Secondary voltage control in the Netherlands
A feasibility study

Deesh Dileep

SCADA

ENERGY MANAGEMENT SYSTEM

CONTROL ENGINEERS

COMPUTATIONAL AID

TUDelft

Delft
University of
Technology

Challenge the future
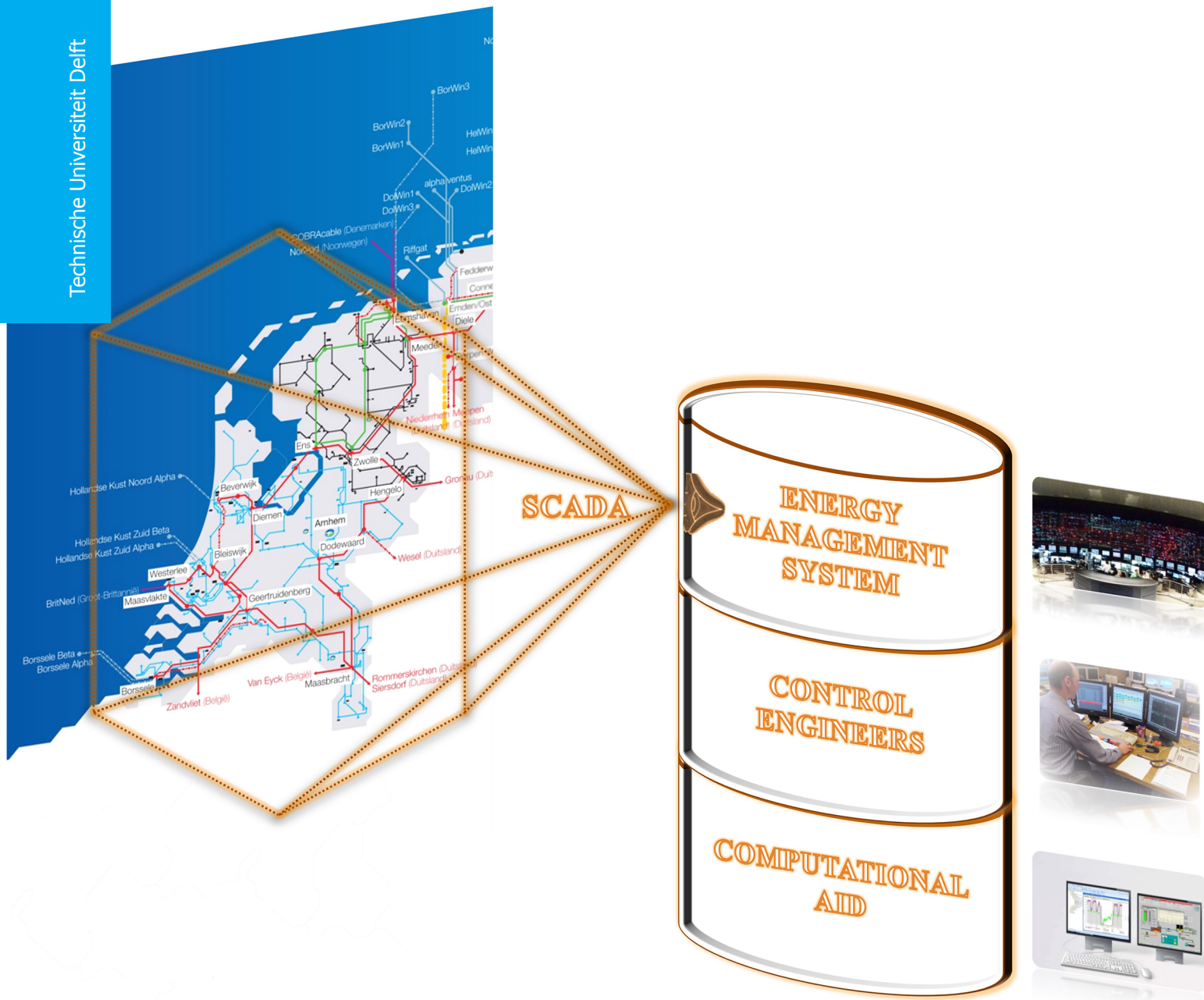
Secondary voltage control in the Netherlands

A feasibility study

by

D. Dileep

in partial fulfillment of the requirements for the degree of

Master of Science

in Electrical Engineering - Electrical Sustainable Energy (Intelligent Electrical Power Grids)

at the Delft University of Technology,
to be defended publicly on Friday August 19, 2016 at 15:00.

Student number:	4394399
Project duration:	November 10, 2015 – August 10, 2016
Supervisor:	Dr. ir. J. L. Rueda Torres
	Ir. S. Franke
Thesis committee:	Prof. dr. P. Palensky, TU Delft
	Dr. ir. J. L. Rueda Torres, TU Delft
	Dr. ir. L. M. Ramirez Elizondo, TU Delft
	Ir. S. Franke, TenneT TSO B.V.

Note: This thesis has been redacted for publication due to confidentiality agreements with TenneT TSO B.V., Netherlands.

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TUDelft Delft University of Technology

Acknowledgement

Abstract

Currently, the European energy sector including that of the Netherlands is in a rapid transition phase. Increasing integration of renewable energy sources, distributed generation, smart grid technologies and other power electronic devices into the grid has given rise to numerous challenges in operating the electricity transmission and distribution systems. Active and reactive power control is essential to maintain stable frequency and voltage values respectively in the power system. However, due to the increasing complexity in electricity market processes, control of active power in steady state time frame is infeasible to system operators at normal state of operation. Therefore, solutions provided by standard offline optimal power flow solvers to re-dispatch real and reactive power generation to increase system efficiency may not be applicable in real-time operational scenarios. Whereas, steady state control of reactive power is still viable to system operators. System operators control reactive power resources in steady state time frame to maintain a good voltage profile within their power system. Keeping steady state voltage values within their security limits is essential for proper functioning of electrical components connected to the power system. Unlike frequency, measured voltage values may vary significantly over a power system. Many system operators control steady state voltage manually with minimum or no advanced real-time computational assistance. Increasing distributed generation and decreasing conventional generation reduces the controllability of voltage within power system. Decreasing controllability of voltage could compel the need for an intelligent control system that can be used as a computational aid in order to support steady state voltage control process.

This master thesis report focuses on the feasibility study conducted for employing an intelligent control system that can be used as a secondary voltage control scheme in the Dutch transmission system. The feasibility report begins with a brief introduction to the research topic and concluding remarks from literature survey conducted on hierarchical voltage control schemes of other European transmission systems. Information on their control scheme system requirements, performance and benefits of using it in their transmission system were used to suggest improvements in the Dutch system and conclude that it might be possible to implement a centralised advisory control scheme similar to that of Belgium in the Netherlands. Currently, the secondary voltage control is performed by control engineers manually for the Dutch transmission system. Their current approach does not involve the use of any control system as a computational aid that uses real-time or measurement data for support. After conducting surveys to observe the existing approach of voltage control in the national control center, it was found feasible to include some kind of aid so as to reduce the probable unforeseen and undesirable consequences that could result from the decision making process of control engineers. In order to design an intelligent voltage control system, several artificial intelligence techniques available for coordinated voltage control were studied in detail. This literature study concluded with rule based controllers being the most suitable control system that can be used for the feasibility study. This was mainly due to its simplicity, adaptability and ease of mapping human expertise as rules.

In this thesis project, a rule based controller was developed based on the expertise of control engineers and requirements of TSOs, in order to perform the feasibility study on employing an intelligent decision making tool. The rule based controller was incorporated with a mixed integer linear programming solver to find solutions for multi-objective reactive power optimization problems of power system. A relatively smaller power system model was used as test system to develop the controller and optimization algorithm. However, this test system had to be modified in order to recreate system operations like in real-world scenarios. Information obtained on the existing approach of control engineers and their priority to use reactive power resources were utilised to define objectives, constraints and controllable devices within the optimization algorithm. After developing the optimization algorithm using the test system and performing simulation based studies on it using a multi-area approach, the controller was modified and transferred to perform simulation based studies using the same method on the modified snapshot system model. Results from successful optimization of various scenarios in the snapshot system model were used to show that an intelligent control system could be employed to

support the decision making process of control engineers. This would reduce the number of tasks they are expected to handle and assist them to foresee all probable consequences that could arise from a particular control action.

However, before employing any kind of voltage control scheme, various improvements will have to be incorporated in order to meet the system requirements. Additional research work has to be carried out in order to find the appropriate transmission network model that can be used by the optimization algorithm. The new network model should be able to provide adequate sensitivity, voltage and reactive power data with respect to real-time scenario (for the optimization process). Objectives and constraints have to be carefully prioritized and selected so as to operate the transmission system securely and efficiently.

Contents

List of Figures

List of Tables

Abbreviations

List of abbreviations

AI Artificial Intelligence

AM Asset Management

ANN Artificial Neural Network

AVR Automatic Voltage Regulator

CB Capacitor Bank

CE Control Engineer

CSVC Coordinated Secondary Voltage Control

CVC Centralized Voltage Control

DG Distributed Generation

DPL DIgSILENT Programming Language

DSO Distribution System Operator

DSVC Decentralized Secondary Voltage Control

EHV Extra High Voltage (referring to 220kV and 380kV grids in this thesis)

EMS Energy Management System

ENTSO-E European Network of Transmission System Operators for Electricity

ES Expert System - Rule Based Controllers

EU European Union

FACTS Flexible AC Transmission System

FFNN Feed Forward Neural Network

FIS Fuzzy Interference System

FL Fuzzy Logic

HV High Voltage

KBCS Knowledge Based Control System

LDF Load Flow

LMC Loss Minimization Control

LP Linear Programming(Optimization)

LV Low Voltage

MPC Model Based Predictive Control

MVMO Mean-Variance Mapping Optimization

No. Number

OLTC On Load Tap Changers

p.u. (or **pu**) per unit

PCC Point of Common Coupling

PVC Primary Voltage Control

RBS Rule Based System

RES Renewable Energy Sources

RP Reactive Power

RPO Reactive Power Optimizer

RVR Regional Voltage Regulator

SART Automatic System for the Regulation of Voltage of power stations(translated from Italian)

SCADA Supervisory Control And Data Acquisition

SN Snapshot

SR Shunt Reactor

SVC Secondary Voltage Control

TSO Transmission System Operator

TVC Tertiary Voltage Control

Glossary

absolute	a mathematical term which denotes the modulus of a real number, the non-negative value without regard for its sign
after-the-fact	after an event has occurred
agent	an autonomous entity which collects information and acts upon an environment based on the information to achieve a goal or set of goals
ancillary voltage control services	voltage control services necessary to support the transmission of electric power from generation point to end users and to maintain reliable operation of the interconnected transmission system
area	associated with a geographical location (also referred to as region)
automatic voltage regulators	device that regulates voltage at a connection point regularly considering a set point magnitude with a small response time, primary voltage controllers
bus	a node within power systems that conducts electricity (also referred to as bus bar)
capacitor bank	capacitive in nature, a set of capacitors in parallel or series used for compensation of reactive power
complex	often associated with problems that are complicated and cannot be solved with straightforward solutions
computational support	used in this context as a computer aid or tool that contains algorithms to support users
controllable RP resources	reactive power resources that can be controlled, which means that they are active, connected and ready to be used in the power system when required
control system	a device, or set of devices, that manages, commands, directs or regulates the behaviour of other devices or systems
control variable	a variable that has been used within the control system for optimization problem
conventional generation	electricity generated using conventional sources like fossil fuels
distributed generation	small scale technologies used to produce electricity near end users
electricity grid code	a technical specification which defines the parameters that the facility connected to or operating the electric power system network has to meet so as to ensure safe, secure and economic functioning of the power system
energy management system	a system of computer aided tools used in electric utility grids to monitor, control or optimize the performance of generation, distribution or transmission system by its operators
expert system	a computer system that can emulate the decision making ability of a human expert for a specified process, in this thesis context expert systems and rule based control systems are considered to be the same

extreme scenarios	power system scenarios or snapshots which are not having a normal state of operation, they may not have all the security constraints respected
forecasts	prediction of power injections and withdrawals to and from the power system (also referred to as congestion forecasts)
fuzzy interference system	a method to map an input space to an output space making use of fuzzy logic principles
genetic algorithm	a method to solve constrained and unconstrained optimization problems based on natural selection, the process that drives biological evolution
green initiative	any initiative which has an objective of reducing greenhouse gas emissions
grey box model	a model that combines a partial theoretical structure with data to complete the model, a combination of white box model and black box model principles
heuristic solver	an approach to problem solving, learning, or discovery that employs a practical method which may not be optimal or perfect, but it is sufficient to achieve immediate goals
hybrid	a combination of two or more sets of principles
inter-area variables	variables exchanged between agents optimizing different areas
Jacobian matrix	a matrix composing of first order partial derivatives of a vector valued function
knowledge based control system	a control system that uses knowledge to solve problems, find solutions or achieve goals
Lagrange function	in this context, it is used to associate with the strategy of using Lagrange multipliers to find the local maxima and minima of a function subjected to constraints.
liberalisation	relaxation of government restrictions mostly in areas of economic, social or political policies
linear	a mathematical model that uses linear operator, they are simpler than non-linear systems
linear programming	a method to achieve the optimal outcome in a mathematical model constituting requirements which are represented using linear relationships
logarithmic barrier function	functions used to replace the inequality constraints by a penalizing term in the objective function which is easier to handle
mapping	process of recording or collecting information and storing in a knowledge base which can be later used to create or support rules within a control system
multi-agent system	system composed of multiple interacting agents within an environment to perform some function or achieve a set of goals
N-1	an N-1 secure power system can maintain reliable operation even if any one of the electrical component within it is disconnected or not available
Newton direction	a method to solve optimization problem applied to the derivative of a twice differentiable function in order to find the roots of the derivative, also known as stationary points.
non-linear	a system in which the output is not directly proportional to the input, most of the systems are inherently non-linear in nature

on load tap changer   a variable connection point selection mechanism that can select the number of turns in discrete steps within power transformer winding

optimization   finding a maximum or minimum value of a function of several variables subjected to a set of constraints using some kind of mathematical, genetic algorithm or heuristic techniques

parallel solver   master agent optimizing a set of areas using its agents in parallel manner

power system   electric power system is a network of electrical components used to generate, transmit and distribute so as to consume electric power

reactive power   the imaginary part of apparent power which transfers no net energy to the load, it exists when voltage and current waveforms are not in phase in an alternating current circuit

real power   the real part of apparent power that, averaged over a complete cycle of the alternating current waveform, results in net transfer of energy in one direction (also called active power)

sensitivity analysis   analysis performed to observe the sensitivity of different variables, sensitivity is the effect of change in magnitude of a variable on the entire function or other variables

sequential solver   master agent optimizing a set of areas using its agents in sequential manner

shunt reactor   inductive in nature, commonly used to absorb reactive power from long high voltage transmission lines or cables within a power system for compensation

snapshot   a state of power system at any point of time taken from energy management system

snapshot system   system model obtained from offline tool along with the snapshot data from energy management system

state estimation   the process of obtaining best estimate of the state of a power system using a set of measurements and a model of the system, sometimes a few measurements are given priority over others

sub-transmission   transmission system with slightly lower voltage rating connected to main transmission system, voltage ratings of the sub-transmission systems depends on its operator and their network topology, sub-transmission systems commonly have higher voltage rating than distribution systems

sustainable energy   technologies that support renewable energy and are designed to improve energy efficiency

test system   power system model used for developing the prototype rule based control system

rule of thumb   principle obtained through experience and is not intended to be strictly accurate, valid or reliable for every situation

transmission system   in this context, a system used to transmit electric power

1

Introduction

In this chapter, a brief introduction to the topic of research will be presented, starting with a general introduction to electric power system and the role of transmission system operators. Introduction to the concept of power system control will also be given in this chapter, while focusing on voltage or reactive power control of power systems. Finally, the problem definition, goals, research questions and outline of this thesis project will be described in detail.

1.1. Electric power system and transmission system operators

Classical electric power systems had a centralised generation scheme with large concentrated generation feeding loads through an electric power transmission and distribution system. Rapid growth and diversification of energy sector due to environmental policies or green initiatives have changed the power system to a more decentralised generation scheme with increasing penetration of distributed generation into the electric power system along with other improvements (implementation of smart grid technologies, higher penetration of renewable energy, liberalisation of energy market leading to complex trading procedures etc.). In any electricity system, it is important to maintain the voltages and frequency within a permissible range for satisfactory and secure operation of all the electrical equipment which are connected to this network [1]. A brief overview of the present day electric power system is shown in figure 1.1.

Transmission system operators: Electricity Transmission System Operators (TSOs) play a central and crucial role in today's energy market, most of which are being liberalised [2]. They have to ensure secure technical operation of the electricity transmission grid while also facilitating the developments in electricity market [2]. The responsibilities and position of TSOs vary to a large extent depending on countries and their laws [2]. Generally, TSOs in the European region have three main functions. Firstly, transmission asset management and investments in long-term development of the transmission system. Secondly, transmission system operations function which involves short-term management of electricity flows in their system. Their final function is to maintain stability of the entire system including energy balance and reactive power management [2].

Transition towards sustainable energy sources: In order to support and accelerate the growth of sustainable and renewable energy production, governments all over the world have been increasing their subsidies and revising operational policies [3]. Environmental impact of conventional generation forms an important reason for governments to enforce a change in their current approach [3]. Fossil fuels are currently being used as the main source of electrical energy by most of the countries around the world [4]. Studies have shown that energy consumption of a country can be directly related to its economic growth [3]. With increasing demand of electrical energy due to economic growth of developing countries and population growth in general, consequently, depletion of fossil fuels has been a growing concern which has been forcing governments to increase their subsidies in the sustainable and renewable energy sector [3].
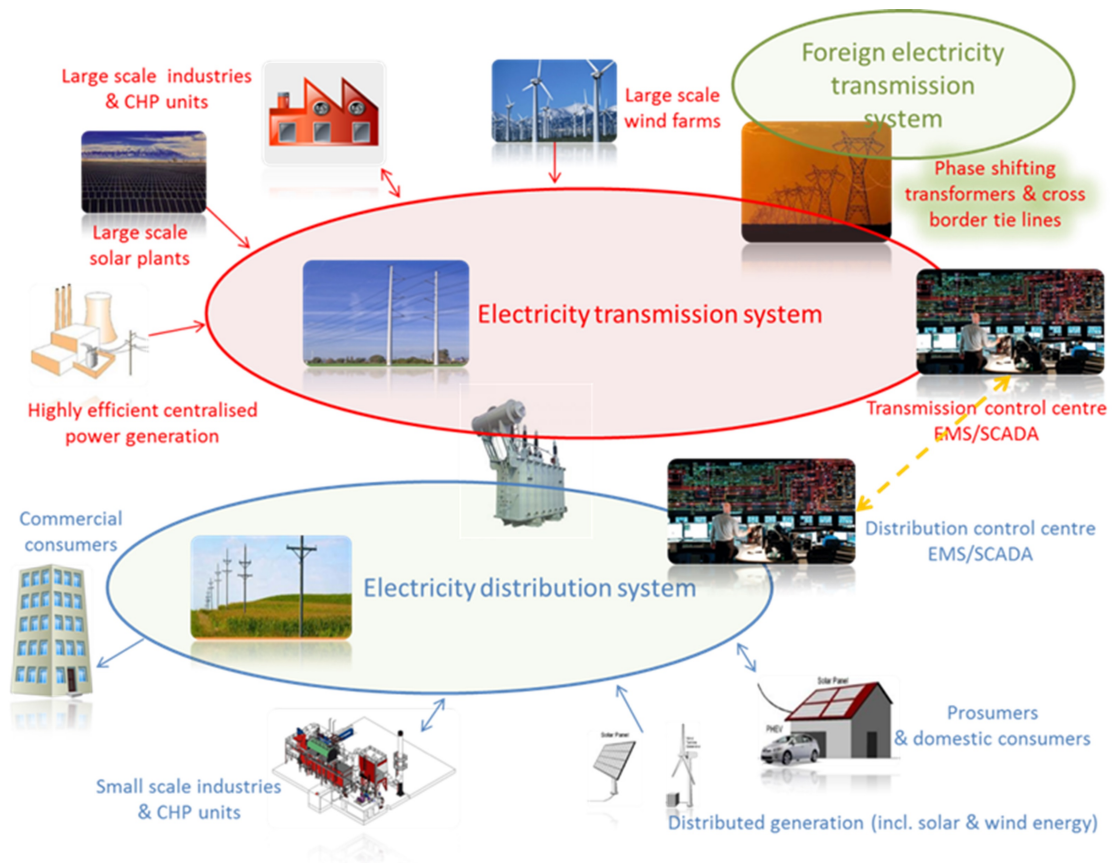
Figure 1.1: Overview of an electric power system

Transition towards distributed generation: In the present scenario, the amount of electrical energy generated by decentralized power generators of relatively smaller size (<50-100 MW) is significantly increasing [5]. These sources (incl. renewable energy sources) commonly referred to as "distributed generators" are spread over the system and are usually located closer to electrical loads in the medium voltage or low voltage distribution system networks [5]. Transition towards the use of renewable energy sources cause further increase in distributed generation, consumers and producers are supported by green initiatives from governments to install solar panels or wind turbines locally [5] & [6].

The increase in distributed generation (including distributed renewable energy generation) can decrease the overall inertia in the system [5]. However, a large scale combination of multiple Distributed Generation (DG) units can emulate a kind of virtual inertia to confine the impact of undesirable frequency deviations [5]. For this purpose DG connected with power electronic converters can be equipped with controllers with a fast response time in order to provide primary frequency control [5]. The possibility of reactive power control within the system is also reduced with an increase in DG [5]. However, other reactive power resources like capacitor banks, synchronous condensers, FACTS devices etc can be introduced into the system in order to overcome this problem [5]. Additionally, with increasing DG penetration distribution system operators (DSO) can take over some functions and provide inertia or reactive power support to TSOs [5] & [6].

Control of power system: A power system must be capable of meeting power demands from both large and small customers of domestic, commercial and industrial types [7]. It should be able to withstand disturbances in the power system with security [7] (security limits are generally defined by law).

Some control and decision processes for optimal utilization of resources could involve month long time constants [7]. While other processes that follow transient phenomena like a lightning strike run their course in a few milliseconds [7]. The slower or higher level control processes are normally handled by computer-assisted control engineers while the faster control functions are trusted with fully automatic control system of either open (no feedback)/closed (with feedback) loop nature [7]. A modern energy management system(EMS) functional diagram which is representative for some TSOs can be shown in figure 1.2 taken from [8]. It should be noted that EMS of TSOs around the world could have more or less functions compared to the one shown in figure 1.2 depending on their interests or role. In a transmission system with liberalised energy market (which is the case in Europe), solutions from optimal power flow solvers cannot be directly applied by TSOs due to the complexity in market processes [3], [9] & [8]. Optimal power flow solvers assume principles of unit dispatch which may be applicable in parts of the world, but not in Europe. Most of the TSOs have control over their reactive power resources while active power can only be controlled in emergency state (or exceptional power system scenarios) [1] & [8].

Steady state control of power systems can be broadly classified into two parts, active power control for maintaining a good frequency in the synchronous power system and reactive power control for maintaining local voltage values within secured limits and a good overall voltage profile in the power system [10]. Even though coordination of active and reactive power control is imminent for a stable power system, they are generally considered as two different problems in literature for simplifying control of power systems [10]. This is because small changes in active power (or reactive power) values are assumed to result in only small changes of power angle (or voltage) values according to the linearized control and state equations of power systems, which will be derived as given in [7] & [10].
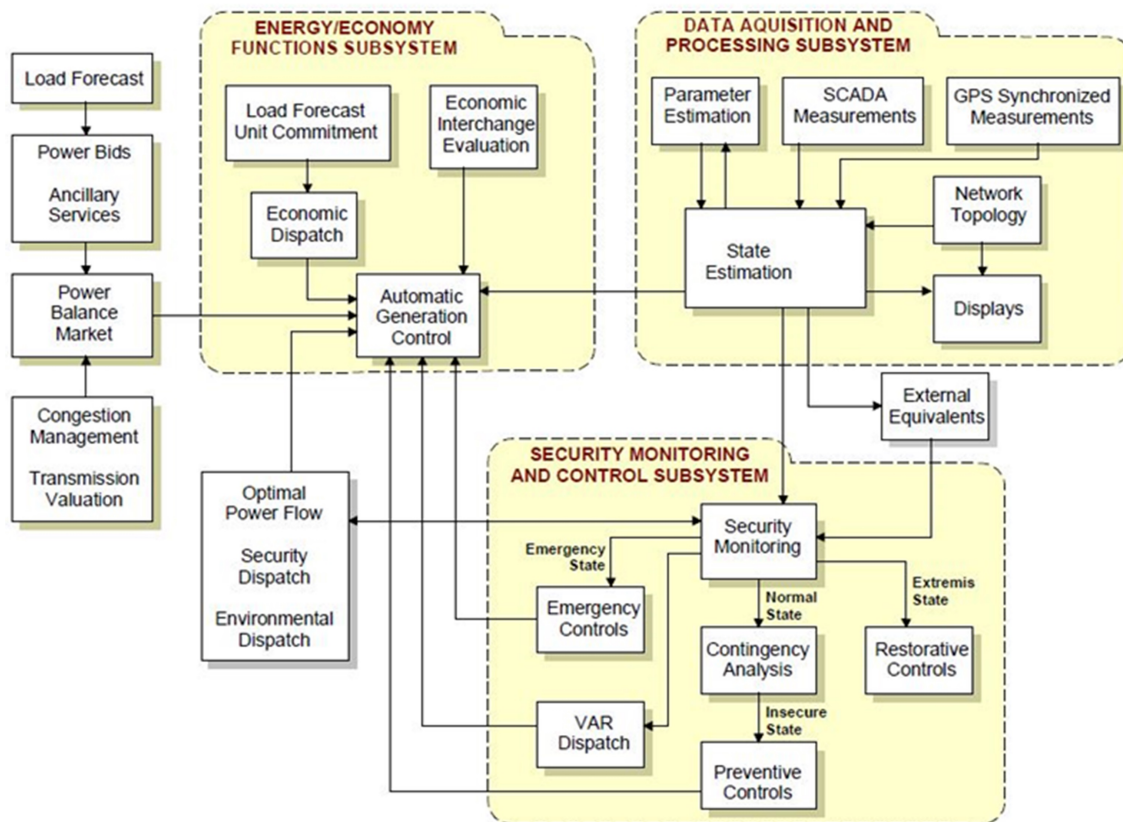
Figure 1.2: Modern energy management system functional diagram [8]

Consider an N-bus power system, where $N \geq 100$ for typical power systems and $N \geq 1000$ for countries with large power systems [7]. The bus voltage V_i can be measured between its phase and ground,

which has a *magnitude* and *angle* as given in equation 1.1.

$$V_i = |V_i| \angle \delta_i \tag{1.1}$$

If bus 1 is chosen as the reference [7],

$$V_1 = |V_1| \angle 0^o \tag{1.2}$$

The bus current at bus i "I_i" is defined as the difference between generator current "I_{Gi}" and load current "I_{Li}" injection at the bus [7].

$$I_i = I_{Gi} - I_{Li} = |I_i| \angle \alpha_i \tag{1.3}$$

The bus power consists of two components, real power "P_i" and reactive power "Q_i" components [7].

$$P_i = |V_i||I_i|cos \angle \phi_i \tag{1.4}$$

$$Q_i = |V_i||I_i|sin \angle \phi_i \tag{1.5}$$

"P_i" and "Q_i" satisfies the complex equation which can be shown as equation 1.6 [7].

$$P_i - jQ_i = V_i I_i \tag{1.6}$$

Where "ϕ_i" in equations 1.4 and 1.5 is the relative phase angle between the "V_i" and "I_i" of bus i[7].

$$\phi_i = \delta_i - \alpha_i \tag{1.7}$$

There is a linear relationship existing between V_i's and I_i's and can be denoted as shown in equation 1.8 [7].

$$I_{bus} = Y_{bus} V_{bus} \tag{1.8}$$

Where "I_{bus}" and "V_{bus}" are N dimensional current and voltage vectors respectively which contain bus voltages and currents. While the bus admittance "Y_{bus}" is a $N \times N$ matrix [7]. "Y_{bus}" is also a symmetric and sparse matrix [7]. If there is no line between buses i and j then y_{ij} is zero. "y_{ij}" are complex elements present in the "Y_{bus}" [7].

$$Y_{bus} = \begin{bmatrix} y_{11} & \cdots & y_{Ni} \\ \vdots & \ddots & \vdots \\ y_{N1} & \cdots & y_{NN} \end{bmatrix} \quad where \quad y_{ij} = |y_{ij}| \angle \gamma_{ij} \tag{1.9}$$

From 1.6 and 1.8,

$$for \ i = 1 \cdots N$$

$$P_i - jQ_i = V_i \sum_{j=1}^{N} y_{ij} V_j \tag{1.10}$$

Separating the real and imaginary parts of equation 1.10 will result in 2×N real equations which can be written as equations 1.11 and 1.12 [7].

$$for \ i = 1 \cdots N$$

$$f_{pi} = P_i + \sum_{j=1}^{N} |y_{ij}||V_i||V_j|cos \angle (\gamma_{ij} + \delta_i - \delta_j) = 0 \tag{1.11}$$

$$f_{qi} = Q_i + \sum_{j=1}^{N} |y_{ij}||V_i||V_j|sin \angle (\gamma_{ij} + \delta_i - \delta_j) = 0 \tag{1.12}$$

These equations are highly non-linear and they are referred to as power flow equations [7]. Consider a transmission system operating at its normal state [7]. Small changes in P and Q can be represented as control vectors ΔP and ΔQ. This will result in small changes of state vectors δ and $|V|$ resulting in vectors $\Delta \delta$ and $\Delta |V|$ respectively [7]. Using equation 1.11 and 1.12, the relation between control and state changes can be expressed as equations 1.13 and 1.14 [7].

$$\text{for } i = 1 \cdots N$$

$\Delta P_i + (\partial f_{pi}/\partial \delta_1)\Delta \delta_1 + (\partial f_{pi}/\partial \delta_2)\Delta \delta_2 + \cdots$

$$+ (\partial f_{pi}/\partial |V_1|)\Delta |V_1| + (\partial f_{pi}/\partial |V_2|)\Delta |V_2| + \cdots \approx 0 \quad (1.13)$$

$\Delta Q_i + (\partial f_{qi}/\partial \delta_1)\Delta \delta_1 + (\partial f_{qi}/\partial \delta_2)\Delta \delta_2 + \cdots$

$$+ (\partial f_{qi}/\partial |V_1|)\Delta |V_1| + (\partial f_{qi}/\partial |V_2|)\Delta |V_2| + \cdots \approx 0 \quad (1.14)$$

The linear relations 1.13 and 1.14 can also be written in a compact form given in equation 1.15.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (1.15)$$

Equation 1.15 can also be re-written in the component form to split real and reactive power components as equations 1.16 and 1.17 respectively.

$$\Delta P \approx J_1 \Delta \delta + J_2 \Delta |V| \quad (1.16)$$

$$\Delta Q \approx J_3 \Delta \delta + J_4 \Delta |V| \quad (1.17)$$

In a typical transmission system, the impedance elements can be assumed to be almost purely reactive which would make values of angles γ_{ij} close to $\pm 90°$ [7]. Generally system operators keep line power angles $\delta_i - \delta_j$ below $30°$ [7]. Under these assumptions, it can be shown that submatrices J_1 and J_4 are more dominant compared to J_2 and J_3 for small changes in state [7] & [10]. Therefore the equations 1.16 and 1.17 can be re-written as equations 1.18 and 1.19 considering only the jacobian submatrices J_1 and J_4.

$$\Delta P \approx J_1 \Delta \delta \quad (1.18)$$

$$\Delta Q \approx J_4 \Delta |V| \quad (1.19)$$

According to 1.19, small changes in control variable Q or reactive power components of a bus would result in change of its state variable, the magnitude of its voltage or $|V|$ [7]. This principle is used in voltage controllers in real time operation of a power system [7] and fast decoupled load flow methods [10]. Therefore, this principle will also be utilized in this master thesis project. By optimizing reactive power injections at buses, steady state magnitudes of bus voltages are maintained within their operational security limits. Reactive power injections can be optimized using reactive power resources available to system operators like shunt reactors, capacitor banks, Mvar feed in of generators and power electronic devices [1].

1.2. Voltage control in electric power system

Steady state grid voltages are still controlled manually by many system operators worldwide [1]. Control of reactive power and voltages are important for improved utilisation of assets in the electric power systems [1]. This thesis does not deal with active power balancing, active power or frequency control related topics and assumes that the effect of small changes in steady state voltage or reactive power flow within a power system on its steady state active power flow is not important [7] & [10]. Reactive power resources like shunt reactors, capacitor banks, synchronous condensers, contracted(for reactive power) production plants and other FACTS devices are generally used by system operators to control local voltage levels in an electric power system [10]. On load tap changers (OLTC) of transformers are also used by them to control the voltage levels [10].

Introduction to hierarchical voltage control scheme: The primary voltage control is performed at production plants and it makes sure that the voltages of generators are maintained close to the set point values with the help of automatic voltage regulators or other means of excitation controls fitted to the

units [1]. The approximate steady state characteristic equation 1.20 of automatic voltage regulators used to define reactive power droop has been taken from [1].

$$U = U_s - X_Q * I_Q \qquad (1.20)$$

Where, U is the voltage measurement at high voltage (HV) bus, U_s is the voltage set point, X_Q is the reactive power droop seen from the grid and I_Q is the reactive current injected by the generator to the grid [1]. A smaller X_Q would make the generator react vigorously to changes at HV injection point so as to keep the voltage constant, consequently, contribution from other generators is less [1]. Higher X_Q would make more generators contribute, however, with more deviations in voltage measurements when compared to the set point value [1].

Secondary Voltage Control (SVC) and Tertiary Voltage Control (TVC) mechanisms were introduced in some European countries to improve voltage quality, security and flexibility of operation [1]. More details on hierarchical voltage control scheme will be presented in chapter 2 of this report. Several system operators have recognised that defining an hierarchical voltage control scheme simplifies the identification of different participants contributing to ancillary voltage control services [1]. An SVC system automatically adjusts the reactive power from certain reactive power resources within a zone/region to control the voltage at a specific node also known as pilot node. Whereas TVC is used to optimize the nationwide voltage [1]. This is performed by determining the voltage set points at pilot nodes based on security and economic constraints. The electricity transmission grid operators in France (RTE) and Italy (TERNA) have already employed this kind of hierarchical voltage control scheme nationwide [1].

1.3. Problem definition

Currently, the secondary voltage control in the Netherlands is achieved manually by utilizing the Control Engineers (CEs) experience and expertise at the national control center. A tolerance of $+/-10\%$ of the rated voltage is allowed for the Dutch transmission system [11], the tolerances of $+/-10\%$ are respected also during contingency cases (like "$N-1$" cases) which could result in measured voltage values within an even smaller margin. Depending on the real time voltage profile, control engineers utilize reactive power resources like production plants, shunt reactors, capacitor banks and transmission lines along with transformers having OLTC (On Load Tap Changers) to control voltage. Due to the increasing amount of Renewable Energy Sources (RES) and underground cables in the network along with decreasing amount of conventional generators, importance of reactive power management increases as required control actions become more complex [1]. It is important to note that only steady state optimization problem is considered in this project, dynamic and stability constraints are ignored (refer [12] for more details on voltage stability issues that could arise in power system, publication [13] also presents a method to perform voltage stability analysis on buses of IEEE test system using voltage stability index).

This master thesis project focuses on carrying out a feasibility study on implementing an intelligent scheme for secondary voltage control in the Netherlands, which is currently carried out by the control engineers manually. The current process does not use an analytical tool or mathematical optimizer (with real-time data) to find an optimal solution; therefore optimization in terms of using cost effective methods and reducing switching actions is assumed possible. Reactive power can be controlled using multiple methods, but due to its complexity, it is not possible for control engineers to analyse the optimal solution considering all the economical and technical constraints within the limited amount of time available to them. Therefore it was deemed necessary to check the benefits involved and feasibility of converting this manual decision making process into a semi-automatic process using some kind of voltage optimization system taking different constrains into account (economic effectiveness, N-1 security constraints, voltage limits, contracts with producers, cross border tie-line power flows etc.).

1.4. Voltage control in the forecasting process

Within the Dutch TSO, planning (or Asset Management, AM) department is responsible for long term planning (up to 10 years). They perform studies to determine the future requirement of reactive power
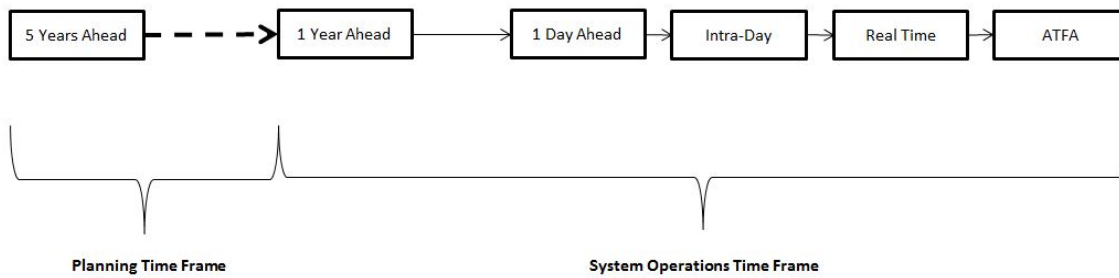
Figure 1.3: Time frame for reactive power planning within the Dutch TSO

sources based on historical data and taking various scenarios into consideration [14]. The outcome of the study results in necessary investments for the future. Subsequently, the system operations department checks these predictions from a year ahead point of view [14]. System operations incorporates necessary changes like additional contracts with producers to counter act the changes in scenarios that could have come up over the years (changes in scenarios, availability of generation units, lines, reactors, capacitor banks etc.). These 10 years or 1 year ahead predictions/forecasts may not be different from that of the actual scenario due to various reasons, but this is not a problem that this thesis will be focusing on.

Figure 1.3 briefly shows the time frame for processes involved at TenneT (the Dutch TSO) [14]. The planning time frame is considered as the responsibility of AM department and this could vary anywhere from 1 year to 10 years (or more) [14]. The Congestion Forecast process also includes a kind of voltage optimizer that checks if there is sufficient reactive power available to the Dutch TSO for a secured system scenario (within voltage limits) with voltage values close to historical voltage set points. This optimizer tries to maintain the reactive power from contracted producers within their limits while also minimizing the number of switching actions. There is no optimal power (or reactive power) flow calculation being performed. Even though operational planning is performed by system operations [14], the results may be different from that of real-time operational scenario. In contrast, this thesis only deals with real-time optimization problem ignoring historical voltage set points.

1.5. Motivation

As mentioned in the introduction of this chapter, there is no intelligent control system using real-time data present at the Dutch national control center. Considering the increasing complexity of electricity system or transmission system (decreasing amount of conventional generators and increasing amount of power electronics), there is a need foreseen for computational support in voltage control. Some kind of intelligent aid has to be provided to the control engineers with the help of already existing systems in order to reduce the undesirable and unforeseen consequences resulting from the decision making process of control engineers and to reduce the number of tasks that they are expected to perform.

1.6. Goal and research questions

During the initial phase, the main goal for this master thesis project has been set based on the problem defined (section 1.3) and it can be described as,

⊕ To check the feasibility of employing a secondary or real time voltage control scheme for the Netherlands and to propose a prototype intelligent voltage control scheme (real-time) which can be used as an aid by the control engineers or dispatchers at national control center.

The most important research questions that will have to be answered are,

○ Gain insight on the current processes used by control engineers; how to map the expertise of control engineers into the intelligent system or secondary voltage control scheme?

○ What are the needs and challenges involved in using a secondary voltage controller for the Netherlands?

○ Questions related to feasibility:
What are the boundary conditions present in the system or what factors will affect the secondary voltage control?

    ⚡ Do reactive power injections from cross border tie-lines prohibit the use of a secondary voltage control? (cross border exchanges form higher composition for Netherlands)

    ⚡ Can snapshots from online tool be used for real-time voltage control? Data analysis will have to be performed for a small set of P, Q and V values over a short span of time (one month). This will provide a brief overview if snapshot data can be used for the intelligent voltage control system. However, this will not be the main focus of this project (book [15] shows how to perform data analysis on measurements).

    ⚡ Ensure that the developed voltage control system can be considered for use by the Dutch TSO and control engineers in the national control center (for the same reason, several economic and security constraints were considered as mentioned later in the report).

1.6.1. Other important aspects to be considered for the feasibility study

The pre-requisites that will be considered important for the proposed intelligent secondary voltage control system have been mentioned below:

⋈ **Cost** related aspects:

    Ψ Minimizing Mvar generated (by producers) to reduce costs and avoid exceeding generator limits of reactive power generation from producers to make results more reliable.

    Ψ Optimal reactive power flow solutions may not be economical due to the costs involved in reactive power generation from contracted generators. In such a case, suggest optimal solutions considering costs involved (also check if all the available options and forecasts of voltage profile can be considered by the control system).

    Ψ Checking if the enhanced secondary voltage control will be able to reduce the costs of reactive power contracts with producers at operational planning stage (of SO) and/or required investments in the network at investment planning stage (of AM).

⋈ **Security** related aspects:

    Ψ Taking "$N-1$" security constraints into account (publication [16] shows an example optimal active power flow problem considering security constraints).

    Ψ Minimizing the number of changes/switching actions required. Make sure that regular switching of shunt reactors or capacitor banks does not take place if a semi-automatic secondary voltage control scheme is implemented.

    Ψ Checking if it's possible to accurately predict the changes in voltage that could result from a switching action. This prediction can be made by using the sensitivities calculated or performing load flow calculations for the options available.

⋈ Optimizing voltage or reactive power control sources for both HV (110/150kV) and EHV grids (220/380kV).

The research questions have been framed focusing on aspects that the Dutch TSO and other TSOs are concerned about. The costs, risks and efforts involved in modifying an existing process should be weighed against the benefits or advantages of employing such a change in control scheme.

1.7. Approach and report overview

This chapter starts with a brief introduction to the topic and why this project is of importance to the field of electric power system engineering. The outline of this thesis project with its main goal and objectives are also explained here. Before starting the thesis work, it was deemed necessary to conduct a literature survey on how other transmission system operators (TSOs) control voltages within their systems. For this purpose a literature review was conducted on three other TSO systems with the help of CIGRE documents, important conclusions drawn from this review are given in second chapter. After concluding that TSOs are able to control voltages within their system effectively, a literature survey was also conducted on the research work published by various institutions for coordinated voltage control using artificial intelligence techniques in power systems. A summary of this literature survey is presented within the third chapter. Based on all these surveys, the objective function, constraints and other functionalities of the optimizer algorithm were proposed. As a part of the feasibility study it was also deemed necessary to perform analysis on the different data (raw and modified data) available within Dutch TSO systems, so as to decide where the algorithm can be employed or tested. Chapter four includes details on both the optimizer algorithm and the data analysis performed. The results from simulation based studies with the optimizer on 80-bus power system (test system) and modified snapshot system models along with its validity checks are explained within the fifth chapter. Last chapter of this report concludes the thesis and gives details on the probable future development work that can follow this thesis project. Figure 1.4 can be referred for an overview of the chapters in this thesis report.

Chapter 1 :

Introduction

- •Introduction to the topic
- •Problem definition
- •Main goal & research questions

Chapter 2 :

Existing voltage control schemes and current approach

- •Literature review on other TSO voltage control schemes
- •Summary of the existing voltage control approach at NCC

Chapter 3 :

Artificial intelligence techniques suitable for voltage control

- •Literature review on emerging artificial intelligence techniques
- •Introduction to multi-agent scheme
- •Technique to be used for this project

Chapter 4 :

Optimizer & model description

- •Objectives and constraints selected for the multi-area based optimization algorithm
- •Description & flow charts of reactive power optimization algorithm
- •Model description - test & snapshot system
- •Analysis on data available
- •Snapshot system area division

Chapter 5:

Results from simulation based studies

- •Results obtained from simulation based studies on test and snapshot system
- •Results from N-1 contingency analysis on snapshot system

Chapter 6 :

Conclusion & future scope

- •Conclusion of the thesis report
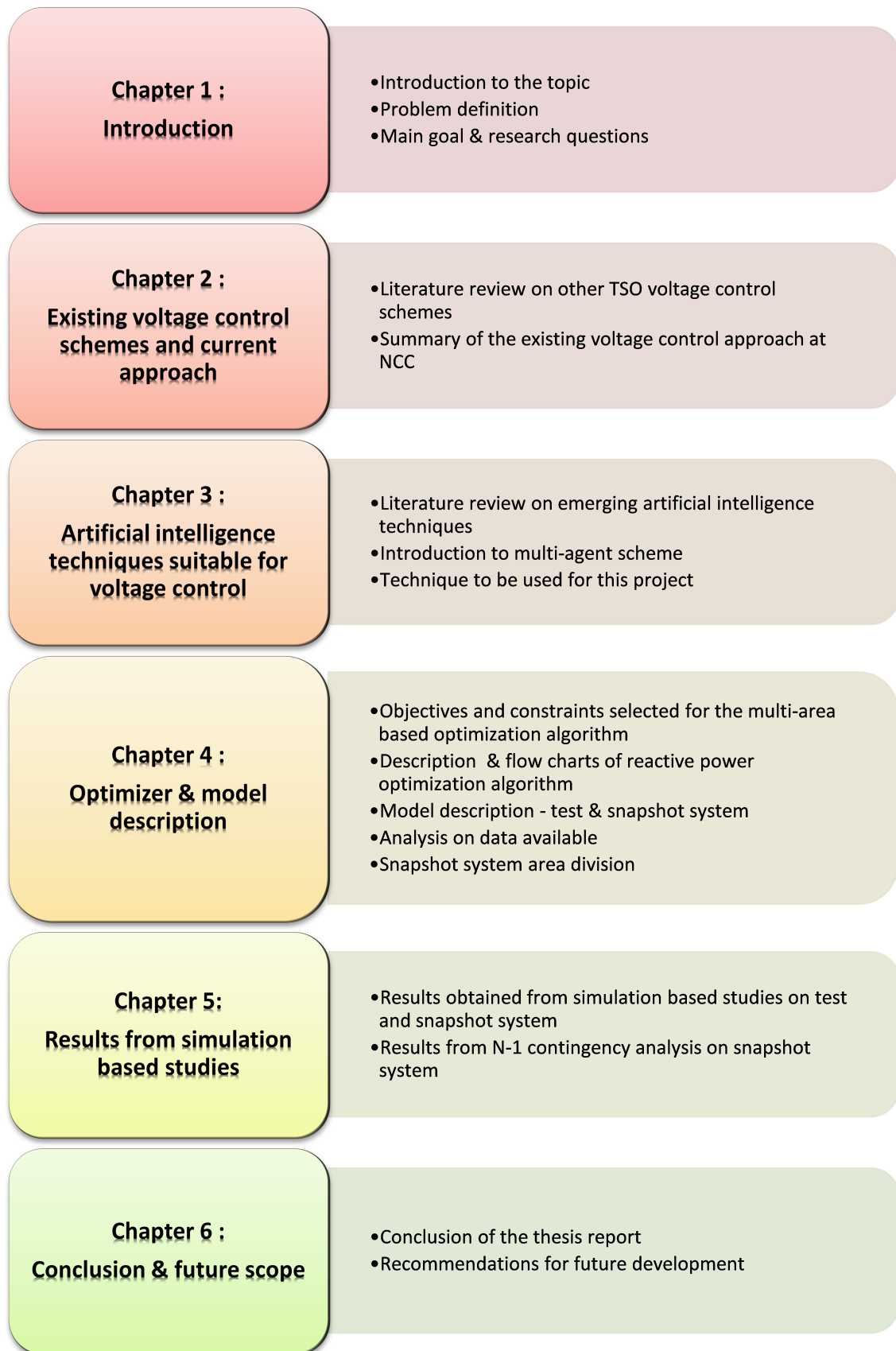- •Recommendations for future development

Figure 1.4: Overview of the chapters in this thesis report

2

Existing voltage control schemes and current approach

In the first chapter of this report, the concept of a co-ordinated voltage control scheme was briefly introduced. During the literature survey, coordinated or intelligent voltage control schemes were found to have two main parts. The first part included the work of transmission system operators and its affiliates (like external consultants) performing various studies on their electrical grid and providing valuable feedback on the technical requirements needed to be fulfilled before employing a voltage control scheme [1]. The second part included the research work or study on emerging Artificial Intelligence (AI) controllers that could be employed on electrical transmission and distribution systems (for more information refer chapter 3). Important conclusions that can be drawn from the literature survey conducted on voltage control schemes used by other transmission system operators will be given in this chapter. Chapter 3 briefly summarises the literature available and the progress that has been made on the conceptual studies performed by research institutions. This chapter also covers the existing voltage control process of system operations in the Netherlands along with other guidelines followed by Control Engineers (CEs) of Europe using [17], [18] and [19].

A simple flow chart to explain the hierarchical voltage control scheme principle is shown in figure 2.1. There are three main levels involved in this type of voltage control scheme which are primary, secondary and tertiary (explained in subsections 2.1, 2.2 and 2.3) differentiated with response time. Depending on the requirements of individual Transmission System Operators (TSOs), this scheme has been modified to fit in their operational systems. The flow chart was taken from [20], which has been used to propose a voltage control scheme for the Spanish transmission system by their TSO (REE). Many countries have employed an open (no feedback) loop voltage control scheme for higher level (or slower) control processes, therefore control engineers at their respective control centers form an integral part of the control process and it's not a completely automatic system [1]. The hierarchical voltage control schemes used by Belgium, France and Italy will be explained briefly within the subsections 2.1, 2.2 and 2.3 respectively. These countries were selected due to the presence of advanced voltage control schemes in their transmission systems and availability of sufficient literature material to conduct a study on their systems. All these TSOs form members of the ENTSO-E, European Network of Transmission System Operators for Electricity [21]. European Union (EU) gave ENTSO-E legal mandates in 2009, so as to steer towards the liberalisation of electricity markets within EU [21]. This means that the TSOs focused on in this chapter will share (and already are sharing) similar operational policies with the Dutch TSO in some cases.

Requirements/Objectives of a voltage control scheme for TSOs[1]

- ⋈ *Steady state voltage quality*: The voltage values of a transmission system should be maintained within its acceptable limits (can also include other constraints) [1].

- ⋈ *Power system security*: The transmission system should be secure at any point of time. Sufficient reserves for reactive power must therefore be available. Voltage control resources should be evenly distributed so as to avoid excessive currents in the electricity grid [1].
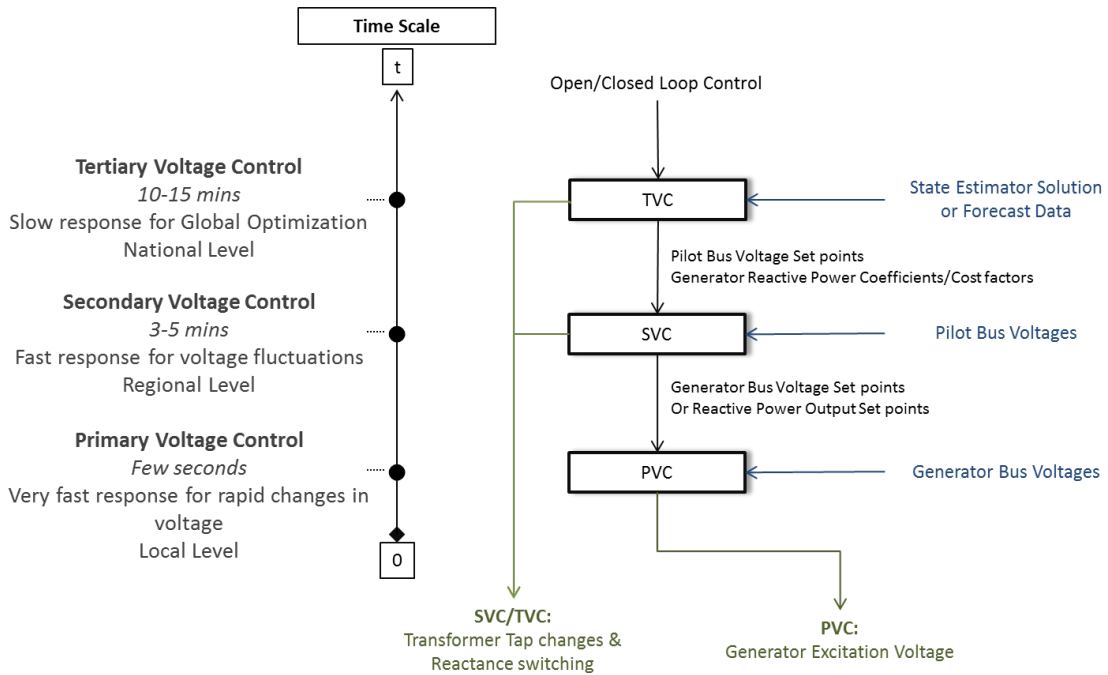
Figure 2.1: A general representation of hierarchical voltage control schemes

⭙ *Operating costs*: The costs of production and losses (of reactive power) should be minimized by the voltage scheme. Thereby avoiding expensive measures to control/maintain voltage level [1].

2.1. Belgian (ELIA) centralized scheme

The Belgian system has a primary voltage control scheme which is employed for the generator as a local control mechanism (or Automatic Voltage Regulators). There is also a tertiary or centralized voltage control scheme present, which is available as an advisory control for the control engineers represented in figure 2.2 taken from [22]. The naming convention used for this scheme is in analogy with the French hierarchical voltage control scheme [22].
According to the Belgian electricity grid codes, it is mandatory to have an AVR (Automatic Voltage Regulator) for generators feeding above 25 MW into the system [22]. Every unit has to make sure that it can vary the delivery of reactive power between $-0.1P_{nom}$ and $0.45P_{nom}$ depending on the CE's request [22]. ELIA found 10% reactive power droop to be satisfactory for generators that is a voltage drop of 10% at a generator's High Voltage injection point would increase the reactive power generation from 0 to rated Mvar [23].

The Tertiary voltage control (TVC) scheme of Belgium includes a system wide optimization based on maximum voltage, minimum losses, best spread and optimal reactive power flow [22]. They form an advisory aid for the control engineers using SCADA or EMS, it is updated every 15 minutes or on the dispatcher's request [22]. The Belgian control engineers have two types of generators available to them; The regulating units which participate in both primary and tertiary voltage control and the non-regulating units which only participate in the tertiary voltage control [24].

Based on the data from the state estimator, a new set of values is calculated for generators, capacitor bank steps and taps of OLTC transformers. These devices contribute to voltage control for the existing Belgian TVC scheme. The Belgian TSO has designed control variables in such a way that certain controllable devices do not reach their maximum or minimum limit before others. This includes minimum and maximum values of reactive power that can be produced by the generators, minimum and maximum voltage limits and maximum reactive power flow limits of interconnecting lines [22].

Operational Benefits of Belgian Scheme [1]:
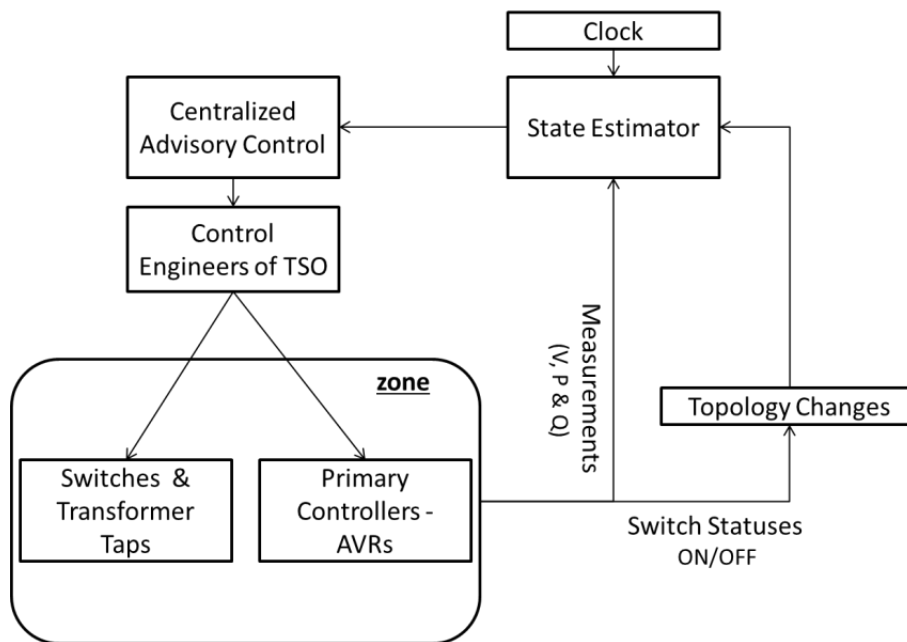
Figure 2.2: Centralized advisory voltage control scheme of Belgium (ELIA) [22]

⋇ TVC found a feasible solution for more than 95% of the cases with a reliable state estimation [1].

⋇ Voltage profile was maintained within 2% margin for all the days.

⋇ Stable sub-transmission system voltages, less switching of capacitor banks and less tap changing of transformers at sub-transmission lines [1]. Where, sub-transmission system is an high voltage transmission system connected to extra high voltage transmission system.

⋇ Reduced losses and increased transfer capacity [1].

2.2. French (RTE) hierarchical scheme

France has employed a hierarchical scheme for voltage control since the early 1970s [22]. Similar to the scheme shown in figure 2.1, the French control scheme also has a local (Primary Voltage Control, PVC), regional (Secondary Voltage Control, SVC) and National (Tertiary Voltage Control) level of co-ordinated voltage control. They are non-overlapping in time due to sufficient difference in the response time constants [22], [25] and [26].

The local primary voltage control keeps the generator voltages close to the set point values. This is an automatic correction process [24]. France was split into non interacting control zones to facilitate SVC. The main purpose of the Decentralized Secondary Voltage Control (DSVC) scheme is to co-ordinate set point values for different generation units within a zone or area [24]. By doing so, it controls the voltage at a particular bus or pilot node which is representative of the zone. The French grid is divided into 35 zones based on electrical distances [22] and [27].

However, the western parts of France have zones which are not completely independent and are sometimes sensitive to the voltage values at its neighbouring zones [27]. These parts of the country have Co-ordinated SVC (CSVC) [19]. CSVC calculates set points for zones or a set of pilot nodes [1]. Figure 2.3 taken from [24] explains the basic principle used for CSVC. Each CSVC gathers information related to pilot nodes, participating generators and critical nodes [24]. This information can be used to determine the voltage set points of PVCs. The highest or tertiary level of voltage control scheme acts on the national level for France and this is not an automated process [1]. The Tertiary control involves determining the set points used for SVC to achieve secure and economic operation [1].
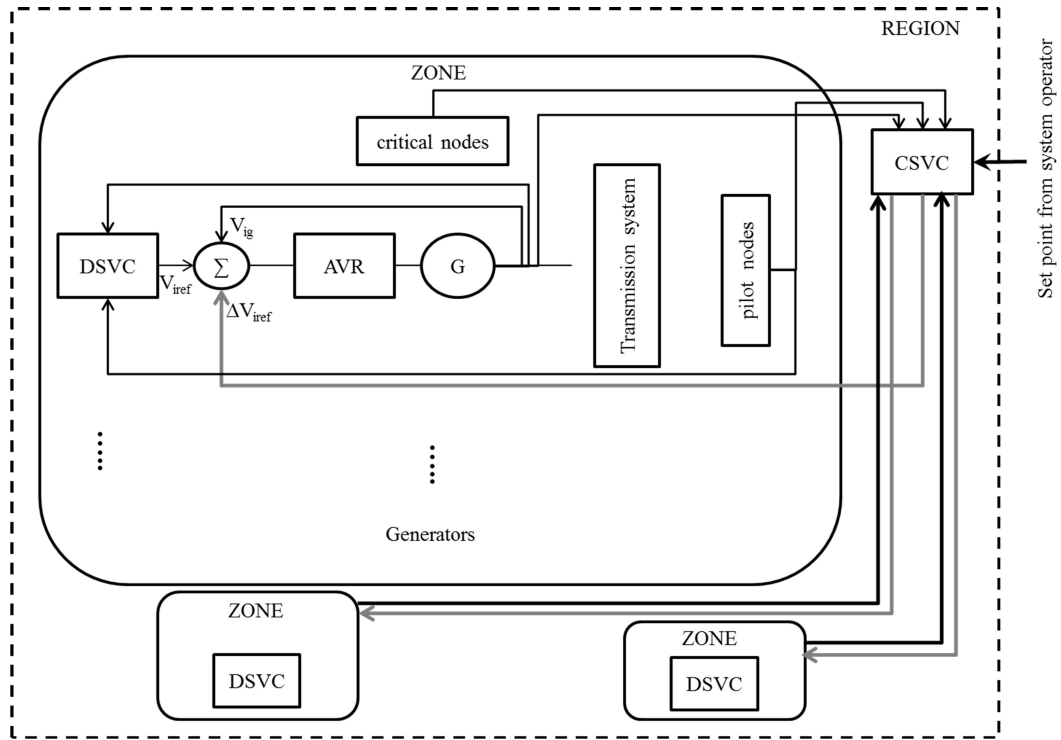
Figure 2.3: Co-ordinated secondary voltage control scheme of France (RTE) [24]

RTE ensures the availability of primary and secondary voltage control reserves through ancillary services contracted with power plants [24]. For this purpose, RTE has specified reactive power sensitive zones where generators are remunerated for generating reactive power [24]. This is not the same in other zones. These reactive power sensitive zones contribute to 1/3rd of the French territory [24].

Operational benefits of *DSVC* and *CSVC* [1] & [25]:

- At contingency and normal operational scenarios the voltages remained within the limits and close to set points. (Improved voltage quality)

- Controllability of voltage improved, thereby leading to high voltage operation of systems and reduced real power losses. (Improved security)

- It was possible to optimize the use of system by preventive control based on experience during peak load hours and transfers. (Economic operation)

2.3. Italian (TERNA) hierarchical scheme

Similar to the French system, a hierarchical voltage scheme is employed for controlling voltage in the Italian transmission network [28]. Primary Voltage Control (PVC) is mandatory for all the generating units connected to transmission and sub-transmission networks of Italy without any financial compensation [28]. The Secondary and Tertiary Voltage Control (SVC and TVC) schemes can be depicted as shown in figure 2.4 taken from [1].

The SVC comprises of a Regional Voltage Regulator (RVR) and Automatic System for the Regulation of Voltage of power stations (SART, Italian abbreviation) [28]. SART is also referred to as Reactive Power Regulators (REPORTs) in some publications [1]. SART regulates the local node voltages by directly controlling voltage set points of the AVR and makes sure that the total generated reactive power is shared amongst the power plants in a well distributed manner [28]. RVRs are present for regional control, they provide information on the required reactive power value to SART. They also control capacitor banks, shunt reactors, OLTC, FACTS and Static VAR compensator devices to avoid saturation of generators [28]. The Italian network is divided into 18 automatically controlled and co-ordinated

areas or zones [28].

TVC at the highest level co-ordinates RVRs in a real time closed loop. It aims to reduce network losses and improve operational voltage security [29]. TERNA has also implemented a LMC (Losses minimization control) which computes forecast values for voltages and reactive levels. Both LMC and TVC together form the National Voltage regulator [29] & [30]. The TVC tries to obtain the optimum solution between both forecasted and realised values. It updates the RVR set points in real time based on the results [29] & [30]. This control scheme has been able to perform well for the Italian system [31]. It has been able to achieve decreased values for real losses, increased reactive power reserves, increased active power transfer capacity and reduced risk of voltage collapse [31].
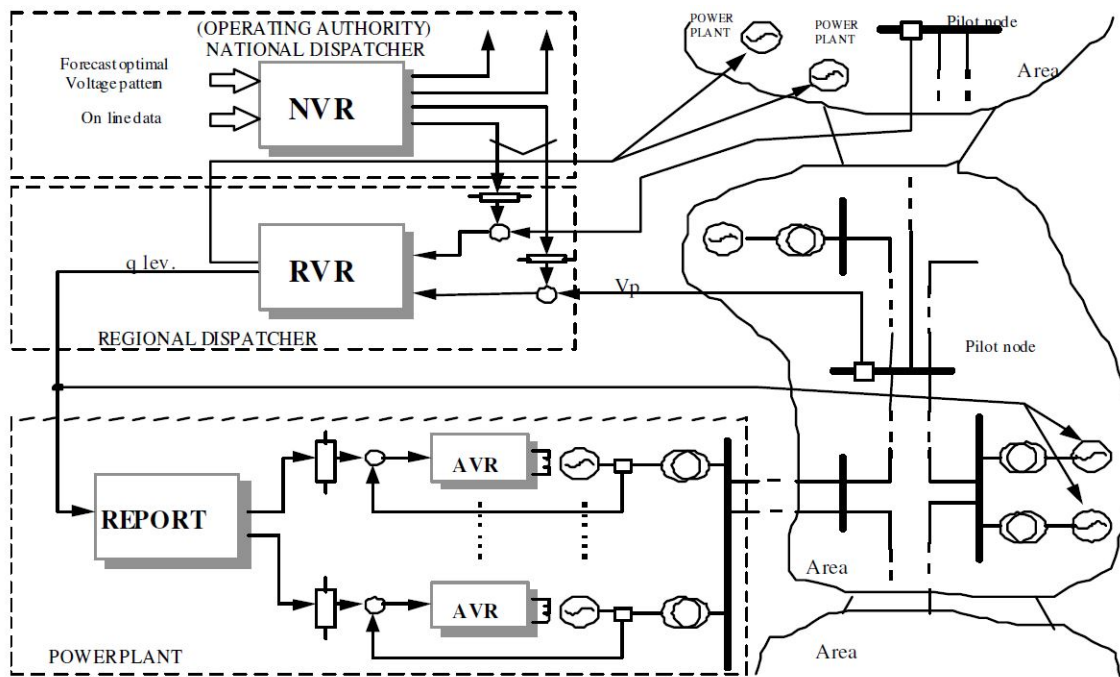
Figure 2.4: Hierarchical voltage control scheme of Italy (TERNA) [1]

Operational Benefits of Italian Voltage Control Scheme [31]:

- Up to 5% real power losses reduced

- 3-5% of increased reactive power reserve

- 20% reduction in time during which customer voltage quality was not guaranteed

- Improved control of voltage in the transmission system

- Cost-Benefit analysis showed a payback period of 4.5 years

2.4. Conclusion

This chapter only briefly summarizes voltage control schemes of Belgian, French and Italian TSOs. All the information mentioned has been taken from publications of [1], [17] & [20] - [31]. Differences between the three TSO voltage control schemes studied from these publications are summarized in table 2.1. As the size of Dutch transmission grid system is not comparable to that of Italy or France, it is not essential for the Dutch TSO to make large investments like them (RTE and TERNA) in secondary or tertiary voltage control schemes from the starting point. The most logical starting step would be to follow the basic principle of Belgian centralized advisory voltage control scheme. That is to employ an intelligent control system which can assist the control engineers using online power system tool

within EMS, offline power system tool or any other existing tool in their decision making process. After gaining sufficient experience with a co-ordinated voltage control system in the secondary voltage control scheme, more levels of control scheme can be added in the Dutch transmission system (if found necessary). This would form a part of the future development.

Table 2.1: Comparison of TSO voltage control schemes

	Belgian - ELIA	French - RTE	Italian - TERNA
Type of control scheme	Centralized voltage control (CVC) scheme: advisory system	Automatic secondary and manual tertiary voltage control schemes	Automatic secondary and tertiary voltage control schemes
Implementation effort	Low	High	Very high
Hardware requirements	High dependence on state estimator output, no additional hardware used	Special measurement units at pilot nodes/substations	SART and RVR − automatic regulators for power plant AVRs and regional voltage regulators
Involvement of control engineers	CEs updates set point(s) manually based on CVC output/advise (manual CVC)	CEs updates CSVC set point(s) manually (automatic SVC and manual TVC)	closed loop control with low/no involvement of control engineers (automatic SVC and TVC)

2.4.1. Summary of requirements for voltage control scheme

⚕ Belgian TSO has mentioned that robust state estimation was found to be essential for their centralized control scheme [1].

⚕ In order to employ a SVC scheme similar to that of Italy or France, availability and controllability of voltage set points within AVRs and other primary voltage regulators are important [1], [24] and [23]. SVC uses controllable reactive power resources in real-time to reach voltage set points at pilot nodes without the involvement of control engineers (as mentioned in subsection 2.1.2 and 2.1.3).

⚕ Italian and French schemes also require reliable telecommunication links between SCADA systems and power plants, regional controllers, pilot node substations [1] etc.

⚕ Requirement of special equipment at substations; France has employed two voltage transducers in 35 substations to read pilot node voltages [1] (security measure in case one fails).

⚕ For closed loop automatic controllers, it is essential to have reliable measurement data.

⚕ Software architecture requirements for the control scheme [1]:

   Ψ Data acquisition and communication
   Ψ Database and administrator
   Ψ Update of regulation and control functions for the software
   Ψ Library
   Ψ Man-Machine Interface

2.5. Voltage control scheme used by control engineers at NCC

In order to propose a prototype intelligent controller that can be used in voltage or reactive power control schemes of TSOs, it is important to map the existing control approach or procedure followed by their control engineers at respective control centers. This chapter discusses on the important factors that should be considered from the existing voltage control procedure followed by the control engineers at the National Control Center (NCC). Information on the existing approach of control engineers has been presented in this report with the help of surveys conducted at NCC.

2.5.1. Parameters observed by control engineers for voltage control

Control engineers continuously monitor busbars at all substations (focusing on 380-220kV buses at NCC and 150-110kV buses at Regional Control center – RCC [32] & [33]) and make sure that the voltage values are well within the limits.

Details of the Dutch transmission grid and component capacities including that of reactive power resources available to the Dutch TSO have been specified in [33].

2.5.2. Voltage profile

Example of a 380kV substation daily voltage profile
Six weeks (25-11-2015 to 4-1-2016) - working days

Figure 2.5: Voltage profile of an example 380kV substation
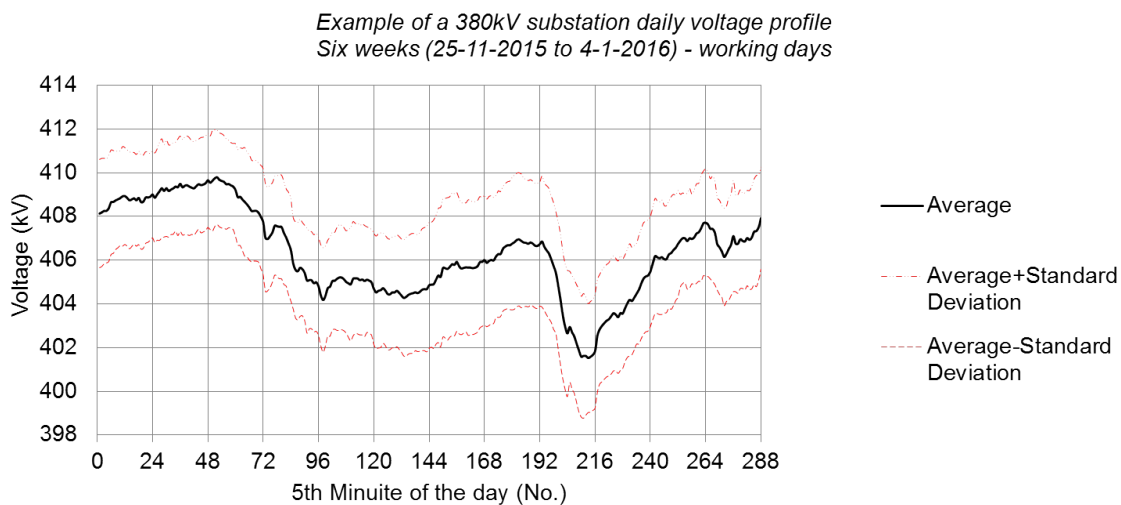
CEs observed a similarity in voltage profiles for working days (and for non-working days). An example working day profile for a 380kV substation is shown in figure 2.5. Five minute measurements from data warehouse were taken to plot voltage profiles for some geographically spread 380kV substations.
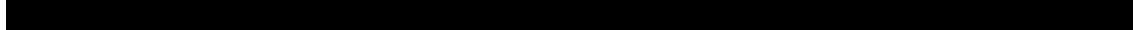
t is important for control engineers to keep good voltage profile all over Netherlands as per the electricity network codes [11]. However, more studies will have to be conducted in order to check the feasibility of using historical voltage profiles for preventive control.

██
██
██
██████████████████████████████
████████████

2.5.3. Controls used by control engineers

Preferable control measures for voltage problems at a substation by control engineers are to use reactive power compensation resources present at the substation itself. ███████████
██
██
██ Con-
trollable reactive power resources used by control engineers at the NCC are similar to that used by
other transmission system operators as also mentioned in the technical brochures of CIGRE [17], [18]
& [19]. These brochures also give some additional examples for devices used in reactive power control
process, it should be noted that the Dutch TSO does not have any FACTS (Flexible AC Transmission
systems) device other than shunt rectors or capacitors banks available for voltage control. Chapter 4
in the CIGRE technical brochure [34] gives a more detailed overview of FACTS devices. Controllable
reactive Power (RP) resources used by control engineers at NCC for coordinated voltage control are
listed based on their priority for control engineers.
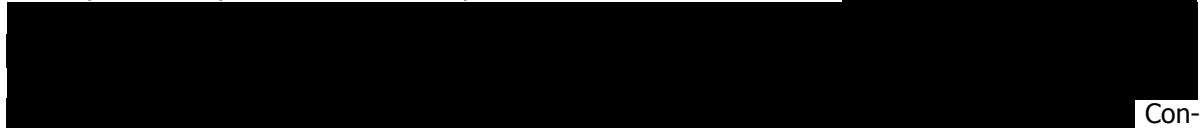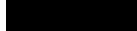
Option 1　*Shunt Reactors (SRs) and Capacitor Banks (CBs)*: When CBs and SRs are available at the critical
　　　　　bus or substation where a voltage problem occurs (voltage problem is a warning limit violation).
　　　　　The circuit breakers corresponding to CBs and SRs are switched to control the voltages at respective buses.

Option 2　*Contracted reactive power generators*: When there are reactive power contracted generators
　　　　　available nearby or connected to the critical bus or substation (bus with voltage warning), they
　　　　　are utilized to control voltage.

Option 3　*OLTC of Transformers*: They are mostly used for controlling the voltages at lower voltage (note:
　　　　　here lower voltage signifies 220kV, 150kV or 110kV level which are also high voltages) side of
　　　　　the extra high voltage (380kV/220kV) transformers. ████████████████████████████
　　　　　████████████████
　　　　　　　　　　Low voltage side network reactance: If a low voltage network has sufficient amount
　　　　　of transmission cables, then it is possible to manipulate the reactance of the regional network
　　　　　for voltage control of extra high voltage lines by increasing or decreasing the voltages at lower
　　　　　voltage sides of transformers (by changing the tap position within OLTC of transformers). For
　　　　　the control system, this is an additional outcome of the tap control measure. When sensitivities
　　　　　of OLTC taps to buses at extra high voltage substations are calculated, the control system will
　　　　　consider this effect. This shows the importance of modelling lower voltage network of extra high
　　　　　voltage transformers and considering their reactance dependence on voltage.

Option 4　██
　　　　　████████████████████████████

Option 5　██
██
██
██
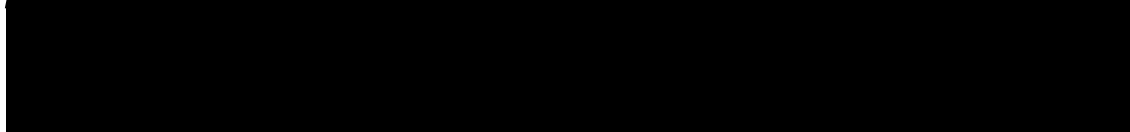
Option 6 *Switching lines or cables* (least priority):Sometimes it is considered useful by the control engineers to disconnect transmission lines (or cables) to control voltage using their considerably high impedance.

Note: Only options 1, 2 and 3 will be used by the prototype proposed to control voltage in this master thesis project. Publication [35] supports the use of these options and shows an example centralized voltage or reactive power optimization algorithm where such controllable RP resources are represented within linearized equations. ██ ██ The last option is a valid and accepted voltage control procedure. In order to switch off transmission cables (or lines), control engineer has to be certain that de-energizing the cable (or line) will not lead to security related problems or overloading of other transmission cables or lines. Adding this control measure into the optimization algorithm would make it mathematically complex to solve and considerably slower [22]. To make sure that the transmission system will be secure when option 6 is used, the controller would have to include contingency analysis for loading of lines which will not be part of this project. This could be an improvement to the project and therefore forms a part of the future development.

2.5.4. Factors that could improve the control scheme

██ ██████████████████████████ It might be useful to find an optimum set point for buses from theoretical studies (based on various constraints and objectives of the transmission system operator). It might not be possible to take all the constraints into account by control engineers in their real-time decision making process of voltage control. Therefore, it will be advantageous to employ an advisory tool that can assist the control engineers. But it will also be necessary to check the extent to which economic benefits can be made using a control scheme and if it is justifiable to make all the necessary changes so as to implement such a tool.

2.5.5. Reactive power injections at interconnections or tie-lines
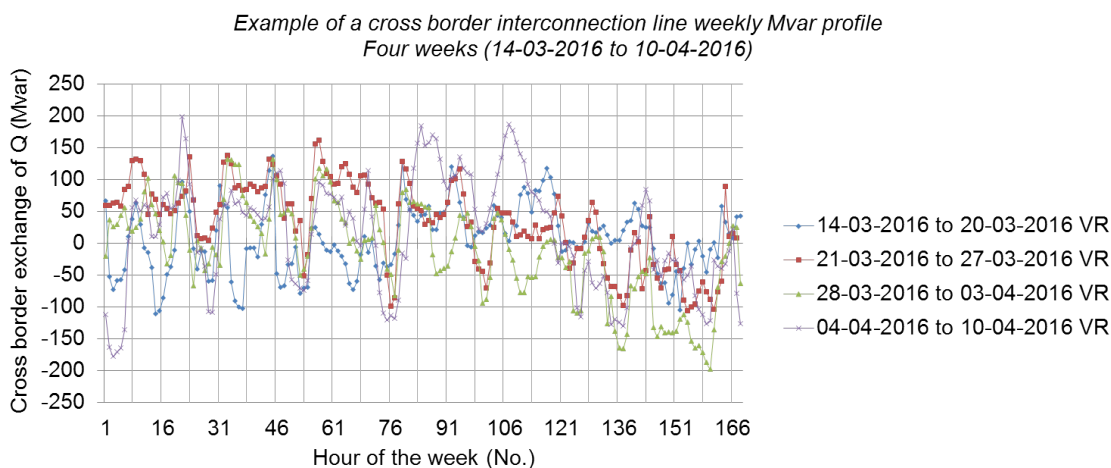
Figure 2.6: Mvar injection through a single transmission line from Germany to Netherlands

CEs monitor cross border tie-line reactive power flows and take actions when necessary. ██████████ ██████████████████████████ Based on a brief data analysis performed, no similarities in profile were observed between weekly/daily historical reactive power injections at cross border tie-lines. For example, figure 2.6 shows Mvar injection comparison between 4 weeks from a substation in Germany

to a substation in Netherlands through a single cross-border interconnection line or tie-line (values taken from data warehouse and VR is the code that indicates Mvar measurements).

2.5.6. ██████████████████████████████████

   ■ ███
██████████████████████████████████

   ■ ███
███
███ voltage control system at both the centers.

   ⚕ State Estimator voltage values are reliable.

2.5.7. Conclusion

Some important conclusions that can be drawn from the survey performed on existing voltage control process at NCC are,

   ⚕ A common voltage control scheme or tool which can be used as a decision making aid will help the control engineers in voltage control process ████████████████████████████████
█████████████████████████████████

   ⚕ ███
████████████████████████████

   ⚕ It should be possible to re-organise control priorities used by control engineers for economic benefits of the transmission system operator and minimized use of resources but this might compromise the security of the system.

   ⚕ ███

   ⚕ Parameters continuously observed by control engineers for voltage control during normal state of operation:

      ■ ███

      ■ ████████████████████████████████████

    The proposed intelligent controller will be considering both these sets of parameters.

   ⚕ Factors that could affect voltage profile of Netherlands (according to control engineers):

      ■ ███
███

      ■ ███
███
███
██████████████████████

3

Artificial intelligence techniques suitable for voltage control

Chapter 2 of this report explained the approach selected by various TSOs for employing hierarchical voltage control schemes effectively in their transmission systems. An overview on the requirements for implementation of a hierarchical voltage control scheme was also given. This chapter focuses on the emerging Artificial Intelligence (AI) techniques studied or worked on by different researchers for co-ordinated voltage control. In simple terms, AI techniques are nature inspired methods used by machines that mimic cognitive functions which are intuitively associated with human minds [36]. These intelligent systems adapt to circumstances and goals, are flexible to changing environments, learn from experience and make appropriate choices based on constraints and finite computation [36]. The following subsections contain important observations and conclusions that can be drawn from a literature survey (on topics related to fuzzy logic dated 1995 to that of multi-agent systems dated 2015) conducted on AI techniques [37] & [38]. While conducting the literature survey, certain aspects of the control systems were focused on which are considered important for TSOs (& therefore also for this project work). These aspects can be broadly classified as,

⚔ Implementation aspects

⚔ TSO specific requirements

⚔ Maintenance aspects

3.1. Expert Systems – Fuzzy Logic (ES-FL)

In this context, Fuzzy Logic (FL) refers to the mapping of numbers into linguistic terms, which are then used in rule-based decisions/commands [37]. FL systems can make use of if and then rules, thereby making it simpler to design and easy to maintain [37] & [39]. Expert Systems (ES) are knowledge based controllers or rule based controllers [40]. The papers surveyed for this section [39] & [40] combine FL & ES within the control system. An approach proposed in [40] utilizes a numerical/conventional and knowledge-based tool to assist the operator in reactive power management, voltage control and optimal power flow. This tool periodically takes network state and topological data from the state estimator for the purpose of real time analysis. In [40], the author(s) have mentioned a general set of rules and guidelines, which are used by the intelligent control scheme along with the binary, discrete and real type of control variables of generators, shunt devices, lines and pumped-storage generation units. This system was successfully implemented in the Spanish control centers according to [40]. A typical voltage control scheme based on ES-FL can be represented as in figure 3.1. These control schemes could use information from real-time analysis on a power system model or use a set of rules/instructions directly without performing analysis on any power system model.

The authors of [41] present a hierarchical type of Fuzzy Interference System (FIS) which has two control levels (higher and lower levels of the control system). The higher level is of interest for this project
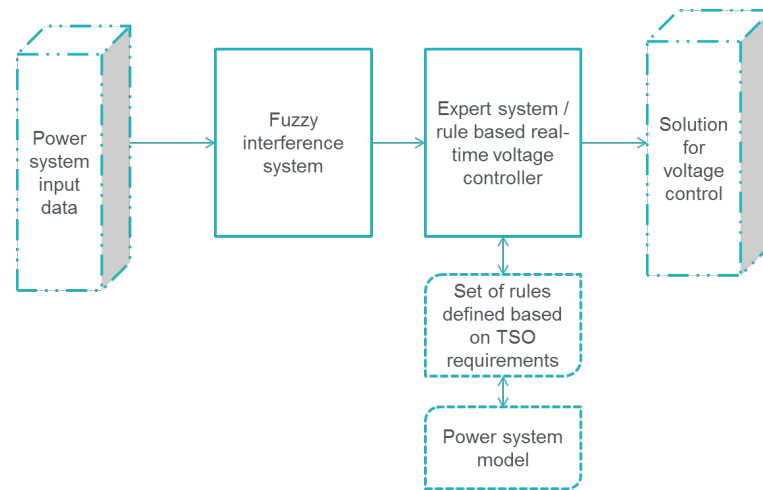
Figure 3.1: ES-FL voltage control scheme

as the Dutch TSO has considerable amount of discrete and binary type of controllable reactive power devices. It also contains a continuous FIS for setting voltage points at power plants and a discrete FIS that switches capacitor banks or shunt reactors. The higher level contains rules which have been formulated by mapping the experience of Control Engineers and with the help of offline studies [41]. The discrete FIS logic can be used for the proposed prototype system while the continuous type of FIS or low level system in this stage is not of interest as the Dutch TSO does not control the voltage set points of generators or AVRs (but if required, policies could be changed accordingly to do so). The biggest advantage of using fuzzy or hybrid rule based control system is the ease of mapping system operator knowledge as rules, transferring control system between models & adapting it to changing operational policies or topology. The fuzzy logic "if & then" rules can be modified easily as they are in linguistic terms and do not necessarily need expert level knowledge of the principles used within the specific system or fuzzy logic systems in general [40] & [41]. They might not be able to give the best or most optimized result when compared to other types of systems. Since these are rule based systems without any beforehand preparation or training enabled, it could take more time to compute solutions in real time for operators when compared to other systems [37], [40] & [41] (Neural Network [42], [43] & [44] or Predictive control [45] & [46] systems).

3.2. Artificial Neural Network (ANN)

ANN systems are learning models which are inspired from the biological neural networks present in animal brains [42] & [44]. They are generally used to estimate solutions for nonlinear mathematical functions which can depend on a large number of input variables, some of these variables can also be unknown [42], [43] & [44]. In the systems considered within this subsection, ANN involves pattern mapping [42], [43] & [44]. It takes in a set of input patterns and corresponding output patterns, based on the data given an implicit correlation is made available in the ANN system. This correlation is used to predict the output for future input data. In [42] a neural network system has been proposed for voltage or reactive power controller based on pattern mapping with an aim to reduce real power loss and in turn improve the voltage profile. ANN proposed by [42] based on pattern mapping would be ideal if the input and output pattern correlation can be generalised or memorised.

In [43] another approach has been presented which has a Feed Forward Neural Network (FFNN) controller. The system is trained using an optimal set of data generated by a genetic algorithm. Genetic algorithms are used to solve large scale optimization problems. They generate solutions using techniques inspired by natural selection process (inheritance, mutation, selection & crossover) [43] & [47]. Figure 3.2 can be used to briefly explain the control scheme present in [43]. FFNN is trained using optimized output obtained from genetic algorithm for the next day using the forecast data available [43]. This allows the FFNN to generalize input-output correlation for the business day and give rapid
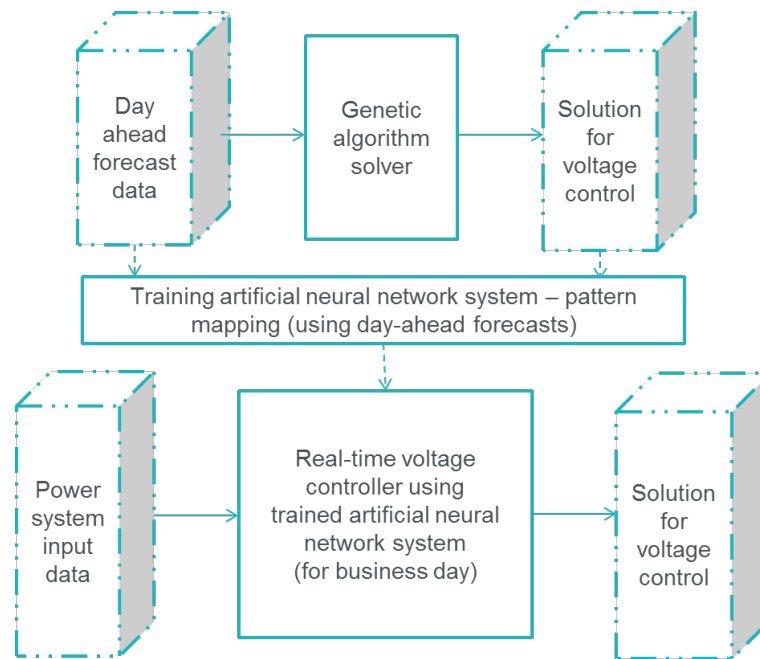
Figure 3.2: Real-time voltage control scheme based on neural network

output to the operators in real-time [43]. This type of system relies on the forecast data available. Such ANN systems can be utilized when forecast information is almost representative of the real time measurement data (if not more) & the intelligent system's real-time computation time is of concern.

In [44] a back propagation algorithm based neural network system has been proposed to construct nonlinear transfer functions for several continuous or real type of input and output variables. Converting continuous outputs to discrete values for shunt reactor & capacitor bank steps could be challenging. Most of these shunt devices within the Dutch transmission system have only one step (only circuit breaker is used to switch) and they have a rating of up to 100 Mvar or more. The recurrence of inadequate input data cannot be incorporated into the pattern mapping based ANN systems which could compromise their results [42] & [44].

Using neural networks from [42] & [44] would also lead to the questions as to how often should the system be trained and for which scenarios. It might not be possible to generalize optimised solutions/output patterns for real world extreme scenarios and give satisfactory results at the same time, which is one of the basic principles used by neural network systems in [42], [43] & [44].

3.3. Model based Predictive Control (MPC)

This type of control system is mainly used for industrial/chemical processes [48]. They are useful to predict the output for future time steps of a process (preventive control) [48]. These control systems use mathematical models of the process to derive output data with respect to input data, therefore deriving mathematical relations and models form an integral part of the design process [48]. Mathematical modelling of the process is also crucial for applying MPC to power system problems [49], [50] & [51]. Figure 3.3 shows a brief outline of a voltage control scheme that would utilize MPC principle. The possibility of deriving mathematical relations from non-linear transmission systems (& these mathematical relations should adapt to rigorously changing transmission system topology) will come into question before MPC systems can be employed. The system designer will also have to mathematically map the knowledge of control engineers at national and regional control centers into such an intelligent system. Whereas, some of these problems can be easily solved by Knowledge Based Control Systems (KBCS - for example: FL based ES [40]) using rules. This is one of the main reasons for designers to opt for KBCS especially when highly variable and uncertain situations are encountered. Transmission

power system voltage problems are more complex (to mathematically represent) and less predictable (using mathematical relations) [49], [50] & [51]. Preventive control would be advantageous to TSOs, but it is not the main objective of this project.

Another approach proposed by [45] uses a predictive optimal algorithm for coordinated secondary voltage control. It considers the changing tendency of reactive power and utilizes a discrete optimal control scheme [45]. The grey box model is used to predict the changing tendency of reactive power in tie-lines and main load nodes [45]. Therefore, the requirement of a mathematical model is minimized or nullified. The optimization problem is solved in [45] using an interior point algorithm, which is a combination of Lagrange function, logarithm barrier function and Newton direction. Using grey box models to represent parts of the transmission system increases uncertainty in the solutions given by control system.

Flexibility or transferability of control schemes based on mathematical models is less (mathematical equations need to be reframed) when compared to ES-FL (changing or adding linguistic terms & rules) or ANN (retraining to obtain new patterns) Systems. Even though paper [46] has designed a control scheme based on MPC along with Coordinated SVC (also [45] using grey box model) and simulated results on the IEEE − 39 Bus system, these kinds of schemes are more convenient for Distribution System Operators (DSOs) who have adequate knowledge of lower voltage electricity system topology [51]. Therefore, accessing data and modelling of required systems is not a cumbersome process. Within TSO systems, most of the distribution network systems are generally aggregated at their respective connection point (could be represented as load models even if they contain distributed generation). Therefore, it is possible that TSOs currently do not have detailed information on the conventional production plants, load and renewable energy contribution within some distribution and lower voltage level electricity systems. Therefore predictive model proposed on [45] would be preferable for TSOs when compared to that proposed in [46]. Most of the papers that were referred to in this survey performed simulations on the IEEE standard test system of New England. While, almost all the authors concluded that much more research work has to be performed before MPC or grey box model based predictive models can be applied into real world Power Systems [45] − [51].
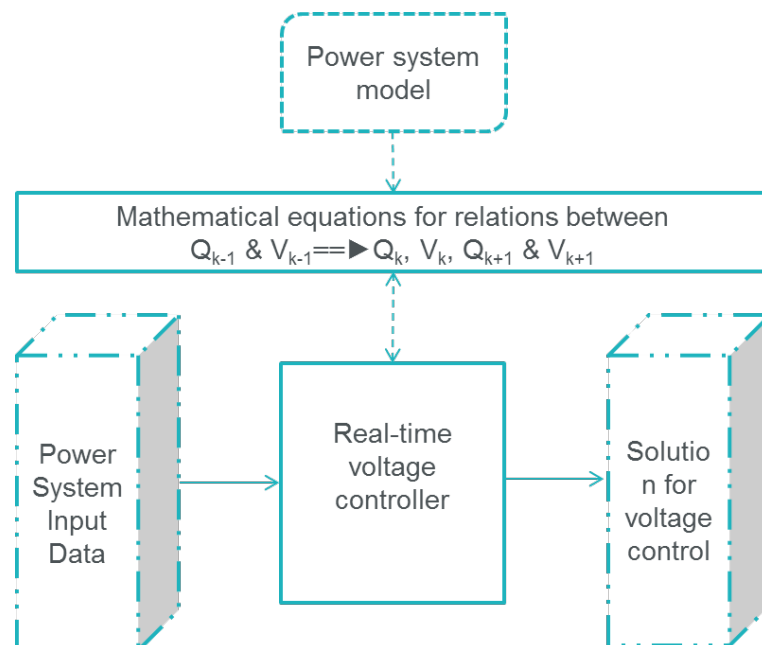

Figure 3.3: Coordinated voltage control scheme based on MPC

3.4. Multi-agent system

A novel multi-agent system has been mentioned in the paper [38]. Other intelligent control systems mentioned in this chapter are emerging AI techniques that can be used for coordinated voltage control. Whereas, multi-agent system is a strategy (or scheme) that can be utilized to employ different control systems for individual areas or agents [38], [52] & [53] as shown in figure 3.4. This scheme is useful when there are autonomously operated areas (considered as individual agents in [38] & also this report) present in the system. The paper [52] introduces the possibility of solving multi-objective problems or multi-criteria problems using an evolutionary multi-agent system. The possibility of designing a layered framework and a chain of command from the top layer (TSO grid) to the bottom layer (DSO grid or other third party systems) makes it even more attractive for system operators [53]. This means that control decisions made by control engineers of DSOs or other parties and TSO can be incorporated into one co-ordinated system [53].

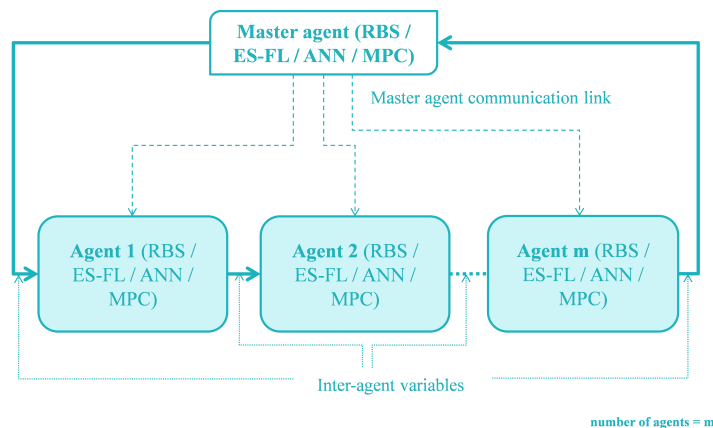For the system presented in [38], the agents (on areas) coordinate with each other through a multi

Figure 3.4: An overview of multi-agent scheme

agent scheme with the help of inter area variables. Area is a geographical term while agent or intelligent agent is an autonomous entity which observes through sensors (input data) and acts upon an environment using actuators (output data) [47]. In this context, agents act upon specified geographical areas. Inter-area variables constitute the variables which are exchanged between agents after individual area optimization. Each agent calculates local optimum for minimized losses (or other local objectives which are predefined) using inter-area variables without affecting those of other agents in [38] (Note: In the proposed prototype, individual agents consider the effect of their controllable reactive power resources on all areas). After completion of the optimization task by the last agent, the last inter area variable is sent to the master agent [38]. The master agent (denotes the centralized control scheme) checks if specified global conditions are satisfied for termination, otherwise it updates the Lagrange multipliers in respective equations and the calculations are again repeated to find local optimum until the specified global conditions are satisfied [38].

In paper [38], loss minimization was considered as the objective function. The author's main aim was to minimize losses while maintaining voltages well within the specified constraint levels. It is possible to change the objective function or add more functions and constraints (as mentioned in [52]) according to individual TSO requirements. This can be done by changing or adding more control variables and/or the equations that they form a part of. Multi-agent or multi-area type of control scheme was found to be attractive because of the policies present in the Netherlands. For example, this type of scheme (as mentioned in [53]) could improve the coordination in control options selected by regional and national control engineers for counter acting the same regional or area based problem.

Reasons for employing multi-area/agent scheme in the prototype system:

⊕ Divides the entire transmission system into parts (or areas), thereby dividing it into smaller mathematical problems and resulting in faster solutions for optimizing the small area.

⊕ Introduces the possibility of defining unique objectives and constraints (including dynamic constraints) for different areas.

⊕ Assures that control devices belonging to a control area are utilized for solving problems within, thereby reducing the risk of utilizing resources which are far away in terms of electrical and geographical distances.

⊕ Assists coordination between control engineers at the national control center and regional control center.

⊕ Possibility to skip the optimization of certain areas by their agents.

Drawbacks of employing multi-area/agent scheme in the prototype system

⊗ Assumes that operation of an agent is independent from neighbouring agents in all aspects which is not entirely true for electric power transmission systems. The effects of controllable reactive power resources within an agent on its neighbouring agents are ignored in this scheme. This problem can be partly solved by calculating the sensitivities on all areas/agents present in the transmission system.

⊗ If individual agents perform optimization sequentially (referred to as "sequential solver" later on), the time required to optimize the overall transmission system could increase due to re-initialization of optimization problem within individual agents as opposed to solving the entire transmission system using just one agent. This problem can be solved by ensuring that individual agents optimize their areas in parallel (referred to as "parallel solver" later on).

⊗ Solutions given by parallel solver will be reliable if the number of changes proposed by individual agents is minimal, or else the non-linearity of sensitivities will become more visible. Parallel computation will reduce the amount of time required for optimizing the entire transmission system considerably (depending on the number of agents).

⊗ Solution given by sequential solver could differ depending on the order of agents performing optimization and the changes proposed by each one of them.

⊗ An optimum number of agents (& areas) has to be determined for the particular transmission system in order to have a reliable operation of this type of control scheme.

3.5. Proposed AI technique and concluding remarks

A set of rules, constraints & objectives (for individual agents and master agent) will have to be satisfied by the intelligent voltage control scheme proposed for TSOs. These rules, constraints & objectives can be defined using the expertise of control engineers and requirements of TSO. The input data could contain inadequate values and they can also recur frequently. FL based ES using sensitivities had already been employed by the Spanish TSO [54] and proposed by the authors in [55] for voltage control schemes due to their high reliability. ANN & MPC based schemes form a good alternative, but designing them requires much more time (ease of implementation, as explained in sections 3.2 & 3.3). Even though the ANN technique is generally used to map non-linear correlations, it is not ideal for TSOs as the input and output pattern correlations cannot be generalised which is the main principle behind pattern mapping. Pattern mapping of voltage control process involves fixing states of controllable reactive power resources for certain voltages, reactive power injections or power system scenarios. MPC is also not preferable for TSOs especially when simplified mathematical relations for the non-linear electrical transmission system have to be prepared in order to calculate changes in reactive power feed and voltage set points directly from power system state. These systems also require training of application managers & spreading awareness amongst control engineers (to increase their confidence in the system) for updating, maintaining or even using such a system. This can be the next step of the project after having gained sufficient experience using a simple prototype controller. Due to such factors and many more as mentioned later on in this section, Rule Based Systems (RBS) using ES principles were found to be most suitable for the proposed intelligent system (decision based on the survey conducted in this chapter). The expertise of control engineers and requirements of TSO will form the basis for rules within the proposed algorithm used for reactive power optimization, wherein the optimization

problem is framed as linear equations with the help of these rules and solved by a linear programming or heuristic solver tool.
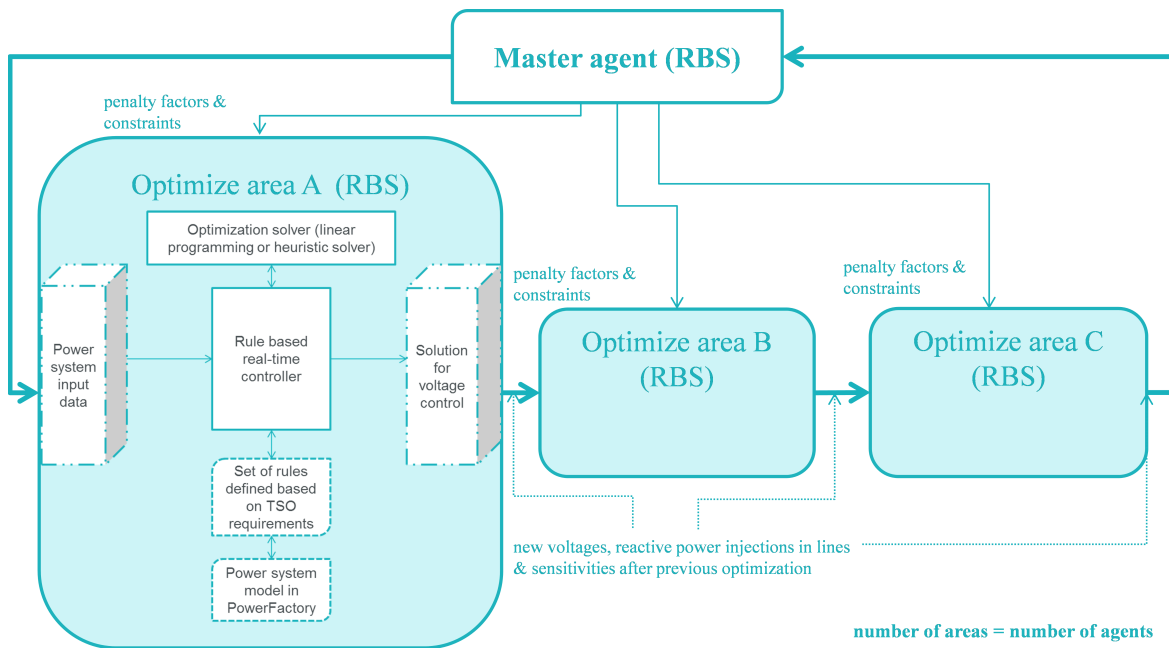

Figure 3.5: Proposed voltage control scheme based on sequential multi-agent approach

ANN in [43] is trained using optimal set of data received from optimization on forecasts using genetic algorithm, therefore the online computation time required would be less in comparison. While, rule based controllers without any beforehand preparation would require relatively more computation time when used for the purpose of real time analysis. The reason for designing an intelligent voltage control scheme in this master thesis project is to perform a feasibility study. Therefore computation speed of the control system is not of importance but it should be able to perform tasks within a reasonable amount of time (which is 5-10 minutes, the suitable response time for secondary voltage control as mentioned in chapter 2). The proposed system will be a prototype and may not be readily implemented into the TSO system. It is possible that the prototype system does not give the best solution to control engineers due to the frequent recurrence of inadequate input data. It is also important to note that there are some rule based algorithms being utilized to optimize voltage at operational planning stage (intraday congestion forecasting process). TSOs & control engineers will prefer to implement a control scheme which uses principles similar to an already existing system (less training required). Therefore, it was decided to use a multi-area type of scheme along with rule based algorithms as shown in figure 3.5. Programming (using C++/DIGSILENT Programming Language) a rule based controller and documenting it was also found to be time efficient when compared to other systems. Table 3.1 shows the factors that defined the criterion for selection process of this thesis, most of which have already been mentioned. Some factors are not present in the table either because they are not important for this project or they are system scenario dependent (for example: reliability of results - dependent on system scenario & capped by deviation of input data from measurement). The comparison is made only for the AI techniques considered or referred to in this chapter.

The final decision was made based on the important aspects as mentioned throughout this chapter & Table 3.1 [56]. Some of them which have not been mentioned in the earlier parts of this chapter are explained below:

⋊ Implementation Aspects and other special requirements: Some of the above mentioned control systems cannot be implemented as they require larger investments in hardware infrastructure (measurement devices & actuating systems). Over the past few years, only a negligible amount of "voltage problems" (or voltage limit violations) were reported by control engineers at NCC.

Table 3.1: Comparison of emerging artificial intelligence techniques

Major factors related to this project	Rule Based or Expert Systems & Fuzzy Logic [40]	Neural Networks [43]	Model Based Predictive Control [46] & [51]
Non-linear modelling	-	+	-
Ease of mapping existing manual voltage control process of control engineers	+	-	-
Computation time required/computation speed	-	+ +	+
Ease of Implementation, Transfer & Adaptability	+	-	- -
Technical skills or training required for maintaining & updating	+	-	-
Implementation & documentation time required	+	-	-

Therefore TSOs will not be ready to invest in solutions for problems that do not occur (or rarely occur). As this thesis work is being conducted to check the possibility of adding a secondary or real time intelligent voltage control scheme as a computational aid to existing process, it is preferred to use a system which can prevent voltage limit violations and keep the system secure by preventing probable voltage collapses (even though they rarely occur) using existing data or infrastructure.

⋈ Possibility/Ease of mapping the existing manual voltage control process: The selected control system should be able to map the knowledge of control engineers, objective functions & constraints of the unique TSO system (objective & constraints are explained in more detail within chapter 4). It is possible that an existing condition or policy can change in the near future (due to rigorous changes in operational policies within Netherlands & Europe).

⋈ Maintenance Aspects: TSOs prefer to employ a control system which has proven technology (or commonly used techniques). They do not want to depend on a single application manager or consultant for maintaining any control scheme or process. Therefore, the selected control system or scheme should also comply with international standards thereby making the maintenance process simpler. It should also be possible to transfer/adapt the same system to different policies and models, so that it can easily adapt to rigorously changing operational policies & topological changes.

4

Optimizer & model description

4.1. Development of a reactive power optimizer

In the introduction chapter of this thesis report, description of goal, research questions and other important aspects of the feasibility study were presented. According to which, the main aim of this project was to check if a voltage control scheme can be introduced into the Dutch transmission system. Therefore multiple questions related to technical and economic feasibility of the voltage control scheme had to be answered. The proposed voltage control scheme should be able to use reactive power resources optimally (reduce reactive currents in the system), be economically efficient to the system operator and maintain security of the transmission system at the same time. This thesis studies the technical feasibility of employing such a voltage control scheme. In order to perform such a study, it was deemed necessary to design a prototype of a intelligent voltage control system that satisfies most of the functional requirements specified in the earlier chapters. This system can also be used to test various scenarios of the Dutch transmission system and find limitations within it.

This chapter will start by introducing the objectives and constraints that were included in the intelligent voltage control system followed by the description of proposed rule based controller and its functionality with the help of flow charts. The control system rules, objectives and constraints were defined using the expertise of control engineers and requirements of TSO (expert system). In order to develop this intelligent voltage control system, a test system model was initially utilized. After completing the development of a reactive power optimization algorithm and performing simulation based studies on the test system model to minimize an objective function, the control system was also used to perform simulation based studies on the modified snapshot system model. Model descriptions along with comparison of test system and snapshot system will be presented in the later part of this chapter. However, results from the simulation based studies on both these power system models will be presented in chapter 5.

4.1.1. Functional objectives of the multi area based RPO

As part of this Master thesis work, a multi-area based Reactive Power Optimizer (RPO) was developed using the DIgSILENT programming language (DPL) in a test system using PowerFactory (refer DIgSILENT guidelines [57] for more information). Simulation based studies were then performed on the snapshot system models (representative of the Dutch electricity transmission grid) for validation. Once the test system from [58] was modified to recreate system operations like in real-time scenarios, development of the RPO in DPL was initiated.

The main objectives & features of the RPO developed using expertise of control engineers and requirements of TSO include:

- Minimizing Mvar injections from the inter-area transmission lines and cables which form a part of the objective set of lines or cables.

☑ Minimizing the total number of switching devices and contracted reactive power generators changed.

☑ Setting priority of RP compensation devices in the descending order of (1) shunt filters, (2) transformer taps & (3) contracted generators (This priority can be changed by modifying the dedicated penalty factors in the main program).

☑ Setting custom penalty factors for individual RP compensation devices.

☑ Setting a constraint limit for the number of reactive power (RP) compensation devices used (both for shunt devices & transformer OLTC taps constraints can be set)

☑ Minimizing continuous switching of devices (on-off-on-off). A matrix file with history of all the shunt filters and controllable OLTCs is stored.

☑ Minimizing the total reactive power generation of contracted generators, thereby reducing costs.

☑ Minimizing the difference between resulting substation voltage and its voltage set point. Possibility of defining voltage set point for a single bus terminal/substation to optimizer.

☑ Voltages at all substations are considered as constraints for the optimization process and N-1 contingency analysis.

Features not included as they were already employed in intraday process voltage optimizer:

☒ Mvar constraints according to specific TSO contracts with multiple generators.

☒ Voltage set points for multiple substations.

The reactive power optimization problem was converted to a mixed integer Linear Programming (LP) problem. To do so, a set of LP equations was formulated using DPL scripts, which was then solved using the LP solver available within the offline power system tool Server. For formulating the reactive power LP optimization problem references of [59], [60] & [61] were used. Where [59] & [60] are examples of LP optimization in power systems and [61] is an introductory manual presenting different approaches to LP problem formulation. Publication [62] was useful as it gives examples for including cost factors into optimization problems.

4.1.2. Linear equations of the RPO
The LP problem was formulated to minimize the multi-objective function of:

$$Minimize\{p_{gmv} \times (\Sigma_{h=1}^{l}|Q_{line_h} + \Delta Q_{line_h}|) + (\Sigma_{i=1}^{m}(p_{sh_i} \times |\Delta n_{sh_i}|)) + (\Sigma_{j=1}^{n}(p_{tap_j} \times |\Delta n_{tap_j}|))$$
$$+ p_{gdelta} \times (\Sigma_{k=1}^{o}|\Delta Q_{gi_k}|) + p_{qgini} \times (\Sigma_{k=1}^{o}|Q_{gi_k} + \Delta Q_{gi_k}|) + p_v \times |V_{tsp} - V_{tactual} - \Delta V_t|\} \quad (4.1)$$

Where, the nomenclature used in equation 4.1 is given in table 4.1.

Solved under the constraints:

$$V_{min} \leq V_s \leq V_{max}$$

$$where,$$

$$V_s = V_{si} + \Delta V_{si}$$

Voltage values at substations are within their specified limits, V_{min} and V_{max} are the minimum and maximum limits of voltage at the substation/busbar terminal.

$$S_{min} \leq S \leq S_{max}$$

$$where,$$

$$S = \sqrt{(P^2 + (Q_{line} + \Delta Q_{line})^2)}$$

Apparent Power injections are within their rated MVA capacity, S_{min} and S_{max} are the minimum and maximum limits used for finding Mvar injections. In this prototype, the difference in active power injection due to change in voltage or reactive power injection is considered negligible. To safe guard the lines & cables, a security factor of $0.9(S_{max})$ is applied to the maximum value constraints of inter-area objective transmission lines within the LP solver.

$$Q_{min} \leq Q_g \leq Q_{max}$$

$$where,$$

$$Q_g = Q_{gi} + \Delta Q_{gi}$$

Reactive power generation of contracted generators are within their specified limits, Q_{min} and Q_{max} are the minimum and maximum reactive power generation limits of the reactive power contracted generator.

$$N_{Tapmin} \leq N_{tap} \leq N_{Tapmax}$$

$$where,$$

$$N_{tap} = n_{tap} + \Delta n_{tap}$$

Transformer tap positions are within the specified tap limits of its OLTC), N_{Tapmin} and N_{Tapmax} are minimum and maximum tap position available on the tap controller of the respective transformer.

$$N_{shmin} \leq N_{sh} \leq N_{shmax}$$

$$where,$$

$$N_{sh} = n_{sh} + \Delta n_{sh}$$

Step positions of controllable shunt device is within their specified limits, N_{shmin} and N_{shmax} are the minimum and maximum step position available for the shunt device.

For snapshot system models, there is only one step available for employing controllable shunt devices. Circuit breakers are controlled to activate or deactivate them. Therefore, to the prototype controller these are binary type of controllable reactive power resources (either 0 or 1).

Table 4.1: Parameters used in the solver for objective function and constraints

Name	Description	Unit
p_{gmv}	Penalty factor for minimizing Mvar injection to or from the objective lines & cables	-
Q_{line}	Initial reactive power injection to or from the objective line or cable obtained from the base case scenario	Mvar
ΔQ_{line}	Resulting change in reactive power injection to or from the objective line or cable obtained by solving the LP problem	Mvar
P	Initial active power injection to or from the objective line or cable obtained from the base case scenario	MW
S	Resulting or final apparent power injection to or from the objective line or cable	MVA
p_{sh}	Penalty factor for minimizing the use of shunt filters(CBs or SRs)	-
n_{sh}	Initial step position of CBs or SRs obtained from the base case scenario	-
Δn_{sh}	Change in step position of CBs or SRs obtained by solving the LP problem	-
N_{sh}	Resulting or final step position of shunt devices (CBs or SRs)	-

p_{tap}	Penalty factor for minimizing the use of transformer taps	-
n_{tap}	Initial tap position of transformer obtained from the base case scenario	-
Δn_{tap}	Change in tap position of transformer obtained by solving the LP problem	-
N_{tap}	Resulting or final tap position of tap controller at high voltage transformer	-
p_v	Penalty factor for minimizing the difference of substation or busbar terminal voltage from required voltage set point given as input to the optimizer	-
V_{tsp}	Voltage set point magnitude given as input for a particular substation or busbar terminal	p.u.
$V_{tactual}$	Initial voltage present at the set point substation or busbar terminal, resulting value from the base case scenario	p.u.
ΔV_t	Resulting change in voltage at the set point substation or busbar terminal obtained solving the LP problem	p.u.
p_{deltag}	Penalty factor for minimizing the absolute value of change in reactive power generation of contracted generators	-
p_{qgini}	Penalty factor for minimizing the absolute value of reactive power generation of contracted generators, this could be used to reduce costs of generation	-
Q_{gi}	Initial reactive power generation of contracted generators obtained from the base case scenario	Mvar
ΔQ_{gi}	Resulting change in reactive power generation of contracted generators obtained by solving the LP problem	Mvar
Q_g	Resulting or final reactive power generation of contracted generators	Mvar
V_{si}	Initial voltage at the substation or busbar terminal obtained from the base case scenario	p.u.
ΔV_{si}	Resulting change in voltage at the substation or busbar terminal obtained by solving the LP problem	p.u.
V_s	Resulting or final voltage at the substation	p.u.
l	Total number of objective lines & cables under consideration	-
m	Total number of controllable shunt devices available	-
n	Total number of parallel set of transformers with tap control available	-
o	Total number of reactive power contracted generators available	-

For representing the absolute value of objectives within equation 4.1, moduli of respective control variables have to be calculated. A control variable is defined in this problem to represent the change in state of a controllable reactive power resource. For determining the absolute value of a control variable in LP solver, two extra constraint equations are necessary per variable [61]. The absolute value of the required variable in LP can be determined as follows:

$$X + Y \geq 0 \qquad (4.2)$$
$$X - Y \geq 0 \qquad (4.3)$$

This can also be written as,

$$-X \leq Y \leq X$$

or,

$$X = |Y|$$

For this purpose, a new variable is specified in the LP problem matrix. This variable X will represent the required modulus or absolute value of original control variable Y in the problem, if its equations are framed as given in equations 4.2 & 4.3 above. It should be noted that this principle is valid only because the LP solver in offline tool uses dual-simplex method to find optimal solution [63].

4.1.3. Multiple objectives of the objective function in RPO

The minimizing objective function (as given in equation 4.1) can be divided into 4 main parts or objectives and they are described in detail within this subsection. It is possible to manipulate the penalty factors in order to change the weighting of each objective. Reference values used for penalty factors will be mentioned in chapter 5 along with the results obtained from simulation based studies.

I **Objective 1** $p_{gmv} \times \Sigma|Q_{line} + \Delta Q_{line}|$: First part of the objective function minimizes the sum of absolute values of Mvar injection in the inter-area transmission lines & cables, which connect different areas and are given as input to the optimization algorithm. The algorithm is designed to have a relatively higher penalty factor associated with its first objective. Two additional constraint equations per objective line are framed similar to equations 4.2 & 4.3 for obtaining absolute value of ($Q_{line} + \Delta Q_{line}$). The reasons for selecting the main objective to be Mvar reduction rather than MW loss reduction:

    ⋈ The main objective of this master thesis project is to check the feasibility of optimizing the usage of reactive power resources. That is compensating reactive power demands locally and reducing undesirable reactive power flows within the transmission system.

    ⋈ By reducing reactive power injections between areas, the reactive power demands are met locally using controllable reactive power resources available to TSO within the areas. Additionally, it is also possible to define intra-area objective transmission lines or cables which might have congestion problems and reduce/increase Mvar injection from/to them.

    ⋈ The MW losses in transmission lines & cables were observed to be relatively small in value (around 3-5MW loss per transmission line). In theory, reducing MW losses is the most pragmatic approach which increases the efficiency of electrical power transmission system. But, the sensitivity differences present between power system model of offline tool & real transmission system in addition to the measurement differences within TSO system might not be negligible when compared to the absolute value of MW loss.

II **Objective 2** $\Sigma p_{sh} \times |\Delta n_{sh}| + \Sigma p_{tap} \times |\Delta n_{tap}| + p_{deltag} \times \Sigma|\Delta Q_{gi}|$: The second part of the objective function has two goals. First goal is to minimize the total change introduced by optimization algorithm. Second goal is to prioritize the preferred controllable device, with less preferred control option having higher penalty factor relative to others (refer subsection 2.5.3 for more details on preferences of control engineers). Minimizing the total change in control variables has two motivations. Firstly, it reduces the number of changes that is recommended. The other reason is that it reduces the amount of change in one iteration of the optimization algorithm, thereby taking non-linearity of calculated sensitivities into account and resulting in an adequate solution. The second part of the objective function can again be divided into three sub-parts. The three sub-parts are dedicated to the three types of controllable RP devices available for use. They are the shunt devices ($\Sigma p_{sh} \times |\Delta n_{sh}|$), transformer taps ($\Sigma p_{tap} \times |\Delta n_{tap}|$) and contracted generators ($p_{deltag} \times \Sigma|\Delta Q_{gi}|$). Penalty factors p_{sh} and p_{tap} are included to have a numerical counter function

to increase the penalty separately for controllable devices which are being regularly used. If the counter option is enabled, p_{sh} and p_{tap} take different values for each controllable device (transformers with OLTC, CBs or SRs) which can either be based on the number of times they have been switched by the optimization algorithm or based on historical data. These device specific individual penalty factors are stored in a matrix ("P_Elm") within optimization algorithm. Two additional constraint equations per control variable are framed similar to equations 4.2 & 4.3 for obtaining absolute values of (Δn_{sh}), (Δn_{tap}) & (ΔQ_{gi}).

III **Objective 3** $p_{qgini} \times \Sigma |Q_{gi} + \Delta Q_{gi}|$: Third part of the objective function is to reduce the absolute value of reactive power dispatch of contracted generators. This is to make sure that the solution introduced by the optimization algorithm has taken economic factor of reactive power generation of contracted generators into account. Two additional constraint equations per contracted generator are framed similar to equations 4.2 & 4.3 for obtaining absolute value of ($Q_{gi} + \Delta Q_{gi}$).

IV **Objective 4** $p_v \times |V_{tsp} - V_{tactual} - \Delta V_t|$: The optimization algorithm includes a provision for keeping voltage set point option at any substation or busbar. Using this function it is possible to change the voltage at a particular substation to the set point value. Depending on the penalty factor assigned, absolute value of differences between the resulting voltage at substation/busbar and the preferred set point given as input is minimized. Two additional constraint equations for the voltage set point are framed similar to equations 4.2 & 4.3 for obtaining absolute value of ($V_{tsp} - V_{tactual} - \Delta V_t$).

The optimization algorithm used in this project only calculates for the change in state of controllable RP resources. The effect induced by this change in their state is represented within the LP solver matrix with the help of sensitivities (dQ/dQ, dV/dQ, $dQ/dTap$ & $dV/dTap$ are obtained using PowerFactory sensitivity calculator). These sensitivities are used to calculate the parameters mentioned below.

The effect of change in states of controllable devices on Mvar injection at transmission lines & cables (for objective 1):

$$\Delta Q_{line} = \Sigma_{i=1}^{m}((\partial Q_{line}/\partial Q_{sh_i}) \times \Delta n_{sh_i} \times Q_{nmax_i}/N_{step_i}) + \Sigma_{j=1}^{n}((\partial Q_{line}/\partial n_{tap_j}) \times \Delta n_{tap_j})$$
$$+ \Sigma_{k=1}^{o}((\partial Q_{line}/\partial Q_{gi_k}) \times \Delta Q_{gi_k}) \quad (4.4)$$

Where Q_{nmax} is the maximum Mvar rating of the controllable shunt device and N_{step} is the total number of steps for the respective device. Similarly, the effect of change in states of controllable devices on voltage value at the set point substation/busbar (for objective 4):

$$\Delta V_t = \Sigma_{i=1}^{m}((\partial V_t/\partial Q_{sh_i}) \times \Delta n_{sh_i} \times Q_{nmax_i}/N_{step_i}) + \Sigma_{j=1}^{n}((\partial V_t/\partial n_{tap_j}) \times \Delta n_{tap_j})$$
$$+ \Sigma_{k=1}^{o}((\partial V_t/\partial Q_{gi_k}) \times \Delta Q_{gi_k}) \quad (4.5)$$

Finally, the effect of change in states of controllable devices on the voltage values at transmission network substations/busbars (constraints for voltage security):

$$\Delta V_{si} = \Sigma_{i=1}^{m}((\partial V_{si}/\partial Q_{sh_i}) \times \Delta n_{sh_i} \times Q_{nmax_i}/N_{step_i}) + \Sigma_{j=1}^{n}((\partial V_{si}/\partial n_{tap_j}) \times \Delta n_{tap_j})$$
$$+ \Sigma_{k=1}^{o}((\partial V_{si}/\partial Q_{gi_k}) \times \Delta Q_{gi_k}) \quad (4.6)$$

ΔV_{si} is different from ΔV_t, as ΔV_{si} does not form a part of the objective function. ΔV_{si} is used to include additional set of voltage constraints for all the substations of the transmission system in order to make sure that the voltage ($V_{si} + \Delta V_{si}$) at all these substations are within the secured limits (of 1.1 p.u. and 0.9 p.u. or constraints from contingency analysis). Whereas ΔV_t from equation 4.5 is introduced in the objective function to ensure that the voltage suggested by optimization algorithm does not have a large difference from the magnitude of prescribed voltage set point.

All the changes in states of controllable devices, reactive power injections and voltages resulting in the LP solver can be added to the original or base case values so as to obtain the final result (using results directly from the LP solver for change in state of control device and their consequences calculated as shown in equations 4.4, 4.5 & 4.6). The original or base case values can be obtained from the

power system scenario in offline tool. They are constant for a particular optimization problem. The objective function can include either the sums of change with the original or base case value (as in the case of objectives 1 and 3) or just the changes (as in the case of objective 2).

4.1.4. Optimization solver for the RPO

As mentioned earlier, the LP solver package was used by the proposed optimization algorithm. This means that no work was done in order to create the LP solver. The LP solver used in this project is an open source mixed integer linear programming solver based on the revised simplex method and branch-and-bound method for integer variables [63]. Comparison of LP solver [63] with a heuristic solver of Mean Variance Mapping Optimization (MVMO) [58] is given in table 4.2.

The MVMO solver from [58] can be modified for use in RPO algorithm. MVMO is similar to other heuristic solvers, however it has a special mapping function which is applied for mutating offspring based on mean and variance of the set containing n-best solutions which have been attained from searching space and are saved in a continuously updating archive [64] & [65]. That is the resulting curve from this mapping function is adjusted in accordance with the searching process [64]. The internal searching space of all variables are restricted between 0 & 1, therefore minimum and maximum boundaries have to be normalized before starting the search for optimal solution [64]. Values suggested by the MVMO solver can be de-normalised for calculating their respective objective function and obtaining the optimal solution [64] & [65]. MVMO has a good balance between search diversification and intensification, helping to find the optimal solution with minimal risk towards premature convergence [64] & [65].

As mentioned in the table 4.2, the mixed integer LP solver is a proven and commonly used tool

Table 4.2: Linear Programming (LP) Solver vs. MVMO Heuristics Solver

LP Solver	Heuristics Solver (MVMO)
Already available in PowerFactory	Not available, but MVMO available for application
+ Discrete and continuous variables available within the LP Solver [63]	- Special coding scheme for integers can be added to MVMO [58]
- Extra equations required for absolute value of variables [63]	+ + No extra equations required for absolute value of variables [58]
+ + Feasible solution can be found by LP solver tool in seconds	- - Develop multi-objective variant of MVMO for relatively faster evaluation
+ Constraints can be easily framed as LP constraint equations within solver [63]	- Can be framed via constraint handling strategy
- Can be used only for solving linear optimization problems [63]	+ Can be used for solving non-linear optimization problems [58]

that meets most of the solver requirements for this project. The MVMO solver was found to consume more time to find an optimal solution and had to be modified so as to solve problems with constraints. These challenges made the MVMO solver from [58] less attractive for this project (compared to the LP solver). The LP solver was found to be more convenient and time efficient for use in the RPO algorithm. Heuristic solvers would become more suitable for optimization if the already stated linear problem is modified to include non-linear constraints or objectives. This could therefore be the next step of this project. The final problem matrix (known a "LP tableau") introduced by LPSolver () DPL command script is similar to that shown in figure 4.3. Inside the optimization solver tool called by LPSolver (), sensitivity Jacobian matrices, constraints, objective coefficients & min-max of variables are defined. Values of the matrix in this figure are intentionally left blank. The purpose of figure 4.3 is to introduce the concept of solving a LP problem using the solver in offline power system tool.
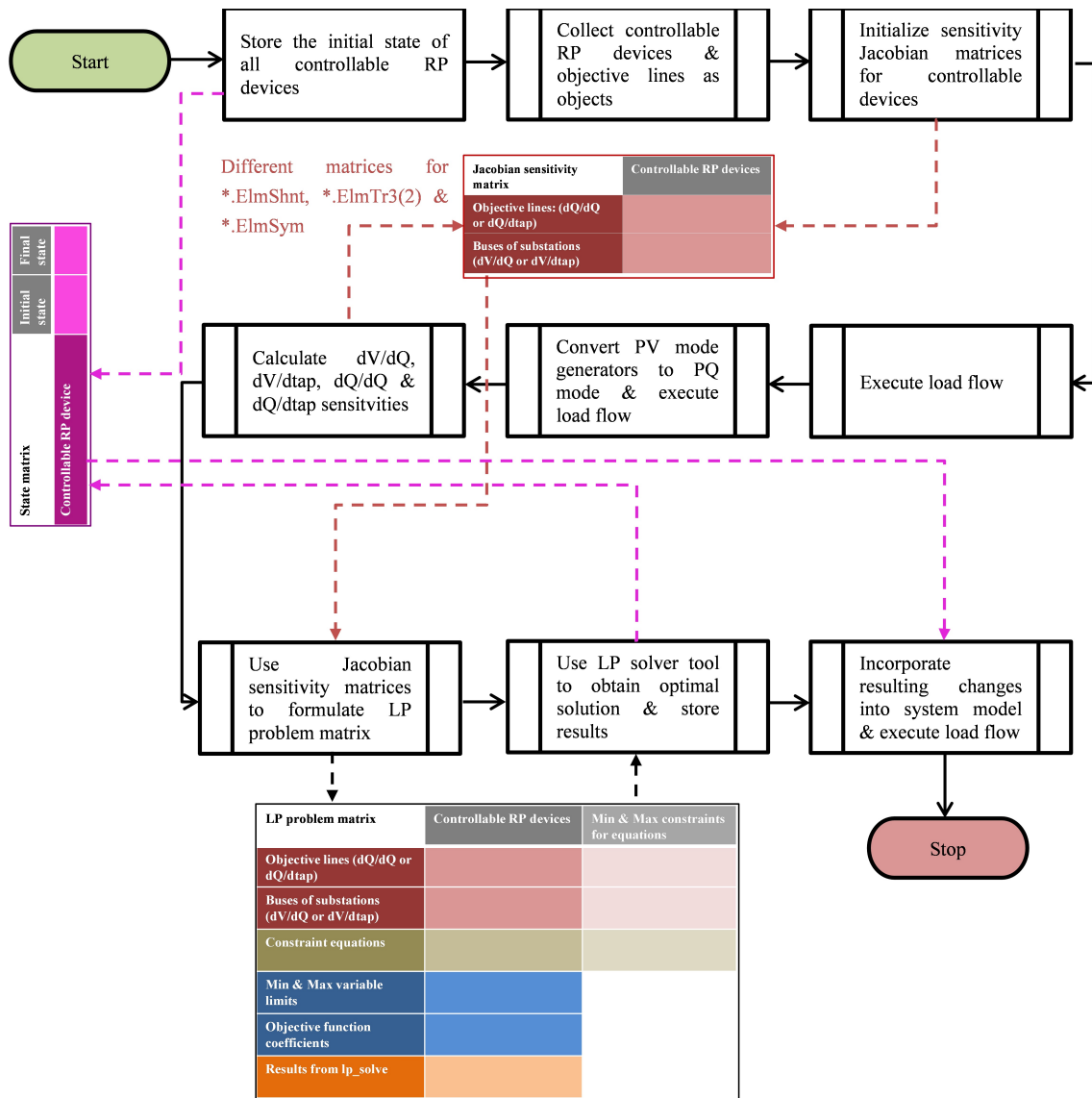
Figure 4.1: Flow chart of RPO algorithm used for an agent (solving one specific area)

4.1.5. Flow charts of the multi area based RPO

The Main () DPL (as shown in figure 4.1) command script is executed for various scenarios in order to compare the differences in results given by optimizer. Main () optimizes only a single area. This makes sure that only controls within the specified area are utilized. Whereas, voltage constraints (>0.9 p.u. & <1.1 p.u. or constraints from contingency analysis) of substations/busbars from all the areas are considered. Once Main () is initiated, a set of objective lines or cables are given as input to the algorithm. These form the objective inter-area lines or cables for which the reactive power injection from them is minimized by the algorithm. Three (for each type of element) DPL command subscripts are executed to collect the controllable devices (energized, in service, switchable etc.) of the specified area as objects and initialize their Jacobian matrices.

Sensitivity Jacobian matrices for the respective type of elements are also initialized in these scripts. Initial states for the respective control elements are stored in memory as a matrix. Similarly, the next set of three DPL command subscripts calculate the sensitivities for each type of controllable device and fill in their sensitivity matrices initialised by the previous set of subscripts. The LPSolver () DPL command script merges these sensitivity Jacobian matrices into the problem matrix (refer figure 4.3) of LP Solver tool along with all the constraints for control variables and defines the objective coefficients
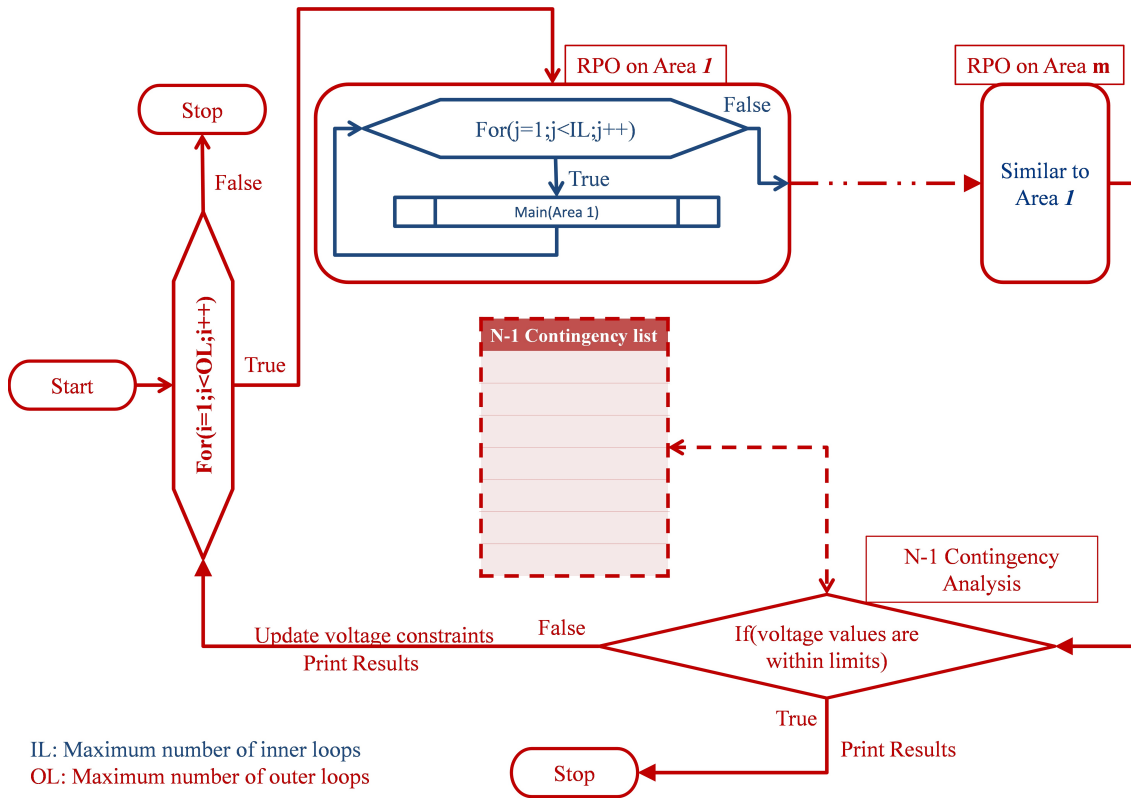
Figure 4.2: Multi-area based Reactive Power Optimizer (RPO)

for variables using the specified penalty factors. The penalty factors given as input to the algorithm are also specified within the problem matrix to replicate the objective function as shown in equation 4.1. The control variables in the problem are change in steps of shunt devices, tap position of transformers with OLTC and Mvar feed in of reactive power contracted generators.

For the linear programming problem matrix shown in figure 4.3,

Number of rows can be defined for the LP problem matrix as:

$$N_{row} = N_{line} + N_{busbar} + 2 \times N_{shntfilt} + E_1 + 2 \times N_{tr23} + E_2 + 2 \times N_{vtsp} + 4 \times N_{gen} + 2 \times N_{line} \quad (4.7)$$

Number of columns can be defined for the LP problem matrix as:

$$N_{col} = 2 \times N_{shntfilt} + 2 \times N_{tr23} + N_{vtsp} + 3 \times N_{gen} + N_{line} \quad (4.8)$$

Where the nomenclatures used in equations 4.7 & 4.8 are explained in table 4.3. It should be noted that the number of controllable devices can change depending on the area under optimization, while the number of objective lines or cables and busbars remain constant throughout the iteration of optimization process. This was included to consider the effect of controllable reactive power resources from the area under optimization on other areas.

Once the LP solver tool has successfully found a feasible solution, the resulting change as a solution for each control variable can be obtained from respective columns of the LP solver problem matrix. After obtaining the changes given as the optimal solution by the solver, they can be added to the initial state values stored in the matrices of respective elements. The new values are then saved into a matrix containing all the values of final state for controllable devices. New states of CBs & SRs-ElmShnt (step), Transformers- ElmTr2-ElmTr3 (tap position) & Contracted Generators-ElmSym (Mvar generation) are stored separately in 3 matrices.

Table 4.3: Nomenclature used in equations that define the number of rows and columns in LP problem matrix

Name	Description
N_{row}	Number of rows in LP problem matrix
N_{line}	Number of objective transmission lines & cables
N_{busbar}	Number of busbars or substations
$N_{shntfilt}$	Number of controllable shunt devices – CBs & SRs
E_1	Extra constraint equation for maximum change in steps of shunt devices
N_{tr23}	Number of controllable transformers with OLTC
E_2	Extra constraint equation for maximum change in taps of transformers with OLTC
N_{vtsp}	Number of voltage set points
N_{gen}	Number of controllable contracted generators
N_{col}	Number of columns in LP problem matrix

Figure 4.3: Matrix defined by LP Solver DPL command script

After the LPSolver command script has been executed successfully, the next DPL command subscript (MakeChanges ()) is executed to make the necessary changes based on the optimal solution given by LP solver. This subscript checks if there is change from the original state of control element (steps/tap position/Mvar generation) and only if there is a difference, the new value is stored within the control element parameter in system model. After changing all the control variables to have new values (when there is a difference), load flow (LDF) is re-calculated. This ends Main () and all its DPL command subscripts. Main () used as an agent can further be combined to from a multi-agent system which can be used to perform a number of iterations per area ("IL" inner loops {Main (Area A) × IL}) and for all the areas combined ("OL" outer loops {**OL** × (Main (Area A) × **IL** ⇒ Main (Area B) × **IL** ⇒ Main (Area C) × **IL**)}). Once the agent executes Main () to provide satisfactory results, master agent calls

agents sequentially for different scenarios and for different combinations of 'OL' & 'IL'. The program flow chart for final master agent program (LoopTest ()) can be shown in figure 4.2 which includes N-1 contingency analysis and a feedback loop with resulting voltage constraints for its agents.

Once satisfactory results were obtained from Main (), individual agents executed Main () on their areas sequentially as called by the master agent. After optimization is completed by all agents on their areas, an N-1 contingency analysis is performed by the master agent for a set of prescribed faults. The maximum and minimum voltages during the faults are analysed by the master agent, if all voltages are within the secured limits then program exits. If there is a violation during N-1 fault, then voltage constraints are manipulated for the particular bus or substation and the master agent calls its agents and re-executes the optimization on base case scenario for all areas while discarding the optimized scenario from previous iteration. The master agent can also call its agents without discarding the optimized scenario. The methodology to be used depends on the function of prototype controller. For snapshot system, the program was made to discard optimized scenario from previous iteration, while for the test system, optimized scenario from previous iteration was re-optimized with the new voltage constraints in order to satisfy N-1 constraints. Finally, changes proposed by the master agent or the intelligent control system should be minimal, therefore it was deemed essential to discard the optimized scenario and re-optimize the base case based on new voltage constraints. The master agent does not perform any optimization in this prototype control system. Main functions of the master agent include:

- ⋊ Model preparation (if new model is being used)

- ⋊ Call agents sequentially

- ⋊ Save the changes in controllable device states suggested by its agents

- ⋊ Perform N-1 contingency analysis and force new voltage constraints to make sure system is N-1 secure

4.2. Model description of test system

The multi-area based reactive power optimizer has been tested on two power system models. The development of multi-area based RPO algorithm was performed on a PowerFactory test system model (taken from [58]). Final validation was performed on various snapshot scenarios using data from EMS and snapshot system model from offline tool. In order to perform analysis using the algorithm, both the power system models had to be modified. The changes made to the test system will be discussed in detail within this section. An additional step was included in this project to use the test system so as to develop the algorithm. Table 4.4 shows a comparison made with respect to the number of elements between the test system and snapshot system, which were used in this thesis project. This table can be used to show the difference in size between their power system models. All the busbars in snapshot system were not considered within the LP solver, instead a single busbar was selected from 380kV, 220kV, 150kV & 110kV substations to represent their voltage values and sensitivities. Also, all the generators in snapshot system are not active nor energized, only a part of all the generators are active for a particular scenario (same for reactive power contracted generators) depending on the electricity market process.

As mentioned earlier, a test system was taken from [58] to develop the optimization algorithm. This test system was modified (shown in figure 4.4) to incorporate the type of controls and other features present in the Dutch transmission system. This test system was preferred when compared to other IEEE standard models because of its resemblance to the existing Dutch transmission system. However, changes had to be incorporated to recreate system operations like in real-time scenarios.
Important changes made to the test system were:

- ✂ Added OLTC capabilities to 3-winding and 2-winding transformers which were initially absent. Total number of taps and ΔV of each tap were made identical to that of the snapshot system.

- ✂ Added shunt filters (parallel Capacitor Banks - CBs and Shunt Reactors - SRs) to the tertiary windings of 3-winding transformers and some substations (busbars). The properties of these shunt filters were made similar to that of the snapshot system CBs or SRs.
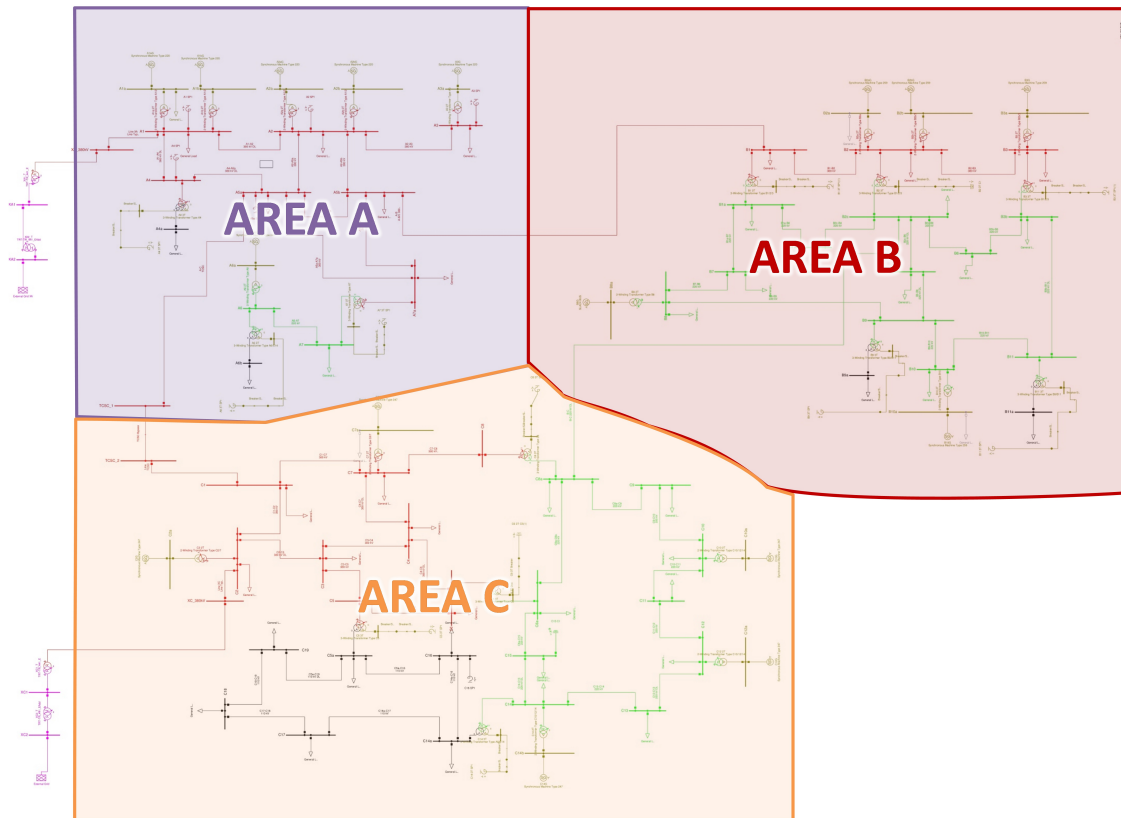
Figure 4.4: Test system used to develop the prototype intelligent controller

✂ Changed the power system scenario to include loads with negative power feed in (this means that the load model has a generation component also). Some of these load models were modified to consume capacitive reactive power.

✂ Generators were included to feed in both capacitive and inductive reactive power, however their reactive power exchange with the system was minimized. It is assumed that synchronous machines larger than 60 MW that don't have a reactive power contract with Dutch TSO minimize their reactive power exchange at the point of common coupling (PCC). All these generators are changed to PQ mode from PV mode (considering the Dutch electricity network code for secondary voltage control).

✂ 5 out of 16 generators are considered to be contracted for reactive power control. The contracted generators are observed by the optimizer using a flag parameter (dpl3 – Non zero = contracted; 0=not contracted). It can also be used to store a cost factor for the contracted generators (cost factor has not been considered in this project).

✂ Introduction of two external grids into the system (X nodes) to represent foreign grids along with cross border tie-lines.

4.3. Snapshot system

The final task in this thesis project involved implementing the multi-area based RPO algorithm on snapshot system model taken from offline tool along with snapshot data from EMS and performing simulation based studies for various snapshot scenarios. This section discusses on the selection process of snapshot system and data which were available for use by the algorithm. Some changes had to be incorporated into its power system model before implementing the proposed algorithm, these changes will also be described in this section. Whereas, the changes made to rule based controller

Table 4.4: Comparison between test system and snapshot system

Number of Elements	Test system $(380-220-110kV)$	snapshot system $(380-220-150-110kV)$
Number of lines & cables:	52	852
Number of Three winding Transformers:	12	32 (parallel sets are considered as one)
Number of Generators: (RP contracted generators)	16(5)	▆▆▆▆▆
Number of busbars with voltage constraints in RPO:	104 (All busbars)	334 (No. of EHV & HV substations, could contain more than 1 busbar)
Number of Shunt Filters:	19	118

before performing studies on the snapshot system scenarios will be discussed in chapter 5.

4.3.1. Available data
Before employing a computational aid or intelligent control system that can be used by control engineers (or for resource planning), it is important to understand the data available for use within TSO system. This analysis was performed to find most adequate data that can be used in the proposed voltage control system. This section of the chapter describes the different types of data available to the Dutch TSO.

The measurements obtained from SCADA (Supervisory Control and Data Acquisition) system (MW, Mvar, kV, CB status, Tap position etc.) are stored in the data warehouse. Online power system tool within the Energy Management System (EMS) receives measurement data and performs state estimation using its power system model. After which the load flow is also executed within the online power system model and injection point values are exported for snapshot preparation [14]. These files are then imported into the offline power system tool, so that load flow calculation can be executed [14]. After which offline tool exports injection point data into files which are stored in archive for after-the-fact studies and other uses [14].

4.3.2. Data analysis
As a part of this master thesis project, data analysis was performed to check which data set would be most suitable for use by the proposed optimization algorithm (analysis of MW, Mvar & kV values). In order to do so, A set of two macro (visual basics- excel [66]) scripts and one C++ program script were prepared. The basic approach selected to perform this task is shown in figure 4.5. Firstly, the C++ program script has to be executed to collect the snapshot data from load flow calculation using files exported from the offline tool. After which the macro script has to be executed in order to collect measurement data from data warehouse which is made available in excel files. Both these data sets are collected and stored for comparison. The results are stored in a workbook for one day and a work sheet within it for every snapshot (SN) file available. The last macro script analyses all the data from result excel files and gives the output as graphs. Moreover, analysis was also performed on historical voltage values at substations and Mvar injections at cross border tie-lines in order to check if they had some kind of similarity in profile. This analysis was performed to check the feasibility of including set points within the RPO algorithm based on historical data. The data analysis was performed over two months for sets of data.

The RPO algorithm, details of which have already been described in the beginning of this chapter, uses the following data as input from the power system model:
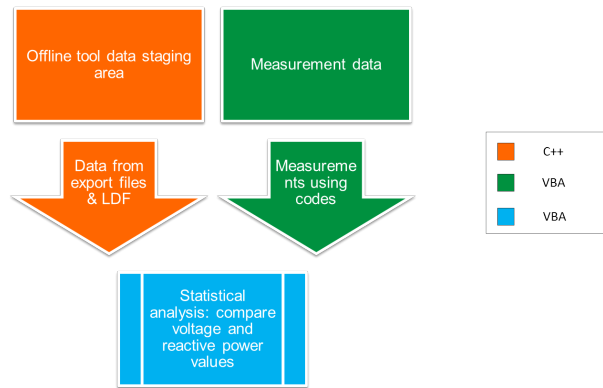
　　⋊ Voltages at HV Substations

Figure 4.5: Approach to perform data analysis

ℵ Reactive Power (RP) Feed of contracted generators & RP injection from objective lines or cables.

ℵ Circuit Breaker status

ℵ Transformer Tap position

Therefore it is essential to make sure that these data sets are adequate when used by the RPO algorithm in order to avoid undesirable solutions.

4.3.3. Observations from data analysis

☞ Active power values are constant throughout the flow of data within the Dutch TSO system. Historically, the offline tools are mainly used to perform studies on active power flows over the transmission lines (& cables) or congestion studies. Therefore the power system model is maintained to achieve adequate active power values, so that they can be used for existing processes.
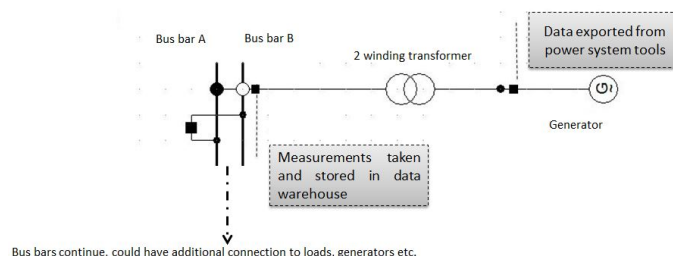

Figure 4.6: A reactive power contracted generator connected to the HV bus of a TSO

☞ Differences in Q-Mvar could result from online and offline power system tools (synchronization of models imminent). State estimation [67] is performed for the measurements using the network model in the online tool. The load flow [68] is calculated for injection points by both online & offline tools. If the optimizer should obtain adequate EHV & HV transmission grid Mvar or kV values, the power system modelling (especially transformers) of both power system tools have to be synchronized (MW losses of transformers are comparatively lower). Non-synchronized modelling of transformers or other devices at either one tool could result in large differences of Mvar. The figure 4.6 shows an example generator connected to EHV grid. If the two winding transformers associated with such generators are modelled differently, load flow results using the transmission system model would give different values for Mvar feed in of these generators. TSOs should consider sychronizing power system models between online and offline power system tools important.

☞ Observed similarity in profile between historical voltages at substations (note: similarity should be in ΔV over time and not absolute values). Voltages at HV buses of 5 substations were observed for 2 months to check if there is a similarity in profile for working days.

☞ The injection of Mvar at cross border tie-lines were observed for 4 weeks spread over 2 months in order to check if there is any similarity in their profile. No similarity was observed in profile between historical Mvar injections at cross-border tie-lines for the days considered.

4.3.4. Conclusion & requirements of the prototype controller

The main aim of performing data analysis was to decide on the model and data that can be used for applying the optimization algorithm. Various options available for this project are shown below which includes the choice made (shown in green) and others along with their reason for rejection (shown in orange).

Power system models:

⋈ Existing snapshot model (it was found infeasible to use the original model without any modification)

⋈ Modified snapshot model

⋈ Independent model (development of the complete 380-220kV grid model of the Dutch TSO was essential, this approach would make it difficult to replicate scenarios)

⋈ IEEE standard models (results from studies will not be useful to the Dutch TSO)

System scenario data:

⋈ Online power system tool export files, Import these files into offline SN model to perform studies

⋈ offline power system tool output – SN files (no shunt filter data available for files along with other export format model limitations)

⋈ Measurements from data warehouse (an additional step of state estimation would be required)

In order to apply any kind of voltage control scheme within offline power system models, it is important to reduce deviation of Mvar from measurements at high voltage grids (including Mvar feed in of reactive power contracted generators) and voltages at substations throughout all the stages of data transfer beginning from measurements at HV grid to offline tool snapshots used for this project. Synchronising the models of devices (like transformers) in online and offline power system tools could significantly reduce the deviations of associated Mvar values. A similarity in voltage profile was observed for historical measurements at substations. However, it is preferred to have magnitude of voltage set points determined based on power system studies (for various scenarios) rather than using values purely based on the historical data sets. Therefore, no voltage set points were considered for this thesis project (except for testing objective 4). A considerable amount of distribution systems could be modelled as load at their connection points by TSOs. While, the detail of lower voltage grid models can impact the sensitivities at high voltage grid (the variation of their reactive power requirement with respect to voltage at connection points). Therefore, amount of detail within the lower voltage grid models cannot be considered less important, even for steady state analysis the effect of impedance at low voltage networks is not completely negligible for some scenarios [69]. This project deals only with steady state optimization and data requirements for the same have been mentioned in this section.

4.3.5. Dividing snapshot system into areas

After developing & performing simulation based studies using the controller and optimizer on test system, the prototype controller had to be transferred to the snapshot system. Before doing so, the snapshot system had to be divided into areas so as to utilize the concept of multi-area RPO effectively. In the test system, this was not an issue as the areas were already well defined with one interconnection between any two areas (two per area in a three area system as shown in figure 4.4). This subsection will briefly explain the process of splitting snapshot system into areas. The reasoning behind changing

the conventional areas will also be described in this subsection.

Reasons for splitting snapshot system model into areas or using multi-area approach:

☞ *Smaller Power System problem – smaller matrix, faster solution*: Dividing the power system into smaller areas introduces the possibility of solving the optimization problem in parallel (solve for agents in parallel). This is not possible if each agent suggests relatively large amount of changes in the state of controllable reactive power resources (non-linearity of sensitivities will become visible). Also, the agents are not completely independent from each other, solution of one agent could have an effect on that of the another. For normal operation with high penalty on change, this is not the case (there are hardly more than 1 or 2 changes suggested in an entire iteration). Therefore, it is feasible to solve individual agent optimization problems in parallel for normal operation. For critical or emergency cases, even faster solution can be computed by using a single agent for solving the area with critical problem.

☞ *Problems are solved within the area (based on control engineers principles)*: Control Engineers at NCC try to control voltage using local resources. This is performed by utilizing RP resources as close as possible to the location or substation at which the voltage change is required. This methodology followed by control engineers supports multi-area based optimization.

☞ *Possibility of defining different objectives & constraints for individual areas or agents*: It is possible to introduce different objective functions and constraints for individual areas or agents. As a part of future development, it is possible to define individual area based unique constraints (including dynamic constraints) and objective function or its penalty factors within the rule based controller. However, all the constraints and objectives have to be linear, the LP solver tool used in this thesis cannot solve the optimization problem if they are not linear.
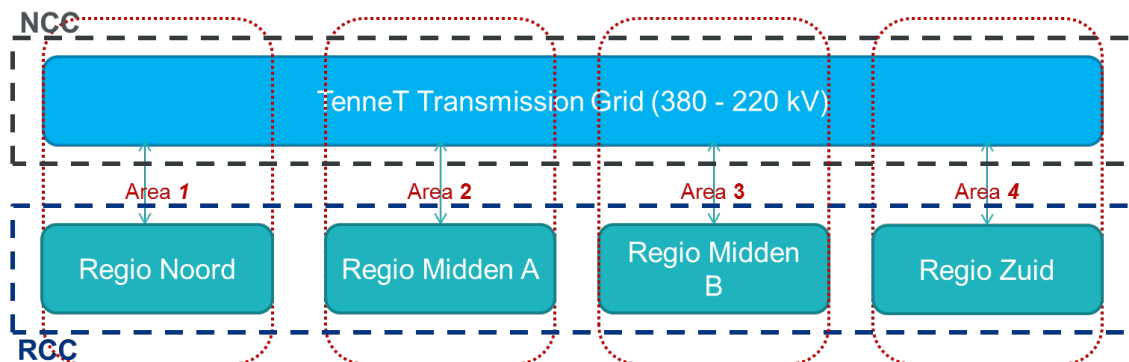

Figure 4.7: Proposed four areas for snapshot system

☞ *Suggested control actions will be more reliable*: There is a possibility that the optimizer suggests a change at region Noord for a problem (voltage limit violation) at region Zuid. Even if the sensitivity of controllable device is small, as the requirement is also small to solve the problem (for high penalty on objective 4). However, this might not be feasible in reality. The optimization algorithm assumes that all generators and other connected systems are in PQ mode (constant reactive power injection) at their connection point for the secondary voltage control (according to the Dutch electricity network code). This does not need to be true always. With increasing distance, the number of connection points increase and the devices (transmission and distribution network) contributing to changes in Mvar or voltage increase. Undesirable contributions from these devices can be minimized to an extent by removing the RP resources with relatively smaller sensitivities or the distant RP resources (electrically and geographically).

☞ *Assist coordination between regional and national control engineers*: Some voltage problems (warning limit violations) can be observed at both regional and transmission high voltage grids. There is a possibility that control engineers at both regional and national control centers utilize their own resources to correct the same problem (generally this will not happen as they

Figure 4.8: Four areas represented geographically in the map of Netherlands

coordinate before performing a control action). This could create a double counter effect on voltage magnitudes at the specific location and nearby substations. A common area based reactive power optimizer introduced to both NCC & RCC can assist the coordination between the control engineers at both centers and help to avoid such undesirable scenarios. Additionally, improved utilization of resources can also be achieved by using a common intelligent advisory control aid. The snapshot system can also be optimized using a single agent if required. Using multi-area scheme does not significantly affect the outcome in any way. Results might be improved as the optimization problem is again broken down into steps. But the same results can also be achieved by manipulating the penalty factor on (objective 2) change in states of controllable devices within the LP solver.

The snapshot system was divided into four custom areas for this thesis project which were as shown in figure 4.7 (Noord, Midden A, Midden B & Zuid). In order to obtain reliable results from the optimizer it was found that merging EHV (380-220 kV) grid with regional grids was essential. The most time efficient method was to merge the EHV (380-220 kV) region into HV (150-110 kV) or the four parts of regional grid. There are multiple methods to define areas (based on geographical or electrical distances), but for simplicity in this project an existing geographical split at regional grid was utilized, resulting in four areas as shown in figure 4.8. Inter-area objective transmission lines were also simpler to define when the concept of regional geographical split was extended to EHV grid. There were less connections between HV (150-110kV) grids of different regions or only single connection if any present at all (a total of seven inter-region/area connections out of which five were between EHV (380kV) substations and two were between HV (150kV) substations). Note that these areas were defined only for this thesis project and no survey or study was conducted to check how the areas were defined in voltage control process.

If EHV grid (380-220kV) is not merged with the regional HV (150-110kV) grids, the effect of changing

tap position of the tap controller at transformers is underestimated by the optimizer algorithm either to EHV (380kV & 220kV) or HV (150kV & 110kV) grids (Refer chapter 5 for more details). In reality, changing OLTC taps affect high voltage and low voltage sides of the transformer simultaneously [70] & [71]. Another important reason for merging was that the original region Noord grid of snapshot system had less controllable reactive power resources available. In reality this was not true, most of the controllable reactive power resources for this area were connected to the EHV grid. Moreover, voltage instability is a non-linear local phenomenon [72]. While a local voltage collapse can lead to a widespread collapse of the system [72].

5

Results from the simulation based studies

In this chapter, the approach used for employing the optimization algorithm will be briefly described followed by discussion of results obtained from the simulation based studies using a reactive power optimizer on (a) test system as shown in figure 4.4 and (b) snapshot system after merging EHV (380kV & 220kV) network with regional High Voltage (HV: 150kV & 110kV) networks. As mentioned in chapter 4, a test system was used to develop the multi-area based Reactive Power Optimization (RPO) algorithm with a multi-objective function.

After its development, the algorithm was used to perform simulation based studies on snapshot (SN) system belonging to the Dutch TSO which had its EHV network merged with the regional networks. All the controllable RP (reactive Power) resources of EHV network were also distributed (as shown in figure 5.1, *for an example SN scenario from 08/02/2016 for the time stamp 06:15AM). When RPO was tested on some snapshot scenarios before merging EHV area into regional areas, solutions given were not reliable as distant resources (in terms of electrical and geographical distance) were being deployed. The final number (No.) of controllable RP resources per area or region (area and region can be considered as the same for this project, Regio/Region is the naming convention used by Dutch TSO) was as shown in figure 5.1 for a particular snapshot scenario.

5.1. Approach used to employ RPO with a multi-objective function

Figure 5.2 gives an overview of the approach selected to implement the multi-area based RPO which has a multi-objective function differentiated using penalty factors. This thesis work can be divided into three phases, the initial phase included defining starting point assumptions and conceptual design of the prototype which have been explained already in chapter 4. In the prototyping phase, the optimization algorithm of RPO was developed in DIgSILENT Programming Language (DPL) on test system. Initially a single objective function was included to minimize and one type of reactive power control device was used to optimize the test system. Using a step-by-step approach, the optimization algorithm was improved to include more objectives, constraints and types of controllable RP resources after verifying their validity at each step.

After including all the prescribed functions of RPO as mentioned in chapter 4 and performing simulation based studies using it on the test system, the last phase of development and final validation phase was initialised. In this phase, RPO was transferred to the snapshot system model which has its EHV network merged to the regional grids and final simulation based studies were performed on it to obtain results. Results from simulation based studies on test system and snapshot system are presented in the following sections 5.2 and 5.3 respectively. The reference values for penalty factors used by opti-
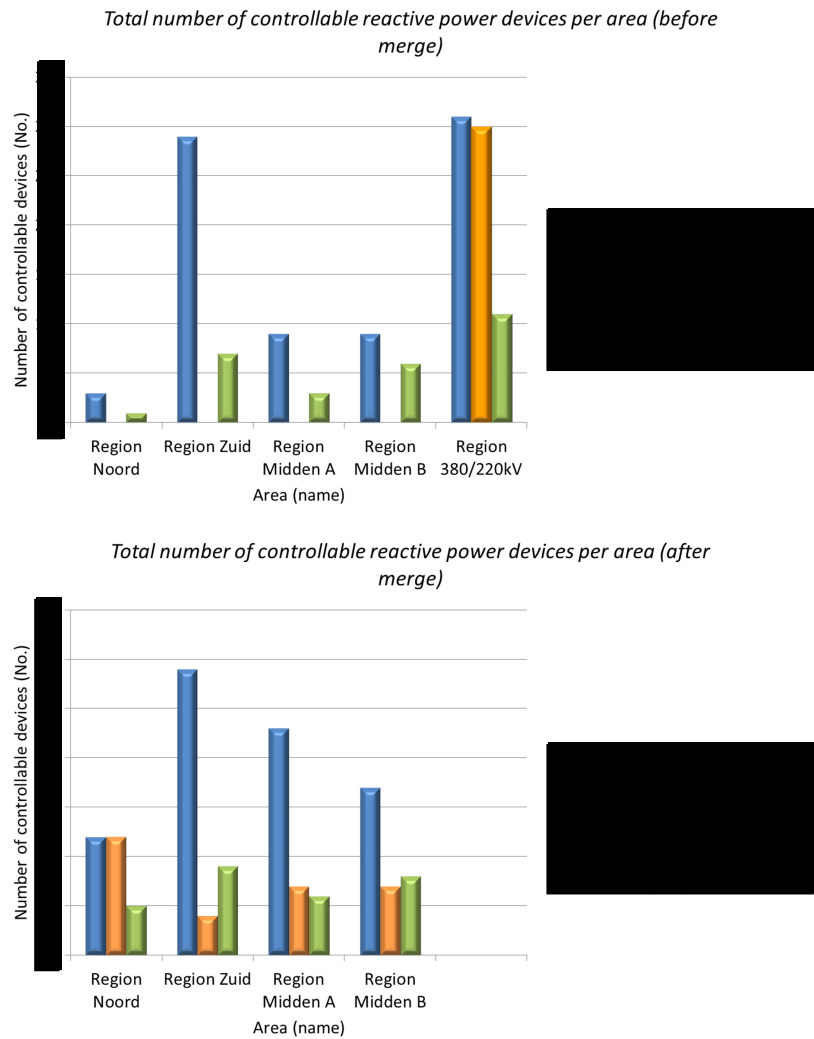
Figure 5.1: Controllable RP resources available per area for a particular scenario (before & after merge)

Table 5.1: Reference values for penalty factors

Penalty factor	Test system	snapshot system
p_{gmv}	1	10
p_{sh}	1	10
p_{tap}	10	100
p_{deltag}	0.5	5
p_{qgini}	0.01	0.01
p_v	10	100

mization algorithm while conducting simulation based studies on test system and on various scenarios of snapshot system are shown in table 5.1. None of penalty factors used in this controller has a unit of measurement.
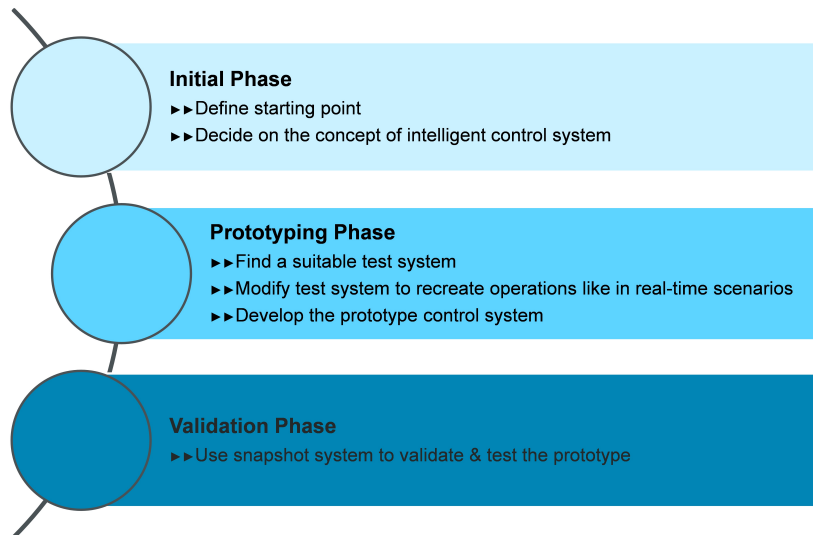
Figure 5.2: Overview of the approach selected to implement RPO

5.2. Results obtained for the test system using RPO with multi-objective function

Initially, validity of the main objective (objective 1 - minimizing Mvar injections in the objective lines) was verified on the test system in PowerFactory. Keeping all the penalty factors constant, the RPO was executed for 4 iterations on all the areas. The N-1 contingency analysis was not performed during this procedure. A graph was plotted based on the results obtained for this analysis as shown in figure 5.3.

It can be seen that with increasing number of iterations, the absolute sum of Mvar injections is decreasing. It takes 3 iterations to optimize the power system Mvar injections due to the penalty applied for changing the state of controllable RP resources (objective 2) within objective function as mention in equation 4.1. After a certain number of iterations, the system is completely optimized (for this scenario after three iterations the system was optimized).

As the next step, individual penalty factors dedicated to each objective were changed to perform a kind of sensitivity analysis of their values on the overall objective function. Firstly, the penalty factor on objective 1 contributing to minimizing Mvar injections was varied while keeping all other penalty factors constant. The result from this analysis can be represented in a graph as shown in figure 5.4. It should be noted that N-1 contingency analysis was switched off for the sensitivity analysis of penalty factors. It can be seen from the figure that after a certain value of p_{gmv}, the result doesn't considerably change. At this point, minimizing Mvar has become the most important objective within the objective function. When the value of p_{gmv} was increased from 2 to 5, the sum of absolute injection of reactive power reduced from all the lines while the reactive power injection from line A-C increased. This shows that the RPO only tries to reduce the sum of absolute Mvar values and not within independent lines or cables.

After performing the sensitivity analysis of p_{gmv} on the objective function, sensitivity analysis of penalty factors belonging to objective 2 (which are to reduce the change in state of controllable resources) was performed. In order to do so all the factors were forced to be zero values, which is the first case in figure 5.5. This means that there is no penalty on changing the state of controllable RP resources and algorithm is allowed to make all the changes necessary to reach the most optimum state (note: due to the non-linearity of sensitivities with large amount of changes, the solution obtained in this case was not optimum as predicted by the optimizer). Figure 5.5 shows results from sensitivity analysis performed on the three penalty factors (p_{sh}, p_{tap} & p_{gdelta}), varying them one by one while keeping others constant. The influence of each penalty factor (p_{sh}, p_{tap} & p_{gdelta}) on the objective 2 (overall
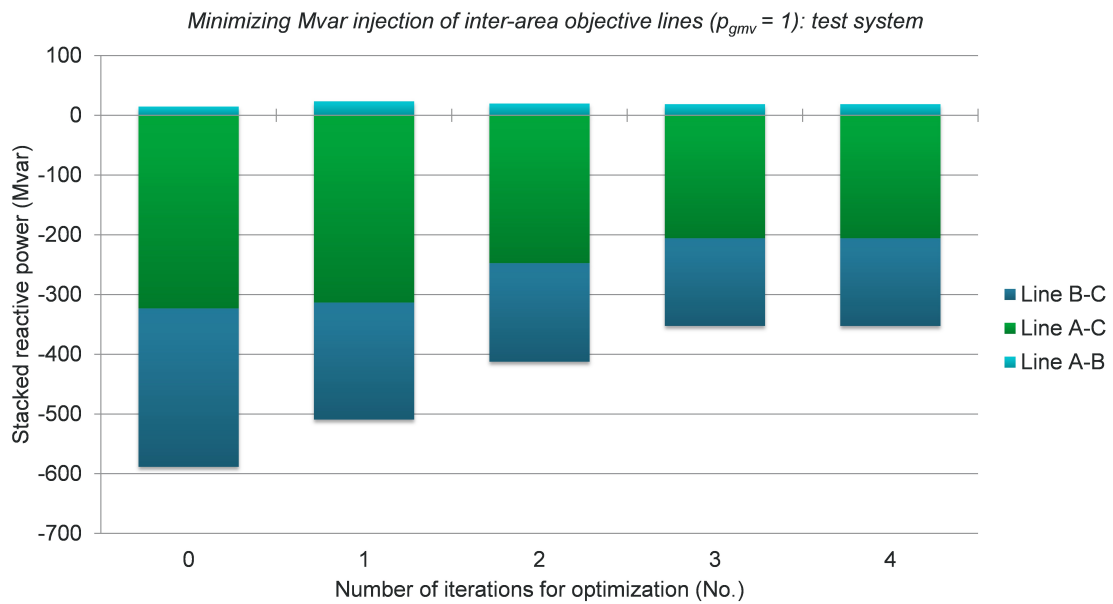
Figure 5.3: Effect of increasing number of iterations on the test system inter-area lines
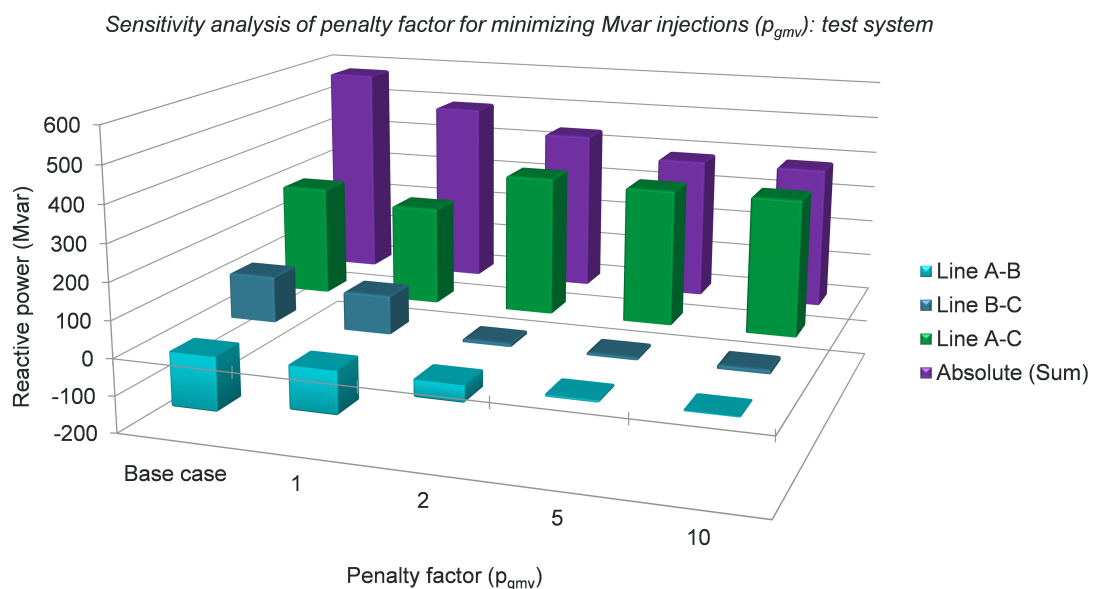

Figure 5.4: Sensitivity analysis of the penalty factor p_{gmv} on the test system inter-area lines

change in the states of controllable RP resources) can also be seen from the figure 5.5. As shown in the last case, it is also possible to keep these penalty factors sufficiently high so that the LP solver gives original solution as the feasible solution or "optimal" solution. This is interesting for the TSOs, as they prefer to induce the lowest amount of change or no change to the state of transmission system in real-time operation. This is followed to take into account the health of transmission system assets.

Objective 3 in the objective function was to reduce the overall reactive power generation from contracted generators. This objective takes an economic factor into account, which is the consumption of reactive power from all the contracted generators. The last objective 4 was introduced to make RPO solutions reach set point values of voltage at a particular substation or busbar. Figures 5.6 and 5.7 shows the effect of changing the penalty factors p_{qgini} and p_v for these objectives and how their values
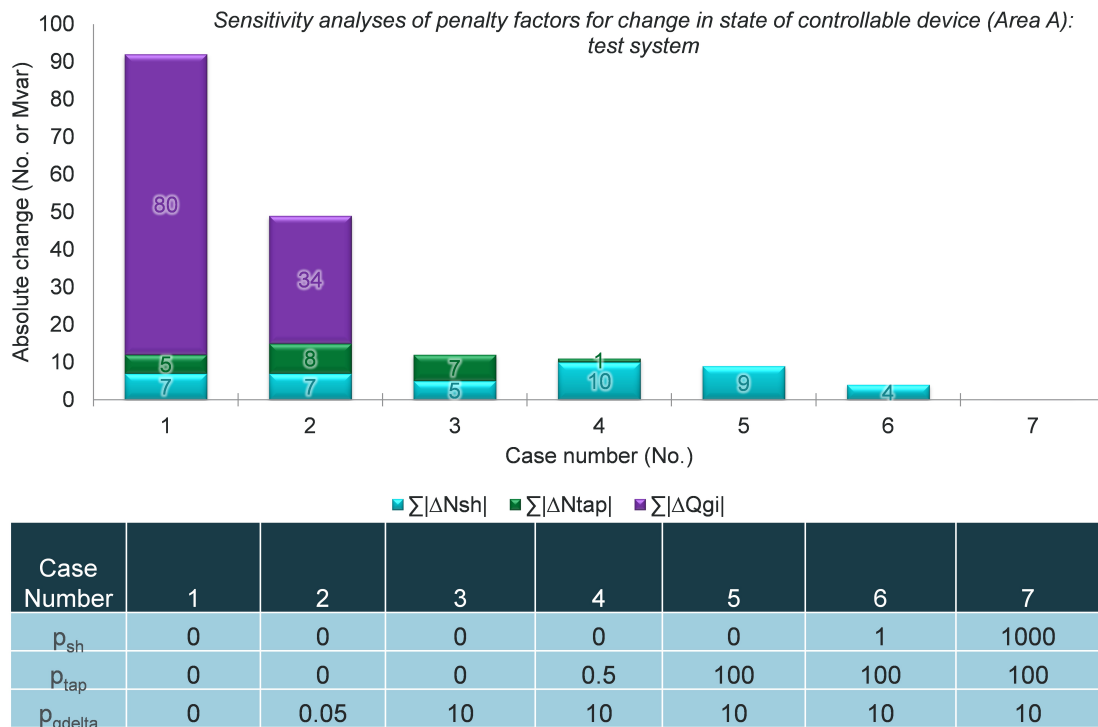
Figure 5.5: Sensitivity analyses of the penalty factors p_{sh}, p_{tap} & p_{gdelta} on the test system
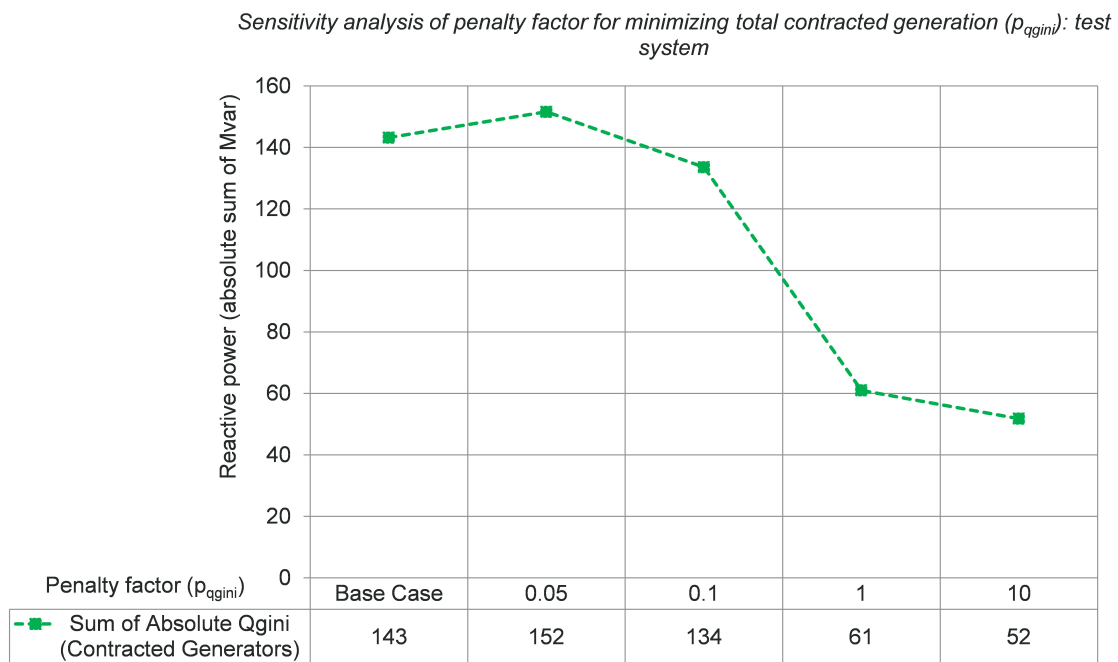
Figure 5.6: Sensitivity analysis of the penalty factor p_{qgini} on the test system

affect the reactive power generation from contracted generators and voltage at set point substation or busbar respectively.

From figure 5.7, it can also be seen that decreasing reactive power injections in the system could result in slightly reduced voltages (trying to reach 1 p.u. depending on the RP resources available). Results are scenario dependent and none of the result graphs presented in this chapter can be gener-
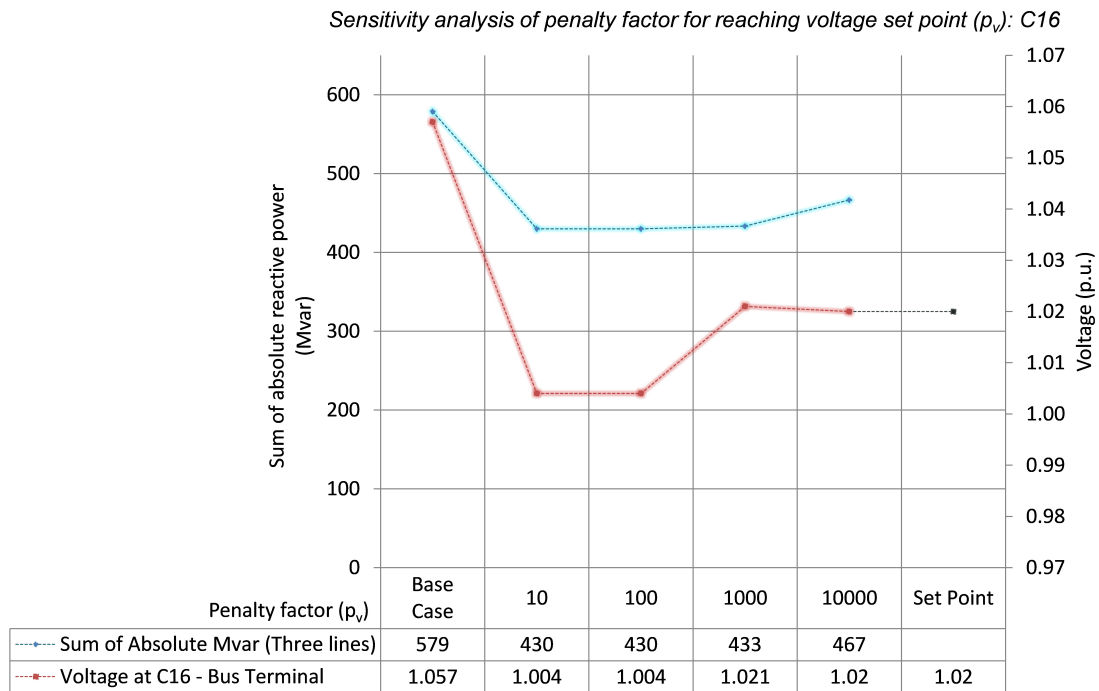
Figure 5.7: Sensitivity analysis of the penalty factor p_v on the test system busbar C16

alised for all scenarios. Achieving higher voltage values in the power system could result in increased or decreased reactive power injections. Therefore, control engineers might have to choose between an optimum reactive power flow approach or high voltage set point approach. In any case there would have to be a compromise made between the importance or weighting of different objectives on the multi-objective function. Importance or weighting of different objectives can be modified within the objective function by changing magnitude of their respective penalty factors.

After developing the RPO algorithm and performing simulation based studies on test system so as to obtain the results presented in this section, it was certain that the multi-area based RPO is optimizing according to the design concepts as mentioned in chapter 4. By performing sensitivity analysis of the penalty factors, it was also possible to assign appropriate penalty factors for reliable operation of the prototype controller.

5.3. Results obtained for the snapshot system using RPO with multi-objective function

Following the implementation of multi-area based RPO on test system, the same algorithm was implemented on the snapshot system in order to perform simulation based studies. Before doing so, a few changes had to be incorporated into the rule based controller and they were:

⋇ A new program was designed to designate contracted generators within the snapshot system based on the list of generators present in its description. This list was manually prepared using documents containing details of reactive power contracted generators.

⋇ A new program was designed to designate regional areas to EHV (380kV-220kV) substations and controllable RP resources based on data present in the description of the program. First, this program defines new areas for EHV substations which was determined by conducting a brief study on their geographical location and connection to HV (150kV-110kV) substations. After redefining areas for EHV substations, controllable devices connected to EHV grid had their areas modified
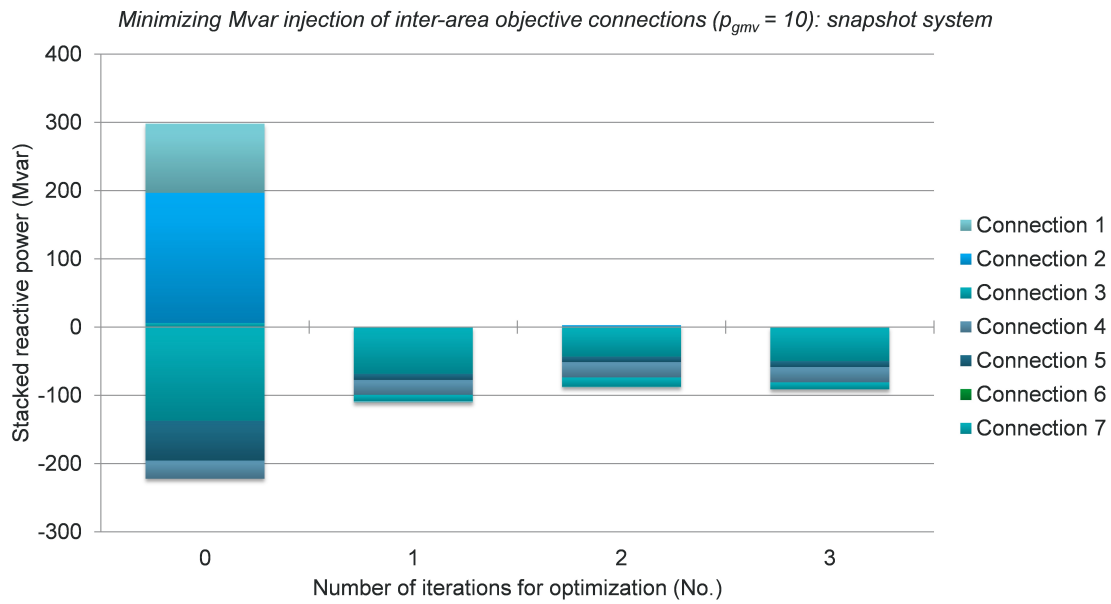
Figure 5.8: Effect of increasing number of iterations on the snapshot system inter-area connections
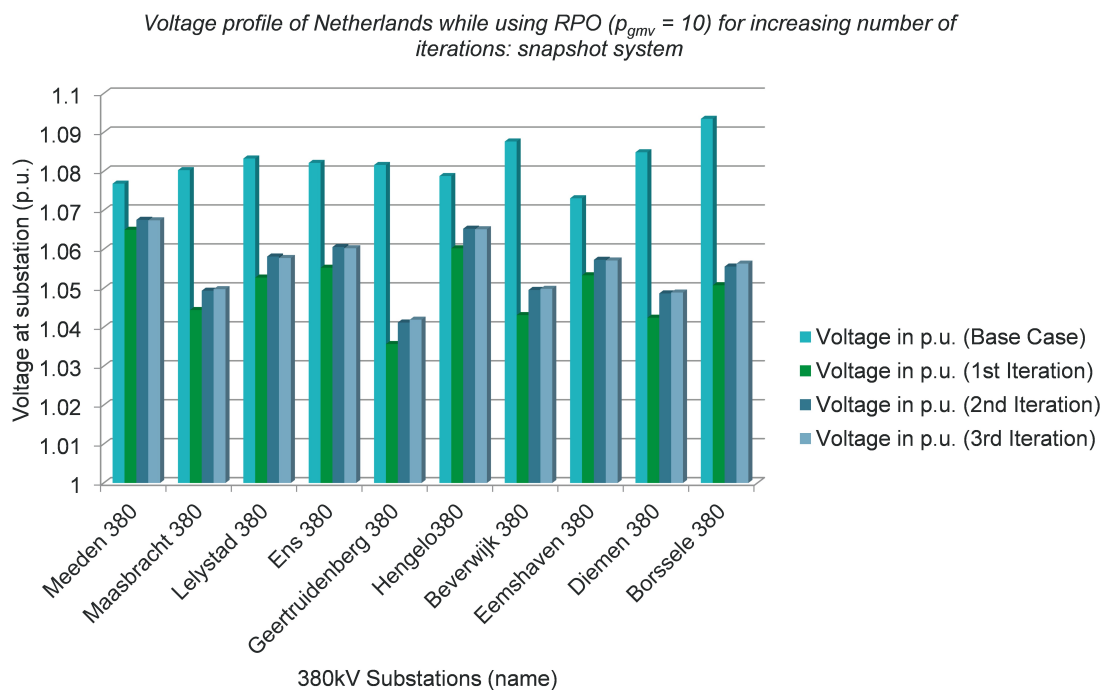
Figure 5.9: Effect of increasing number of iterations on the snapshot system voltage profile

based on the substation they were a part of.

⋊ The controller was re-designed to consider a parallel set of transformers as one controllable device with the help of tap controller elements already available in the snapshot system. The sensitivity of each transformer within the parallel set differs according to the busbar it is connected to in the substation. These differences are small but not completely negligible. Therefore, sensitivity of each parallel transformer is calculated and then summed with that of others to from one sensitivity value for the entire parallel set. Note: calculating transformer sensitivities is the most

time consuming feature of this controller, as it has to execute load flow for calculating sensitivity of each transformer. This takes more than half of the total time consumed to execute one iteration (total time consumed for one iteration is approximately 450 seconds, but can vary depending on the processor type and load flow computation time). This also means that finding transformer sensitivities faster could considerably reduce the time required to execute one iteration of the prototype controller or RPO on all areas.

⋊ The controller was re-designed to consider only substation busbars instead of all busbars present in the system for voltage constraints and other sensitivity related calculations. Unlike the test system, there were numerous terminals and busbars in the snapshot system. Most of them were not relevant to the optimization problem, therefore only the busbars at substations were considered for voltage constraints.

⋊ A program to create N-1 contingency list was scripted, this is required as multiple snapshots were being studied on and a new contingency list had to be created for every new project. In the test system, new voltage constraints resulting from N-1 contingency analysis were used to optimize solution from first iteration. Whereas for the snapshot system, solution obtained from first iteration is discarded and controller optimizes the base case scenario with new voltage constraints from contingency analysis. This new approach was adapted to consider the fact that optimizing a solved scenario from first iteration gives a solution with more number of changes in the states of controllable devices with respect to the base case scenario. A large number of changes can be suggested by the algorithm if more number of iterations is required to find an N-1 contingent solution.

After implementing all the changes to prototype controller, simulation based studies were performed on snapshot system following the procedure similar to the one used in section 5.2. This was performed to check the validity of RPO optimization on various scenarios of the snapshot system. All the results presented in this section are taken from analysis performed on a low load scenario with relatively higher voltages as the base case. The foreign grid buses are represented as PV nodes with the help of generators. Figure 5.8 shows an optimization result from the prototype controller, with increasing number of iterations the amount of reactive power injection decreases. For this scenario it was possible to obtain the most optimum Mvar injections (objective 1) in inter-area connections within 3 iterations using a penalty factor p_{gmv} of 10. The number of iterations required to optimize the system will depend on its scenario and penalty factors used, decreasing the penalty factor p_{gmv} would increase the number of iterations due to slower change in system state. This also results from the penalty on changing states of controllable devices, which is an outcome from objective 2. Unlike test system with three inter-area objective lines, snapshot system has seven inter-area connections. One connection can have two or more electric power transmission lines. The total number of lines in these connections was found to be 19 for the snapshot system. For ease of representation, the data is summed for these lines or cables within each connection. In figure 5.9, it can be seen that the overall voltage profile of Netherlands decreases from base case values (but it is still much higher than 1 p.u.) in the first iteration, whereas during the next set of iterations, the overall voltage profile of Netherlands slightly increases. Therefore the most optimum state proposed by this controller based on objective 1 need not always have low voltage values (or 1 p.u.). To represent the overall voltage profile of Netherlands, results from 10 substations were used as shown in figure 5.9.

The sensitivity analysis of penalty factor p_{gmv} was also analysed for the snapshot system's inter-area Mvar injections. This can be represented as shown in figure 5.10, the Mvar injections decrease with increase in penalty factor for objective 1. After a certain value of p_{gmv}, objective 1 becomes the most prominent part of the multi-objective function and overrules the effect of other objectives. Increasing the penalty factor beyond this value will not show a considerable difference in results given by the optimization algorithm. For this scenario, the effect of penalty factor p_{gmv} on the voltage profile of the snapshot system can be shown in figure 5.11. It can be seen from figure 5.9 and 5.11 that the most optimum cases of Mvar injections in inter-area objective connections are present when voltage values are slightly lower around 1.04-1.06 p.u. rather than the base case voltage values of 1.06-1.09 p.u. This would also be a more secure solution in terms of voltage (values closer to 1.09 p.u. increases the possibility of upper limit voltage violations during N-1 contingency analysis).
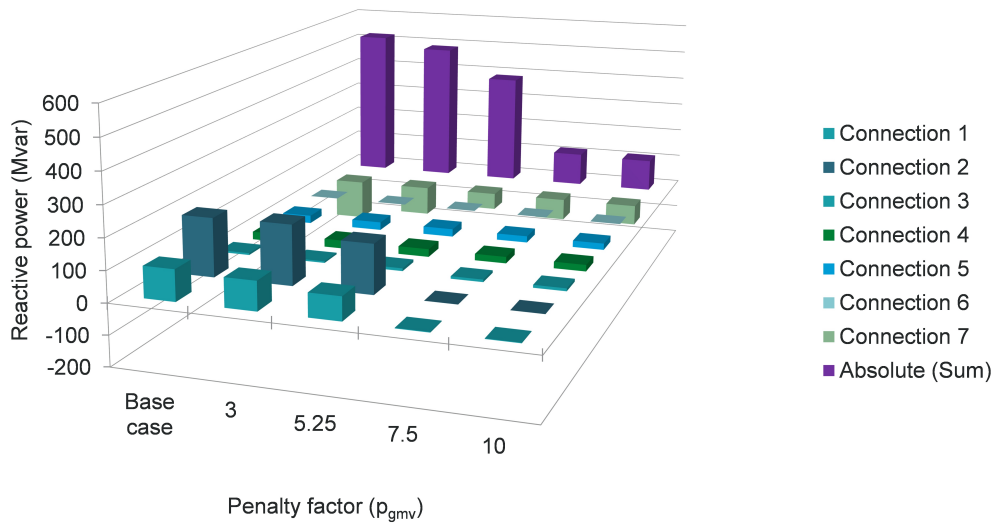
Figure 5.10: Sensitivity analysis of the penalty factor p_{gmv} on the snapshot system inter-area connections

Figure 5.11: Sensitivity analysis of the penalty factor p_{gmv} on the snapshot system voltage profile

After performing studies on sensitivity analysis of p_{gmv}, sensitivity analysis of penalty factors within objective 2 was conducted. This was performed to check if the results obtained as shown in figure 5.5 for the test system can be recreated in the snapshot system. As shown in figure 5.12, it was possible to increase or manipulate penalty factors on the change in state of controllable RP resources (objective 2) so as to reduce their use by RPO algorithm. The three penalty factors (p_{sh}, p_{tap} & p_{gdelta}) were varied one by one, while keeping the other penalty factors constant resulting in 8 cases. Note that due to a large change in Mvar generation proposed by the optimizer, unlike figure 5.5 the unit used here
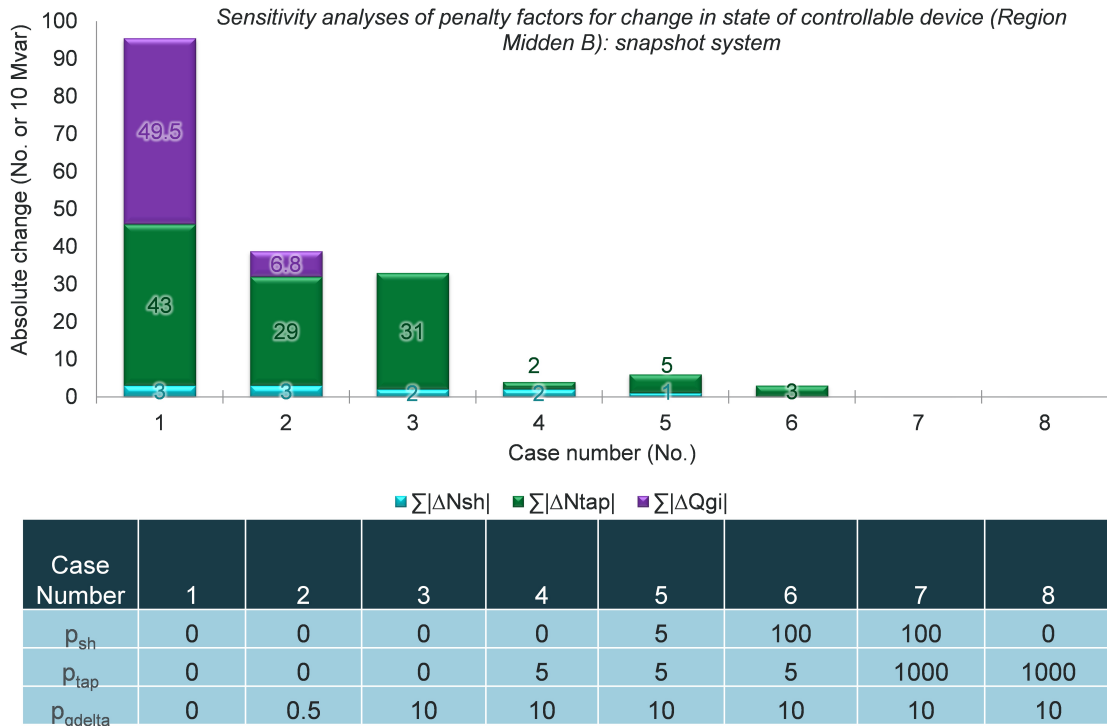
Figure 5.12: Sensitivity analyses of the penalty factors p_{sh}, p_{tap} & p_{gdelta} on the snapshot system
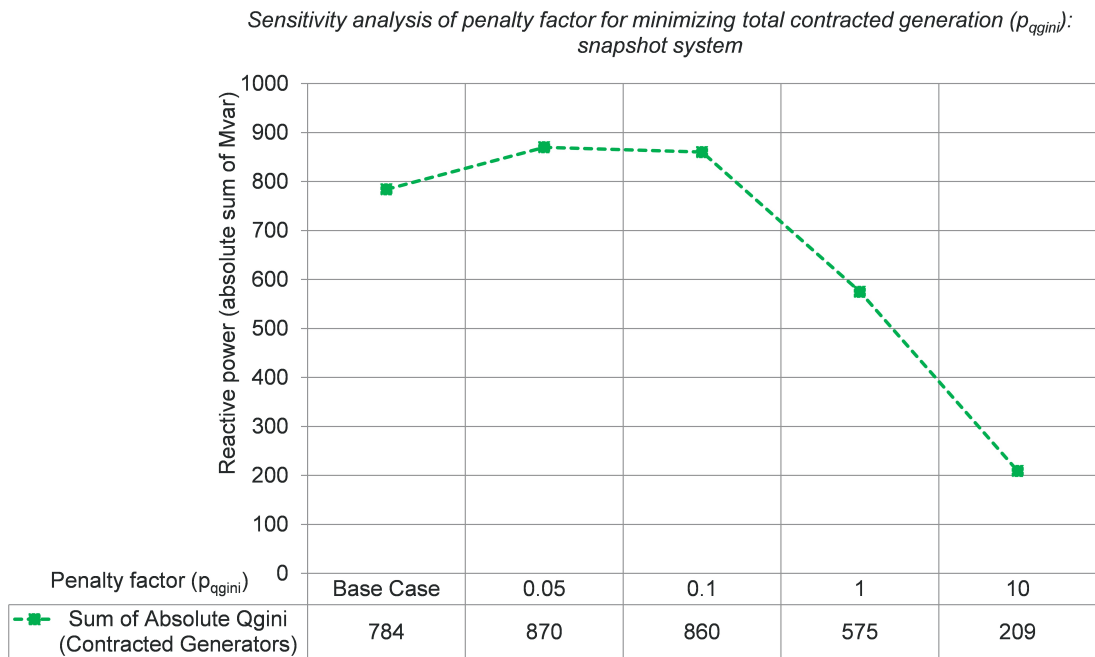
Figure 5.13: Sensitivity analysis of the penalty factor p_{qgini} on the snapshot system

is 10 Mvar. Therefore, the change proposed for Mvar generation in case number 1 from figure 5.12 is 495 Mvar. The large change is due to the availability of a relatively larger number of generators in the snapshot system. The algorithm finds an optimum between objectives 1, 3 & 4 by changing the states of all necessary RP resources in the case number 1. Objective 2 is forced to be zero in the case number 1 by making all dedicated penalty factors zero. For this scenario, increasing the penalty factors p_{tap} and p_{gdelta} indirectly influenced the amount of shunt devices being used or switched. In case number

3 (figure 5.12), the number of shunt devices being switched reduced from "3" to "2" when the penalty factor p_{gdelta} was changed from "0.5" to "10". It can also be seen from the case number 8 (figure 5.12) that forcing the optimization algorithm to not change the tap position in OLTC of transformers resulted in no overall change, even though it was allowed to change the state of shunt devices (CBs and SRs).

In figure 5.13, the effect of increasing penalty factor p_{qgini} can be seen on the overall reactive power contracted generation in the snapshot system. If reducing p_{qgini} to zero doesn't violate any voltage constraint or affect other objectives, then increasing this factor compensates the second objective and try to reach zero when possible even though it increases the change in Mvar generation from RP contracted generators proposed by the optimizer. However, if any other objective or constraint opposes the reduction of Mvar generation, then the optimization problem becomes relatively more complex and the algorithm tries to find an optimum between the three or more objectives that satisfies all the constraints.

Sensitivity analysis of penalty factor for reaching voltage set point (p_v): GT380

Penalty factor (100 p_v)	Base Case	100	200	300	330	600	1000	Set Point
---◆--- Sum of Absolute Mvar (7 Connections)	520	338	404	433	501	512	514	
---■--- Voltage at Geertruidenberg 380kV Substation	1.082	1.031	1.044	1.05	1.073	1.074	1.075	1.075

Figure 5.14: Sensitivity analysis of the penalty factor p_v on the snapshot system with set point at GT380

The last and fourth objective within the objective function for minimization was to make sure that voltage set point can be attained for a particular substation. In the analysis performed here, a set point of 1.075 p.u. is kept at the 380kV substation GT380 or Geertruidenberg 380 which is also mentioned in figure 5.14. Figure 5.15 also shows the overall voltage profile of Netherland resulting from this analysis. It can be seen that when penalty factor p_v is increased, the set point value of 1.075 is reached but the minimization of Mvar injections or objective 1 is compromised for it. It can also be seen that there is a good correlation between overall voltage profile in the Netherlands and voltage value at GT380 (keeping a set point for GT380 affects the resulting voltage values at 380kV substations).

It was observed that one should be careful while assigning a preference between RP resources within the algorithm. This can result in solutions where the algorithm suggests changing the state of a geographically or electrically distant RP resource instead of a resource closer or with higher sensitivity due to their relative preference set using penalty factors (p_{sh}, p_{gdelta} and p_{tap}). To show this effect, results from a study performed to find an N-1 contingent solution is presented in figure 5.16. In the

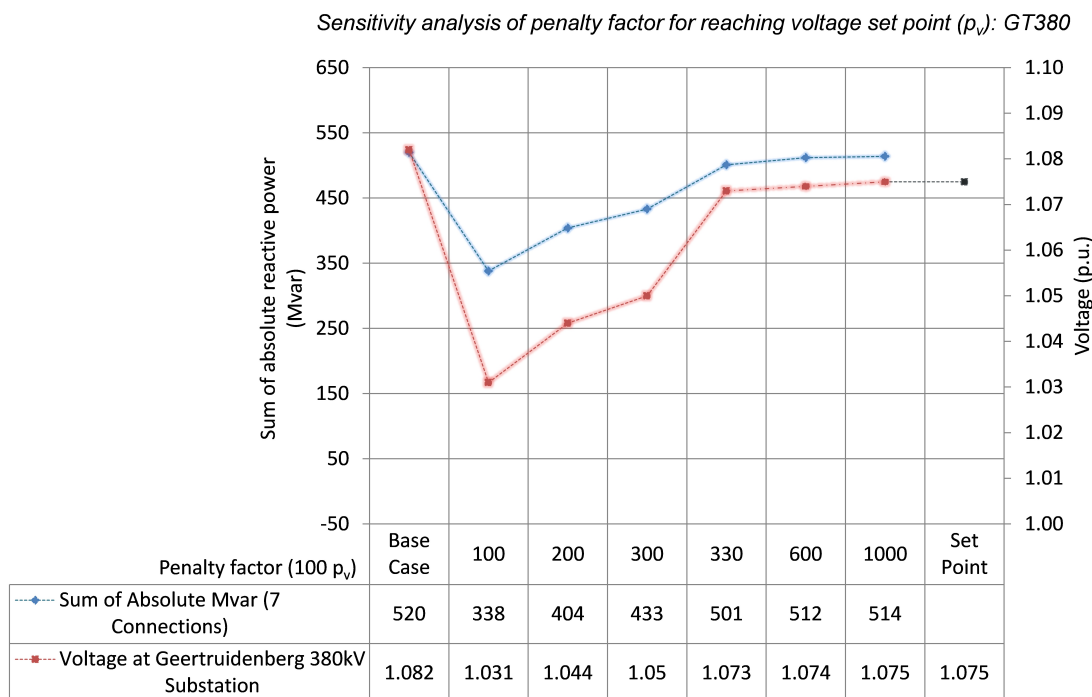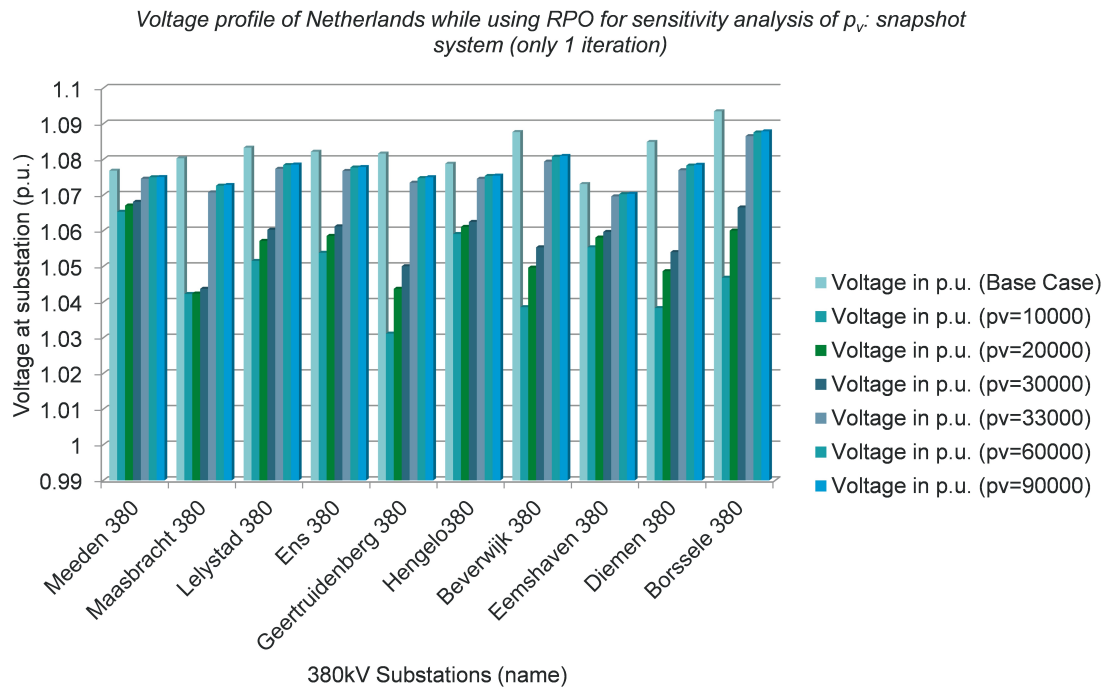Figure 5.15: Sensitivity analysis of the penalty factor p_v on the snapshot system voltage profile
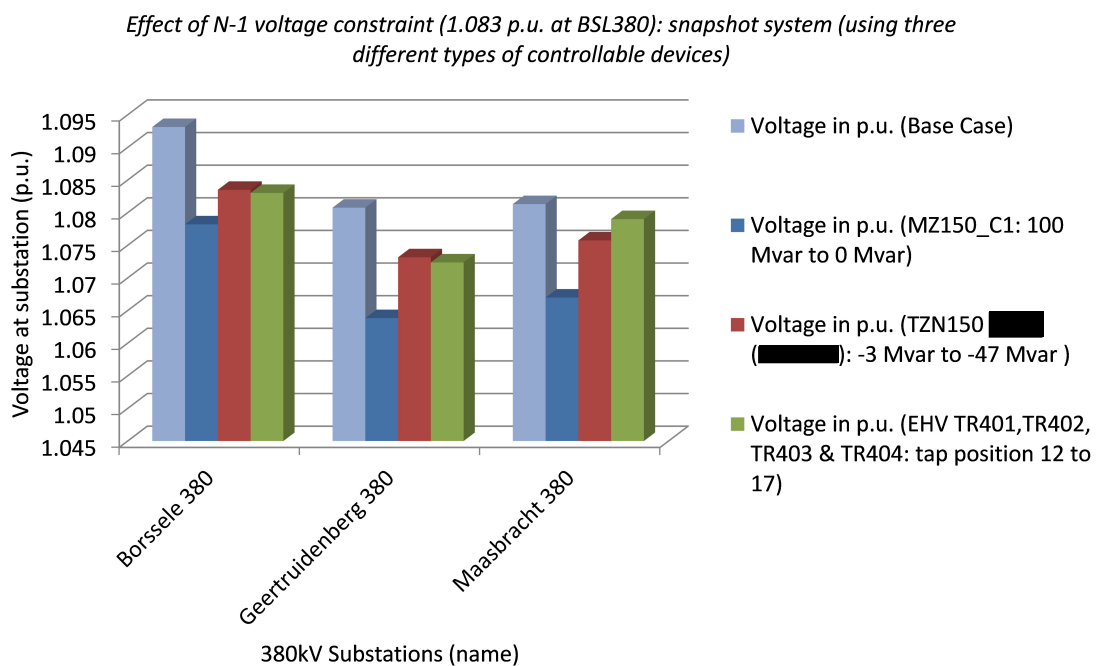
Figure 5.16: Voltage profile resulting from the N-1 contingency analysis solution for a violation at Borssele 380 (BSL380)

base case of this scenario, there was an upper limit voltage violation at BSL380 during N-1 contingency analysis (1.104 p.u.) and a new voltage constraint of 1.083 p.u. was set by the algorithm. When the penalty factors within objective 2 p_{sh}, p_{gdelta} and p_{tap} were reduced to a low value one by one while others were given sufficiently high value (so that they are not used by the algorithm), three cases arise as shown in figure 5.16 using three different types of controllable RP resources in order to solve the same base case problem. It can be seen that in the second case (figure 5.16) reactive power feed in

of contracted generator was changed, which was the most effective (but also costly) option while in other cases devices distant from the BSL380 substation were used. Therefore, it is important to define relative penalty factors carefully within the objective 2.

In this section, the results obtained for simulation based studies on the snapshot system model belonging to Dutch TSO were presented. These studies were performed to check the effect of optimization process on the voltage profile of Netherlands and the resources preferred by the algorithm to reach these optimal solutions. The validity of this prototype rule based controller was also verified on the snapshot system by performing simulation based studies similar to that done in section 5.2 for the test system. From these studies, it was found that reactive power optimization is feasible for Netherlands if the objectives and their penalty factors within the objective function are carefully tuned. Additional research has to be conducted to check if the snapshot system model can be improved to obtain adequate power flows (active and reactive power flows), voltage magnitudes and sensitivities within EHV & HV grid for use in the voltage control process. The snapshot system model used by the optimization algorithm should also include a part of the foreign grid connected to the Dutch transmission system along with their voltage control strategy (constant voltage, constant reactive power or no voltage-reactive power control) in order to obtain adequate sensitivities for the border nodes. Changes proposed by the optimizer are directly affected by the sensitivities calculated. Differences in the sensitivities for different control strategies are also large therefore leading to completely different change in state of controllable RP resources proposed by the prototype RPO algorithm. This effect was analysed by calculating the sensitivities for controllable shunt devices while changing modes from PQ (constant reactive power feed in) to PV (constant voltage at connected bus) for all the active generators connected to EHV and HV grid of the Netherlands. Figure 5.17 shows four screenshots of this analysis, where the effect (in kV) of changing steps associated with the controllable shunt devices (capacitor banks: 1-40 & shunt reactors: 41-81, binary type of controllable devices for the Dutch TSO) on ten 380kV substations of the Netherlands can be observed. The effect of these shunt devices are compensated significantly by just ten generators with a large feed in of active power at PV mode (with a very low reactive power droop) in the snapshot system. However, for the optimization process, all the active generators were assigned to be in PQ mode with respect to the Dutch electricity network code for minimizing changes in their steady state Mvar feed in (which is their secondary voltage control).

380kV Substations	
ID No.	Substation name
1	Meeden 380
2	Maasbracht 380
3	Lelystad 380
4	Enschede 380
5	Geertruidenberg 380
6	Hengelo 380
7	Beverwijk 380
8	Eemshaven 380
9	Diemen 380
10	Borssele 380

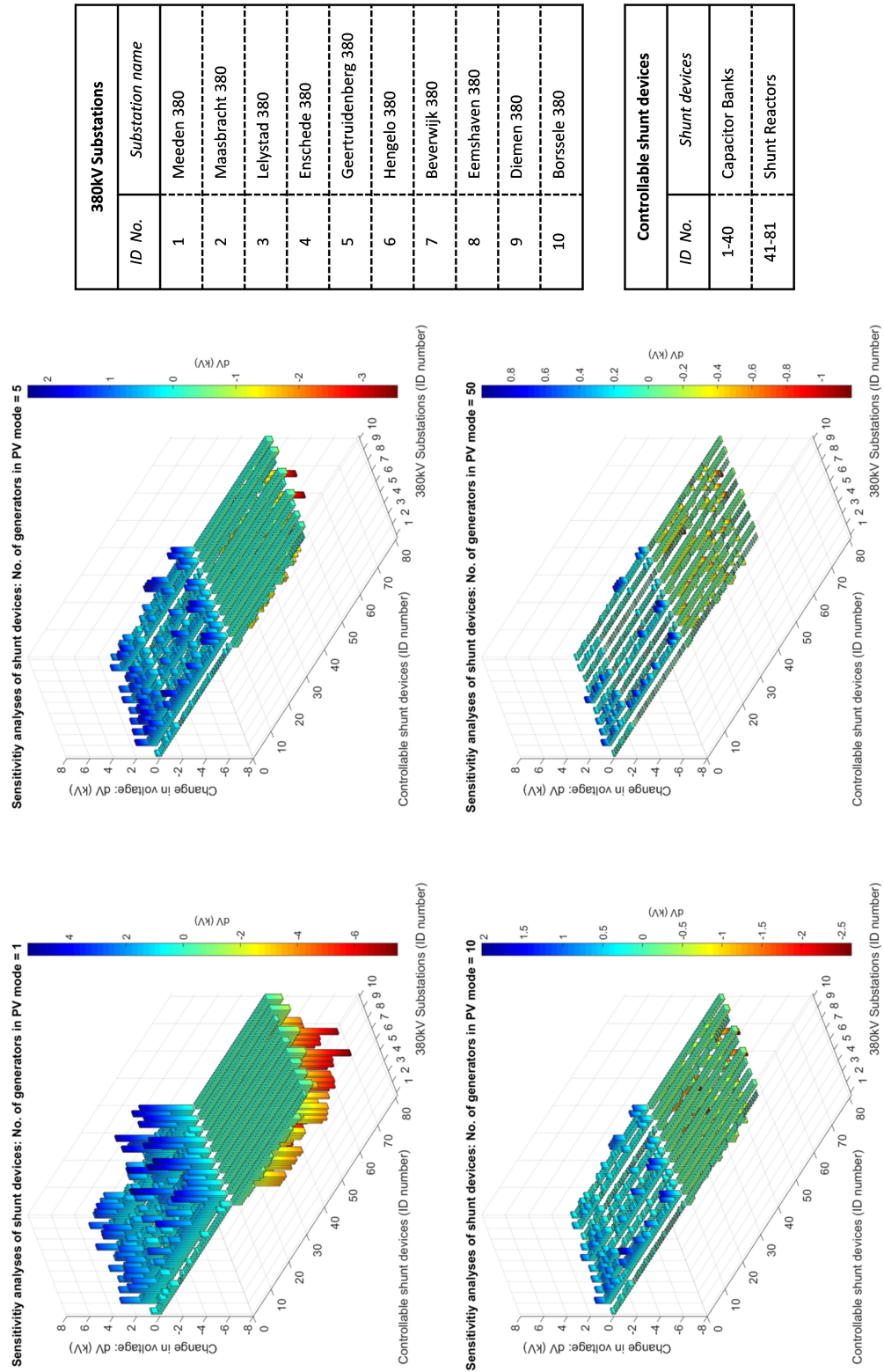| Controllable shunt devices	
ID No.	Shunt devices
1-40	Capacitor Banks
41-81	Shunt Reactors

Figure 5.17: Sensitivity analyses of the shunt devices

6

Conclusion & future scope

In this final chapter, a brief summary of the thesis project will be described highlighting the important observations and conclusions drawn with reference to the previous chapters 2 - 5. This chapter has been divided into four main sections. The first three sections include a summary of the important remarks that were drawn while conducting this thesis project. While, the last section describes about the future scope and a few recommendations for future development of this project.

6.1. Concluding remarks from literature survey

In this section, an overview of the concluding remarks that were drawn from the literature survey will be described. This survey included the study on hierarchical voltage control schemes of TSOs, existing voltage control approach of control engineers at NCC (National Control Center) and AI techniques available for coordinated voltage control. From the review in chapter 2 on voltage control schemes of other TSOs namely the Belgian, French and Italian TSOs, it was assumed that a voltage controller or a reactive power resource optimizer could be employed within the Dutch transmission system. This assumption was later on verified by analysing the results from simulation based studies conducted on various scenarios. The Belgian approach of a simple centralized advisory system to control engineers was found to be most feasible for the Netherlands to start with, when compared to that of the French or Italian implementations of hierarchical voltage control schemes. This was mainly due to the requirement of high investments in hardware. Employing voltage control schemes with closed loop secondary controllers (having low or no involvement of control engineers) and high investments in hardware can form the next step of a development process after gaining sufficient experience using a relatively simple centralized advisory system.

With the completion of literature survey on other voltage control schemes, a survey was conducted with regard to the existing voltage control approach of control engineers at NCC. This was done for two main reasons, firstly, to research possible improvements in the existing voltage control approach used by control engineers. Secondly, to map the existing voltage control approach of control engineers. After completing the survey, it was found feasible to include some kind of intelligent advisory tool in the existing voltage control process of control engineers, this could reduce the amount of undesirable and unforeseen consequences resulting from their decisions for voltage control and also the amount of tasks they are expected to perform. This study gave an overview of the controllable reactive power resources available to control engineers for steady-state voltage control or secondary voltage control at NCC (along with their priority for use).

After conducting survey on other TSO voltage control schemes and NCC control engineers voltage control approach, a literature survey was also conducted on the available AI (Artificial Intelligence) techniques which are commonly used for the purpose of coordinated voltage control. The most common AI techniques of ES & FL (Expert Systems – rule based systems & Fuzzy Logic) controllers, ANN (Artificial Neural Network) controllers and MPC (Model based predictive control systems) controllers

were studied in detail within chapter 3. Based on the study, expert systems or rule based controllers were found to be most suitable for this project. This was due to the ease of adding or removing rules for voltage control based on policy changes (and control engineers wishes/requirements), higher certainty of solutions and the simplicity of rule based controllers. Fuzzy interference systems for inputs and outputs can be added to the prototype rule based controller used in this feasibility study as the next step of development, thereby making it an hybrid controller.

6.2. Concluding remarks on data available

Based on the data analysis performed on Dutch TSO system, some important conclusions that can be drawn are:

- The active power values within snapshots were found to be almost equal to measurements from the same time stamp. The snapshot models and other offline models are used mainly to study on the power flows within their transmission system (even though voltage optimization is being performed on forecast models to check the availability of reactive power resources). From the study, it was observed that reactive power deviates due to the modelling differences in the offline and online tools (especially transformer models).

- Based on the survey conducted, it was found that congestion forecast models that are currently available could compute less accurate reactive power flows (for use in the voltage control process). Additionally, results from these forecasts are also exported as files based on inadequate format and they contain only basic electrical models which doesn't include any three winding transformer or shunt filter (capacitor bank or shunt reactor) model.

- In order to implement any type of control scheme in the offline power system tool, it is important to upgrade the communication link between the online (within EMS) and offline power system tools used by the Dutch TSO. This is to make sure that adequate transfer of real-time data (real time snapshot data) can take place between them.

6.3. Concluding remarks from simulation based studies

Using the knowledge obtained from literature surveys and studies on data available, a methodology for implementing the prototype controller was selected. Also, the final multi-objective function and constraints were proposed for the optimization algorithm in the controller based on these studies (as given in chapter 4). Chapter 5 discussed about the results that were obtained by employing this prototype controller on the 80-bus power system model used to develop the optimization algorithm and the modified snapshot system model. Some results were also obtained by performing simulation based studies on various scenarios of the snapshot system. These studies were performed in order to validate the objectives and functions built within the optimizer algorithm. In most of the scenarios within snapshot system, the voltage values at substations were within their operational security limits, also for N-1 contingency cases. Scenarios with voltage violations during N-1 contingency analysis had to be discovered within the snapshot system in order to test the performance of optimization algorithm. In all the test case scenarios, this prototype optimization algorithm had successfully optimized the power system in normal and steady state operation while satisfying all the specified conditions. This shows that it is feasible to employ an intelligent control system using real-time data at NCC to support control engineers in their decision making process of voltage control, provided that all the other system requirements are satisfied for employment (refer chapter 2 for details on system requirements).

Some other important remarks that can be concluded from the studies performed using this algorithm on power system models are:

- The main objective of minimizing Mvar injections in the inter-area objective connections was successfully attained by the controller. Even though increasing the penalty on this function results in reducing more Mvar injections, after a certain value, increasing the penalty factor (p_{gmv}) associated with the objective will not result in minimization due to larger changes. As the amount of change increases, sensitivities become largely non-linear and the result predicted by optimization

algorithm will not be same as that obtained in the power system model. This is not a problem for real-time application, as control engineers and system operators will also not prefer to employ more than 2 or 3 changes every 15 minutes (considering the health of transmission assets). Therefore, the sensitivities can be assumed linear for these cases as they are small changes in the power system.

⋈ Other objectives of minimizing changes in the states of reactive power resources, minimizing Mvar feed in of contracted generators and reaching voltage set points were also successfully attained by the optimizer as shown in the results (chapter 5). It should be noted that manipulating a penalty factor to increase the dominance of associated objective might compromise the main objective of minimizing Mvar injections at inter-area transmission lines or cables.

⋈ The Dutch TSO has a good controllability of voltage in their transmission system due to the presence of reactive power contracted generators throughout the EHV & HV grids. A decreasing amount of reactive power contracted generators could affect the controllability of voltage. Especially when specific voltage set points have to be achieved. For example, in the scenario used for results in chapter 5, it was found that keeping voltages around 1.04-1.06 p.u. would have been more efficient (in terms of RP resource utilization & reactive power injection at inter-area transmission lines) than the original values of around 1.07-1.09 p.u.

⋈ Employing the multi-area scheme introduces the possibility of solving optimization problem in parallel and thereby reducing the time required. If the penalty factor on changing state of controllable devices is high, then the number of changes introduced per area will not be more than one. Therefore, the sensitivities used for optimization problem can be assumed linear and the problem can be solved in parallel. The prototype controller also suggested changes within HV transmission grid for some N-1 voltage violations at EHV substation. A common control aid could help co-ordinate voltage control actions between control engineers (RCC & NCC) and lead to improved utilization of controllable RP resources available to the Dutch TSO.

⋈ Even though the prototype controller cannot obtain the appropriate sensitivities at substations connected to cross border tie-lines due to the lack of adequate foreign grid models within it, the controller was used on two extreme cases (with external foreign grid busbars in PV (constant voltage at bus) and PQ (constant reactive power injection) modes). The prototype controller had successfully optimized the power system for both these cases with reliable results. Therefore it was found feasible to implement an intelligent control system for the secondary voltage control scheme within the transmission system of the Dutch TSO for optimizing reactive power resources (in order to reduce reactive power injections from/to inter-area transmission lines or cables). By adding foreign grid models within the controller, it should also be possible to control voltages by predicting adequate sensitivities at substations with the cross border tie-lines.

6.4. Future scope and recommendations

Throughout various stages of this project, decisions had to be made in order to select between various approaches available. The final approach for this thesis work (preparing a prototype controller for the feasibility study) was selected mainly based on time availability & technical feasibility. From simulation based studies using the prototype rule based controller, it was found feasible to employ an intelligent control system that can support in voltage control process of control engineers at NCC, Netherlands. However, before implementing this tool for secondary voltage control scheme in the Netherlands, some improvements have to be incorporated into the prototype control system and transmission network model. Some important recommendations for future development of this project are mentioned in the following subsections.

6.4.1. Transmission network model

Irrespective of the power system tool (online or offline) used, an adequate electricity transmission network model (380kV, 220kV, 150kV & 110kV grid model for the Dutch transmission system) should be available to the optimization algorithm. As the optimization algorithm utilizes sensitivities, it is essential to make sure that their calculated values are comparable to that observed in real time operation (EMS).

Inadequate sensitivities at even a few busbars could make the prototype system unreliable for use in on-line voltage control process. In addition to the transmission network model of Netherlands, it is also important to have adequate sensitivities at substations connected to foreign transmission grids. This necessitates the need for an improved foreign grid model or at least a part of it to consider their effect on the Dutch transmission grid. Currently only the phase shifting transformers along with one or two foreign grid busbars or substations are modelled within the prototype controller. It will be advantageous to experimentally examine the differences in calculated sensitivities with respect to that observed in real-time operation (EMS). The possibility of integrating such a prototype controller directly to the EMS or online tool should also be examined, so as to minimize the modelling efforts in different tools.

6.4.2. The Dutch electricity network code for generating stations

The optimization algorithm assumes that all generating stations connected to the Dutch transmission system follow the Dutch electricity network code, which is to make sure that minimum absolute value of reactive power (close to zero Mvar) is supplied to the transmission system. This should be true for all cases except for generating stations that are contracted for ancillary services (controllable reactive power resources), in which case they should supply the reactive power requested by the control engineers. It is also mandatory for these generating stations to have automatic voltage regulators for primary voltage control. This means that the generating stations should change their voltage set points so as to maintain appropriate steady state values of reactive power feed at PCC. In real-time operational scenarios, this might not be always true (effect of generator mode (PV/PQ) can be observed in figure 5.17). Implementation of a coordinated set point control strategy for primary voltage controllers belonging to these generating stations (connected to the Dutch transmission system) could improve the effectiveness of secondary voltage control schemes.

6.4.3. Including switching of transmission cables or lines

In this thesis project, the possibility of switching transmission cables or lines to control voltage was ignored. In order to add this feature, contingency analysis of the Dutch transmission system with respect to loading will also have to be considered. Only voltage violations introduced by N-1 contingency analysis were considered by the optimization algorithm presented in this thesis. A transmission line or cable can be switched on/off if its loading is minimal and reactive power contribution is relatively high.

6.4.4. Non-linear solver

For the current optimization algorithm, multi-area based reactive power optimization problem contains a set of linear equations for both its objective function and constraints. A linear solver is utilized (refer chapter 4 for more details) to solve the optimization problem in order to minimize the objective function. This means that the same algorithm can neither be used for non-linear constraints nor a non-linear objective function. This is the main reason why heuristic solver was found to be of interest for this thesis. The optimization algorithm will be more preferable for use by the Dutch TSO if it can solve non-linear optimization problems and include non-linear constraints within the optimization problem.

Bibliography

[1] N. Martins et al., *Coordinated voltage control in transmission networks,* CIGRE Technical Brochure 310 **Task Force C4.602**, 1.1 to 2.11 (February 2007).

[2] H. P. A. Knops, *Position of the transmission system operator (TSO) in the european electricity systems,* IEEE conference of PowerTech **Vol. 1** (June 2003), 10.1109/PTC.2003.1304107.

[3] S. Bhattacharyya, *Concepts, Issues, Markets and Governance*, Energy Economic (Springer, 2011).

[4] EIA, *Internaitonal energy statistics,* (2008-2012), online; retrieved on 01-12-2016 [cited 01-03-2016].

[5] M. Reza, *Stability Analysis of Transmission system with high penetration of distributed generation*, PHD Thesis, Faculty of Electrical Engineering (TU Delft, Netherlands, December 2006).

[6] E. Coster, *Distribution grid operation including distributed generation*, PHD Thesis, Faculty of Electrical Engineering (TU Eindhoven, Netherlands, September 2010).

[7] O. I. Elgerd, *Control of electric power systems,* IEEE Control Systems Magazine **Vol. 1, No. 2**, 4 to 16 (June 1981).

[8] A. P. Sakis Meliopoulos, *Basics of power system control and protection,* School of Electrical & Computer Engineering, Georgia Institute of Technology **NSF/ECEDHA education workshop** (July 2011).

[9] Yann Rebours, *A comprehensive assessment of markets for frequency and voltage control ancillary services*, PHD Thesis, School of Electrical and Electronic Engineering (University of Manchester, England, 2008).

[10] P. Kundur, *Power System Stability and Control*, Power system engineering (New York: McGraw-Hill, 1993).

[11] A. C. . M. website Besluit codewijziging criteria voor spanningsdips, *Besluit van autoriteit consumenten markt tot wijziging van de voorwaarden als bedoeld in artikel 31, eerste lid van de elektriciteitswet,* (2013), online; retrieved on 05-02-2016 [cited 01-03-2016].

[12] J. F. Baalbergen, *Coordinated agent-based control for on-line voltage instability prevention*, PHD Thesis, Faculty of Electrical Engineering (TU Delft, Netherlands, 2013).

[13] M. Farrokhseresht et. Al, *Optimal power flow for reactive power compensation increasing the cross-border transmission capacity,* IEEE international conference on Environment and Electrical Engineering **Vol. 2**, 2135 to 2140 (June 2015).

[14] J. B. M. van Waes Movares, P. J. van de Ploeg, S. A. De Graaff & S.J.M. Bruijns, *Implementation of grid forecasting processes at TenneT: from strategic planning to after-the-fact analysis,* CIGRE **C2-208** (2014).

[15] Patrick F. Dunn, *Measurement and data analysis for engineering and science*, 2nd edition (CRC Press, Taylor & Francis group, January 2010).

[16] E. J. de Oliveira, V.M. Crisafulli, R. P. Poubel, L. M. Honorio and A. L. M. Marcato, *Transmission line reinforcements considering security constraints,* IEEE conference on PowerTech, Eindhoven , 1 to 5 (2015).

[17] P.A. Chamorel et al., *Methods for reactive power optimization,* CIGRE Technical Brochure 27 **Task Force 38-01-03** (1987).

[18] T. Johanson et al., *Reactive power compensation analysis and planning procedure,* CIGRE Technical Brochure 30 **Task Force 38-03-01** (1987).

[19] J. Dixon, L. Moran, J. Rodriguez & R. Domke, *Reactive power compensation technologies, state of the art review,* IEEE Proceedings **Vol. 93, No. 12**, 2144 to 2164 (December 2005).

[20] J. L. Femhdez, F. Martinez, C. Salle & J. L. Sancha, *Spanish practices in reactive power management and voltage control,* IEE Colloquium on International Practices in Reactive Power Control, IET , 3.1 to 3.4 (April 1993).

[21] ENTSO-E, *Who is ENTSO-E?* (retrieved on 1-02-2016), web page; [cited 5-03-2016].

[22] D. Bekaert, *Reactive power management in planning and operating the transmission grid,* PHD Thesis, Faculty of Engineering, Katholieke Universiteit Leuven, Belgium, ISBN 9789460185274 , 84 to 87 (July 2012).

[23] J. Van Hecke, N. Janssens, J. Deuse, & F. Promel, *Coordinated voltage control experience in belgium,* no. 38-111, Paris **CIGRE Conference**, 6 (August 2000).

[24] O. A. Mousavi & R. Cherkaoui, *Literature survey on fundamental issues of voltage and reactive power control,* Deliverable Literature Survey for MARS project, EPF Lausanne – Power System Group, Switzerland (June 2011).

[25] M. Ernoult, J. Y. Leost, J. P. Paul & J. Verseille, *Reactive power compensation and voltage control on the French EHV system: present situation and prospects,* CIGRE International Conference on Large High Voltage Electric Systems **C8-08** (1986).

[26] Gestlonnaair du Réseau de Transport d'Electricité, *Référentiel Technique, Chapitre 4 - Contribution des utilisateurs aux performances du RPT (French),* RTE, France (July 2006).

[27] J.P. Paul, J.Y. Leost & J.M. Tesseron, *Survey of the secondary voltage control in france : present realization and investigations,* IEEE transanctions on Power Systems **Vol. PWRS-2, No. 2**, 505 to 511 (May 1987).

[28] I. Siviero, *The need to coordinate generation and transmission planning and to ensure a secure and efficient reactive power provision: two key aspects of the restructured electricity industry,* Doctoral Thesis, Università degli Studi di Pavia (2009/2010).

[29] M. Pozzi, M. Sforna & G. D. Sandro Corsi, *The coordinated automatic voltage control of the italian transmission grid—part ii: Control apparatuses and field performance of the consolidated hierarchical system,* IEEE Transaction on Power System **Vol. 19, No. 4**, 1733 to 1741 (November 2004).

[30] C. Cavallo, M. Pozzi, S. C. Claudio & A. Canizares, *Comparing secondary voltage regulation and shunt compensation for improving voltage stability and transfer capability in the italian power system,* Electric Power Systems Research **Vol. 73**, 67 to 76 (2005).

[31] M. Pozzi, C. Sabelli & S. Corsi, *The coordinated automatic voltage control of the italian transmission grid—part i: Reasons of the choice and overview of the consolidated hierarchical system,* IEEE Transaction on Power Systems **Vol. 19, No. 4**, 1723 to 1732 (November 2004).

[32] Jan Vorrink (Manager of National Control Centre TenneT TSO B.V.), *System integration panel,* (19th March 2014, Amsterdam), online; retrieved on 1-01-2016 [cited 1-02-2016].

[33] TenneT TSO, *Kwaliteits- en capaciteitsdocument 2011,* (2011), online; retrieved on 05-02-2016 [cited 01-03-2016].

[34] T. M. Papazoglou et Al., *Voltage and var support in system operation,* CIGRE Technical Brochure 504 **Working Group C2.13** (August 2012).

[35] I. Hano, Y. Tamura & K. Matsumoto, *Real time control of system voltage and reactive power,* IEEE Transaction on Power Apparatus and Systems **Vol. PAS-88, No. 10**, 1544 to 1559 (October 1969).

[36] P. David, M. Alan & G. Randy, *"Chapter 1: Computational Intelligence and Knowledge" & "Chapter 4: Searching"*, Computational Intelligence: A Logical Approach (Oxford University Press, 1998).

[37] A. Katbab, *Fuzzy logic and controller design-a review,* IEEE Proceedings on Visualize the Future , 443 to 449 (March 1995).

[38] H. V. Pham, S. N. Ahmed & I. Erlich, *Multi agent system based solution of the optimal reactive power dispatch problem in autonomously operated multi area systems,* IEEE conference of PowerTech, Eindhoven , 1 to 6 (July 2015).

[39] Y. Dote, *Introduction to fuzzy logic,* IEEE Proceedings IECON 21st International Conference on Industrial Electronics, Control, and Instrumentation **Vol. 1**, 50 to 56 (November 1995).

[40] J.L.M. Ramos, A.G. Etposito, J.C. Cerezo, E.M. Ruiz & F.C. Salinas, *A hybrid tool to assist the operator in reactive power/voltage control and optimization,* IEEE Transactions on Power Systems **Vol. 10, No. 2**, 760 to 768 (May 1995).

[41] A. B. Marques, G. N. Taranto & D. M. Falcao, *A knowledge-based system for supervision and control of regional voltage profile and security,* IEEE Transaction on Power Systems **Vol. 20, No. 1**, 400 to 407 (February 2005).

[42] K. S. Swarup & P. S. Subash, *Neural network approach to voltage and reactive power control in power systems,* Proceedings of 2005 International Conference on Intelligent Sensing and Information Processing **Vol. 2**, 228 to 233 (2005).

[43] S. Toma, T. Senju, Y. Miyazato, A. Yona, K. Tanaka & C. Kim, *Decentralized voltage control in distribution system using neural network,* IEEE 2nd International Power and Energy Conference , 1557 to 1562 (2008).

[44] M. Biserica, Y. Besanger, R. Caire, O. Chilard & P. Deschamps, *Neural networks to improve distribution state estimation-volt var control performances,* IEEE Transransaction on Smart Grid **Vol. 3, No. 3**, 1137 to 1144 (2012).

[45] P. Ye, Q. Bian, J. Song & B. Yao, *Predictive optimal algorithm based coordinated voltage control for large power system,* IEEE International Conference on Power System Technology, PoweCon , 1 to 6 (2006).

[46] Morattab A.,Dalal A., Akhrif O., Saad M. & LefebvreS, *Model predictive coordinated secondary voltage control of power grids,* IEEE International Conference on Renewable Energies for Developing Countries (REDEC , 1 to 6 (November 2012).

[47] M. Melanie, *An Introduction to Genetic Algorithms*, PHD Thesis, School of Electrical and Electronic Engineering (MA: MIT Press, Cambridge, 1996) p. 2 to 24.

[48] A. Linder & R. Kennel, *Direct model predictive control—a new direct predictive control strategy for electrical drives,* IEEE European Conference on Power Electronics and Applications , 1 to 10 (2005).

[49] L. Jin, R. Kumar & N. Elia, *Application of model predictive control in voltage stabilization,* in Proceedings of American Control Conference , 5916 to 5921 (2007).

[50] L. Jin & R. Kumar, *Coordinated dynamic voltage stabilization based on model predictive control,* IEEE/PES Power Systems Conference and Exposition , 1 to 8 (2009).

[51] G. Valverde & T. Van Cutsem, *Model predictive control of voltages in active distribution networks,* IEEE Transaction on Smart Grid **Vol. 4, No. 4**, 2152 to 2161 (2013).

[52] L. Siwi & S. Natanek, *Solving constrained multi-criteria optimization tasks using elitist evolutionary multi-agent system,* IEEE World Congress on Computational Intelligence , 3358 to 3365 (2008).

[53] A. A. Aquino-lugo, R. Klump & T. J. Overbye , *A control framework for the smart grid for voltage support using agent-based technologies,* IEEE Transactions on Smart Grid **Vol. 2, No. 1**, 173 to 180 (January 2011).

[54] A. Gomez Exposito, J. L. Martinez Ramos, J. L. Ruiz Macias & Y. Cuellar Salinas, *Sensitivity-based reactive power control for voltage profile improvement,* IEEE Transactions on Power Systems **Vol. 8, No. 3**, 947 to 945 (August 1993).

[55] V. H. Pham & I. Erlich, *Online optimal control of reactive power sources using measurement-based approach,* IEEE PES European Conference on Innovative Smart Grid Technologies (ISGT-Europe) , 1 to 5 (October 2014).

[56] M. A. Golkar & M. A. Golkar, *Reactive power control in distribution systems by using advanced techniques,* IEEE International Youth Conference on Energetics (IYCE) , 1 to 6 (July 2011).

[57] DIgSILENT, *Powerfacotry v14: Basic software features and calculation functions,* (2013), online; retrieved on 10-02-2016 [cited on 14-03-2016].

[58] J. L. Rueda & F. M. Gonzalez-Longatt, *Chapter 12 – Mean-Variance Mapping Optimization Algorithm for Power System Applications*, PowerFactory applications for power system analysis (Springer International Publishing, Switzerland, 2014).

[59] D. S. Kirschen & H. P. Van Meeteren, *MW/Voltage Control in a Linear Programming Based Optimal Power Flow,* IEEE Transactions on Power Systems **Vol. 3, No.2**, 481 to 489 (May 1988).

[60] S. K. Mukherjee, A. Recio & C. Douligeris, *Optimal Power Flow by Linear Programming Based Optimization,* Southeastcon '92, Proceedings., IEEE, Birmingham, AL **Vol. 2**, 527 to 529 (April 1992).

[61] T. S. Ferguson, *Linear programming: A concise introduction,* (retrieved on 15-02-2016), online; [cited 14-03-2016].

[62] H.Peng, D. Liu & B.Tian, *Multi-objective non-linear programming method of optimizing foundation deformation modulus of jinping high arch dam,* IEEE International Joint Conference on Computational Sciences and Optimization, Sany, Hainan , 730 to 734 (April 2009).

[63] M. B. . J. Dirks, *Introduction to lp_solve 5.5,* (retrieved on 21-02-2016), web-page; [cited 16-03-2016].

[64] W. Nakawiro, I. Erlich & J. L. Rueda, *A novel optimization algorithm for optimal reactive power dispatch: A comparative study,* 4th International Conference on Electric Utility Deregulation and Restructuring Power Technologies , 1555 to 1561 (July 2011).

[65] J.L. Rueda & I. Erlich, *Optimal dispatch of reactive power sources by using MVMO optimization,* IEEE Symposium Series on Computational Intelligence, Singapore (April 2013).

[66] T. Syrstad & B. Jelen, *Chapter 1 - Introduction*, Excel 2016 VBA and Macros - Mr. Excel (Pearson Education, 2015).

[67] A. Monticelli, O. Alsac, N. Vempati & B. Stott., *Generalized state estimation,* IEEE Transaction on Power Systems **Vol. 13, Iss. 3** (August 1998).

[68] J. J. Grainger & W. D. Stevenson, *Chapter 9 – Power-Flow solutions*, Power System Analysis (McGraw-Hill, University of Michigan, 1994).

[69] J. Machowski, A. Cichy, F. Gubina & P. Omahen, *External subsystem equivalent model for steady-state and dynamic security assessment,* IEEE Transaction on Power Systems **Vol. 3, Iss. 4** (November 1988).

[70] E.T. Jauch, *Advanced transformer paralleling,* Transmission and Distribution Conference and Exposition IEEE/PES **Vol. 1** (2001).

[71] D. Dohnal, *On-load tap changers for power transformers,* F0126405 MaschinenfabrikReinhausen knowledge base (2013).

[72] F. Gubina & B. Strmcnik, *A simple approach to voltage stability assessment in radial network,* IEEE transaction on Power Systems **Vol. 12, No. 3** (August 1997).