURES OF CLUSTERING VALIDATION
-118 BUS TEST NETWORK

Zoning methodologies	***Validation criteria –f(x)***	***optimum{f}***	***x:/f optimum***
HCSD	$\mathbf{max\{\Delta \boldsymbol{RD}(\boldsymbol{k})\}}$	0.074	6
HCVS*	$\mathbf{max\{A\boldsymbol{D}(\boldsymbol{k})\}}$	5.461	6
SKC	$\mathbf{max\ \{\boldsymbol{\gamma}\ (\boldsymbol{k})\}}$	0.486	7
FCM	$\mathbf{min\ \{\boldsymbol{V_{XB}}(\boldsymbol{k})\}}$	1.199	8

For HCVS methodology results appearing on Table 4.4 are attained with a reduced set of controllable elements. This is due to the fact that the consideration of the full control set resulted in disconnected clusters. This can be explained by the definition of the proximity metric which is essentially a Euclidean distance that uses many co-ordinates (i.e. number of dimensions equals number of control elements). What happens here is that for increased ratio of controllable elements, there might be little difference in the distances between different pairs of samples which may cause the distance function to lose its usefulness and produce erroneous results. Hence, the first 19 larger control elements are used for HCVS at the stage of formulating the electrical distance metric. This accounts to a 65% reduction of the initial set. Figure 4.11 elaborates on the selection of this threshold and presents zonings when a) 100% of control elements are considered, b) 70% and c) 35% of them.

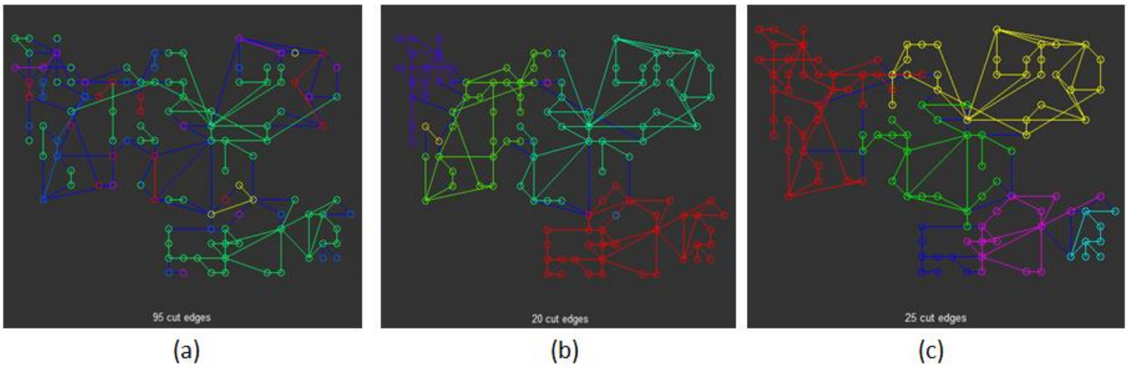


Fig. 4.11 Selected HCVS zoning based on clustering validation a) at 100% control elements, b) 70% control elements and c) 35% control elements

Figures 4.12 presents the zoning decisions made by each of the zoning methodologies.

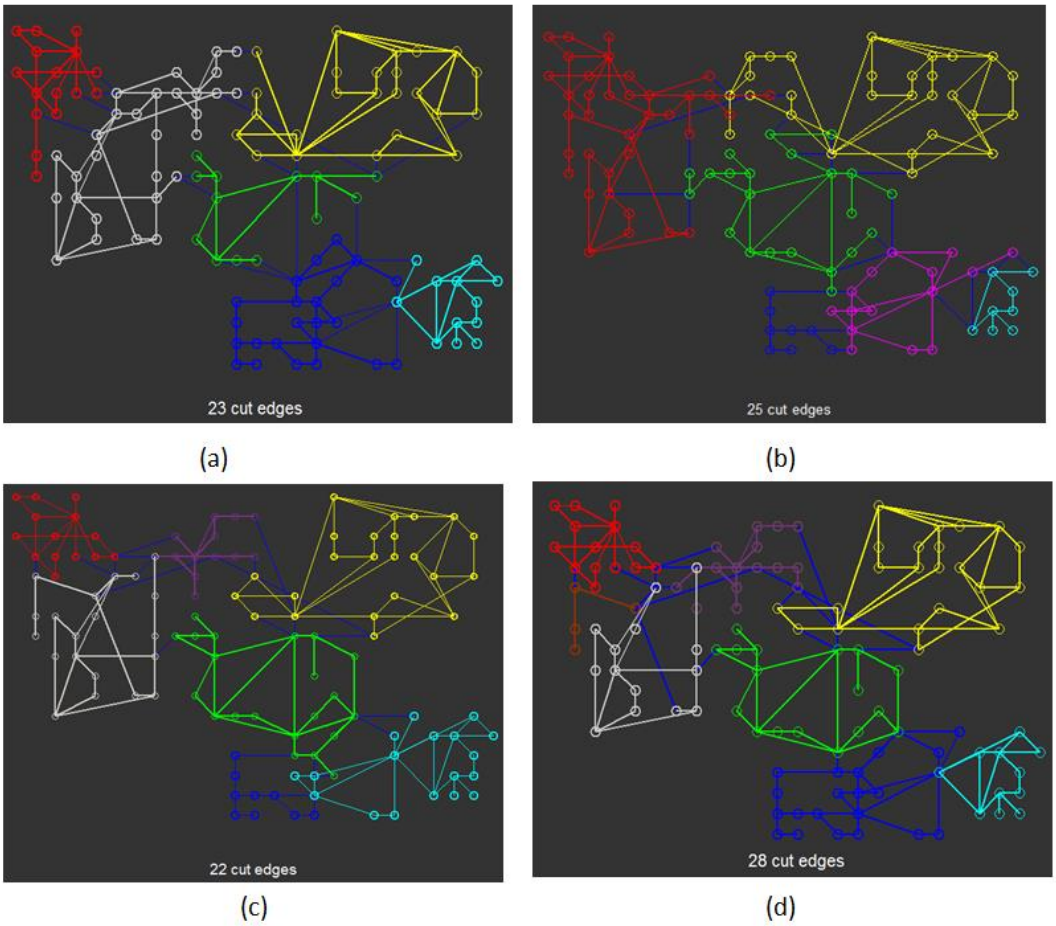


Fig.4.12 Zoning outcomes for the 118 bus test network based on methodologies; (a) HCSD, (b) HCVS, (c) SKC and (d) FCM

As can be seen, the zonings are given as subgraphs due to scaling up on number of buses. Same colours are used to indicate similar zones, i.e. zones containing big percentage of zones as in a previous zoning. It is evident that the different zoning methodologies, sharing the same control objective and network, make different decisions similarly to the previous network examined. The selected pilot nodes within the zones are presented in Table 4.5:

TABLE 4.5
PILOT NODE SELECTION
-118 BUS TEST NETWORK

Zoning methodologies	**Pilot nodes**
HCSD	{9, 43, 67, 78, 108, 118}
HCVS*	{30, 44, 82, 84, 94, 108}
SKC	{5, 30, 37, 67, 84, 106, 118}
FCM	{5, 9, 17, 20, 67, 94, 108, 118}

Regarding selection of the control elements; an arbitrary limit is imposed for synchronous resource participation in CVR, i.e. generators and condensers with reactive capacity greater than 150 MVAR (~61% of the total control elements).

❖ *Evaluation –Static RCM and accurate measurement*

The performance CVR achieves on the 118 bus test network with respect to the four zoning methodologies is now compared. Static RCM is considered and accurate measurements; $\{\widehat{\Delta V_P}, \widehat{\mathrm{Q}}_{\mathrm{g}}\} = \{\Delta V_P, \mathrm{Q}_{\mathrm{g}}\}$ in block C of the framework. The probabilities associated with the system load level and load deviation identical to the ones considered in the previous example (Figures 4.8 and 4.9).

Simulation results for the case of accurate measurement are presented in table 4.6. The CVR algorithm is common to all zoning methodologies and the measurements introduce no uncertainty to the problem. However, results reveal that the selection of the zoning methodology affects the performance the voltage control algorithm achieves. As can be seen in table 4.6, SKC methodology achieves the highest performance for this case study. FCM and HCSD share the same proximity metric, however similarly to the results on the 39-test network FCM outperforms HCSD. This is anticipated as Fuzzy Clustering in principle can avoid some minima of crisp clustering. It is noteworthy that HCVS achieves the lowest score among all, contrary to results on the 39 bus test network. This is explained by the short-coming of the deployed Electrical Distance and the need to reduce the number of dimensions in order to avoid poor/disconnected clustering outcomes. While it considers the quasi-steady zonal control characteristics, it should be used with caution for high ratios of g/l elements or when the g elements participating in CVR are not pre-specified.

TABLE 4.6
ZONING METHODOLOGY EVALUATION
-118 BUS TEST SYSTEM

Zoning Methodology	**HCSD**	**HCVS**	**SKC**	**FCM**
OPI (%)	90.98	89.58	92.65	91.77

❖ *Evaluation –Static RCM and noisy pilot bus measurements*

This paragraph is concerned with the robustness of a zoning methodology to measurement errors on the 118 bus test system. The analysis described above is repeated (exact network and probabilistic modelling). However, this time CVR acts upon a voltage deviation vector which bears an error ε. The probabilities associated with the error ε are expected to be obtained from available system data. In absence of such data for the test system, in this example a normal distribution is arbitrarily used. The considered distribution is $x = N(0,1)$. The considered errors are of increasing magnitude and are derived as in Table 4.7 and equation (4.30).

TABLE 4.7
ERRORS IN ROBUSTNESS EVALUATION
-118 BUSES TEST SYSTEM

$\boldsymbol{cases}$	**error2**	**error4**	**error6**	**error8**	**error10**
$\boldsymbol{\varepsilon}$	$2 * \|\|x\|\|$	$4 * \|\|x\|\|$	$6 * \|\|x\|\|$	$8 * \|\|x\|\|$	$10 * \|\|x\|\|$

$$\widehat{\Delta \mathrm{V}}_{\mathrm{P}} = |1 - \varepsilon| \cdot \Delta \mathrm{V}_{\mathrm{P}} \tag{4.30}$$

The probabilistic analysis is run first with accurate data (ε =0). Then it is repeated with each of the series error2, error4, error6, error8 and error 10. Figure 4.13 presents the OPI performance of each zoning methodology with respect to the measurement error on the 118 bus test network. Obviously, increasing the level of measurement errors deteriorates the zoning methodologies OPI performance.

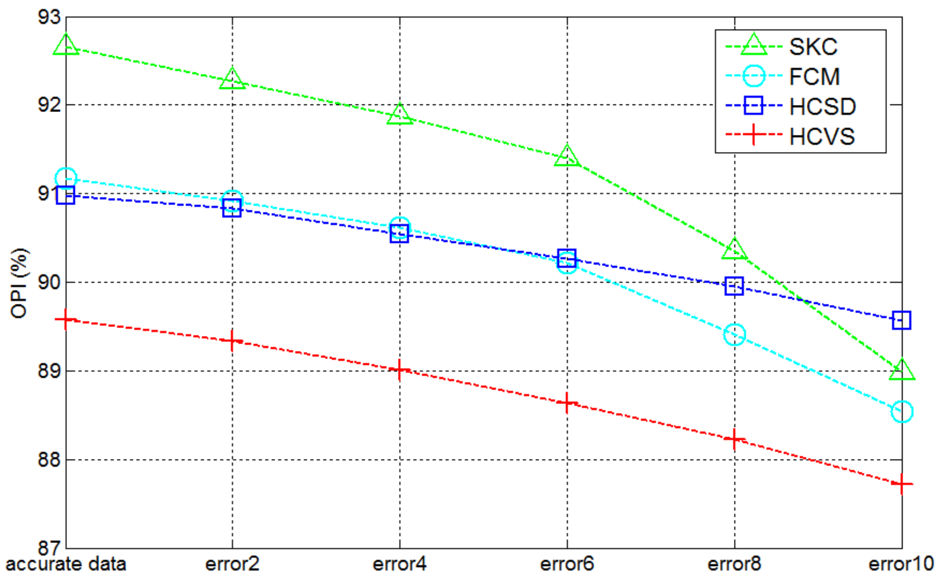


Fig. 4.13 Zoning methodologies comparison under various measurement errors -118 bus test network

Based on the slope of their corresponding OPI curves, HCSD appears to be the most robust to measurement errors, similarly to the analysis on the 39 bus test network. This is partly due to using the complete linkage merge criterion which is non-local; the entire structure of the clustering influences merge decisions, hence neighbouring effects are reduced. Similarly to results on the 39 bus test network, errors of increasing magnitude alter the order of appropriateness of the zoning methodologies. For instance, on the 118 bus test network HCSD is the third best methodology when CVR deploys accurate data; however for highly erroneous data it seems to have the best potential.

The analysis on both the 39 bus and 118 bus test networks indicate that a zoning methodology should be selected in accordance with the expected accuracy of the voltage measurements CVR receives.

4.5 Concluding Remarks

This Chapter developed two novel zoning methodologies, Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) and formulated them as clustering optimization problems using Complex Network Analysis. Two more approaches that have been adopted by industry, Hierarchical Clustering with Single Distance (HCSD) and Hierarchical Clustering in VAR Space (HCVS) were also assessed. These four zoning methodologies are representative of the whole spectrum of clustering algorithms and are the most appropriate candidates for Hierarchical, Exclusive and Overlapping Clustering.

HCSD, HCVS, FCM and SKC methodologies all use proximity metrics that require as input only the Jacobian matrix of the system, which is readily available and is updated periodically as the conditions vary. Due to this input, it follows that all zoning methodologies are structure and state dependent. As evidenced from the simulations, all of these methodologies have the ability to identify obvious boundaries and can provide a deterministic output on networks with none obvious boundaries through tuning. It is noteworthy that all the aforementioned Zoning methodologies satisfy a single control objective hence no compromise is needed as it would have been in the case of multi-objective clustering. From this design choice it follows that HCSD, HCVS, FCM and SKC, all are very efficient for the application of Coordinated Voltage Regulation (CVR), they would however be suboptimal with respect to other control objectives.

Furthermore, simulations revealed that different zoning methodologies, sharing the same control objective and network, make different decisions. To that end the probabilistic framework presented in Chapter 4 has been deployed to investigate *how different zoning based RCM approaches serve the CVR control objective*. In this investigation, the focus has been on both performance and robustness that CVR controller achieves in conjunction with a zoning based RCM approach. The results pointed to three interesting findings:

(a) Zoning definitions determine the nature of the corresponding Reduction of the Control Model (RCM). However, similar zoning outcomes (coming from different zoning definitions) could result in the same RCM being selected.

(b) SKC and HCVS based RCM appear to have the best potential. The high performance of HCVS can be explained by the electrical distance that it deploys which considers the quasi-steady zonal control characteristics. HCVS should be used with caution though for high ratios of g/l elements or when the g elements participating in CVR are not pre-specified.

(c) The selection of a zoning based RCM affects both the performance and the robustness of the CVR controller. Hence, a zoning based RCM should be selected in accordance to the expected accuracy of the voltage measurements CVR receives.

The formulation of SKC and FCM methodologies, the evaluation of a representative sample of zoning methodologies on the CVR problem and the key observations in (a)-(c) are the main novel contributions of this Chapter.

Chapter 5

Consideration of adaptive RCM in CVR

This chapter investigates Reduced Control Models determined in an online event-driven fashion (adaptive RCM) in pursuit of improved Coordinated Voltage Regulation (CVR). This is due to the fact that a single RCM (static RCM) cannot be optimum for all network operating conditions and configurations. This chapter investigates four novel research questions with regards to adaptive RCM in CVR: (a) is adaptive RCM feasible from a computational perspective on realistic size networks? , (b) What should trigger the adaptive RCM? (c) What is the Value of adaptive RCM from a control perspective? , and (d) Which are the Major implementation challenges?

5.1 Adaptive RCM for CVR

This section introduces adaptive Reduction of the Control Model (RCM) which is a relatively new concept in Coordinated Voltage Regulation (CVR) literature and largely unexplored. Subsection 5.1.1 provides the definition of adaptive RCM. Subsection 5.1.2 reviews the existing literature on adaptive RCM and provides the underlying motivation which drives this research.

5.1.1 Adaptive RCM for CVR: Definition

Coordinated Voltage Regulation (CVR) manages mid-term (i.e. steady state mechanism with 1 min resolution [3], see also Chapter 1, Section 1.1) and is based on Reduced Control Models (RCM), i.e. simplified models of the system suitable for voltage control. It is a fact however that a single Reduced Control Model (*static RCM*) cannot be optimal for all network configurations and operating conditions. This Chapter investigates non-static Reduced Control Model definitions in pursuit of improved CVR. A non-static RCM can be derived in two possible ways:

(a) With case-based reasoning: A number of possible RCMs can be predefined by sampling a number of network states with criteria such as possibility of occurrence or criticality. When conditions vary, a predefined RCM may be deployed based on the maximum similarity the current network state has to any of these sampled network states. RCM with case-based reasoning is suitable on networks with limited observability, and the author believes it will be useful for CVR in the transition towards smart-er transmission grids. It does however rely on maintaining an RCM database and carrying out online search with in it, and also on appropriate interpretation for cases that are equally far from a number of offline defined options.

(b) Online Adaptive definition: As conditions vary a new RCM is generated that best suits the current network state. Certain thresholds can be posed to avoid frequent/pointless reconfigurations of RCM. Hence, RCM is reconfigured when CVR performance drops below a predefined threshold or following/in anticipation of a significant event.

The second definition of *adaptive RCM* is selected for this work, since this thesis targets future power grids [115] where observability is not an issue and the deployment of RCMs is driven by the need for CVR secure convergence, reliability and engineering simplicity rather than economy of measurements.

Regarding the *Reduction of the Control Model* (RCM) it is important to note that Research into it is developing in two directions. The first deploys heuristics to divide the system into weakly coupled zones and then identifies, with exhaustive search, pilot nodes and controlling elements to base the control on [17, 21, 89]. This approach is referred to as *zoning based RCM*. The second direction uses heuristics and artificial intelligence techniques to identify the most suitable pilot nodes by minimizing, in a system wide fashion, the linearized version of a particular CVR control objective function [81, 80, 82]. Approaches of the second research direction cannot be incorporated in *adaptive RCM* schemes, due to their long execution times. Indicatively, evolutionary algorithms, that according to [82] are currently the best candidate solution, need several hours to converge. ***Zoning based RCM*** is thus examined within the **adaptive scheme**, due to being significantly faster. To that end, adaptive RCM has as a backbone a varying number of zones with non-static/flexible boundaries.

Within Coordinated Voltage Regulation (CVR), adaptive RCM refers to the definition of the Reduced Control Model in an event driven online fashion. Adaptive RCM is solely zoning based and it is based on a varying number of zones with non-static boundaries.

An abstract illustration of the concept is presented in figure 5.1 below.

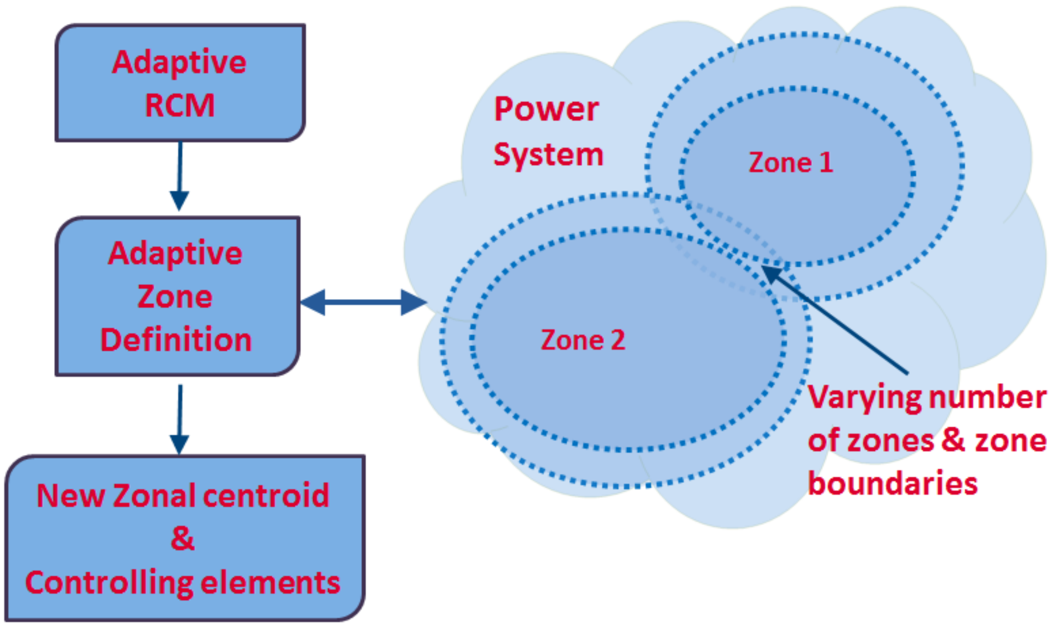


Fig. 5.1 Adaptive RCM in CVR

5.1.2 Adaptive RCM for CVR: Literature review & Motivation

The term adaptive Reduction of the Control Model (adaptive RCM) is relatively new in CVR literature, where static RCM definitions have been largely deployed in CVR since the early 80's [17]. Advances in substation communication and increased measurement availability paved the way to adaptive RCM. A novel AVC system based on online adaptive zone definition has been implemented in China to better suit the very rapidly developing power industry. The approach was firstly introduced at the IEEE PES General Meeting of 2009 [21] where a technique based on Hierarchical Clustering in VAR control space (HCVS) was presented. Reference [22] elaborated on the adaptive zone-definition based AVC system and presented lessons learnt from its field application in China. Work in [30] applies the HCVS approach on the PJM (i.e. Pennsylvania, Jersey, Maryland) system for a number of critical scenarios and concludes that the decoupled characteristics for PJM power grid is not fixed for different cases i.e. it justifies the case for adaptive zoning based RCM, similar to [22].

References [21, 22, 30] discussed above constitute seminal work on the consideration of adaptive RCM in the CVR. They do however tackle simultaneously a number of research questions, ranging from CVR hardware and software implementation to overall CVR problem formulation and they are not focussed on adaptive RCM. Adaptive RCM is relatively new in CVR literature and hence largely unexplored. The above work has not discussed a number of important research questions related to adaptive RCM, such as the ones listed below:

(a) Feasibility of adaptive RCM in CVR from a computational perspective on realistic size networks, i.e. prior to the application of any network reduction technique.

(b) Investigation into what triggers/should trigger the adaptive RCM.

(c) Investigation of the value of adaptive RCM in CVR from a control perspective.

(d) Major implementation challenges; Implications of adaptive RCM in smart control rooms and infrastructure.

The above research questions are tackled in the following Sections (5.2-5.5). This research outcome can also be found in references [16, 116] published by the authors. *It is noteworthy that references* [16, 116] *together with* [21, 22, 30] *are the only published work on adaptive RCM in CVR literature.*

5.2 Feasibility from a computational perspective

This section investigates the feasibility of adaptive Reduction of the Control Model (RCM) in Coordinated Voltage Regulation (CVR) from a computational perspective along with relevant speed up heuristics. Results are presented on a realistic size network (i.e. with no reduction).

As discussed in chapter 2, zoning methodologies can be classified as Hierarchical, Exclusive and Overlapping. Based on this taxonomy, four zoning methodologies have been selected in Chapter 4, Sections 4.2 and 4.3 as representative of the whole spectrum;

- RCM Methodologies based on Hierarchical Clustering (agglomerative)
  - ✓ Hierarchical Clustering with Single Distance (HCSD)
  - ✓ Hierarchical Clustering in VAR control space (HCVS)
- RCM Methodologies based on Exclusive Clustering
  - ✓ Spectral K-way Clustering (SKC)
- RCM Methodologies based on Overlapping Clustering
  - ✓ Fuzzy C-Means (FCM)

Hence, HCSD, HCVS, SKC and FCM methodologies are examined in this Section for their applicability in adaptive RCM schemes. A desirable property of the adaptive scheme would be the ability to quickly update the RCM based on the new calculated Jacobian matrix. Ideally RCM would be carried out fast enough, in order to also allow CVR to act upon it within its first cycles of operation, i.e. in less than 1min [11]. To get an answer for a realistic size network, for this investigation, the 2383 bus Polish system is used [111]. This system contains 130 generators that have a capacity above 50 MW and overall 151 synchronous control elements that can produce more than 20 MVAR. The annual peak load demand equals 25 GW. Computational times reported in this section are calculated on a PC with 3.2 GHz quad core CPU and 8 GB RAM. Despite the fact that computational speed is anticipated to increase, one must bear in mind that so will the scale and complexity of problems they should tackle.

Figure 5.2 comparatively presents the zoning methodologies computational cost. Note that times reported are the mean value of 100 runs.

HCSD and HCVS methodologies are based on agglomerative hierarchical clustering and their computational complexity depends only on the number of nodes to be clustered. In light of the above one might improve computational time, by collapsing leaf-nodes prior to the agglomerative clustering, as they would in any case cluster within their immediate upstream neighbours. The above option is not deployed in results presented in figure 5.2 as we are seeking for answers on the applicability issue for networks that have not undergone and thus do not have as a pre-requisite any reduction.

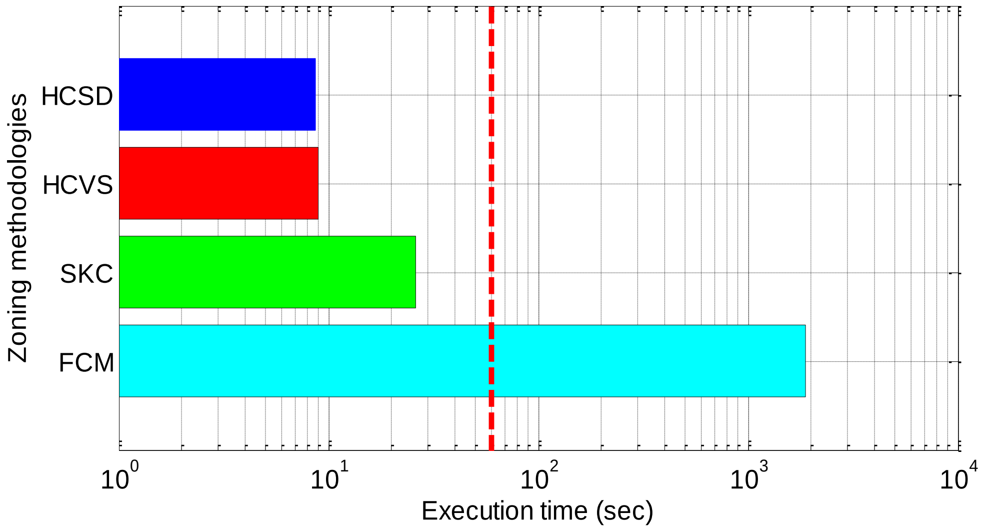


Fig. 5.2 Zoning methodologies' computational cost for the 2383 bus Polish system

The computational complexity of SKC and FCM methodologies is $O(nki)$ and $O(nk^2i)$ respectively [117]. Parameter n accounts for the number of buses to be classified, k is the number of clusters and i the number of maximum iterations.

Regarding SKC methodology the relative eigengap heuristic introduced in Chapter 4, Section 4.3.1 can specify the most desirable number of clusters k prior to the k-means optimization and thus speed up computation time. Parameter k can be bounded within a range $\{k_{min}, k_{max}\}$ that makes sense from an engineering point of view. The upper limit applied here accounts for the number of reactive resources that have a reactive margin above 20 MVAR. The range examined is $\{10{,}151\}$. An investigation into the relative eigengap for the 2383 bus Polish system is shown in figure 5.3 and reveals 17 zones as the optimum answer for SKC.

Based on eigen-gap heuristic, SKC solves the classification problem adequately fast (~7 sec). However the calculation of eigenvalues requires an additional of 21 sec, hence increases the computational cost. Computational times reported in figure 5.2 for the SKC account for both the time needed for eigenvalues calculation and the time required for the k-means optimization. For the latter though the eigen-gap heuristic is deployed particularly for the case of 17 zones, as explained above.

For the FCM methodology the whole $\{10{,}151\}$ range of values needs to be examined, in absence of any relevant heuristic. Figure 5.3 shows how the FCM methodology scales over this range. Times reported in figure 5.2 for the FCM methodology correspond to the

$k_{max} = 151$. It is noteworthy that even at $k_{min} = 10$ zones, computation time exceeds the 60 sec threshold

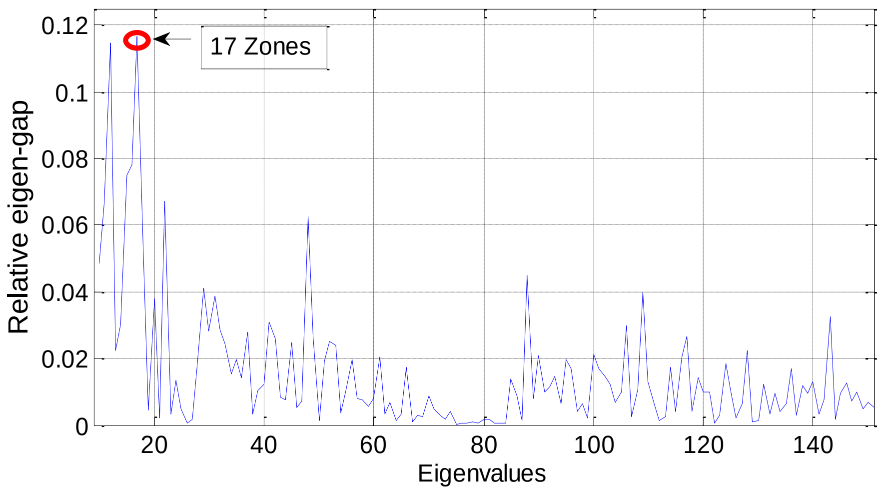


Fig. 5.3 Relative eigen-gap heuristic to determine number of zones for SKC

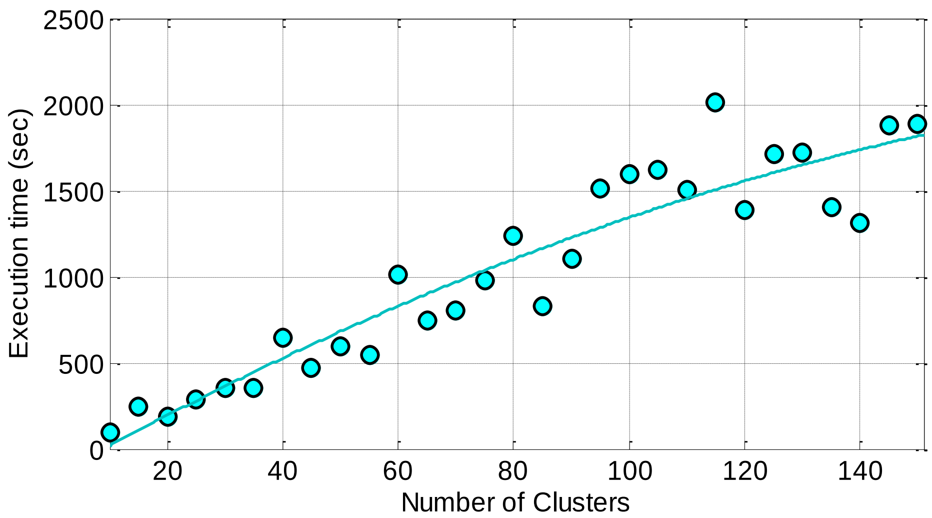


Fig. 5.4 Scalability of FCM for various numbers of zones/clusters

Overall, it can be concluded that HCSD, HCVS and SKC methodologies can determine the Reduction of the Control Model (RCM) in an online fashion, contrary to FCM on a realistic size network that has not undergone any reduction. In particular, methodologies based on agglomerative hierarchical clustering appear to have the best potential. The deployment of relative eigen gap heuristic speeds up SKC and allows its application in the adaptive scheme. In principle it is possible to speed-up FCM as well, see for instance references [118, 119]. However, this is out of the scope of this Chapter, as results of Chapter 4, Section 4.4 indicated that FCM is not that promising in terms of performance it allows to CVR controller, compared to other zoning methodologies (e.g. HCVS and SKC).

5.3 What should trigger the adaptive RCM?

This Section investigates what should trigger the reconfiguration of the Reduced Control Model (RCM). Initially the case study network is presented (Subsection 5.3.1). Subsection 5.3.2 selects a number of representative scenarios on the case study network. Lastly, Sub-section 5.3.3 analyses these scenarios with regards to triggering the adaptive RCM.

5.3.1 Case Study Network: IEEE 30-Bus Test System

The IEEE 30-Bus electrical network represents a portion of the American Electric Power System in the Midwestern US. See figure 5.5 below for a schematic diagram. This network is selected due to the fact that analysis of Chapter 4, Section 4.4 has shown that Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) methodologies all provide identical RCM on this network. Data for the steady-state analysis can be found in reference IEEE Common Data Format by [111]. A brief presentation is given here.

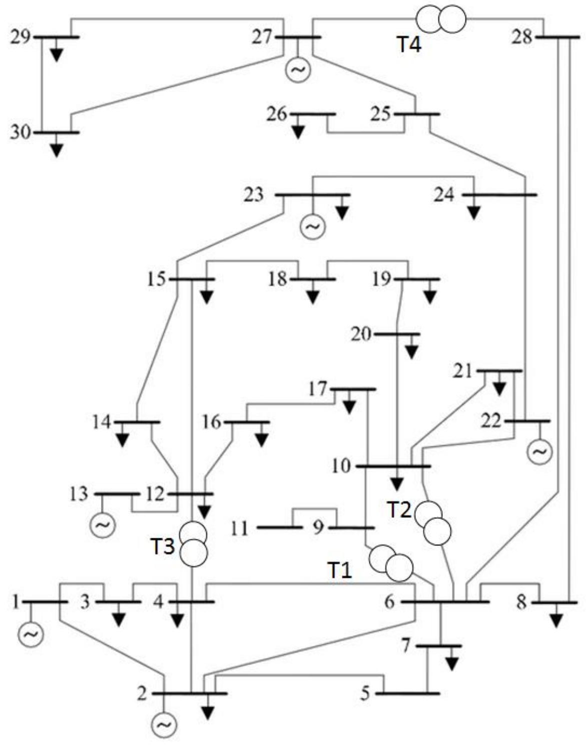


Fig. 5.5 One line diagram- IEEE 30 Bus system [111]

This electrical network contains 132 kV-33 kV voltage levels. It has 30 Buses and 41 branches, hence it is meshed with average degree <k>=2.73. It contains 21 loads served by 6 synchronous generators connected to buses 1, 2, 13, 22, 23 and 27. There are four

Transformers, i.e. T1, T2, T3 and T4 in the lines 6-9, 6-10, 4-12 and 27-28 respectively.

5.3.2 IEEE 30-Bus Test System: Scenario Selection

A number of representative scenarios are next considered on the IEEE 30-Bus Test System including (1) different loading conditions (i.e. scenarios L1-L4), (2) different settings for the transformers (i.e. scenarios TR1-TR4) and (3) different topological changes (i.e. TOP1-TOP4). An explanation of their selection is also provided where needed.

(1) Four loading scenarios are considered and are tabulated in Table 5.1. Minimum, Average and Maximum load are defined as 33%, 68% and 100% respectively of a typical load duration curve. Scenarios L1-L3 are derived assuming uniform ramp up of all loads over the specified base case loading. However, in Scenario L4 the specified overall load increase is allocated randomly to the individual loads (i.e. non-uniform load patterns).

TABLE 5.1

REPRESENTATIVE LOADING SCENARIOS

ID	Scenario
L1	Uniform ramp up Minimum load-Average load
L2	Uniform ramp up Average load-Maximum load
L3	Uniform ramp up Minimum load-Maximum load
L4	Non Uniform ramp up Minimum load-Maximum load

(2) The network contains four regulating transformers, i.e. T1, T2, T3 and T4. The tap changers are modelled with ranges from 0.95 to 1.05 with a step of 0.01 p.u. representing a tap operation. As such 12 tap positions are possible for each transformer and are referred to as {5-4,-3,-2,-1,0,1,2,3,4,5} with tap position 0 (i.e. 1.0 p.u. for the secondary side) selected as the initial setting. Overall 11^4 configurations can be achieved. Among those, of particular interest are scenarios TR1-TR4 tabulated in Table 5.2. TR1 scenario accounts for maximum stepping up of all transformers T1, T2, T3 and T4 over minimum loading conditions to deal with over-voltages. TR2 scenario accounts for maximum stepping down of all transformers T1, T2, T3 and T4 over maximum loading conditions to deal with under-voltages. TR3 scenario accounts for the peculiar case where system is in average loading conditions and loads in the network demonstrate a sharp instantaneous drop with the exception of loads on buses 7, 8, 10, 16, 19, 20, 21 that demonstrate a sharp instantaneous increase. Hence, T1 and T2 step up to the highest tap possible, while T3

and T4 step down to the lowest tap possible. Lastly, scenario TR4 accounts for the case of system being in maximum load with random non-uniform load increase taking place. Hence, T1, T2, T3 and T4 step up to different settings.

TABLE 5.2

REPRESENTATIVE OLTCs SCENARIOS

ID	Scenario							
	Tap setting: Initial State				Tap setting: Final State			
	T1	**T2**	**T3**	**T4**	**T1'**	**T2'**	**T3'**	**T4'**
TR1	0	0	0	0	-5	-5	-5	-5
TR2	0	0	0	0	+5	+5	+5	+5
TR3	0	0	0	0	+5	+5	-5	-5
TR4	0	0	0	0	+3	+3	+4	+1

(3) Topological changes refer to N-1 line tripping. The IEEE-30 bus test system contains 41 lines. Prior to scenario selection, N-1 Contingency analysis of this network is performed by iteratively switching off one line and checking for convergence. This is an important step, as non-convergent cases, either call for a new solution of the Real Power problem [120] prior to AVC or signify that the Operator must move to emergency control and AVC is not of interest.

The analysis revealed that convergence was not found upon switching off branches connecting buses 9 to 11, 12 to 13 and 25 to 26. This intuitively makes sense as the first two cases disconnect a load bus with no redundancy and the last case disconnects a synchronous generator which again has single access to the network. Four line trips are then considered out of the remaining 38 lines and the selection is done based *on a novel index, developed as part of this research. This novel index is termed Variation of Pilot Node Centrality and referred to as* $VPNC$. The proposed $VPNC$ index is formulated below.

Variation of Pilot Node Centrality (VPNC) :

The Variation of Pilot Node Centrality VPNC index describes the effect the removal of the i-th line of a zone C has on the centrality of the zonal pilot node m. The centrality of the pilot node of zone C is defined in (5.1)

$$L_m = \sum_{m,n \in C} D_{mn} \tag{5.1}$$

And the variation of Pilot Node Centrality is defined in (5.2)

$$VPNC_i = \frac{L_m^i}{L_m} \tag{5.2}$$

Where L_m^i accounts for the revised centrality of pilot node m, following the removal of line i. In cases where line i is a boundary line, $VPNC_i$ is calculated with respect to the pilot node of both adjoining areas and is assigned the maximum value of the two.

Note that $VPNC_i \geq 1$. Overall, the greater the *VPNC* value, the greater the variation of pilot nodes centrality following the line removal.

And the following nomenclature:

D_{mn}	Electrical distance between buses m and n
m	Zonal Pilot node
L_m	Zonal centrality of node m
L_m^i	Zonal centrality of node m, upon removal of line i

The VPNC for each line removal is presented in figure 5.6 below along with the convergence of the study case. Using the ranking of figure 5.6, four scenarios are selected, i.e. TOP1, TOP2, TOP3 and TOP4 accounting for a high, average to high, average to low and low VPNC index. These scenarios are tabulated in Table 5.3.Ultimately, Tables 5.1, 5.2 and 5.3 contain 12 representative scenarios that are worth-examining with respect to whether they should trigger adaptive RCM or not.

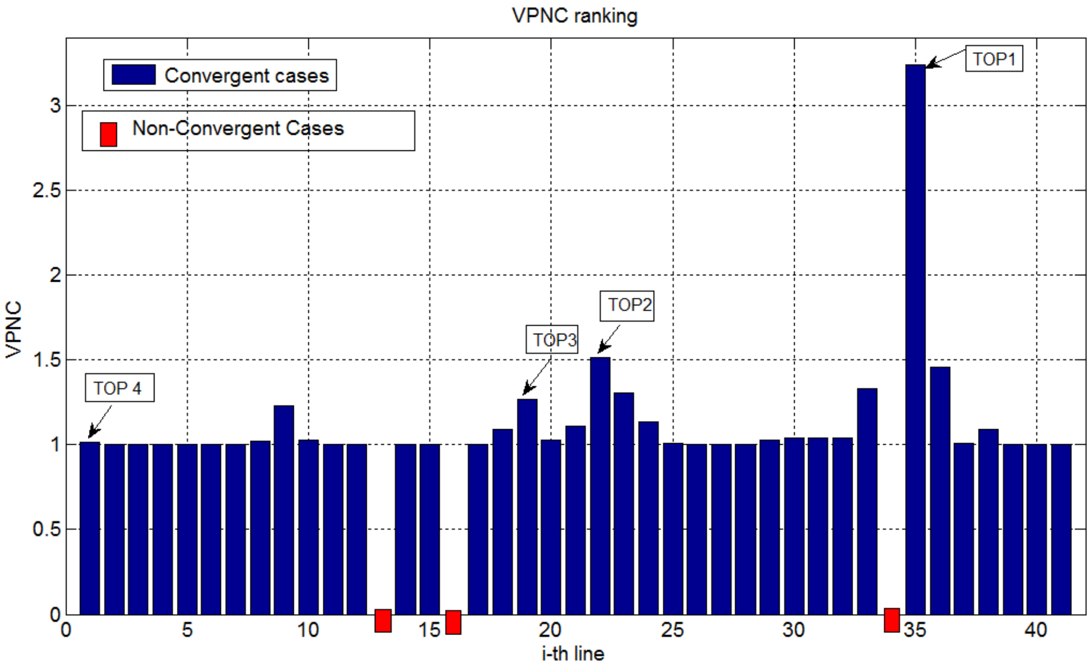


Fig. 5.6 VPNC Ranking of line removal

TABLE 5.3

REPRESENTATIVE SCENARIOS OF LINE TRIPS

ID	Scenario
TOP1	Trip 35th line among buses 25-27 ($VPNC_{35} = 3.239$)
TOP2	Trip 22nd line among buses 15-18 ($VPNC_{22} = 1.516$)
TOP3	Trip 19th line among buses 12-16 ($VPNC_{19} = 1.271$)
TOP4	Trip 1st line among buses 1-2 ($VPNC_{1} = 1.012$)

5.3.3 What should trigger the adaptive RCM? *Results & Discussion*

This Sub-section presents results on what should trigger the adaptive RCM, by analysing the scenarios selected in Sub-section 5.3.2 above on the IEEE 30 Bus system.

All scenarios derived in Sub-section 5.3.2 have been analysed with regards to whether they should trigger adaptive RCM or not. Table 5.4 lists the results; 1st column contains the scenario ID, while 2nd column reports whether the scenario resulted in different zoning boundaries. Note, that different zoning boundaries do not necessarily result in different Reduction of the Control Model (RCM), hence the 3rd column reports whether a scenario which triggers new zoning boundaries results also in a new RCM.

TABLE 5.4

DRIVERS TO ADAPTIVE RCM

ID	Zone Division	RCM
L1	Unaltered	NA
L2	Unaltered	NA
L3	Minor alterations on zone boundaries	Unaltered
L4	Minor alterations on zone boundaries	Unaltered
TR1	Minor alterations on zone boundaries	Unaltered
TR2	Minor alterations on zone boundaries	Unaltered
TR3	Minor alterations on zone boundaries	Unaltered
TR4	Minor alterations on zone boundaries	Unaltered
TOP1	Major alteration on zone boundaries	Major Alteration
TOP2	Different number of zones and boundaries	Major alteration
TOP3	Different number of zones and boundaries	Major alteration
TOP4	Minor alterations on zone boundaries	Unaltered

As can be seen in Table 5.4 it is mainly topological changes or topological changes under different loading conditions & OLTC settings that trigger the adaptive RCM. TOP1, TOP2 and TOP3 scenarios all trigger adaptive RCM, contrary to scenario TOP4. The proposed in this research index, i.e. Variation of Pilot node Centrality is particularly useful in understanding and assessing when adaptive RCM should be triggered. Another criteria could be the saturation of certain synchronous control resources or constrained generators access to the network following for instance a topological change. Merely loading changes or different tap configurations on the OLTC may alter slightly the zones boundaries, they should not however trigger adaptive RCM. The above findings are elaborated below, using scenarios L4 and TOP2.

- **Scenario L4**

Figure 5.7 presents the eigen gap analysis for scenario L4; State A is that of minimum loading, while state B is generated with non-uniform ramp up of all nodes, up to maximum loading.

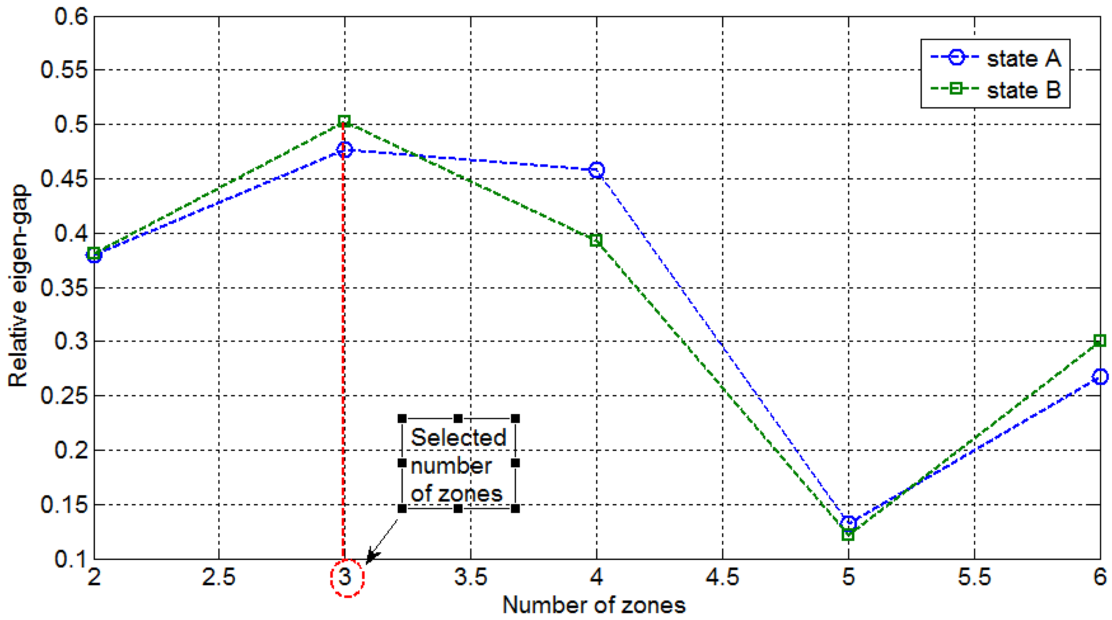


Fig. 5.7 Scenario L4: Eigen gap analysis

As can be seen from figure 5.7 the number of zones remains unchanged. However, figure 5.8 reveals that zone boundaries slightly change in scenario L4. This only moves bus 24 to the neighbouring zone, while pilot nodes and controlling resources in each zone remain unchanged, as can be seen in figure 5.8.

- **Scenario TOP2**

Figure 5.9 presents the eigen gap analysis for scenario TOP2; State A is that of maximum loading and initial topology, while state B is generated with maximum loading and line 22 between buses 15-18 tripped. As can be seen from figure 5.9 state B triggers re-zoning and admits a strong decomposition into 4 zones instead of 3 that best suits the initial topology and state.

Figure 5.10 presents the adaptive RCM for the scenario TOP2. The left part of the figure presents the initial RCM of state A, while the right part of the figure presents the new RCM corresponding to state B of scenario L4. The latter demonstrates a different number of zones, pilot node set and allocation of the controlling resources, compared to that of state A.

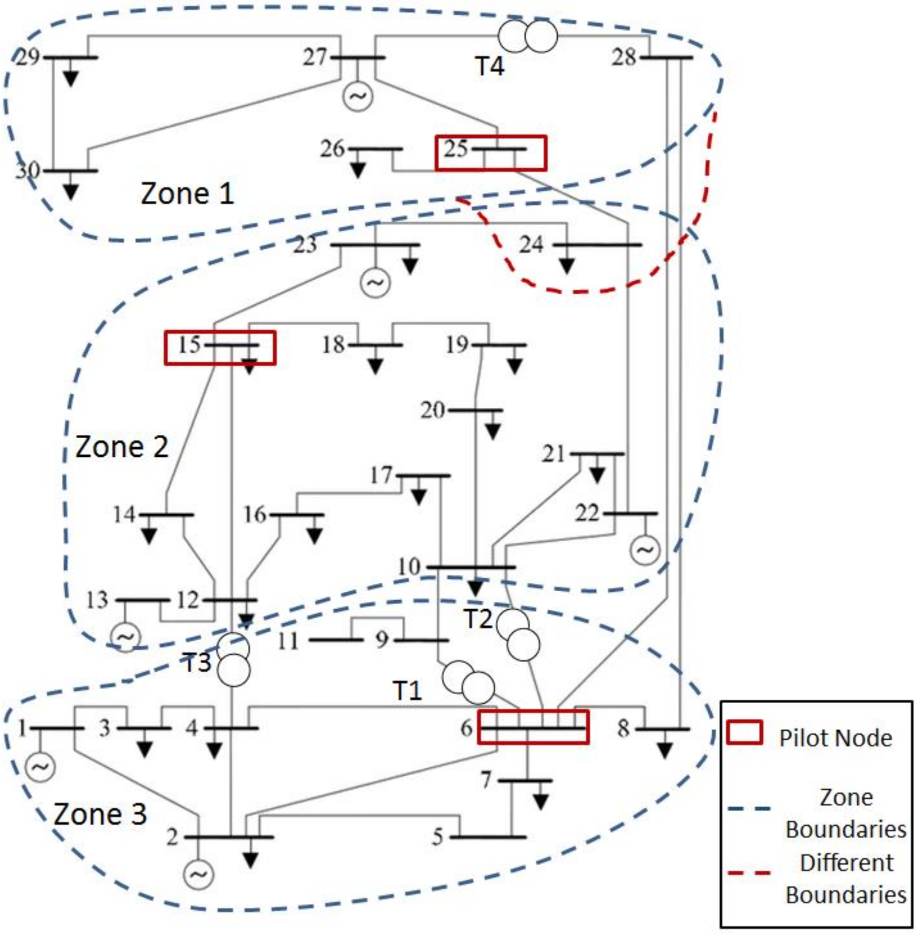


Fig. 5.8 Scenario L4: Zoning based RCM

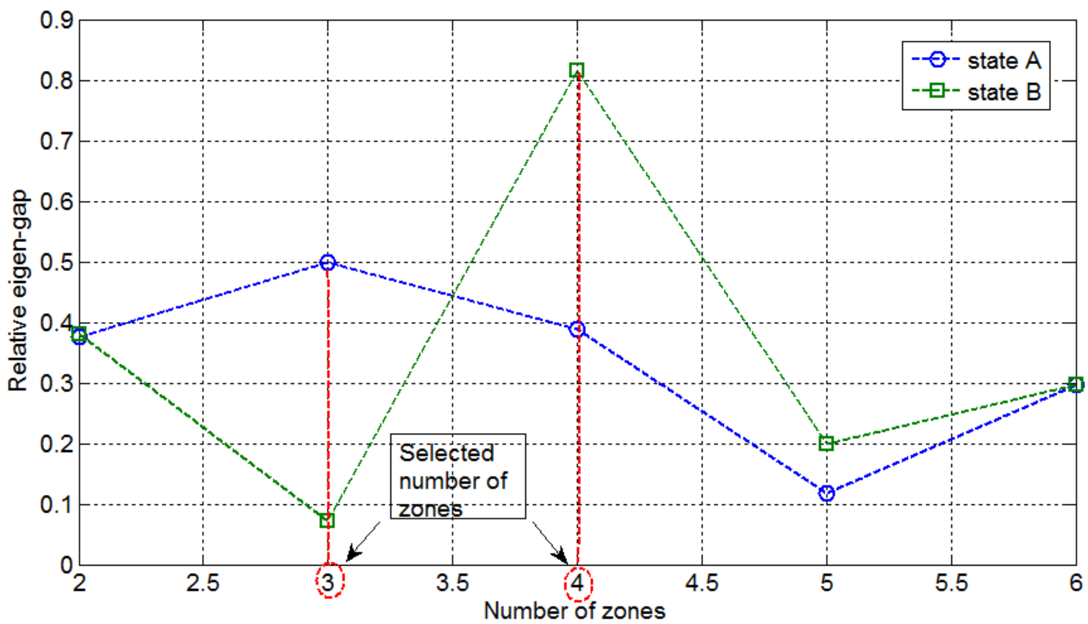


Fig. 5.9 Scenario TOP2: Eigen gap analysis

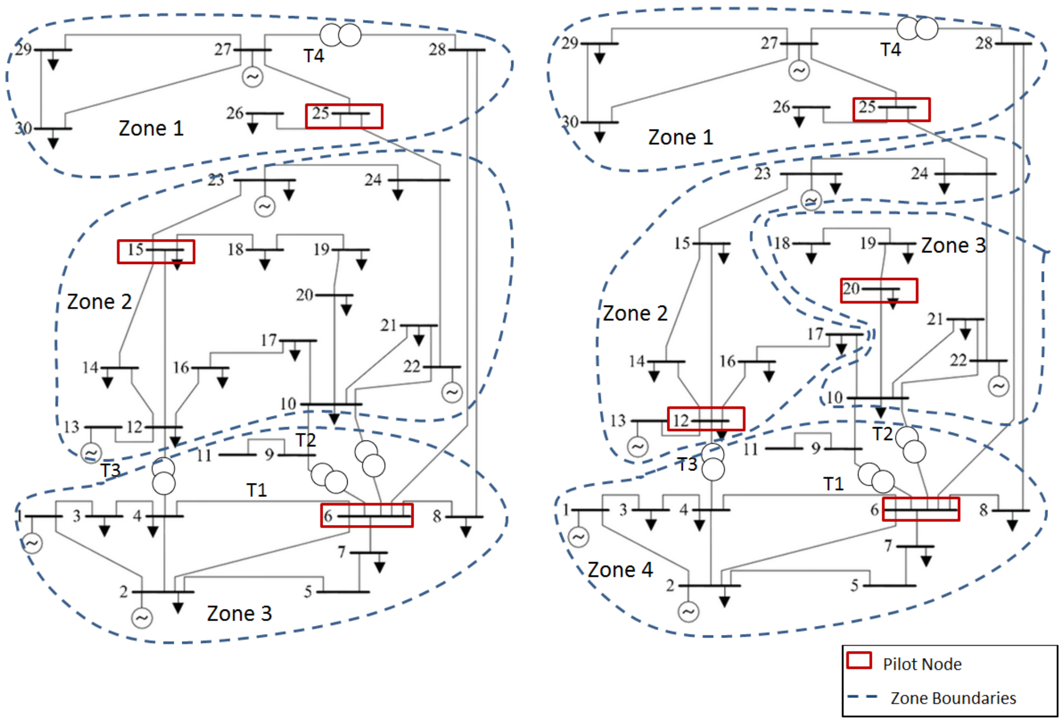


Fig. 5.10 Scenario TOP2: Left side -Zoning based RCM for state A, Right side-Zoning based RCM for state B

5.4 Value of adaptive RCM from a control perspective

This section identifies and discusses the main benefits that can be achieved with adaptive Reduction of the Control Model (RCM) and consequently addresses its value from the perspective of the control engineer.

Large blackouts in Europe have motivated the study and implementation of Coordinated Voltage Regulation (CVR) as a way to enable online optimization. Within this context, this Sub-section argues that adaptive RCM can provide primarily more secure but also more economic CVR in presence of contingencies. Two study cases are presented below, to demonstrate (a) improved security with adaptive RCM in CVR and (b) improved economy with adaptive RCM in CVR.

- **Study Case 1**: The system is assumed to be in maximum loading conditions, as this is when the effect of CVR is most significant (i.e. State A), when the 35 line gets tripped similar to scenario TOP1 of Table 5.3 above and reactive load increases sharply by 20% (i.e. State B).

Figure 5.11 presents the eigen gap analysis for Study case1 for each of the States A and B. Despite the fact that states A,B both admit a decomposition into three zones, the zoning boundaries and the resulting RCM differ, as figure 5.12 demonstrates.

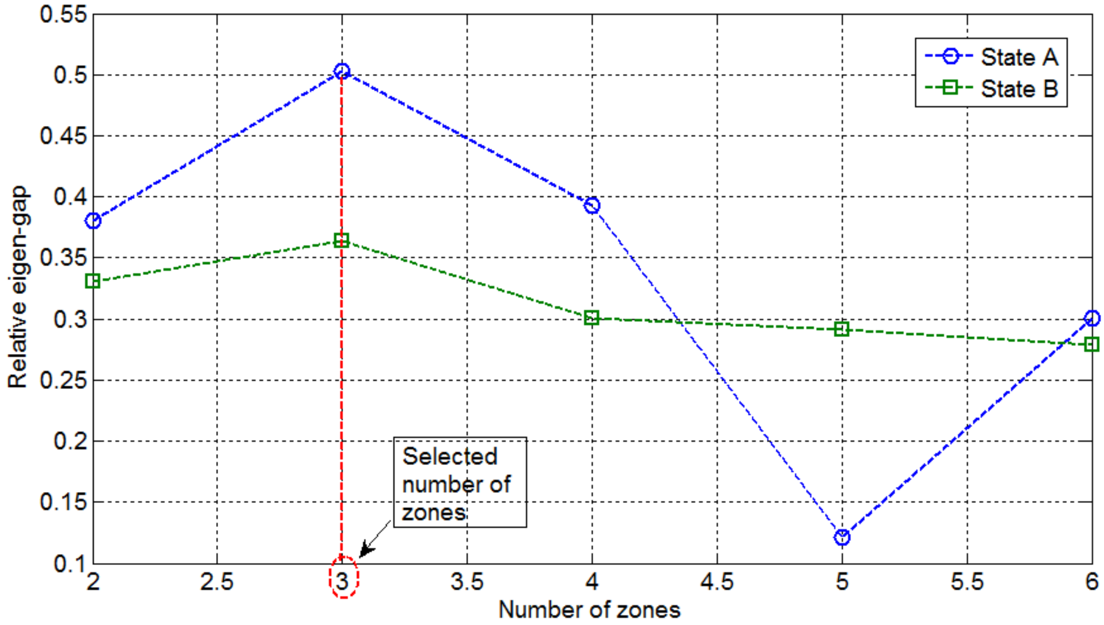


Fig. 5.11 Study case 1: Eigen gap analysis

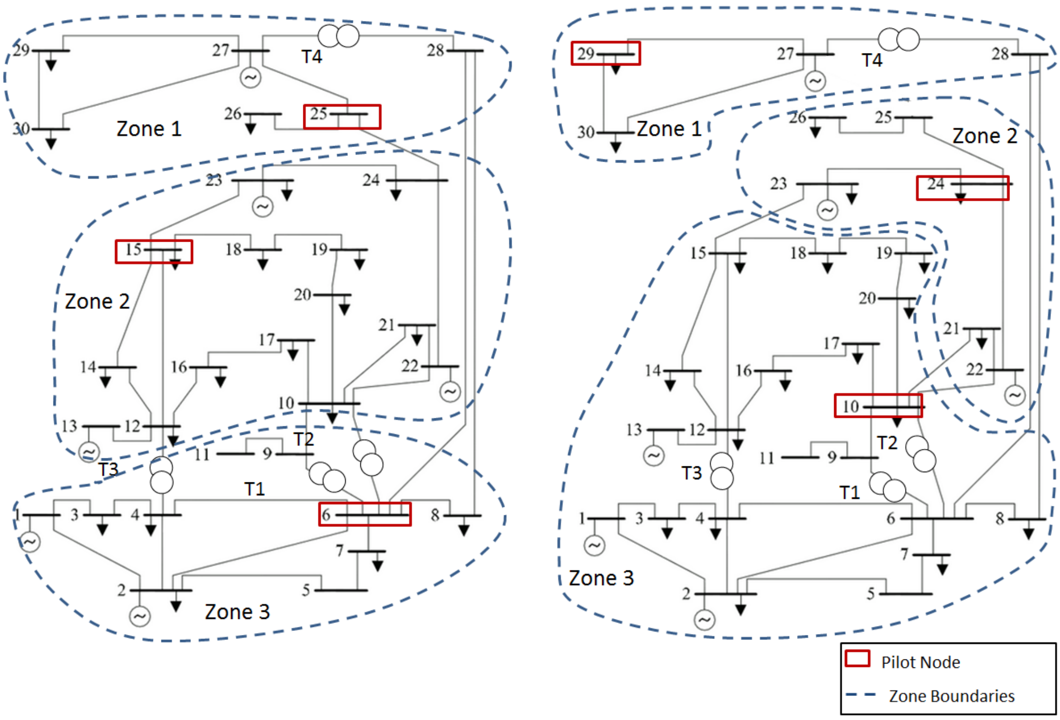


Fig. 5.12 Study case 1: Left side -Zoning based RCM for state A, Right side- Zoning based RCM for state B

Ultimately, Coordinated Voltage Regulation (CVR) with *static Reduction of the Control Model (RCM)* deploys the zoning based RCM of the left side of figure 5.12 for both states A and B. On the contrary, CVR with *adaptive RCM* deploys the zoning based

RCM of the left side of figure 5.12 for state A and it will deploy the zoning based RCM of the right side of figure 5.12 if network conditions resemble those of state B.

In the following, voltage profile after CVR control is presented in figure 5.13, when state B triggers the control, in two configurations; (a) CVR is used in conjunction with static RCM and (b) CVR is used in conjunction with adaptive RCM. As can be seen from figure 5.13, CVR in conjunction with adaptive RCM manages to keep the voltages within bounds and also adequately close to the pre-specified by ROPF set-points. On the contrary, CVR in conjunction with static RCM fails to keep voltage within limits and results in two significant voltage violations. This is mostly due to the fact that pilot node 25 fails to represent the load buses of Zone 1 and synchronous generator on bus 27 has nearly zero regulating effect on bus 25.

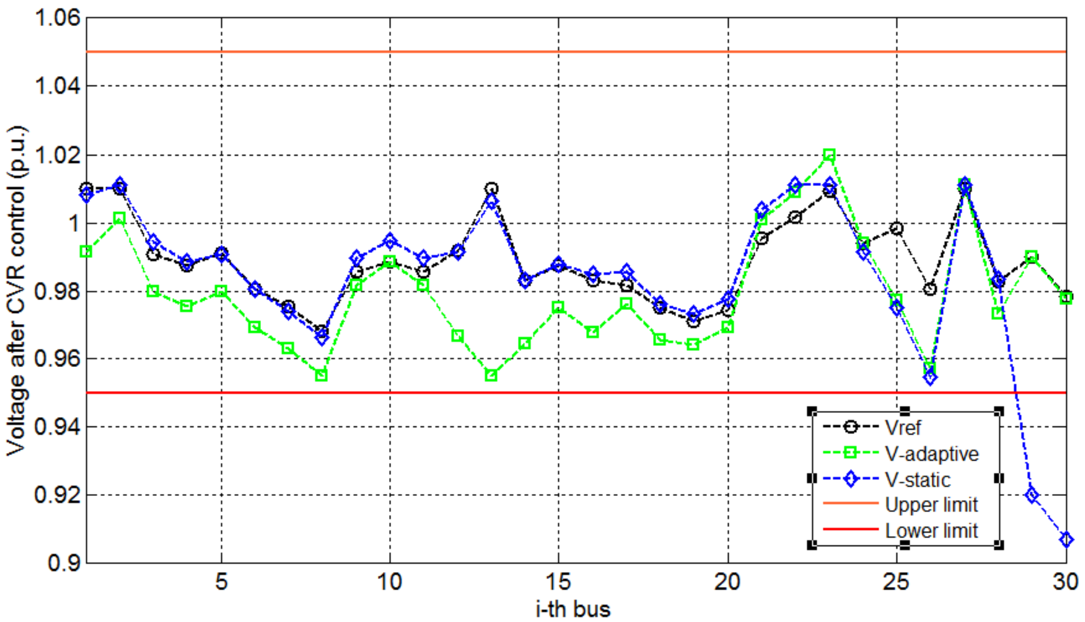


Fig. 5.13 Case 1: Voltage profiles after CVR control with static and adaptive RCM

With regards to overall evaluation of this CVR cycle, it is more appropriate to use the Voltage Criticality Index (VCI) rather than the Overall Performance Index (OPI), given that there are voltage contingencies after the CVR control. Justification of both VCI and OPI indices can be found in Chapter 3, Section 3.2.2. VCI is formulated below;

For the i-th PQ bus, its proximity to voltage limits can be quantified by equation in (5.3).

$$J_i = \frac{|V_{ac} - \mathrm{V}_{\mathrm{ref}}|}{|V_{lim} - V_{ref}|} \qquad (5.3)$$

Voltage Criticality Index can be defined as in (5.4).

$$VCI = \sum_{i=1}^{N_{bus}} \gamma_i \cdot J_i.^2 \qquad (5.4)$$

Where γ_i is a logic variable and equals 1 if voltage is outside limits, otherwise it is set to 0. Index ac signifies value after control, ref signifies reference value and lim the respective voltage limit. The greater the VCI value the more and wider the violations. VCI performance for CVR in conjunction with static and adaptive RCM are shown in Table 5.5.

TABLE 5.5
CVR PERFORMANCE OF STUDY CASE1
USING VCI INDEX

Case	**VCI (p.u.)**
CVR with static RCM	9.41
CVR with adaptive RCM	0

The above example indicates that adaptive RCM can improve system stability and performance in presence of contingencies, before CVR reaches its limits. When CVR reaches its limits, protection will respond if it is voltage based or in the general case, emergency control will take place. Practices vary from one System Operator to another though. Often, manual control is in place subject to the engineer's experience. The Control engineer might wait a few cycles of operation for the contingencies to be cleared without acting, however in the examined scenario this would not have brought voltage back within limits.

A first resort in emergency control and a plausible action in the examined scenario is Under Voltage Load Shedding (UVLS). Overall, the goal of the UVLS scheme is to shed load to restore reactive power relative to demand, to prevent voltage collapse and to contain a voltage problem within a local area rather than allowing it to spread in geography and magnitude and result in loss of a great deal of load in an uncontrolled fashion [121].

UVLS practices also vary from one System Operator to another. For the examined scenario, we refer to NERC standards due to the origin of the study case network. NERC [122] would drop several hundred megawatts of load in pre-selected blocks within load centres 29 and 30, triggered in stages as local voltage drops to a designated level—likely 94%—with a several second delay. If the first load-shed step does not allow the system to rebalance, and voltage continues to deteriorate, then the next block of load would be dropped. The exact amount of load shedding is unclear here, due to the fact that this analysis is state based and not in the time domain, however under NERC standards load shedding is what inevitably would happen in CVR with static RCM. On the contrary, were CVR to deploy adaptive RCM the system would remain in normal operation.

- **Study Case 2**: The system is assumed to be in maximum loading conditions, as this is when the effect of CVR is most significant (i.e. State A), when the 19th line gets tripped similar to scenario TOP3 of Table 5.3 above and reactive load increases sharply by 20% (i.e. State B).

Figure 5.14 presents the eigen gap analysis for Study case 2 for each of the States A and B. State A admits a decomposition into three zones, while state B admits a strong decomposition into four zones. Figure 5.15 presents the zoning boundaries for states A, B and the resulting new RCM.

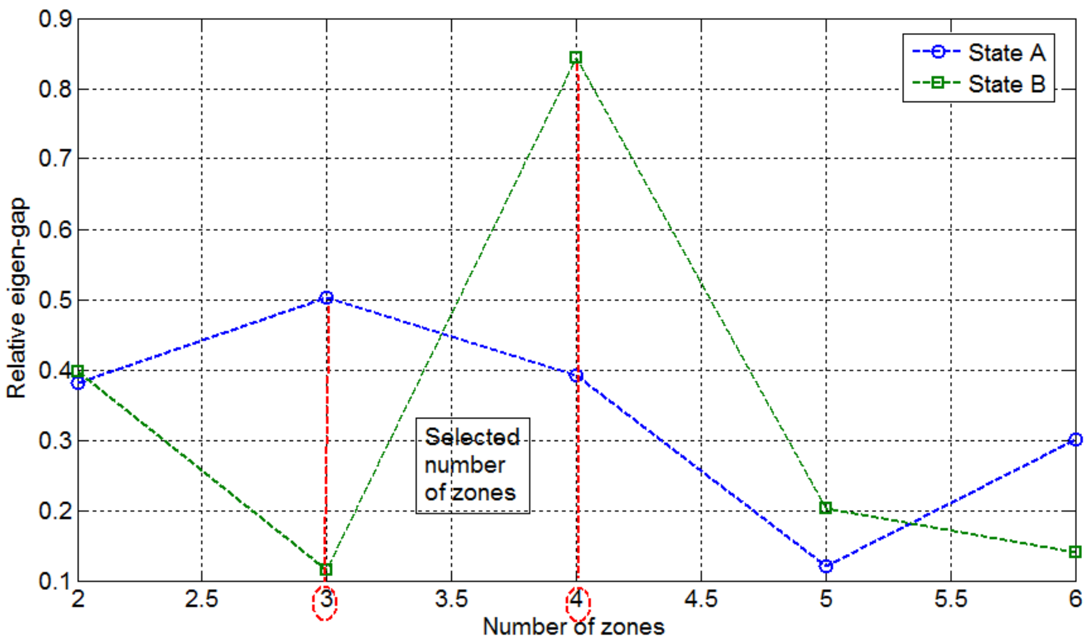


Fig. 5.14 Study case 2: Eigen gap analysis

Ultimately, CVR with *static RCM* deploys the zoning based RCM of the left side of figure 5.15 for both states A and B. On the contrary, CVR with *adaptive RCM* deploys the zoning based RCM of the left side of figure 5.15 for state A and it deploys the zoning based RCM of the right side of figure 5.15 if network conditions resemble those of state B.

In the following, the voltage profile of all load buses after a round of Coordinated Voltage Regulation (CVR) is presented in figure 5.16, when state B triggers the control, in two configuration; (a) CVR is used in conjunction with static RCM (i.e. V_static) and (b) CVR is used in conjunction with adaptive RCM (i.e. V_adaptive). As can be seen, both cases keep voltage within limits. Of course, the extracted voltage profiles in both cases are non-identical to the target profile and this is due to the fact that a Reduced Control Model (RCM) is used in CVR in the first instance. It is noteworthy though that CVR with adaptive RCM follows more closely the reference targets. For few buses static RCM is closer to the reference targets compared to the adaptive RCM, however these are cases that adaptive RCM results in higher voltages and thus reduced losses. On the contrary, for a few buses static RCM is further from the reference targets compared to the adaptive RCM and achieves voltages close to lower limits, which signifies reduced economy and security.

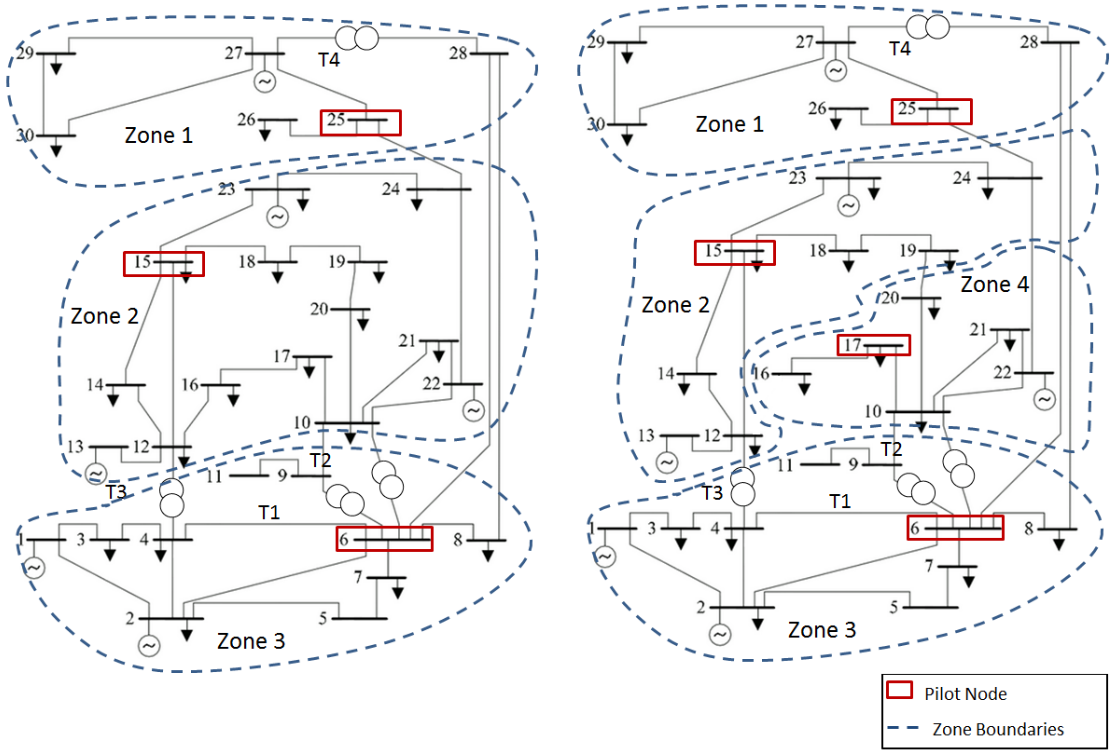


Fig. 5.15 Study case 2: Left side -Zoning based RCM for state A, Right side- Zoning based RCM for state B

In the following, the voltage profile of all load buses after a round of Coordinated Voltage Regulation (CVR) is presented in figure 5.16, when state B triggers the control, in two configuration; (a) CVR is used in conjunction with static RCM (i.e. V_static) and (b) CVR is used in conjunction with adaptive RCM (i.e. V_adaptive). As can be seen, both cases keep voltage within limits. Of course, the extracted voltage profiles in both cases are non-identical to the target profile and this is due to the fact that a Reduced Control Model (RCM) is used in CVR in the first instance. It is noteworthy though that CVR with adaptive RCM follows more closely the reference targets. For few buses static RCM is closer to the reference targets compared to the adaptive RCM, however these are cases that adaptive RCM results in higher voltages and thus reduced losses. On the contrary, for a few buses static RCM is further from the reference targets compared to the adaptive RCM and achieves voltages close to lower limits, which signifies reduced economy and security.

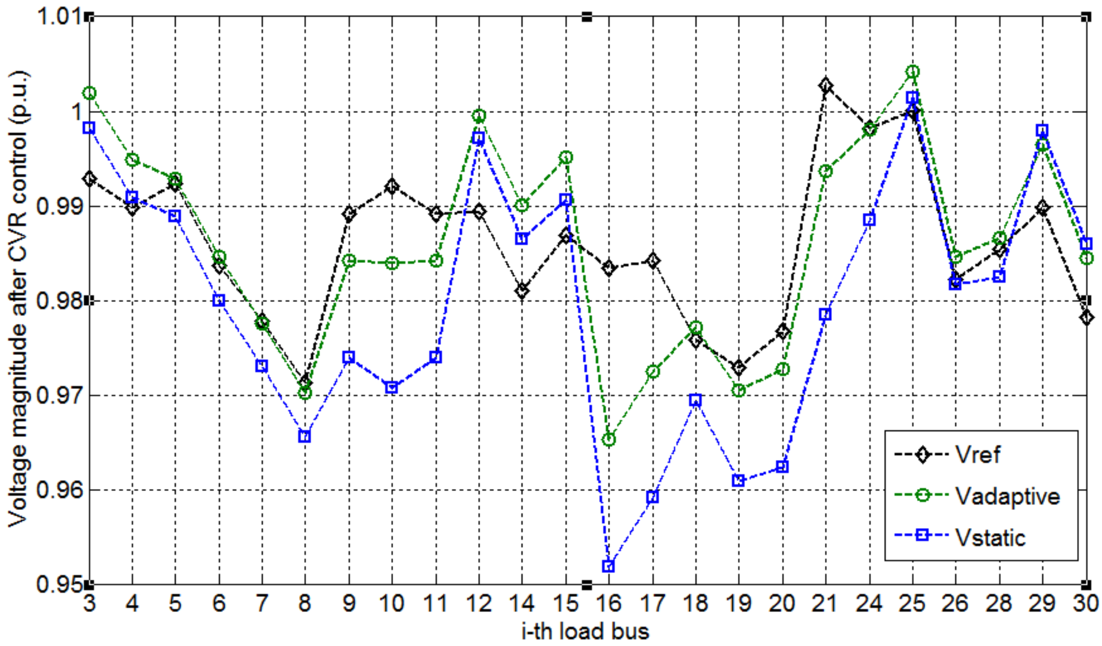


Fig. 5.16 Case2: Voltage profiles after CVR control with static and adaptive RCM

It is also noteworthy that the above results are achieved with comparable deployment of reactive reserves for static and adaptive RCM, as table 5.6 indicates. The overall increase in the reactive reserves deployed compared to the ROPF solution is explained obviously from the 20% reactive load increase.

TABLE 5.6
CVR PERFORMANCE OF STUDY CASE2
USING PI INDEX

Case	$\sum_{i\in CVRgen} Qgen_i$ **(MVAr)**
ROPF- reference values	98.04
CVR with static RCM	117.89
CVR with adaptive RCM	117.03

In addition to this, Table 5.7 compares the increase in real losses for both the case of static and adaptive RCM. This is expressed as a ratio using as baseline the real losses of the ROPF solution. The results of table 5.7 indicate that adaptive RCM is more economic compared to static RCM. This result shows that the voltage profile with adaptive RCM is more desirable to the one achieved with static RCM.

TABLE 5.7
REAL LOSSES RATIO FOR
STATIC AND ADAPTIVE RCM

Case	$P_{losses} ratio$
CVR with static RCM	+0.17%
CVR with adaptive RCM	+0.11%

With regards to overall evaluation of this CVR cycle, it is more appropriate to use the Overall Performance Index (OPI) index rather that the Voltage Criticality Index (VCI), given that voltage remains within bounds after the CVR control. The performance OPI of one iteration of the CVR is assessed based on the average absolute relative error for the N load buses, as in (5.5):

$$\mathrm{OPI} = 1 - \frac{1}{\mathrm{N}} \cdot \sum_{\mathrm{i}=1}^{\mathrm{N}} \left| 1 - \frac{\mathrm{V_{ac}(i)} - \mathrm{V_{ad}(i)}}{\Delta V(\mathrm{i})} \right| \qquad (5.5)$$

Where ac signifies value after control and ad signifies value after disturbance. ΔV accounts for the difference between the voltage after disturbance and the specified voltage target from ROPF. VCI index is obviously zero for both the static and adaptive case. However, to further support the argument that in the general case adaptive RCM enhances both the security and economy of CVR a relaxed VCI definition is used exceptionally that is formulated as follows:

$$VCI_{rel} = \sum_{i=1}^{N_{bus}} J_i.^2 \qquad (5.6)$$

i.e. compared to equation 5.2 the logic variable is dropped. Table 5.8 compares CVR with static RCM to CVR with adaptive RCM using both OPI and VCI_{rel} indices.

TABLE 5.8
CVR PERFORMANCE OF STUDY CASE2
USING PI INDEX

Case	OPI (%)	$\mathbf{VCI_{rel}}$ (p.u.)
CVR with static RCM	58.91	1.895
CVR with adaptive RCM	89.14	0.545

As can be seen, static RCM is characterized by a significantly lower OPI value and a much higher $\mathbf{VCI_{rel}}$ value compared to that of adaptive RCM. The above indicates that adaptive RCM allows more secure and economic CVR in presence of significant contingencies.

Regarding frequency of adaptive reconfiguration of the RCM, according to [22], Jiangsu Power Grid deployed this action 6 times in 2008. Adaptive reconfiguration of the RCM might be deployed more frequently in more stressed networks, particularly if they are characterized by increased operational uncertainty. Overall, the author considers adaptive reconfiguration of the RCM as one of the actions CVR can take before CVR reaches its limits and emergency control takes place. Within this context, this Section provided novel insight into potential benefits that can be achieved with adaptive RCM. While benefits cover both aspects of economy and security, adaptive RCM in CVR is more meaningful as a means to improve security, i.e. stability in presence of contingencies.

5.5 Major implementation challenges

This section identifies and discusses the main implementation challenges the inclusion of adaptive Reduction of the Control Model (RCM) in Coordinated Voltage Regulation (CVR) presents.

Irrefutably, RCM enabled CVR in transmission grids relies on the availability of online measurements at a number of substations and two-way reliable communication between certain substations, controlling elements and a Supervisory Control Centre.

In today's transmission grids, the only real-time data that exits the substation through the RTUs are collected at the Control Centre where the Supervisory Control and Data Acquisition—Energy Management System (SCADA-EMS) can display and further analyse the data for the operator to take supervisory control actions, mostly manual ones. The only standardized closed-loop control done at the control centre is Automatic Generation Control (AGC), and some European and Chinese systems have now incorporated Automatic Voltage Control (AVC). In actuality not much data is transmitted out of the substation today and this limited volume of data is gathered by SCADA at a slow rate, about every 2-10 sec.

Currently, Coordinated Voltage Regulation (CVR) uses raw data from SCADA as input, rather than using State Estimation (SE) results, similarly to AGC. The SE results are the optimized value depending on all the related measurements, so sometimes a topology error, an incorrect parameter or some unimportant measurements with low accuracy may result in large residuals on the important points after estimation. Hence, CVR not depending on the SE is a recommended approach particularly in highly observable networks, however this highlights the need for accurate data monitoring and reliable communications for data acquisition.

The inclusion of adaptive RCM in CVR can improve system stability and performance in presence of severe contingencies, as demonstrated in Section 5.4 above. It presents though a number of challenges in its implementation that are discussed below:

(a) Within the adaptive RCM scheme, *any strong with regards to voltage control and highly connected substation may become pilot substation* for the CVR. Even so, adaptive RCM does not jeopardize the desired engineering simplification of on-line automatic control that CVR is designed to deliver. All Reduced Control Models produced in an adaptive fashion are of roughly equal size, which means relatively fixed computational costs for the CVR and safe convergence of the optimization problem, as well as flat and high reliability for the acquisition of control and feedback signals. *It does however require increased sensing and telecommunication capabilities.*

(b) It requires increased awareness both at a local-substation level and at a Supervisory-control centre level. This can take the form of robust local state estimators at substations in addition to measurements for improved local awareness and cyber security (e.g. bad data detection at the substation level). Also new functionalities at the control room for improved awareness, including an assessment of how well suited a current RCM is.

(c) Adaptive RCM challenges the supporting control and data CVR architecture.

Within the adaptive RCM based CVR, there are two main configurations of the control architecture:

(1) Forming a hardware-based control centre in each zone, in addition to the Supervisory Control Centre that co-ordinates the individual zones, similarly to the European CVR schemes which are based on fixed zone definition.

(2) Forming zones that are separated logically and not by physical equipment. In this case Secondary Voltage Regulators (SVRs) and the Co-ordination of the SVRs are implemented at the same Control Centre (CVR) using software modules, similarly to the Chinese CVR implementation [22]. Controlling elements can be equipped with a Secondary High-Side Voltage Control (HSVC). An HSVC never knows, and never needs to know, the specific control zone to which it has been assigned by the RCM

(re)configuration module. It simply sends data upwards and receives commands from the Supervisory Control Centre for CVR. The RCM configuration module determines which substations should play the role of the pilot nodes, so that voltage measurement from a judiciously selected subset of substations is sent to the Supervisory Control Centre to enable improved Wide-area CVR.

For a network with N load-substations and K Synchronous controlling elements, configuration in (1) would require an additional N*K communication links and would increase respectively by N*K messages the data traffic, compared to the configuration in (2). From the point of engineering simplicity, configuration in (2) is most plausible, provided that in case of upward-communication interruptions (i.e. pilot node measurement to Supervisory Control Centre for CVR) all Zonal Controlling elements reside to High Side Voltage Control (e.g. with 1.0 p.u. or a predefined set point).

To the author's opinion, items in (a)-(c) are the most significant implementation challenges, mostly because they are subject to transmission grids becoming smarter. It is noteworthy, however, that the enabling requirements for adaptive RCM are gradually becoming available through the on-line remote sensing and command infrastructures that are deployed by the utilities under the umbrella of smart grids.

5.6 Concluding Remarks

This Chapter defines adaptive RCM as zoning-based Reduced Control Models that are determined in an online event driven fashion. Experiments carried out on a realistic size network that has not undergone any previous reduction demonstrate the feasibility of the Hierarchical Clustering (i.e. Hierarchical Clustering with Single Distance and Hierarchical clustering in VAR Space) and Exclusive Clustering based (i.e. Spectral K-way Clustering) techniques in the adaptive scheme from a computational perspective.

Large blackouts in Europe have motivated the study and implementation of Coordinated Voltage Regulation (CVR) as a way to enable online optimization. With this in mind, we consider zoning reconfiguration as one of the actions CVR can take to improve system stability and performance in presence of contingencies, before CVR reaches its limits and emergency control takes place. Within this context, this Chapter provides novel insight into the value of adaptive RCM from a control perspective, and concludes that adaptive RCM can result in avoidance of potential load-shedding, following a significant event.

An alternative to adaptive RCM not explored in this Chapter is the case-based reasoning RCM. The author acknowledges that this approach will be recommended in the transition towards smart-er transmission grids, when observability is still limited. Adaptive RCM in this Chapter does not consider any observability limitations, due to the fact that it targets future power networks [115]. In this case it is believed that the deployment of RCMs is driven by the need for reliability, engineering simplicity and guarantee of CVR convergence rather than economy of measurement points at a planning phase.

This Chapter concludes by identifying the major implementation challenges in the consideration of adaptive RCM in CVR. It is explained that adaptive RCM does not jeopardize the desired engineering simplification of on-line automatic control that CVR is designed to deliver it does however rely on increased monitoring and communications. The latter are becoming available through the on-line remote sensing and command infrastructures that are deployed by the utilities under the umbrella of smart grids.

Chapter 6

CVR from a whole system perspective

The previous chapters have focused on multiple zones for Coordinated Voltage Regulation (CVR) which belonged to the transmission grid, within the authority of a single Independent System Operator (ISO). This Chapter aims to investigate CVR from a whole system perspective, hence beyond the determination and control of the individual CVR zones. To that end, (a) a horizontal and vertical zone division is presented ranging from EHV down to MV and multiple ISO areas, CVR zones and CVR sub-zones are defined. Additionally, (b) the required degree of co-ordination is investigated for the voltage control of both horizontal and vertical zones. Indicative Results are presented on the 68-bus test system which has been modified to include an MV feeder.

6.1 Voltage zones from EHV down to MV

This section contains a presentation of voltage zones, ranging from EHV to MV.

In chapters 3-5, zoning enabled Coordinated Voltage Regulation (CVR) has been examined as a means to deliver reliable online optimization in transmission grids. Overall, CVR co-ordinates a number of distributed zones, which can be referred to as *CVR zones*. As discussed in Chapters 2, 4 CVR zones can be defined in a number of ways (e.g. by Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS), Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM) approaches) and they might be static or adaptively determined in an online event driven fashion. So far, the analysis has focused on multiple CVR zones belonging to the transmission and sub-transmission network, within the authority of a single Independent System Operator (ISO).

With regards to mid-term voltage regulation (i.e. steady state control with 1 min resolution), an ISO is a *CVR area*. A CVR area is ultimately a collection of individual CVR zones that cover the area of an ISO. Contrary to CVR zones, CVR areas (or more simply ISO areas) are defined largely by geography, history and asset ownership (or by asset management in deregulated markets) and their division is static. Hence, multiple CVR areas would comprise an interconnected system and multiple CVR zones would comprise a single CVR area. Both CVR areas and CVR zones include EHV & HV buses and hence suggest a *horizontal zone division* of the transmission grid. See figure 6.1 for an illustration of horizontal zone division.

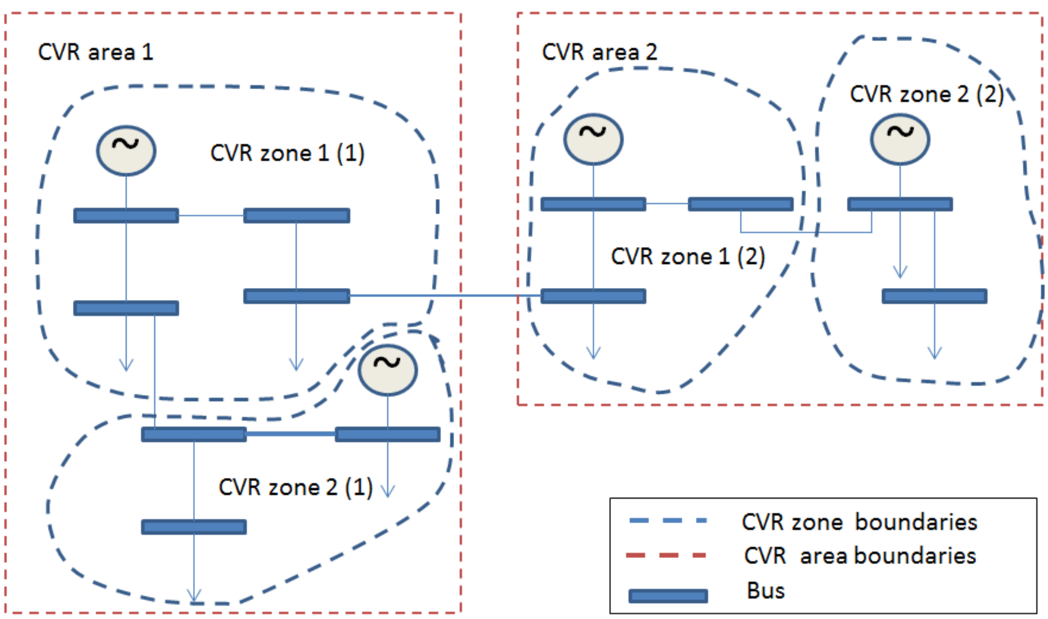


Fig. 6.1 Horizontal zone division in transmission grids

A CVR zone includes a number of buses that constitute the primary side of a substation. Such buses are represented in the CVR zone with an equivalent load for the distribution feeder below. The substation together with the adjoining feeder forms an additional zone, which is referred to as CVR sub-zone. Eventually a CVR zone includes a number of CVR sub-zones which contain MV buses and are coupled to the primary HV bus of the CVR zone. Hence, CVR zones suggest a vertical zone division from the primary HV of the substation down to the distribution network. See figure 6.2 for an illustration of vertical zone division.

An interconnected transmission grid is comprised of multiple ISO areas/CVR areas. In each ISO area/CVR area a CVR controller co-ordinates a number of distributed CVR zones. CVR areas and CVR zones suggest horizontal zone division at transmission level. CVR zones include a number of CVR sub-zones. The latter contain MV buses coupled to the primary HV substation and as such constitute vertical zone division.

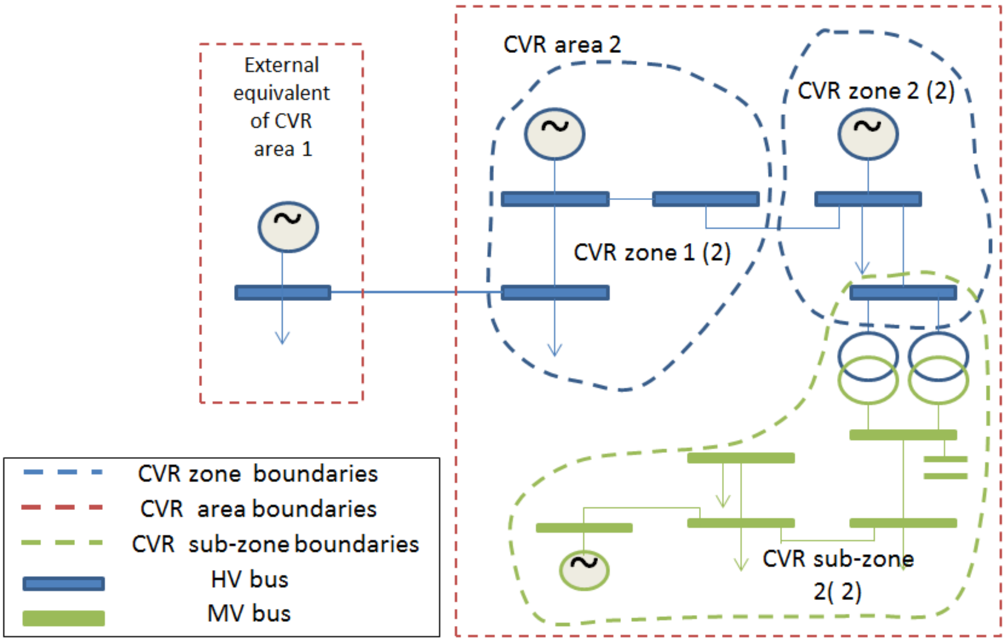


Fig. 6.2 Vertical zone division: CVR sub-zone coupled to CVR zone.

6.2 Horizontal zones & Coordination of Voltage Regulation

This Section is concerned with the required degree of Co-ordination of Voltage Regulation (CVR) in horizontal zones, i.e. CVR areas and CVR zones. Please note that Co-ordination of CVR areas is referred to as inter-area co-ordination. Owing to the fact *that multiple CVR zones form a CVR area, co-ordination of CVR zones is referred to as intra-area co-ordination. Within this context, Subsection 6.2.1 presents a novel methodology to assess the required degree of co-ordination, for both cases of inter-area (i.e. various CVR areas) and intra-area (i.e. various CVR zones within an ISO/ CVR area). Sub-section 6.2.2 identifies ISO areas and CVR zones on the 68 bus test system. Lastly, Sub-section 6.2.3 applies the proposed methodology on the 68 bus test system and presents and discusses results of this assessment.*

6.2.1 A methodology to assess the required degree of co-ordination in horizontal zones

Overall, CVR zones and areas can be controlled with either of the following schemes:

- **Case 1: Central Coordination**, i.e. a central control authority has access to all network models and respective control variables and optimizes system-wide real losses, remaining reactive reserves or both, while ensuring voltage lies within the specified bounds. This approach theoretically can deliver global optimum solutions, it is however less robust as it relies on a Central Coordinator and lots of information exchange, including sensitive data an individual ISO possibly does not like to share with other ISOs (i.e. for the case of inter-area coordination).
- **Case 2: Distributed Control**, i.e. each area/zone is a single control authority which manages voltage in its interior by efficient use of its synchronous resources. This approach possibly results in sub-optimal solutions, it is however the most robust to communication-failures and does not require any regular exchange of information among the various areas/zones, i.e. it is the complete opposite of case 1 discussed above.
- **Case 3: Distributed hierarchical Control**, i.e. a combination of cases 1 and 2. It can be found in several different configurations, e.g. Centralized control of some individual zones combined with distributed control of ISO areas or Centralized control of some individual zones combined with irregular exchange of information of the ISO areas regarding boundary variables.

In the ideal case, a problem can be solved with distributed control and yet meet optimal or near optimal performance. The methodology presented below is developed to facilitate an assessment of the required degree of both inter-area and intra-area co-ordination. Eventually, it can be used to select any of the configurations above (i.e. Case1-Case3) for any examined case study network.

The proposed methodology contains four Steps which are explained below. A schematic representation of the methodology can be found in figure 6.3.

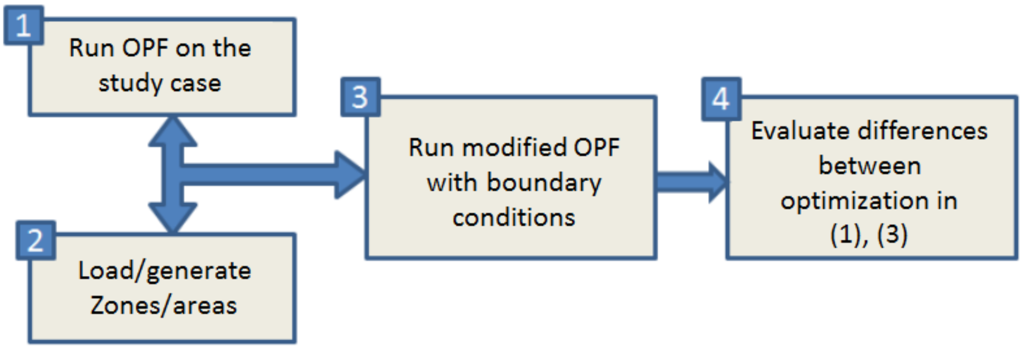


Fig. 6.3 Schematic representation of the proposed methodology

- **Step 1:** The first step solves a full AC Optimal Power Flow (OPF). This OPF minimizes cost of operation while satisfying network constraints. This optimization requires a model of the network.

The optimization problem is formulated below:

$$minf = \sum_{i \in PV} (c_{g2_i} \cdot P_{g_i}{}^2 + c_{g1_i} \cdot P_{g_i}) \qquad (6.1)$$

With the constraints:

$$h(x) = \begin{cases} P_{G_i} - P_{D_i} = V_i \cdot \sum_{j \in I} V_j \cdot (G_{ij} \cdot cos\theta_{ij} + B_{ij} \cdot sin\theta_{ij}) \\ Q_{G_i} - Q_{D_i} = V_i \cdot \sum_{j \in I} V_j \cdot (G_{ij} \cdot sin\theta_{ij} - B_{ij} \cdot cos\theta_{ij}) \\ i = 1, \ldots, NB \qquad \theta_s = 0 \end{cases} \qquad (6.2)$$

$$P_{G_i}{}^{min} \leq P_{G_i} \leq P_{G_i}{}^{max} \qquad i = 1, \ldots, NPV \qquad (6.3)$$

$$Q_{G_i}{}^{min} \leq Q_{G_i} \leq Q_{G_i}{}^{max} \qquad i = 1, \ldots, NPV \qquad (6.4)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i = 1, \ldots, NB \qquad (6.5)$$

$$S_i \leq S_i^{max} \qquad i = 1, \ldots, NL \qquad (6.6)$$

And the following nomenclature:

NL	Set of branches
NB	Number of buses

NPV	Number of PV buses
P_{G_i}, Q_{G_i}	Active and reactive power of the generator
$P_{G_i}{}^{min}, P_{G_i}{}^{max}$	Real power limits of the generator
$Q_{G_i}{}^{min}, Q_{G_i}{}^{max}$	Reactive power limits of the generator
P_{D_i}, Q_{D_i}	Active and reactive power of the load on bus i
V_i, θ_i	Voltage magnitude and phase angle of bus i
θ_s	Phase angle of the slack bus
G_{ij}, B_{ij}	Real and imaginary part of bus admittance matrix
S_i, S_i^{max}	Apparent flow on the i-th line and upper bound
c_{g2}, c_{g1}	Quadratic and linear cost for the generator
V_i^{min}, V_i^{max}	Voltage magnitude limits for bus i

- **Step 2:** The second step generates a zoning when the assessment refers to intra-area co-ordination. This can be done with any of the methodologies discussed in Chapter 4. Here Spectral K-way Clustering (SKC) methodology is used for the case of intra-area analysis, however any other could have been used instead without loss of generality. SKC formulation can be found in Chapter 4, Section 4.3.1. When the assessment refers to inter-area co-ordination, a zoning is deployed which corresponds to ISO/CVR area division.
- **Step 3:** This step solves a modified full AC Optimal Power Flow (OPF). It receives as input a model of the network and the zoning of Step 2. This OPF minimizes primarily cost of real power while satisfying network constraints. An additional term of the objective function is the minimization of reactive flows on the boundaries. Ideally, reactive flows on the boundaries should be equal to the reactive losses. This would mean two things; (a) that each area can solve the voltage control problem by explicitly using its own resources and (b) that the effect of neighbouring compensation is negligible and thus not of interest. The optimization problem is a modification of the OPF solved in step 1:

The required modification compared to formulation of step (1) is presented below:

- The objective function of the 2nd optimization problem is modified in order to minimize the boundary reactive flows in addition to the operational cost:

$$\begin{aligned} minf = \sum_{i \in PV} \left(c_{g2_i} \cdot P_{g_i}{}^2 + c_{g1_i} \cdot P_{g_i} \right) + \\ \mu \cdot \sum_{j \in NL} QE_j^2 \cdot A_{cut\,j} \end{aligned} \tag{6.7}$$

And the following nomenclature:

μ	Weighting co-efficient
QE_j	Reactive flow on the i-th line
$A_{cut\,j}$	Logic variable indicating whether a line j is a boundary one or not

- **Step 4:** This step evaluates the difference between the solutions of the two optimization problems of steps (1) and (3) respectively.

Two evaluation metrics are used and are formulated below:

(1) The Ratio of Reactive Charging of the generators termed as RRC.

$$RRC = \frac{\sum_{i \in PV} \left| Q_{1g_i} \right|}{\sum_{i \in PV} \left| Q_{3g_i} \right|} \tag{6.8}$$

(2) The Average Ratio of Reactive Flows on the boundary lines termed as ARRF.

$$RRF = \left| \frac{QE_{1j} - Q_{loss\,j}}{QE_{3j}} \right| \tag{6.9}$$

$$ARRF = \frac{\sum_{i \in NL} A_{cut_i} \cdot RRF_i}{NE} \cdot 100\% \tag{6.10}$$

And the following nomenclature:

Q_{1g_i}	Reactive output of generator i- from step 1
Q_{3g_i}	Reactive output of generator i- from step 3
QE_{1j}	Reactive flow on line j –from step 1
QE_{3j}	Reactive flow on line j –from step 3
Q_{loss_j}	Reactive losses on line j
NE	Number of boundary lines

A_{cut_i}	Logic variable indicating whether a line j is a boundary one or not

It follows, that an Average Ratio of Reactive Flows (ARRF) close to 0% combined with Ratio of Reactive Charging (RRC) close to 100% demonstrate the appropriateness of purely decentralized control. On the contrary, the more ARRF and RCC indices deviate from these targets they indicate the case for central co-ordination. The proposed methodology is developed by the author in MATLAB. It is generic in that it can accommodate any methodology or definition for the zone division and also it is voltage control algorithm agnostic. The only limitation comes from the need to perform several runs at first in order to set an appropriate weighting coefficient in equation (6.7) so that decisions on the P vector remain unchanged for both the optimization problems of step 1 and step 3 respectively.

6.2.2 ISO areas and CVR zones on the 68-bus test system

This Sub-section describes the 68 bus test system and it further identifies ISO areas/CVR areas and CVR zones on it.

The test system chosen is presented in figure 6.4 below. It contains 68 buses and 86 branches, hence it is meshed with an average degree <k>=2.54. The average x/r ratio is 13.94 hence it belongs to transmission. It comprises 5 interconnected areas; The New England test system (i.e. generators G1 to G9), the New York Power System (i.e. generators G10 to G13) and three other neighbouring areas represented by External Reduced equivalent models, (i.e. generators G14, G15 and G16 respectively). The inter-area ties between different ISO areas are highlighted. The full system details can be found in [123, 124].

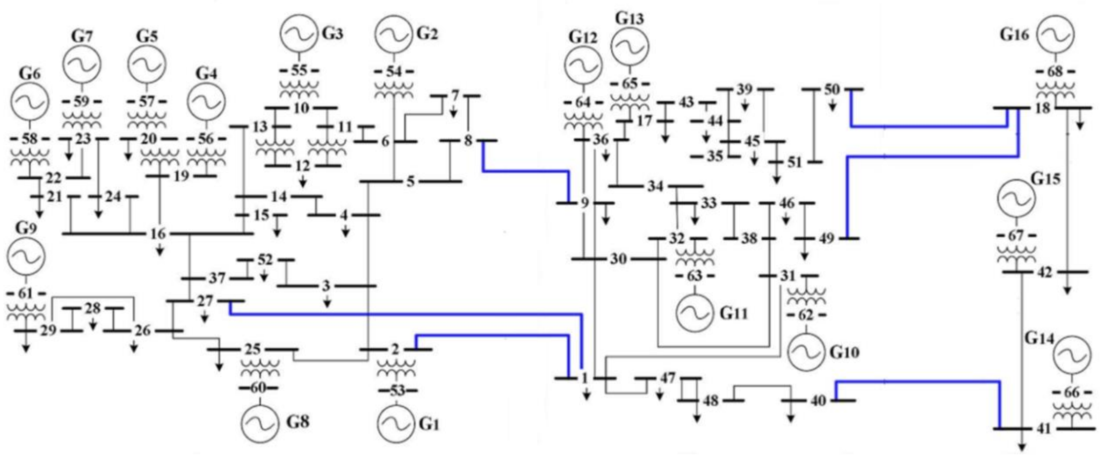


Fig. 6.4 One line diagram of the 68-bus test system [111]

Figure 6.5 presents the complete horizontal zone division on the 68-bus test system, i.e. ISO areas/CVR areas and individual CVR zones for the ISO areas/CVR areas.

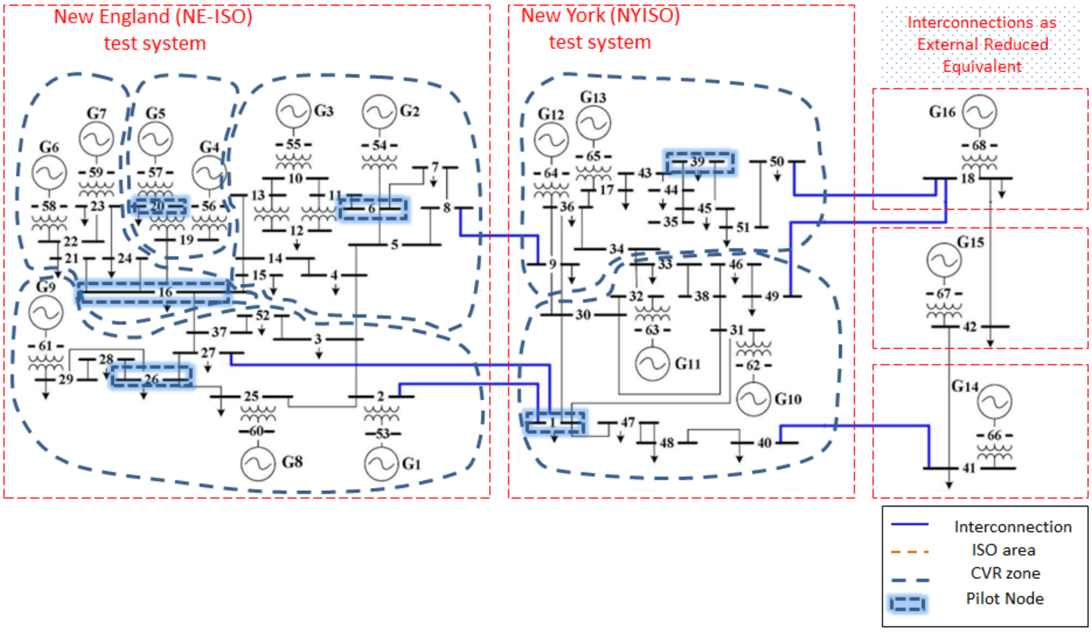


Fig. 6.5 Horizontal zone division of the 68-bus test system

As can be seen from figure 6.5, the 68-bus test system is composed of five ISO areas. The New England ISO contains four CVR zones, while the New York ISO contains two CVR zones. Both are extracted with SKC methodology. Pilot buses for each CVR zone are also ringed. CVR zones are not identified in the neighbouring areas due to the fact that they are presented with External Reduced equivalent networks.

6.2.3 Inter-area and intra-area co-ordination on the 68-bus test system

This Sub-section applies the proposed methodology on the 68 bus test system in order to assess the required degree of inter-area and intra-area co-ordination.

The CVR zone division and the ISO area division of Sub-section 6.2.2 above are considered here (see also figure 6.5). Initially, the assessment refers to the need for co-ordination of the five ISO-areas (i.e. Inter-area co-ordination).

- **Investigation into the case of Inter-area co-ordination**

The assessment is done following the methodology proposed in 6.2.1. Figures 6.6 and 6.7 below present the real and reactive generators' set-points resulting from the decisions vectors of the optimization problems solved in step1 and step 3, respectively. Demand is assumed to be at its maximum and the individual loads have various power factors, as obtained from the dataset in [111]. Another interesting case would be this of very low load demand in conjunction with various leading load power factors.

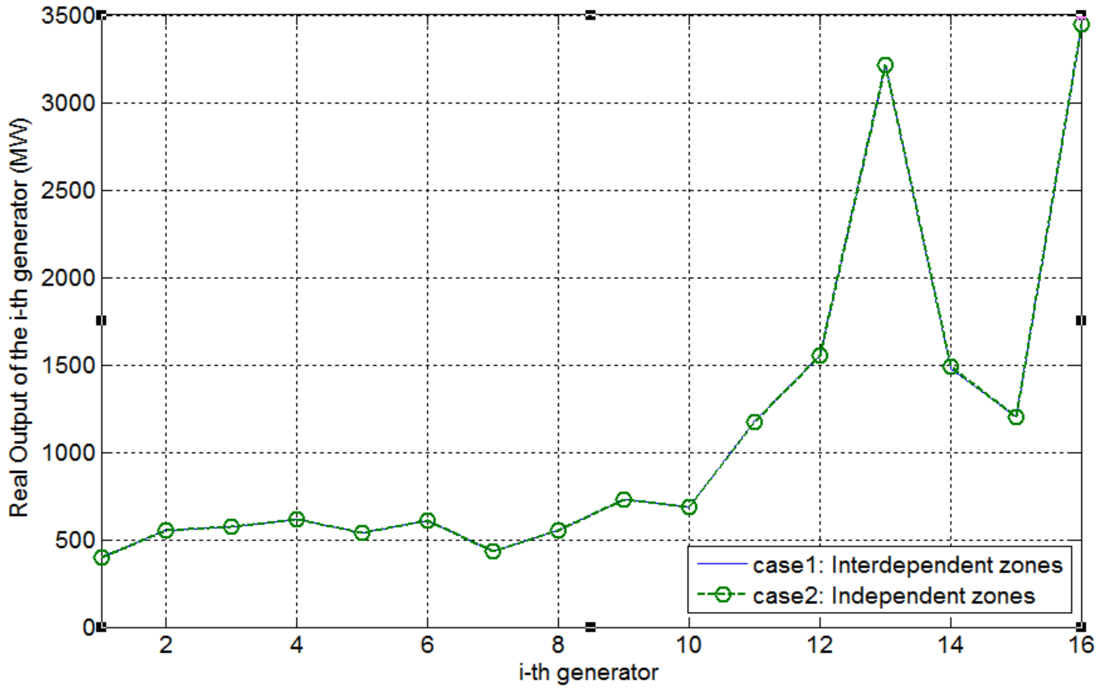


Fig. 6.6 Generator real power set-points; Interdependent vs Independent zones

Solution of step 1 is referred to as case of "Interdependent zones", while solution of step 3 is referred to as case of "Independent zones". As can be seen from Figures 6.6 and 6.7, set-points of the real power remain unchanged (i.e. identical operational costs), however, reactive set-points vary in order to minimize reactive flows on boundaries that is the second objective of the optimization problem in step 3.

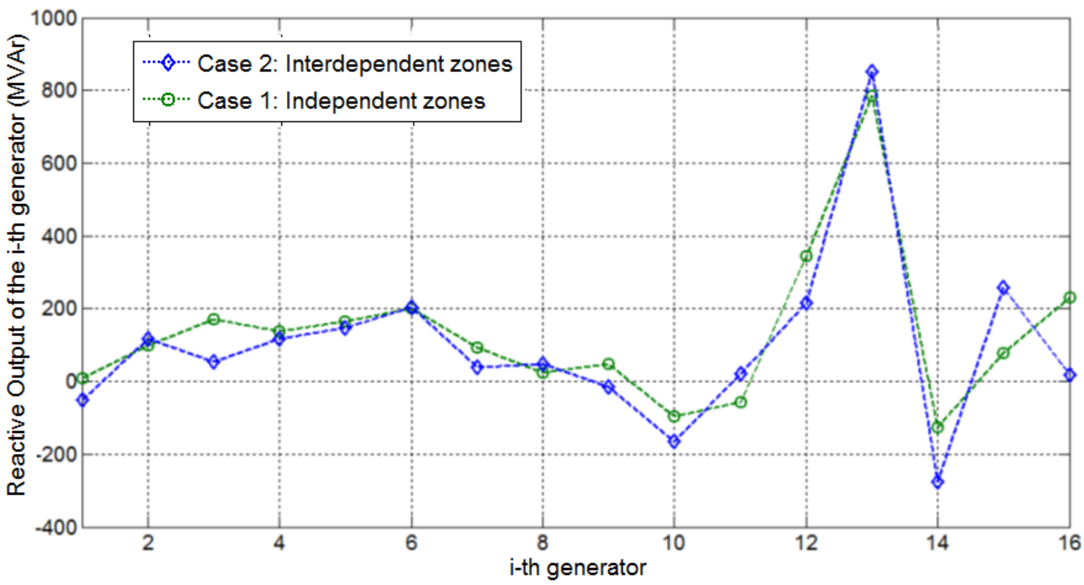


Fig. 6.7 Generator reactive power set-points; Interdependent vs Independent zones

Following that, reactive flows on the boundaries are compared for the cases of "Independent" and "Interdependent" zones. Figure 6.8 presents the results of the analysis.

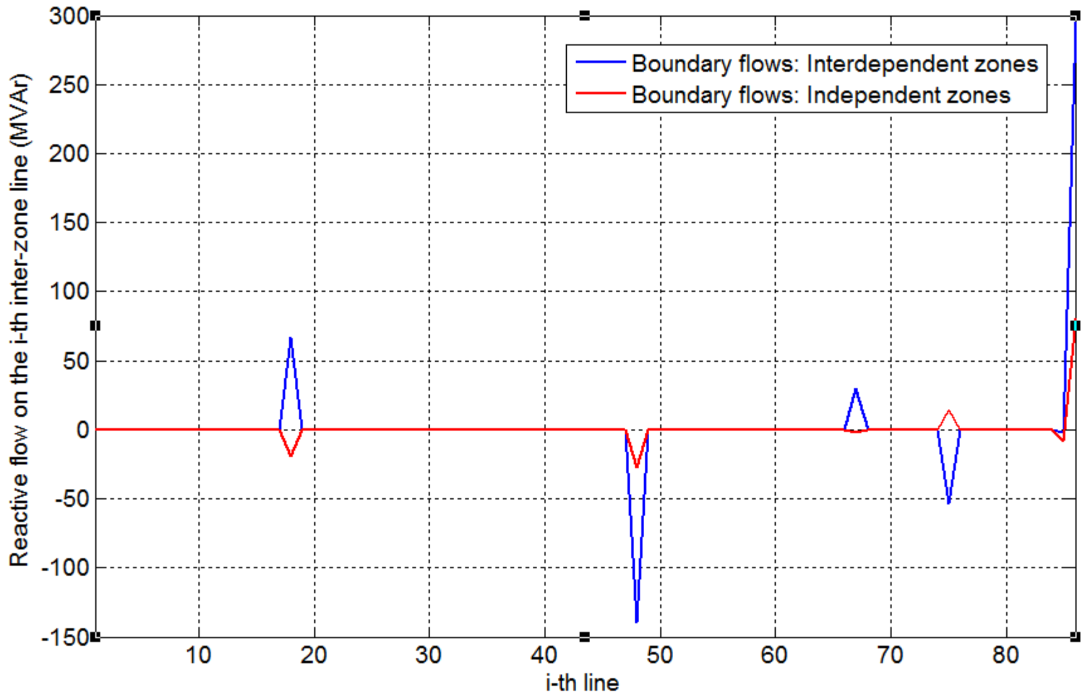


Fig. 6.8 Reactive flows on boundary lines; Interdependent vs Independent zones

Please note, only boundary lines are assigned a value from the analysis. As can be seen, the remaining reactive flows are negligible and it is only the 86th line which links buses 8 to 9 that gets a non-negligible value. Yet, flow on the 86th line is nearly 35% of the average reactive flow of the network lines.

Table 6.1 contains an assessment of the case of inter-area co-ordination, using the RCC and ARRF indices described in Sub-section 6.2.1 above (i.e. Step 4 of the methodology).

TABLE 6.1
ASSESSEMENT OF INTER-AREA CO-ORDINATION
ON THE 68 BUS TEST SYSTEM

Index	5 ISO Area- test system
RCC	98.1%
ARRF	4.13%

The near 100% value of RCC index, together with the low ARRF index demonstrate that the 5-area test system does not require inter-area co-ordination. This is due to the fact that the benefit of co-ordination would not be important, unless in the exceptional case of a severe emergency [125]. The 5 areas can manage their voltage in a distributed fashion and only irregularly exchange schedule on boundary flows, for instance on the North interconnection of New York-New England ISO.

- **Investigation into the case of Intra-area co-ordination**

The above analysis is repeated for the case of intra-area co-ordination. The analysis investigates whether the zones of CVR should control voltage in a purely decentralized or in a coordinated fashion. The assessment is done following the methodology proposed in 6.2.1 on the 4-CVR zones New England test network. Figures 6.9 and 6.10 below present the real and reactive generators' set-points resulting from the decisions vectors of the optimization problems solved in step1 and step 3, respectively.

Solution of step 1 is referred to as case of "Interdependent zones", while solution of step 3 is referred to as case of "Independent zones". As can be seen from Figures 6.9 and 6.10, generator real power set -points remain unchanged (i.e. identical operational costs), however, reactive set-points vary in order to minimize reactive flows on boundaries which is the second objective of the 2nd optimization problem. Contrary to the assessment of the inter-area co-ordination, the variation of reactive set points is significant and requires an additional of 245 MVAR for the solution of the 2nd optimization problem, i.e. 22% more reactive power compared to the case of Interdependent zones.

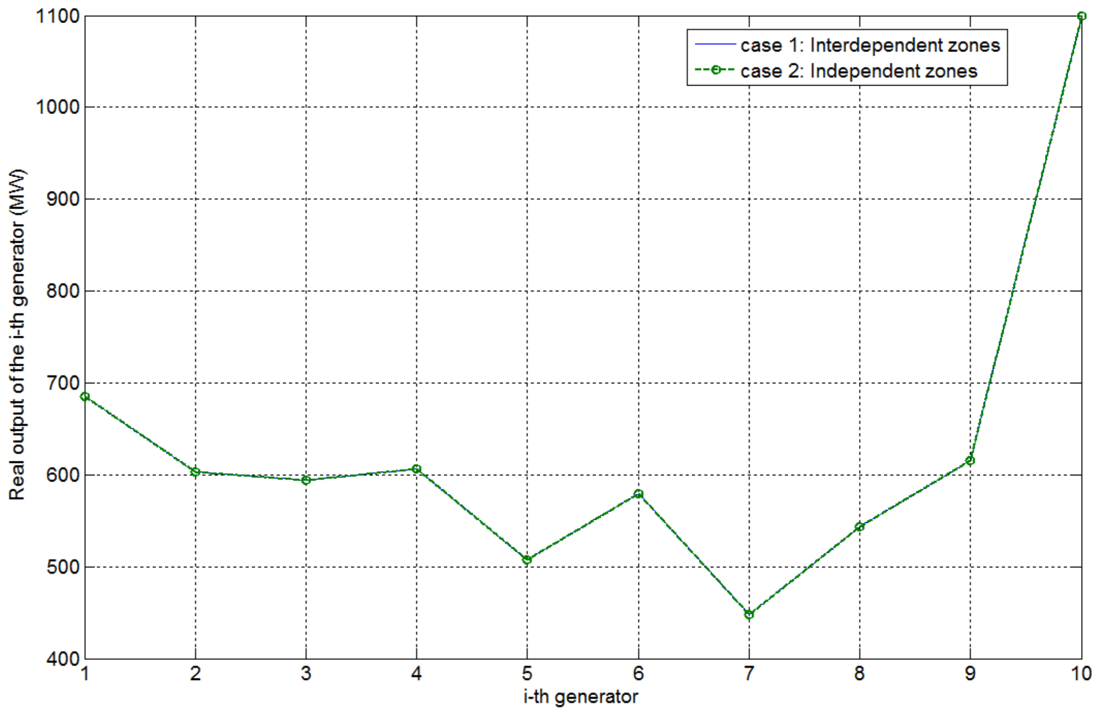


Fig. 6.9 Generator real power set-points; Interdependent vs Independent zones

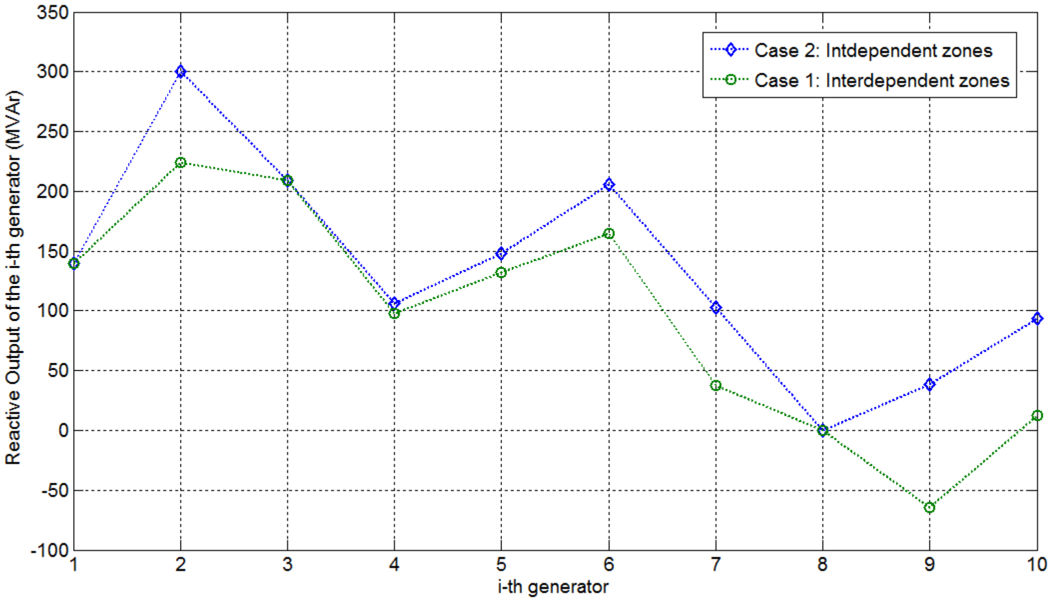


Fig. 6.10 Generator reactive power set-points; Interdependent vs Independent zones

Following that, reactive flows on the boundaries are compared for the cases of "Interdependent" and "Independent" zones. Figure 6.11 presents the results of the analysis. Please note, only boundary lines are assigned a value. While the sum of the reactive flows on the boundaries is reduced, the remaining reactive flows are non-negligible this time. As a point of comparison with results of figure 6.8, average reactive flow on network lines of the 4 CVR zones New England network is 63.3 MVAR.

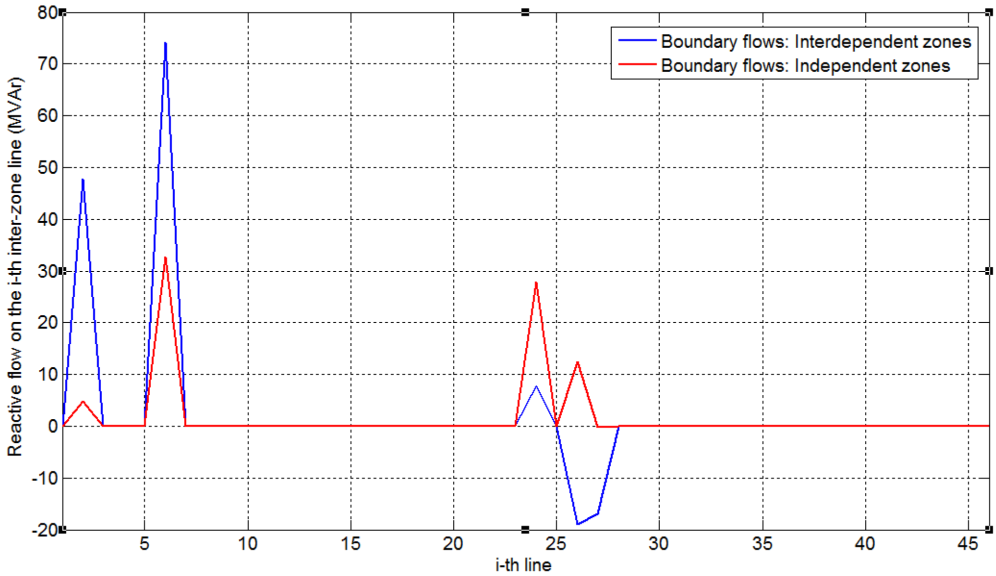


Fig. 6.11 Reactive flows on boundary lines; Interdependent vs Independent zones

Table 6.2 contains an assessment of the case of intra-area co-ordination, using the RCC and ARRF indices described in Sub-section 6.2.1 above (i.e. Step 4 of the methodology).

TABLE 6.2

ASSESSEMENT OF INTRA-AREA CO-ORDINATION

ON THE 39 NEW ENGLAND (NE) TEST SYSTEM

Index	NE 4 CVR zones
RCC	79.85%
ARRF	81.72%

The moderate value of RCC index in conjunction with the very high ARRF index demonstrate that the 4 CVR zone New England test network requires intra-area co-ordination. This is due to the fact that the neighbouring compensation effect is significant (ARRF=81.72%) and in a distributed fashion the individual CVR zones would over-react (RCC=79.85%). This is an outcome very much anticipated given that a wealth of literature (e.g. [93, 81]) has suggested Coordination for the individual SVRs on this particular network. Additionally, despite the fact that voltage has localized nature in transmission grids, boundary lines on this particular network are not that long to stall the inter-area effects.

Overall the analysis of Section 6.2.3 suggests that distributed hierarchical Control is the most appropriate scheme for Voltage control of the 68 bus test network. The configuration includes Centralized control of the individual CVR zones within each CVR area/ISO area, combined with distributed control of CVR areas/ISO areas possibly with irregular exchange of information of boundary schedules.

6.3 Vertical zones & Coordinated Voltage Control

This Section is concerned with the Co-ordination of Voltage Control in vertical zones, i.e. CVR sub-zones. The analysis of this Section is scoped to the case of intra Sub-zone co-ordination. Within this context Sub-section 6.3.1 presents a vertical CVR sub-zone on a modification of the 68 bus test system to include an MV network. Sub-section 6.3.2 presents different configurations of co-ordinated voltage control; (a) control with no co-ordination, (b) control with indirect coordination based on the use of time delays and (c) control with direct co-ordination based on a novel AI-Planning based approach. Lastly, Sub-section 6.3.3 applies the aforementioned control approaches (a)-(c) on the study case CVR sub-zone.

6.3.1 CVR sub-zones

This Sub-section describes the 33 kV Reigate network that is added to the 68 bus test *network and constitutes the CVR zone under study.*

The test system chosen is presented in figure 6.12 below within boundaries of green colour, as an addition to the 68 bus test system (described in Sub-section 6.2.2 above). The added network contains 38 buses from 33kV down to 11 kV, and one HV bus (i.e. bus notated 48 in the New York ISO) that is the primary of the substation and links the CVR sub-zone to the main CVR zone. It is an MV network, classified as distribution. It contains 48 branches, hence it is meshed despite of being a distribution network, with an average degree <k>=2.46. It contains 9 distributed generators and 17 OLTCs to control voltage. The 33 kV network is taken from the AuRA-NMS project and full system details can be found in [126].

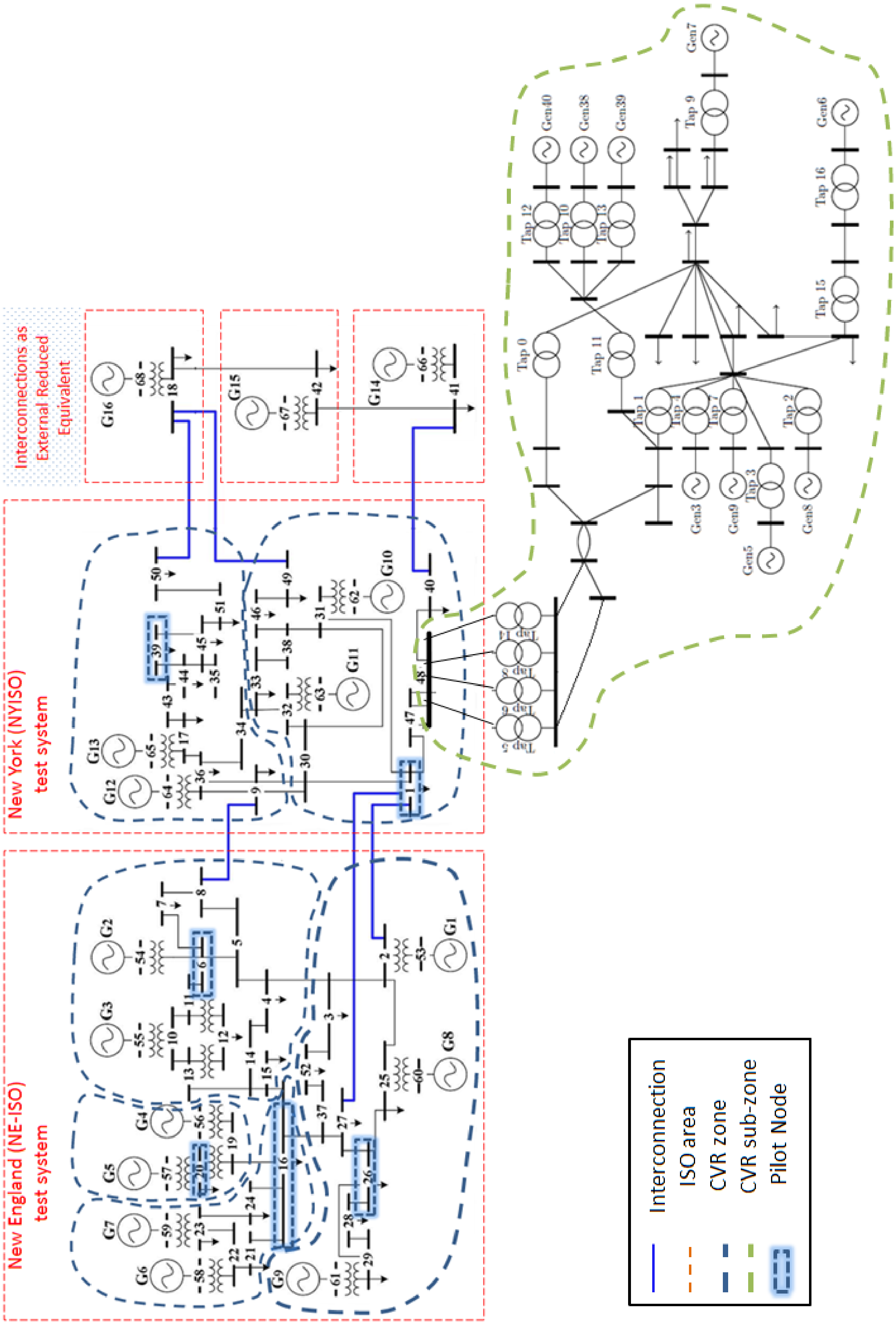


Fig. 6.12 The 68 bus test system with the addition of the 33kV CVR sub-zone

6.3.2 Control approaches for the CVR sub-zone

This Sub-section presents different configurations of the co-ordinated voltage control for the CVR sub-zone; (a) control with no co-ordination, (b) control with indirect coordination based on the use of time delays and (c) control with direct co-ordination based on a novel AI-Planning based approach.

(a) Voltage Control with no co-ordination.

This approach is the most basic configuration i.e. purely decentralized control. Each Voltage controlling device has a point of measurement, a set-point/target for the voltage magnitude on that point and a control law/control gain particular to the controlling device. Hence, this approach relies on monitoring but it does not require any communications. Below we elaborate on the case where the voltage controlling device is an OLTC;

In its simplest form, the OLTC in figure 6.13 is controlled with no co-ordination with other voltage control devices [120].

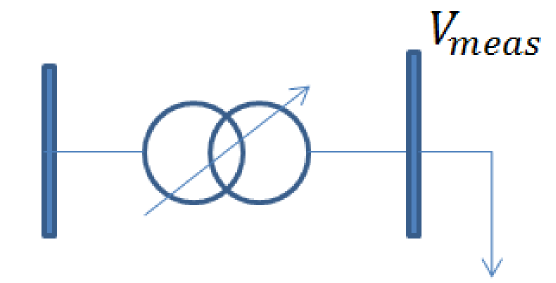


Fig. 6.13 Basic Voltage control with no co-ordination

Voltage is measured on the bus with the indication $\boldsymbol{V_{meas}}$. If the measured voltage is outside the allowed bounds $\{V_{min}, V_{\max}\}$ the transformer would step up or down (depending on which bound is violated) to bring voltage to a pre-specified set-point V_{target}, according to equation 6.11 below. This is the case of Voltage Control.

$$t_{new} = \frac{V_{target}}{V_{meas}} \cdot t_{old} \tag{6.11}$$

Alternatively, the OLTC may regulate voltage. In this case, the OLTC would act to restore voltage to V_{target} value when there is a deviation that exceeds a pre-specified range (e.g. $\Delta V_{meas} = 0.1$). This would most probably signify more economic network operations in terms of losses, it would however require more frequent operations of the OLTC and subsequent wear for the equipment.

And the following nomenclature:

V_{target}	Pre-specified set-point for voltage magnitude
V_{meas}	Measured voltage magnitude
V_{min}, V_{max}	Lower and upper voltage bound
t_{new}	New turns ratio of the transformer
t_{old}	Previous turns ratio of the transformer

(b) Voltage Control with in-direct co-ordination.

This approach is well-established in today distribution networks. It requires monitoring but not communications. Each Voltage controlling device has a point of measurement, a set-point/target for the voltage magnitude on that point and a control law/control gain particular to the controlling device, similar to the approach in (a). Unlike (a), this approach includes co-ordination and this is achieved through the use of time delays. This is elaborated below for the case of multiple OLTCs [127].

Each transformer of figure 6.14 maintains the voltage of the end bus through adjusting its tap ratio, as in equation 6.13 before.

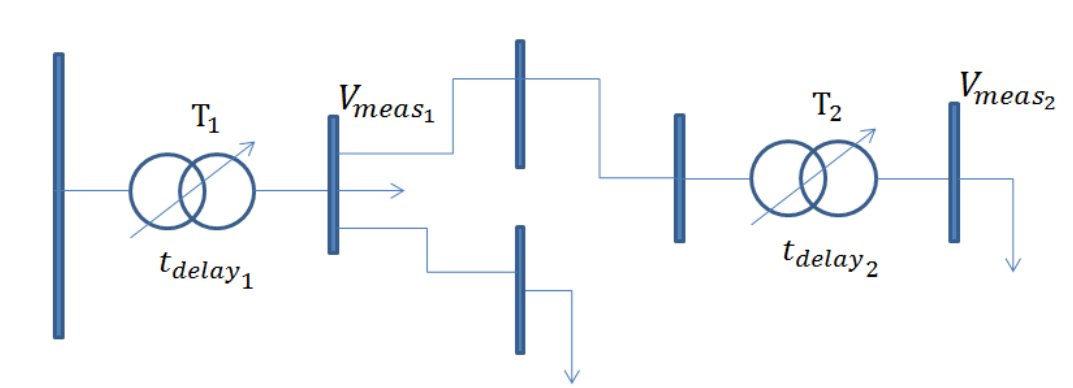


Fig. 6.14 Co-ordinated Voltage control with time delays

Co-ordination is achieved through the use of time-delays, hence transformers operate sequentially. This is achieved without communication between the control devices and is an example of passive co-ordinated operation. The order of operations between transformers is fixed, according to the network design, and follows the voltage drop [127]. The time delay defines the amount of time that should elapse between the moment when measured voltage exceeds the tolerance interval until the appropriate step up/step down command is issued to the tap changer. In the considered example of figure 6.14, should system loading change (and hence voltage), an opportunity is given to the T1 to act first, by assigning time delays as:

$$t_{delay_1} < t_{delay_2} \tag{6.12}$$

And the following nomenclature:

t_{delay_1}	Time delay for transformer T1
t_{delay_2}	Time delay for transformer T2
V_{meas_1}	Measured voltage magnitude for transformer T1
V_{meas_2}	Measured voltage magnitude for transformer T2

(c) Control with direct co-ordination.

This approach refers to direct co-ordination of the voltage control problem. It is a responsive control approach similarly to (a)-(b), however it relies not only on monitoring but also on communications and knowledge of the CVR sub-zone model. Voltage control of the CVR sub-zone can be done in a number of ways, (e.g. [128, 129, 130]). In here a novel approach based on AI Planning is used. The strongest point of this approach is its secure and fast convergence along with its ability to consider temporal constraints if applied in a multi-stage control fashion [131, 132]. On the negative side, its applicability is limited to CVR subzones as it faces scalability issues for large size networks. Overall, this is a novel approach to controlling a CVR sub-zone. The formulation of the AI Planning approach has collaboratively been carried out by the author and King's College project partners. Please note the PDDL modelling has been carried out exclusively by King's College partners. The approach is explained briefly below. The reader is advised to refer to [133] for a full formulation of the approach.

AI Planning is a branch of Artificial Intelligence that is concerned with identifying an action/sequence of actions to deliver an objective; hence it delivers a plan, as far as a possible solution/possible plan exists.

In the AI planning approach for CVR sub-zone voltage control, the system voltage is expressed as a function of the *background voltage* and *voltage adjustment*. System voltage is therefore a mixed metric expression. Background voltage corresponds to an initial State A of the system. If in this representation a number of voltage variables are outside the allowed bound $\{V_{min}, V_{\max}\}$ the planner has to find an action or sequence of actions to reach State B, i.e. a network State where all voltage variables are within the allowed bound. The actions deliver the desired voltage adjustment and constitute the suggested plan. For a schematic explanation see figure 6.15.

Unlike approaches (a), (b), the planner in (c) checks that voltage on all buses lies within bounds after the control. As such, it is expected to deliver more secure Voltage Control of the CVR sub-zone. However, it relies on communications, as the Planner can be perceived as the software encrypted in a Central Co-ordinating agent within the CVR sub-zone.

Regarding the domain, it briefly contains:

(a) a PDDL [134] model describes the elements of the problem that are directly reasoned about by the planner (e.g. buses)

(b) an encapsulated type, representing a structured object that is manipulated by the planner (e.g. the OLTCs)

(c) an interface between the planner and a specialised external solver in order to lift the computational burden of analysing the effect of a possible action with full AC load flow equations.

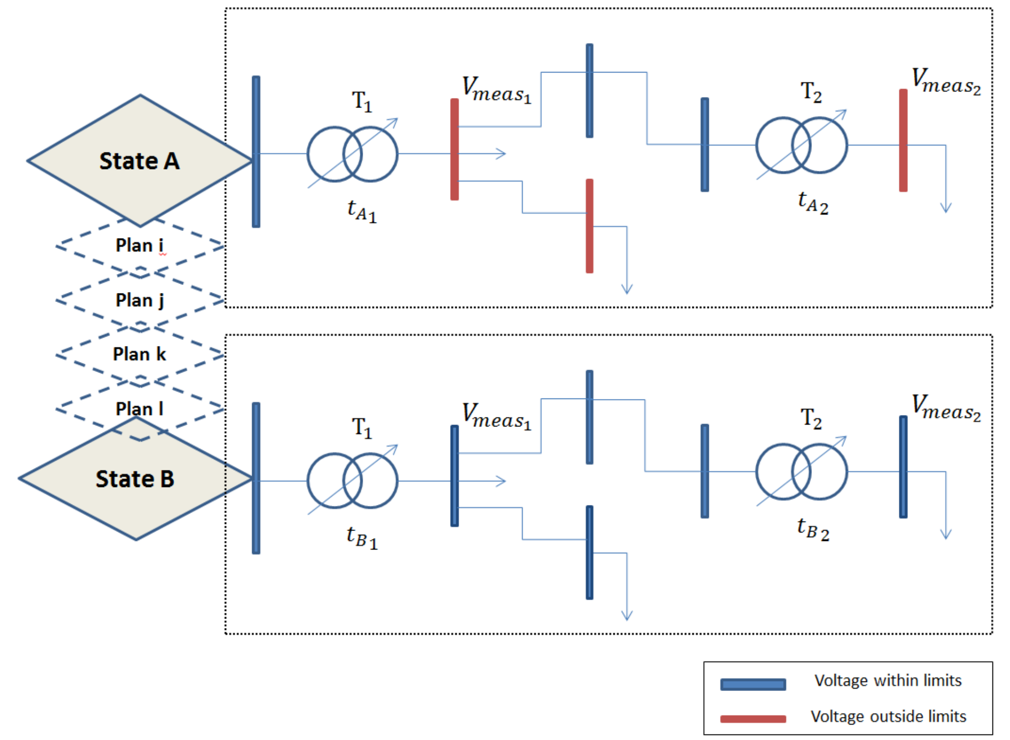


Fig. 6.15 Co-ordinated Voltage control with AI-Planning

And the following nomenclature:

V_{meas_1}	Measured voltage magnitude for transformer T1
V_{meas_2}	Measured voltage magnitude for transformer T2
t_{A_1}, t_{A_2}	Turns ratios for transformers T1, T2 in State A
t_{B_1}, t_{B_2}	Turns ratios for transformers T1, T2 in State B

6.3.3 Results & discussion on the 33 kV CVR sub-zone

This Sub-section applies control approaches (a)-(c) introduced in Sub-section 6.3.2 above on the 33 kV sub-zone of Sub-section 6.3.1.

Figure 6.16 presents the CVR sub-zone under study. Control approaches (a)-(c) which present different degrees of co-ordination are applied to this CVR sub-zone.

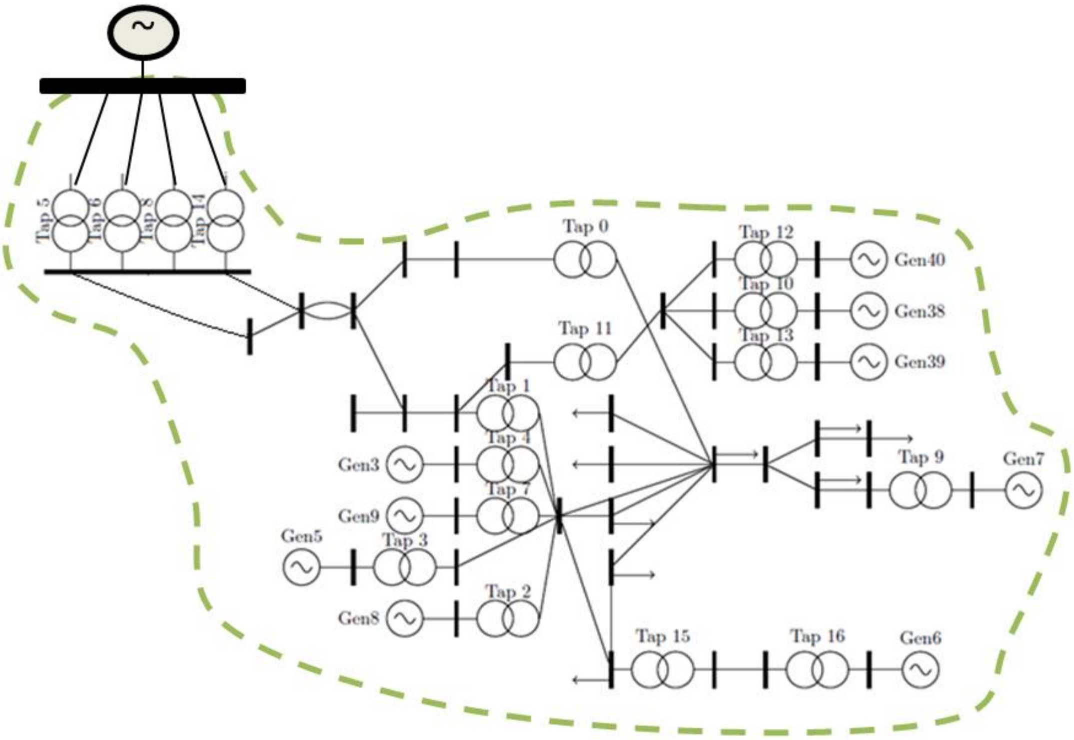


Fig. 6.16 CVR sub-zone under study

In the considered CVR sub-zone for the control approach (b) that relies on time delays, should system loading change (and hence voltage), an opportunity is given to the HV/MV transformers to correct the voltage first (T5, T6, T8 and T14). This rationale is extended to lower voltage control devices and transformers (T1, T0 and T11), which operate next, owing to the fact that the network does not export power. The next longest time delay relates to transformer T15, as in principle most of the time voltage would drop between the bus that T1 controls and the bus T15 controls. The remaining transformers are the last ones to act, as they are the ones responsible for ensuring secure generator access to the network, thus controlling generators voltage and not load buses voltage. With respect to the delays, please note, sequential trigger is also considered within each group in the state space.

Table 6.3 below summarizes the results of the analysis. The first column lists 6 scenarios. Each of them corresponds to 24 hour operation according to data set [135]. The 6 scenarios are evenly distributed within the data set to account for two winter days, two summer days and two days of shoulder season. Columns 2-4 indicate voltage control performance for each of the control approaches (a)-(c).

Control performance is expressed as in equations (6.13)-(6.14).

$$V_{per} = \sum_{t \in N_{instances}} \sum_{k \in N_{bus}} V_{tk} \tag{6.13}$$

$$V_{tk} = \begin{cases} V_{tk} - V_{k_{max}} & if\ V_{k_{max}} \leq V_{tk} \\ V_{k_{min}} - V_{tk} & if\ V_{k_{min}} \leq V_{tk} \\ 0 & if\ V_{k_{min}} \leq V_{tk} \leq V_{k_{max}} \end{cases} \tag{6.14}$$

As such the voltage performance V_{per} is the sum of all instances $N_{instances}$ analysed in all 6 scenarios all across the buses N_{bus}. Based on the above equations the voltage performance index V_{per} will be zero if a control-strategy keeps voltage in all network buses within the specified limits $\{V_{k_{min}}, V_{k_{max}}\}$ and will get a positive value otherwise.

TABLE 6.3
VOLTAGE CONTROL PERFORMANCE FOR THE CVR SUB-ZONE
FOR CONTROL APPROACHES (a)-(c)

Scenario ID	**Voltage Control Performance V_{per}**		
	Un-coordinated (case-a)	**Indirect Co-ordination (case-b)**	**Direct Co-ordination (case-c)**
SC_1	0.321	0.000	0.000
SC_2	0.168	0.031	0.000
SC_3	0.099	0.000	0.000
SC_4	0.214	0.102	0.000
SC_5	0.412	0.144	0.000
SC_6	0.082	0.000	0.000

As can be seen from Table 6.3 full direct co-ordination of the voltage control is the most appropriate approach for the examined CVR sub-zone (i.e. case-c). The AI-Planning based approach delivers in all examined scenarios secure voltage control. Please note, however, that if the objective was regulation (subject to minimizing some objective function) and not control, an AC OPF would have been used instead. Un-coordinated control (i.e. case-a) results in voltage violations in all scenarios analysed. This is due to the fact that OLTCs over-react as the individual controllers make a false estimation of the disturbance they have to resolve.

Indirect co-ordinated control through time delays (i.e. case-b) is a particularly interesting approach. In 50% of the cases it delivers secure voltage control and keeps voltage all across the network within bounds. This is due to the fact that the network under study is meshed unlike most of distribution radial networks and additionally it contains 9 Distributed Generators (DGs). Despite the fact that the CVR sub-zone does not export power, at times the direction of flows within the CVR sub zone were found to contradict the logical hierarchy of the delays. In such cases, voltage on the buses with no monitoring could fall outside bounds. Please note, that, were the network to export power, it is highly possible that it would be even harder to come up with a logical hierarchy of delays.

Overall approach (b) is well-established, it is though recommended particularly for radial networks, as active power flow from MV to LV side is pre-requisite for correct operation. In either case, direct co-ordinated voltage control is the most appropriate choice for a more complex and possibly meshed topology CVR sub-zone, like the one examined here.

6.4 Concluding Remarks

This Chapter investigates Coordinated Voltage Regulation (CVR) from a whole system perspective; hence it goes beyond the CVR zone analysis within the authority of a single Independent System Operator (ISO). It effectively extends Chapters 3-5 by addressing the following two items; (a) Zone division in an interconnected system ranging from EHV down to MV, and (b) required degree of co-ordination for the voltage control of these zones.

Towards item in (a), *horizontal* and *vertical zone division* is derived for the voltage control problem. The analysis considers multiple ISOs in an interconnected transmission grid. *With regards to mid-term voltage control*, an ISO can be regarded as a *CVR area*. A CVR area is ultimately a collection of individual CVR zones that cover the area of an ISO. Both CVR areas and CVR zones entail EHV & HV buses and hence suggest a *horizontal zone division* of the transmission grid. CVR zones entail a number of CVR sub-zones. The latter contain MV buses coupled to the primary HV substation and as such constitute *vertical zone division*.

Additionally, the required degree of co-ordination has been investigated for the voltage regulation of both horizontal and vertical zones (i.e. item in (b)). To that end, a novel methodology has been developed to assess the required degree of co-ordination of Voltage Regulation in horizontal zones. The methodology is generic in that it is voltage control algorithm agnostic and can accommodate any zone division or case study network. It can further assess the required degree of co-ordination of Voltage Regulation for both inter-area (i.e. various CVR areas) and intra-area (i.e. various CVR zones within an ISO/ CVR area) cases.

Lastly, the required degree of co-ordination has been examined for the case of a vertical CVR sub-zone. This analysis considered only intra sub-zone co-ordination. This is due to the fact that while monitoring is anticipated to increase in future distribution grids, wide area communication among electrically distant feeders (i.e. electrically distant CVR sub-zones) is not envisaged. Within this context, different configurations of co-ordinated voltage control are considered within a CVR sub-zone, i.e. (a) control with no co-ordination, (b) control with indirect coordination based on the use of time delays and (c) control with direct co-ordination based on a novel AI-Planning based approach. These control approaches have been applied on a 33 kV meshed distribution network taken from AuRA NMS [126]. Direct co-ordinated voltage control (i.e. approach-c) appears to be the most appropriate choice as anticipated, it requires however communications in addition to monitoring, contrary to approaches (a) and (b). The above outcome will hold true for any CVR sub-zone that has meshed topology and is complex with regards to the control points it includes.

Overall, this Chapter investigated the required degree of co-ordination, among horizontal zones and among vertical zones, under the assumption that transmission and distribution deal with CVR independently. This is in fact a valid assumption based on current operation practices, where voltage control in distribution is done -in general- independently of what happens in transmission and the only linkage is how the transmission-distribution interfaces are controlled (typically with voltage targets agreed by both the TSO and the DNO). An interesting extension could be the investigation of the most appropriate degree of co-ordination among vertical and horizontal zones, moving towards future power networks with more “blurry” boundaries between transmission and distribution.

Chapter 7

Conclusion

This Chapter presents a brief overview of this thesis and points to the key findings. Additionally it summarizes the main contributions of this thesis. Lastly, it discusses broader implications of the findings and points future research directions that could effectively extend this work.

7.1 Overview & Key findings

This section presents a brief overview and key findings of this Thesis.

Automatic and *Co-ordinated Voltage Regulation* (CVR) contributes significantly to economy and security of transmission grids. The role of CVR will become more critical as systems are operated closer to their capacity limits due to technical, economic and environmental reasons. CVR has 1 min resolution and owing to the inherent complexity of the task, CVR is enabled through *Reduction of the Control Model (RCM)* i.e. simplified models of the network suitable for Voltage Control. RCM not only enables CVR bus also affects its performance and robustness. To that end, this thesis contributed towards improved Automatic & Coordinated Voltage Regulation (CVR) in transmission grids through thorough investigation of the Reduction of the Control Model (RCM).

In this thesis RCM is zoning based for the following two reasons; 1) its low computational cost favours online application, and 2) it constitutes the only research direction adopted in actual AVC implementations. Zoning is a mixed integer optimization problem and becomes intractable when moving beyond a handful of nodes. Hence different heuristics have been deployed to perform the classification task. Multiple Zoning approaches have been deployed both in academic literature and actual practice. It is noteworthy though that once a zoning is derived, RCM is defined in practice and in academic literature with very little ambiguity. *Effectively, proposing a novel zoning based RCM methodology for CVR is equivalent to introducing a new formulation of the zoning optimization problem.*

Mathematically, zoning is the task of clustering i.e. identification of communities in a complex network representation. Clustering algorithms can be classified as Hierarchical, Exclusive and Overlapping. A literature review on zoning for CVR, revealed a wealth of approaches in all classes of clustering algorithms. Two well established hierarchical clustering based approaches, i.e. Hierarchical Clustering with Single Distance (HCSD) [17] and Hierarchical Clustering in VAR Space (HCVS) [21] have been identified as suitable benchmarks owing to the fact that they have been used in actual AVC implementations. With regards to Exclusive Clustering and Overlapping Clustering, the literature review revealed that none of the existing approaches has a complete formulation. Therefore, as a first goal this thesis developed two new zoning based RCM approaches for the CVR application; 1) Spectral K-way Clustering (SKC) methodology that deployed Exclusive Clustering and 2) Fuzzy C-Means (FCM) methodology that deployed Overlapping (Fuzzy) clustering. HCSD, HCVS, SKC and FCM in this thesis are formulated as Clustering Optimization Problems using Complex Network representation of the transmission grid. Those four zoning methodologies are representative of the whole spectrum of clustering algorithms as most appropriate candidates for Hierarchical, Exclusive and Overlapping Clustering respectively.

Furthermore, simulations revealed that different zoning methodologies, sharing the same control objective and network, make different decisions. Internal validation criteria provided the most appropriate outcome for each zoning methodology, they are however specific to each approach and may produce contradicting decisions if combined, as reference [113] points out. As a reasonable approach, the optimized through validation zoning outcomes have been compared directly on the application of interest.

Hence, a novel generic probabilistic framework has been developed in order to model and evaluate Coordinated Voltage Regulation (CVR). The modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the CVR solution. This modelling is extended to a Monte-Carlo framework that can be used to evaluate CVR in conjunction with any configuration of its component elements. This novel framework is deployed to investigate *how different zoning based RCM approaches serve the CVR control objective*. In this investigation, the focus has been on both the performance and robustness that the CVR controller achieves in conjunction with a zoning based RCM approach.

The analysis pointed to four key findings;

a) Zoning definitions determine the nature of the corresponding RCMs. However, similar zoning outcomes (coming possibly from different zoning definitions) could result in the same RCM being selected.

b) The selection of a zoning based RCM affects both the performance and the robustness of the CVR controller. Hence, a zoning based RCM should be selected in accordance with the expected accuracy of the voltage measurements CVR receives.

c) Hierarchical Clustering in VAR Space (HCVS) and Spectral K-way Clustering (SKC) methodologies appear to have the best potential and this is highly likely to be the case for networks with similar characteristics to the case studies examined in here (i.e. similar average degree <k>, ratio of controlling to controlled elements and X/R ratio). However, in the general case one is advised to try several zoning methodologies on a network prior to selecting one, as in principle zoning methodologies are heuristics with no guarantee of performance.

d) HCVS achieves competitive performance compared to the rest of the zoning methodologies. This can be explained by the electrical distance it deploys which considers the quasi-steady zonal control characteristics. HCVS should be used with caution though for high ratios of g/l elements or when the g elements participating in CVR are not pre-specified as for high ratios it might lead to disconnected clusters.

Additionally, this thesis investigated zoning based Reduced Control Models (RCM) determined in an online event-driven fashion (adaptive RCM) in pursuit of improved Coordinated Voltage Regulation (CVR). This is due to the fact that a single RCM (static RCM) cannot be optimum for all network operating conditions and configurations. This thesis investigated four novel research questions with regards to adaptive RCM in CVR; (a) is adaptive RCM feasible from a computational perspective on realistic size networks? , (b) what should trigger the adaptive RCM? , (c) what is the Value of adaptive RCM from a control perspective? , and (d) which are the Major implementation challenges?

The analysis pointed to four key findings;

a) Hierarchical Clustering with Single Distance (HCSD), Hierarchical Clustering in VAR Space (HCVS) and Spectral K-way Clustering (SKC) methodologies can determine the Reduced Control Model (RCM) in an online fashion, contrary to Fuzzy C-Means Clustering (FCM) on a realistic size network that has not undergone any reduction. In particular, methodologies based on agglomerative hierarchical clustering appear to have the best potential. The deployment of relative eigen gap heuristic speeds up SKC and allows its application in the adaptive scheme.

b) It is mainly topological changes that trigger the adaptive RCM and particularly the ones that substantially affect the centrality of the pilot node set. Merely loading changes or different tap configurations on the OLTC may alter slightly the zone boundaries. They do not however trigger adaptive RCM.

c) Overall, adaptive reconfiguration of the RCM can be considered as one of the actions CVR can take before CVR reaches its limits and emergency control takes place. While benefits cover both aspects of economy and security, adaptive RCM in CVR is more meaningful as a means to improve security, i.e. stability in presence of contingencies.

d) Adaptive RCM does not jeopardize the desired engineering simplification of on-line automatic control that CVR is designed to deliver it does however rely on increased monitoring and communications which is the main implementation challenge. The latter are becoming available through the on-line remote sensing and command infrastructures being deployed by the utilities under the umbrella of smart grids.

Chapter 6 of this thesis extended the scope of this research beyond the authority of a single-transmission level Independent System Operator (ISO) and addressed the following two items; (1) Zone division in an interconnected system ranging from EHV down to MV, and (2) required degree of co-ordination for the voltage control of these zones.

The analysis pointed to three key findings;

a) With regards to mid-term voltage control, an ISO can be regarded as a CVR area. A CVR area is ultimately a collection of individual CVR zones that cover the area of an ISO. Both CVR areas and CVR zones include EHV & HV buses and hence suggest a horizontal zone division of the transmission grid. CVR zones include a number of CVR sub-zones. The latter contain MV buses coupled to the primary HV substation and as such suggest vertical zone division.

b) Regarding voltage regulation of horizontal zones, the proposed in this research methodology can successfully assess the required degree of co-ordination for both inter-area and intra-area cases. (Please note that Co-ordination of CVR areas is referred to as inter-area co-ordination. Owing to the fact that multiple CVR zones form a CVR area, co-ordination of CVR zones is referred to as intra-area co-ordination.)

c) Regarding voltage control of vertical zones, different configurations of coordinated voltage control have been examined within a CVR sub-zone, i.e. (a) control with no co-ordination, (b) control with indirect coordination based on the use of time delays and (c) control with direct co-ordination based on a novel AI-Planning based approach. These control approaches have been applied on a 33 kV meshed distribution network. Results indicate that direct coordinated voltage control (i.e. approach-c) appears to be the most appropriate choice as anticipated, it requires however communications in addition to monitoring, contrary to approaches (a) and (b). The above outcome will hold true for any CVR sub-zone that has meshed topology and is complex with regards to the control points it includes.

7.2 Contributions of this thesis

This section summarizes the contributions of this Thesis.

(1) This thesis contributes a novel framework to model and evaluate performance and robustness of Coordinated Voltage Regulation (CVR). This framework is generic in that it is not tied to any specific control module, Reduction of the Control Model (RCM), Reactive Optimal Power Flow (ROPF) implementation or specific filtering technique. The modelling of the main functions includes sufficient detail in order to capture the main system requirements and features, as actually implemented in the

CVR. In its Monte-Carlo extension this framework can be used to facilitate the selection and design of any of CVR components. The author developed the entire coding in MATLAB and the implementation is both efficient and easy to integrate with other Power System tools.

(2) This thesis contributes to the State of the art two novel zoning methodologies; Spectral K-way Clustering (SKC) and Fuzzy C-Means Clustering (FCM). Both are formulated as Clustering optimization problems using Complex Network Analysis. Compared to existing formulations that use Spectral and Fuzzy Clustering, both the SKC and FCM formulations in this research; a) deploy proximity metrics tailored to the control problem of CVR (i.e. electrical distance based on voltage sensitivities), b) deliver reproducible output and c) include clustering validation and this is achieved using inexpensive validation indices (i.e. eigen-gap and Xie&Beni index, respectively).

(3) This is the first work to evaluate a representative subset of zoning methodologies (i.e. SKC, FCM, HCSD, and HSVC) in the CVR application. In this evaluation, the focus is on both the performance and robustness that the CVR controller achieves in conjunction with a zoning based RCM approach. Results point to both the merits and limitations of the zoning methodologies under study.

(4) This is the first work to provide answers to four novel research questions with regards to adaptive RCM in CVR; (a) is adaptive RCM feasible from a computational perspective on realistic size networks? , (b) what should trigger the adaptive RCM? , (c) what is the Value of adaptive RCM? and (d) what is the major implementations challenges. Regarding question in (a) the role of relative eigen gap heuristic is presented in speeding up the SKC methodology. Regarding question (b) a novel index termed Variation of Pilot Node Centrality is introduced in order to carry out scenario selection.

(5) This is the first work to present *horizontal* and *vertical zone division* for the voltage control problem, beyond the single ISO and to address the required degree of co-ordination for the voltage control of both *horizontal* and *vertical* zones. To that end, a novel methodology has been developed to assess the required degree of co-ordination of Voltage Regulation in horizontal zones. The methodology is generic in that it is voltage control algorithm agnostic and can accommodate any zone division or case study network. Regarding vertical zone division various degrees of co-ordination are examined and particularly for the case of full co-ordination a novel AI Planning based approach is presented.

7.3 Broader Implications

This section summarizes broader implications of the work presented in this thesis.

(1) The presented framework for modelling and evaluation of Coordinated Voltage Regulation (CVR) can essentially be used for a number of important investigations; It can be used to select and design a CVR control module, assess robustness of different filtering techniques and sensor technologies (e.g. PMU based CVR as proposed in [94]) or assess vulnerability to malicious attacks.

(2) Using this framework, various zoning methodologies have been compared for the first time, providing a benchmark for other existing ones/proposed in the future. This comparison is meaningful and very much needed; Zoning methodologies have been used in commercial hierarchical AVC implementations (e.g. HCSD is used in the French AVC implementation and HCVS is used in the Chinese AVC implementation). Hence the reported results are also valuable even for today's Systems and can be deployed to improve economy and security of existing CVR schemes.

(3) The findings in this thesis provide sufficient evidence that adaptive reconfiguration of the RCM can be considered as one of the actions CVR can take before CVR reaches its limits and emergency control takes place. In this sense, the inclusion of adaptive RCM in CVR can potentially improve system security, defer potential load-shedding, allow system to accommodate more stochasticity and decrease the risk of large black outs.

(4) Lastly, this research is a step towards moving to Autonomic Control of Power Systems [115]. The reconfiguration of the zoning based RCM achieves improved control without much of human intervention. At the same time, the individual CVR zones can act autonomously to prevent/mitigate contingencies within their control authority even when communication with a central-coordinator is interrupted.

7.4 Future Research

This section summarizes future research directions that could effectively extend this work.

(1) The proposed framework for CVR modelling and evaluation neglects voltage dynamics, based on the assumption that the associated control loops are time dynamically decoupled, i.e. the time constant of the power plant reactive power

control loop is chosen to be sufficiently higher than that of the primary voltage control loops and sufficiently lower than that of the secondary voltage regulation. While this is an acceptable simplification, as discussed in [120], the inclusion of dynamics could allow the deployment of the framework for a wider number of applications and investigations.

(2) The current work has focused on technical feasibility of adaptive RCM in CVR and value from a control perspective, assuming communications and measurements is not an issue. Future work could focus on techno-economic evaluation of most appropriate thresholds for the RCM reconfiguration and the implications for measurements from a planning perspective, as we move from 2020 to 2050 networks.

(3) The last Chapter of this thesis investigated the required degree of co-ordination, among horizontal zones and among vertical zones, under the valid assumption that transmission and distribution deal with CVR independently (i.e. as it is today). An interesting extension could be the investigation of the most appropriate degree of co-ordination among vertical and horizontal zones, moving towards a whole system approach to CVR, where boundaries between transmission and distribution are more blurry. This would require a joint optimization of operational costs (i.e. Reactive Reserves of Synchronous generators and losses reduction) and maintenance aspects (i.e. wear and tear of switching devices at the secondary side of a substation).

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