EMERGENCY VOLTAGE SUPPORT IN INTERACTIVE COLLABORATION OF TSO/DSO

Lappeenranta–Lahti University of Technology LUT

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Teemu Rissanen

Examiner(s): Professor Jamshid Aghaei

Postdoctoral Researcher Mousa Afrasiabi

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Electrical Engineering

Teemu Rissanen

Emergency voltage support in interactive collaboration of TSO/DSO

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Examiner(s): Professor Jamshid Aghaei and Postdoctoral Researcher Mousa Afrasiabi

Keywords: Voltage Emergency Support, Reactive power Support, Collaboration of TSO/DSO, Distributed Energy Resources, Active Distribution Network.

Increasing amount of distributed energy resources and decreasing amount of conventional large scale power plants are changing the power systems to become more decentralized. This leads challenging situations with the system level voltage control. In the past decades mostly transmission system operators (TSOs) have been taking care of the voltage control in large power systems. As more generations are moving from TSO side to DSO side significant changes are required to maintain reliable and secure systems. Collaboration between TSO and DSO is a key factor in future power systems.

Distribution systems have been passive systems according to voltage control in the past decades. Currently Active Distribution Networks (ADNs) are studied and developed widely. ADNs have possibility to control distributed energy resources in efficient way and ADNs can provide direct voltage support to TSO. To build and implement ADNs for efficient use, significant investments are required for the control systems. Investments are not the only challenge, also regulations and common ways to build ADNs and to develop collaboration between TSO and DSO are becoming one of the major challenges.

In this work first a literature research is performed for the topics of TSO/DSO collaboration in voltage emergency situations. The objective is to develop adaptive and less intrusive control system for the voltage emergency support. The key facilities to utilize for voltage emergency support from DSO to TSO are distributed generation units, tap changer of substation transformers, capacitor banks and load shedding. Adaptive control logic for voltage emergency support was developed and tested in IEEE 39 bus system using PSCAD simulation software.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT School of Energy Systems

Sähkötekniikan koulutusohjelma

Teemu Rissanen

TSO/DSO interaktiivinen yhteistyö jännitteiden tuentaan hätätilanteissa

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Avainsanat: TSO/DSO yhteistyö, jännitteen tuenta, hajautetut loistehoreservit, hajautetut energialähteet, aktiiviset jakeluverkot.

Hajautetun tuotannon kasvu ja suurien tuotantoyksiköiden poistuminen muuntaa voimajärjestelmää enemmän hajautetummaksi. Tämä johtaa järjestelmätason haasteisiin jännitteen säädön suhteen. Aiemmin pääosin siirtoverkon operaattorit ovat vastanneet jännitteensäädöstä suurissa voimajärjestelmissä. Tuotannon siirtyminen yhä suuremmissa määrin jakeluverkkoihin vaatii muutoksia jännitteensäätötapoihin jotta varmistetaan järjestelmän oikea toiminta ja luotettavuus. Yhteistyö siirtoverkon ja jakeluverkon operaattoreiden välillä on merkittävä tekijä tulevaisuuden voimajärjestelmissä jotta taataan suuri sähkön toimitusvarmuus.

Jakeluverkot ovat pääsääntöisesti olleet passiivisia verkkoja jännitteensäädön suhteen. Aktiivisia jakeluverkkoja (eng. Active Distribution Network) kehitetään ja tutkitaan laajalti, sillä akviinen jakeluverkko kykenee hyödyntämään hajautetut resurssit ja tukemaan tarvittaessa siirtoverkkoa. Aktiivisten jakeluverkkojen luominen vaatii investointien lisäksi sääntelyä ja yleisiä toimintatapoja.

Tässä työssä suoritetaan aluksi kirjallisuustutkimus siirto- ja jakeluverkkojen väliseen yhteistyöhön tilanteissa jossa siirtoverkon jännite uhkaa romahtaa. Tarkoituksena on luoda adaptiivinen ja vähemmän tunkeileva ratkaisu jännitteen tuentaan hätätilanteissa. Pääkeinot jännitteen hätätuentaan ovat hajautetut tuotannot, käämikytkimet, kondensaattoriparistot sekä kulutuksen poislyönnit. Ratkaisuksi kehitettiin ohjauslogiikka joka adaptiivisesti hyödyntää jakeluverkon resursseja hätätilanteessa. Kehitetty ratkaisu testattiin suorittamalla simulointeja muokatussa IEEE 39 verkkomallissa PSCAD-ohjelmistolla.

SYMBOLS AND ABBREVIATIONS

Roman characters

B	Susceptance	[pu]
E	Equivalent voltage source	[V]
F	Frequency	[Hz]
H	Inertia	[s]
P	Equivalent Real Power	[W]
P_{L}	Real Power Supplied to Load	[W]
P_{g}	Real Power of GU	[W]
Q	Equivalent Reactive Power	[VAr]
Q_{c}	Reactive Power Capacity	[VAr]
Q_{L}	Reactive Power supplied to load	[VAr]
Q_{g}	Reactive Power of GU	[VAr, pu]
Q_{0}	Rated reactive power	[VAr, pu]
R	Resistance	[Ω, pu]
S	Nominal Power	[VA]
t_{c}	Time delay for ALARM 2 to activate capacitor	[s]
t_{rev}	Time delay for tap changer reverse operation	[s]
t_{L1}	Time delay for 1st load shedding	[s]
t_{L1}	Time delay for 2nd load shedding	[s]
t_{L3}	Time delay for 3rd load shedding	[s]
t_{L4}	Time delay for 4th load shedding	[s]
t_{uvp1}	Set point 1 for under voltage protection	[s]

t_{uvp2}	Set point 2 for under voltage protection	[s]
t_{uvp3}	Set point 3 for under voltage protection	[s]
V	Voltage	[V, pu]
V_d	Distribution Network Voltage	[V, pu]
V_{dmax}	Distribution Network Max. Voltage	[V, pu]
V_{dmin}	Distribution Network Min. Voltage	[V, pu]
V_d^{DGU}	Voltage of Distributed Generation	[V, pu]
V_d^{LTC}	Voltage set point of line tap changer	[V, pu]
V_g	Generator Voltage	[V, pu]
V_{ref}	Reference voltage for excitation system	[pu]
V_t	Transmission Network Voltage	[V, pu]
V_{tmin1}	First Min. value for transmission network voltage	[pu]
V_{tmin2}	Second Min. value for transmission network voltage	[pu]
X	Reactance	[Ω, pu]
X_g	Equivalent reactance	[Ω]
X_d	Synchronous reactance	[Ω]
NP	dP/dV voltage index for real power	[-]
KPF	dP/dF frequency index for real power	[-]
NQ	dQ/dV voltage index for reative power	[-]
KQF	dQ/dF frequency index for reactive power	[-]
dF	Specific factor in PSCAD software	[-]

Greek characters

δ	determines allowable voltage deviation +/- in OLTC	[V, pu]

Abbreviations

RES	Renewable Energy Resource
TN	Transmission Network
DN	Distribution Network
DG	Distributed Generation
TSO	Transmission System Operator
DER	Distributed Energy Resource
DSO	Distribution System Operator
ADN	Active Distribution Network
OLTC	On-load Tap Changer
LV	Low Voltage
PV	Photo-voltaic
GU	Generation Unit
TL	Transmission Line
OEL	Over Excitation Limiter
MV	Medium Voltage
VJV18	Finnish Grid Code made by Fingrid Oy
HV	High Voltage
DGU	Distributed Generation Unit
AVR	Automatic Voltage Regulator
HVDC	High Voltage Direct Current
UFLS	Under Frequency Load Shedding
UVLS	Under Voltage Load Shedding
BESS	Battery Electrical Storage System

PSCAD	Power System Simulation Software
PI-model	Used to model transmission systems in π–section
ST1A	IEEE based static excitation model
PCC	Point of Common Coupling
UEL	Under Excitation Limiter
SLD	Single Line Diagram
ALARM 1	Alarm stage 1 for emergency voltage support between TSO/DSO
ALARM 2	Alarm stage 2 for emergency voltage support between TSO/DSO
ALARM 3	Alarm stage 3 for emergency voltage support between TSO/DSO
ALARM 4	Alarm stage 4 for emergency voltage support between TSO/DSO
V230	Represents transmission network voltage in the simulations
VG33	Represents distribution network voltage in the simulations

Table of contents

Appendices

1 Introduction

1.1 Introduction

Power generating systems in Europe have been strongly centralized in all countries for the past decades. Increasing amount of renewable energy sources (RES) and decreasing amount of traditional large scale power plants, such as coal fired plants and in some countries also nuclear power plants, is transforming the power system from unidirectional to multidirectional (ENTSO-E, 2016, pp. 46-47). Root cause for the change is the pressure to aim for fossil free energy production to avoid global warming.

In centralized power system networks the electrical power is mainly transmitted from power plants through transmission networks (TNs) to the distribution networks (DNs) and then to the end-users. Basically this means power is transmitted from higher voltage levels to lower voltage levels where the distribution takes place. Increasing amount of distributed generations (DG’s) is changing power systems in aspect of power generation from centralized to more decentralized which therefore leads to situation where the power flow is not unidirectional anymore. This means that the power flow can also flow from low voltage side to high voltage side. This change will have significant effect for voltage controls, because mainly the voltage has so far been controlled by TSO in DNs and by the fact that more controllable resources for voltage control are now located in DNs. Main challenges for TNs in the future are voltage fluctuations, cascading trips and different fault-induced delayed voltage recoveries. Main challenges for DNs in the future are how to harness all the distributed energy resources (DERs) for efficient use. Advanced control systems together with interactive collaboration between transmission system operators (TSO) and distribution system operators (DSO) are required. (Sun et al., 2019) (Zegers, 2014).

In this thesis the voltage emergency support between TSO and DSO is studied. The work focuses in particular on how Active Distribution Network (ADN) can support transmission network in voltage emergency situation by utilizing its DERs. Literature survey is carried out to resolve common solutions for voltage support between TSO and DSO. Finally a new concepts is developed and verified in IEEE 39 Bus system with simulations. Simulations are made with PSCAD software.

1.2 Project background

Several factors are increasing the demand of developed collaboration between TSO/DSO. Key factors of demand are energy markets and decreasing amount conventional power plants, increasing amount of RES and different congestion and balancing challenges.

1.2.1 Voltage control in collaboration of TSO/DSO

Voltage control in transmission grids and distribution grids is changing more complex during the next decade. As mentioned, main reason is increased wind and solar power together with distributed energy resources (DER). Distribution grids will have new load patterns which are mixing the unidirectional power flow since distributed generation is increasing. These factors are leading to the need of active distribution networks (ADN) together with new coordinated voltage regulators. The collaboration between distribution networks and transmission networks is becoming more crucial.

Typical and known issue at DSO side in past was voltage drop at the end of the LV feeder lines. This was typically fixed with OLTC together with voltage drop compensation. Now one of the known issues is actually voltage rise due to increased PV production, especially at the end of the LV feeder lines. LV systems have high R/X ratio, which makes them more vulnerable to voltage level, which practically means that the power is strongly depended on voltage level. These PV rich DN's are causing congestion of transformers when the loads are increasing due to higher voltages. If the PV installation will reach critical limits, a conservative limit could be taken into use to limit PV production or even installation. (Kulmala, 2014) (Procopiou et al., 2021).

It is also noticeable especially in Europe that many large scale power plants such as coal and nuclear are driven down. These plants have been actively maintaining the grid voltage in transmission level by producing reserve reactive power when needed and maintaining high inertia for the system. Now implementations are needed to operate DER's and DGU's more effectively to produce that reserve reactive power from distribution networks to transmission networks in case of voltage emergency situations. Voltage emergency situations can take place when large generation units (GU's) or important transmission lines (TL) are tripped or in outage. This topic is more studied in this work. (Zegers, 2014)

To receive all benefits from ADN's flexibilities, certain control logics and techniques must be implemented. Selections must be made between centralized and decentralized solutions or even mixed. This topic is widely discussed and differed solutions are studied, but many countries are still lacking especially regulations or way of working between TSO and DSO.

1.2.2 Energy markets and decreasing amount of large scale power plants

Market prices are driving down the profitability of large and conventional power plants such as thermal and nuclear and increasing the amount of smaller power plants with RES (Stattnet, 2016, s. 4). System frequency is maintained with the balance of power production and consumption together with the power exchange. Large imbalances might take place after forecast errors when the market resolution is insufficient to offer momentary balance as well as the production is not as adjustable as it was. Because of this, market resolution will been decreased from 1 hour to 0.25 hour to provide faster response to power balancing in Nordics at 2023 (Fingrid a, 2021).

One of the key challenges is that smaller power plants do not have similar extent of frequency support as larger plants since the inertia is lower. When inertia is too low for the system, frequency can drop too fast to activate load shedding before reserves are even activated. System inertia is greatly affected by shut downs of nuclear power plants and increase of RES and higher imports through HVDC. (Stattnet, 2016, s. 5)

1.2.3 Congestion of transmission lines and transformers

Congestion of the transformer between transmission and distribution network can be a problem in areas where generation and loading in the distribution side are increasing. If DSO can solve the problem by decreasing consumption with active power curtailment or performing network changes or activating storages, then in this case advanced TSO-DSO interaction is not necessary. In some countries TSO operates the HV/MV transformer and

TSO has ability to disconnect DSO side feeders or send signals to DSO to start load shedding when necessary. Generally congestion of HV/MV transformer itself seems not problematic because it is commonly avoided at network planning phase with n-1 criteria. (Zegers, 2014, pp. 10-18)

1.2.4 Balancing Challenges between TSO/DSO

Distribution grids equipped with large amounts of RES might face significant balancing challenges. Large amounts of RESs located in distribution grids are vulnerable for forecast errors and therefore their production is not continuous and reliable. Balancing challenges appears to be increasing significantly in the coming years. As generally TSO is response for the grid balance and DSO is not basically participating on it. When DSO is supporting TSO with its flexibility in balancing, this flexibility must be qualified to prove that customer has availability and reliability which are necessary to take this flexibility to balancing markets. DSO has here significant role because the grid configuration and its current loading is known basically by DSO. DSO should always overrule the market inputs when necessary according to the flexible resources. (Zegers, 2014, p. 25)

1.2.5 On-going projects for TSO/DSO interaction and collaboration

There are several projects on going which are developing new models or platforms for TSO-DSO interaction. These platforms are aiming to have successful integration of RES together with consumers to build smart, secure and more resilient energy systems. Aim is to unlock local flexibility and to build a common market places with clear roles between users and provider. The outcome should include high grid stability and security of supply. There were several European level projects reaching first stages in 2020 on this topic, such as SmartNet, CoordiNet, InteGRid and INTERPLAN which were funded by European commission. (Herndler, 2020) (Fingrid et al., 2020)

For example CoordiNet-project identified some main challenges during the project. First challenge was how to define products and services which are compatible with current regulations. These regulations to be full filled are for example Network Codes and Clean Energy Packages. These regulations have been made for traditional networks and thereby it might be challenging to integrate new innovations into use. Second challenge was to analyse how scalability or reliability can these solutions be in European level. Third challenge were how to activate different stakeholders to participate on this kind of project. Many of the resource owners do not have deep knowledge of their generation, demand or storage possibilities. Thereby the full potential cannot be realized. (Herndler, 2020, s. 21)

1.3 Objectives and research question

The main objectives for the thesis are:

- Identify the key factors causing the increasing demand of voltage emergency support between TSO/DSO.
- Study the common solutions implemented for voltage emergency support between TSO/DSO.
- Develop adaptive and less intrusive solution for voltage emergency support in interaction of TSO/DSO.
- Implement applicable simulation network in PSCAD for the studies of voltage stability and voltage emergency support between TSO/DSO.
- Verify and study the proposed solution for voltage emergency support between TSO/DSO in the simulation model.

Research question is:

- How can DSO provide adaptive voltage support to TSO when transmission system has emergency voltage situation?

1.4 Structure of the thesis

The thesis can be divided into a six parts. Chapter 1 represents the introduction of the topic and project backgrounds. Chapter 2 represents the results of literature survey performed on voltage stability in power systems, voltage control in interaction of TSO and DSO, and voltage emergency control solutions between TSO/DSO. Chapter 3 includes the problem statement and solution strategy including the proposed control logic for voltage emergency support. Chapter 4 represents the implementation of simulation network for the voltage emergency studies using PSCAD. Chapter 5 represents the simulation results and discussions. Chapter 6 includes the conclusions of the topic, simulations, proposed control logic and suggestions for future work.

2 Literature Survey and backgrounds

In this chapter the main objects and backgrounds for the thesis are presented. Concisely the aim for collaboration of TSO/DSO is to ensure power system stability. As described previously, as long as the reactive power resources are moving from transmission systems to distribution systems, the TSOs responsible for securing the power system is becoming more challenging. TSOs can face voltage stability issues in cases of tripping of important transmission lines or tripping of large generation units especially if the reactive power capabilities are already nearly its limits. In these situations DSO has significant role to support TSO. DSO can activate different resources underlying in ADNs and operate their networks in a way to provide voltage support to TSO. In this chapter voltage stability is presented and also several emergency voltage controls for DSO to support TSO.

2.1 Power system stability

The power system stability can be divided into three different parts such as voltage stability, frequency stability and angle stability (Kundur et al.). All of these has to be maintained all the time to avoid system collapses and black outs. According to this work, voltage stability is one of the key elements for the studies and in this chapter the key points are presented.

2.1.1 Voltage stability

A simple system is presented in the Figure 2.1 which shows a generator supplying a load through reactance X. This generator in the system is now modelled with equivalent generator source which could also be modelled as equivalent voltage source E with an equivalent reactance X_g. V represents the voltage at receiving end, also called as load voltage.

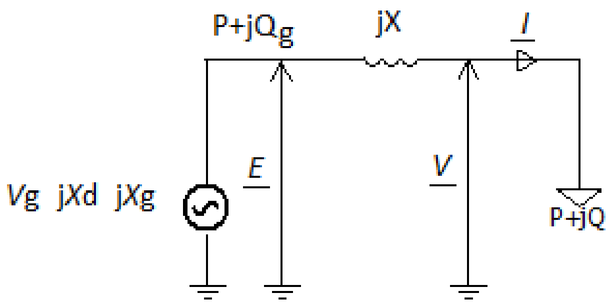

Figure 2.1 Equivalent circuit to present voltage stability

If this generator would have an automatic voltage regulator (AVR) and it would keep the voltage V_g in the generator terminals equal to equivalent voltage E then the equivalent reactance would be zero. If the generator would operate at its excitation limits meaning when its field voltage would remain constant, then the equivalent generator should be modelled using its synchronous emf E_f together with synchronous reactance X_d. (Machowski, 2008, p. 300)

The real and reactive power supplied to the load can be explained as:

$$P_L(V) = VIcos\delta = \frac{EV}{X}sin\delta \quad (1)$$

$$Q_L(V) = VIsin\delta = \frac{EV}{X}cos\delta - \frac{V^2}{X} \quad (2)$$

where δ is the power angle difference between E and V. If δ is eliminated by using the identity $\sin^2\delta + \cos^2\delta = 1$ it gives the equation for receiving end voltage:

$$V = \sqrt{\frac{E^2+2XQ\pm\sqrt{2XQ-E^2-4X^2(P^2+Q^2}}{2}} \quad (3)$$

But other interesting form is:

$$\left(\frac{EV}{X}\right)^2 = [P_L(V)]^2 + \left[Q_L(V) + \frac{V^2}{X}\right] \quad (4)$$

This is so called static power-voltage equation which takes into account the voltage characteristics $P_L(V)$ and $Q_L(V)$.

When continuing to edit equation (4) that $P_L(V) = P_n$ and $Q_L(V) = Q_n = P_n \tan \varphi$ it gives:

$$P_n{}^2 + P_n{}^2 tan^2\varphi \ + 2P_n \frac{V^2}{X} = P_n{}^2 + \left(\frac{EV}{X}\right)^2 - \left(\frac{V^2}{X}\right)^2 \qquad (5)$$

Noticing that $\tan \varphi = \sin \varphi / \cos \varphi$ and $\sin^2\delta + \cos^2\delta = 1$ it gives:

$$P_n{}^2 + P_n{}^2 \frac{V^2}{X} \sin \varphi \cos \varphi = \frac{V^2}{X^2}(V^2 - E^2)\cos{}^2\varphi \qquad (6)$$

The left part is incomplete square of sum, to develop further it can be transformed to:

$$P_n + \frac{V^2}{X}\sin \varphi \cos \varphi = \frac{V}{X}\cos \varphi\sqrt{V^2 - E^2)\cos{}^2\varphi} \qquad (7)$$

If voltage at load is presented to be per unit as V / E it gives:

$$p = -V^2\sin \varphi \cos \varphi + v\cos \varphi\sqrt{1 - v^2\cos{}^2\varphi} \qquad (8)$$

where,

$$v = \frac{V}{E},\ p = \frac{P_n}{\frac{E^2}{X}} \qquad (9)$$

V and *P* curves points out the dependency of voltage on real power when the power factor or load is a parameter. *V*(*P*) curves are also called as *nose curves*. It can be derived from equation 8 to determine different power transfer capacities with different power factors. Five different nose curves with different power factors are plotted in the Figure 2.2. Following power angles φ for the curves were used: A) 45° lag, B) 30° lag, C) 10° lag D) 0° lag and E) 31° lead.

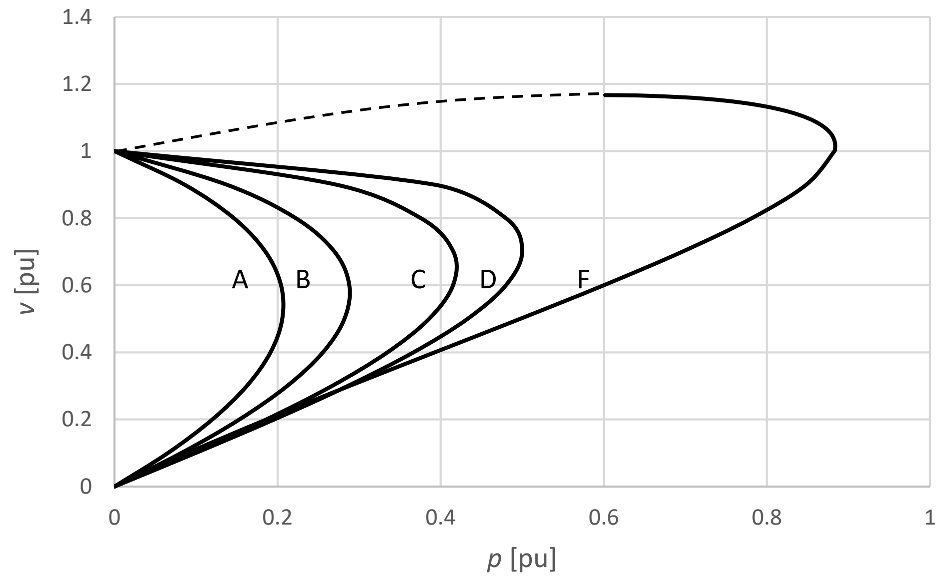

Figure 2.2 Five different nose curves with different φ values.

When looking different nose curves in Figure 2.2, the upper parts where the voltage is near 1.0 pu are stable regions for the operation. The system comes unstable in the lower parts of the characteristic i.e. when the voltages are lower (Machowski, 2008, p. 301). Head of the nose in the curve can be determined to be a knee point for the stability after that is passed the voltage will collapse. Curves A, B and C are loads with inductive power factor, D with cos φ = 1 and F represents capacitive power factor.

If considering a situation shown in Figure 2.3 where power system characteristics are at first according to curve D, then a sudden failure occurs such as tripping of a parallel transmission line, the characteristics of the system will change accordingly to curve C. In this case the system voltage would most likely collapse since the nose curve exceeds the knee point.

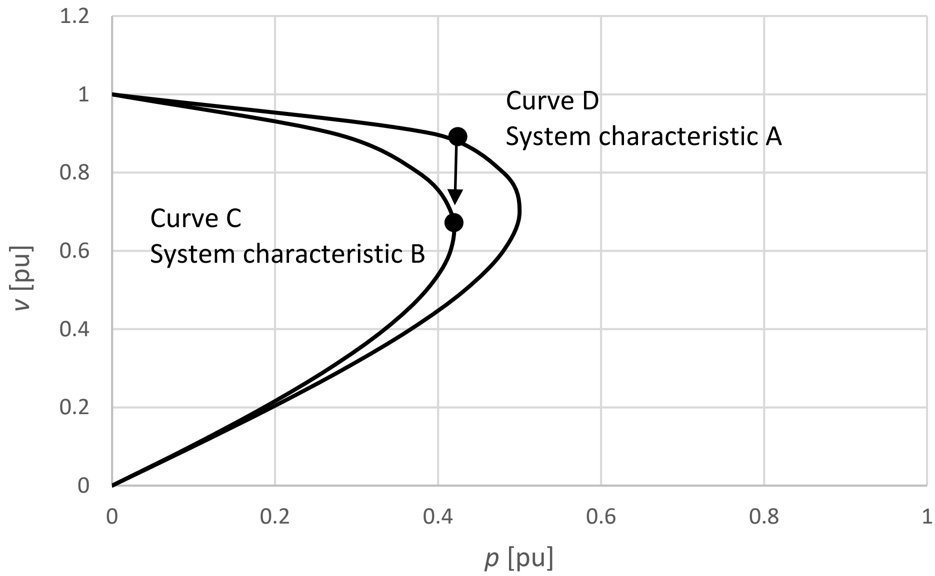

Figure 2.3 Change in the system characteristic such as line tripping might have critical effect on system nose curve and thereby for the voltage stability

2.1.2 Load characteristics

Load characteristics are important to take into account when studying power systems including voltage or frequency variations. According to the source IEEE publish (IEEE, 1993, s. 472) it is crucial to model load characteristic when studying voltage collapse scenarios. It was shown that traditionally used load characteristics were not accurate anymore at low voltages.

On a steady state mainly the voltage together with system frequency are determining the load. Load dependency of voltage and frequency can be expressed as $P(V,f)$ and $Q(V,f)$, this is also called as *static load characteristics*. These can be splitted to *voltage characteristics* $P(V)$, $Q(V)$ and *frequency characteristics* $P(f)$, $Q(,f)$.

Different type of loads have different dependencies for the voltage and frequency. For example lightning bulbs, which actually are not existing anymore in the house holds, but as an example, lightning bulb does not require reactive power and their frequency dependency zero, but its filament temperature and therefore resistance is depending on voltage level. This means that light does not have exactly constant impedance model (Machowski, 2008, pp. 105-106). If considering simple heater without any thermostat control it could be modelled as constant impedance since the power is only depending on the voltage, less voltage is less power. Great example for voltage characteristics is an induction motor which has constant speed and constant torque, this type of machine would have constant power during voltage deviations, power would remain unchanged but current would change. Unless the voltage decreases under stalling voltage which is the lowest operation voltage induction motor. (Machowski, 2008, pp. 106-107)

Different load models can thereby be divided into constant impedance model, constant current model, and constant power model. However wide power system loads are combinations of these and can be modelled as exponential function (PSCAD b):

$$P = P_0 \left(\frac{V}{V_0}\right)^{NP} (1 + K_{PF} * dF) \qquad (10)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{NQ} (1 + K_{QF} * dF) \qquad (11)$$

where,

P	= equivalent real power
P_0	= rated real power
V	= rated load voltage
NP	= dP/dV voltage index for real power
K_{PF}	= dP/dF frequency index for real power
Q	= equivalent reactive power
Q_0	= rated reactive power
NQ	= dQ/dV voltage index for reative power
K_{QF}	= dQ/dF frequency index for reactive power
dF	= specific factor in PSCAD software. Defined as minimum of 10, 90/K_{PF} and 10/ K_{QF}

If neglecting frequency indexes and choosing NP and NQ to be 0, constant load can be modelled, by changing them to 1 constant current can be modelled and by 2 constant impedance can be modelled in the voltage characteristics.

2.2 Voltage control solutions in TSO/DSO collaboration

The aim of the voltage control in power systems is to maintain a specific voltage level and thereby avoid under- and over voltages. As in traditional national power system TSO supports DSO side mainly by controlling the MV transformer tap changer to adjust the voltage. Developed DSO’s with ADN’s can also support TSO’s in cases when for example when reactive power capacity is reached or tap changer limit is reached. In developed interaction between TSO and DSO corrective actions are performed before these limits are reached.

In this chapter first voltage control in transmission and distribution networks are presented. Afterwards different solutions for voltage support between TSO and DSO are presented. These control schematics are collected from several literature researches. These researches have implemented solutions for the challenges which are occurring when the unidirectional power flow changes to multidirectional, and due to increasing amount of RESs and DERs in DNs.

2.2.1 Voltage control in transmission networks

The aim of voltage control in transmission system is to maintain good quality of electricity and to ensure system security and also to minimize transmission losses. Voltage levels are kept in specific range according to Table 1 e.g. in Finnish transmission grids. The upper limit is mainly to avoid risk of insulation break downs and also to keep corona losses minimal, even though corona losses can also depend on climate. The lower limit is to prevent high currents and to ensure higher transmission capacity and therefore stability. Voltage control in transmission systems is carried out with synchronous generators and reactive power compensation units. (Partanen, 2020)

Table 1 Voltage limits in transmission networks in Finland (Fingrid b, 2018, p. 37)

Nominal system voltage [kV]	Normal range [kV]	Exceptional and disturbance range [kV]
400	395-420	360-420
220	215-245	210-245
110	105-123	100-123

All power generating resources which are connected to the power system in Finland shall apply the requirements according to Finnish grid code known as “VJV18” made by Fingrid Oyj. Specifications of the grid code are based on the European Network Code. (Fingrid b, 2018, p. 6)

Basically all large generation units are equipped with synchronous generators. Synchronous generators have major role in reactive power production especially as reactive power reserve since the response is fast. Synchronous generators are actively and steplessly controlling the reactive power production or consumption in their connection point. Reactive power production is controlled with excitation, when over excitation produces reactive power to the power system and under excitation absorbs reactive power from the power system. Reactive power capacities of synchronous generator can be obtained from its PQ-diagram. In informative PQ-diagram all machine specific limits are presented such as turbine power limit, over heating limits and static limits but also real limiter settings since limiters will activate before the static values are reached. PQ-diagram with machine specific limits presented in Figure 2.4.

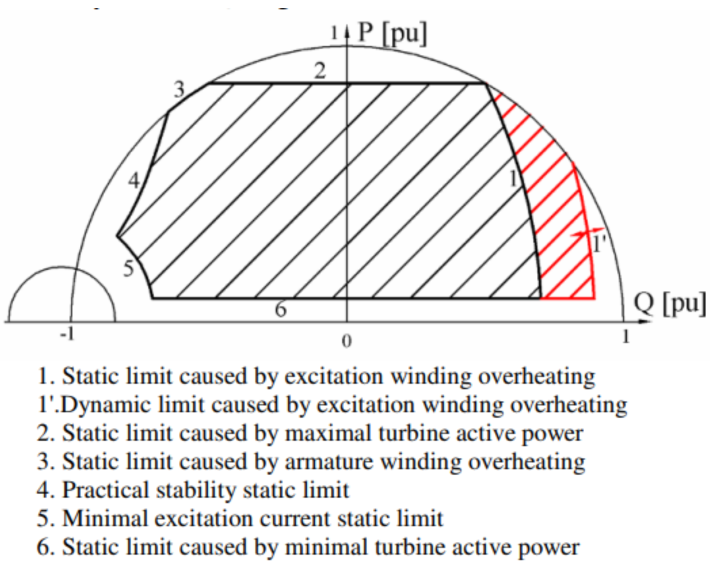

Figure 2.4 PQ-diagram of synchronous generator with different limits. (Hanić et al, 2010)

By default all generators should be equipped with constant voltage control (Fingrid b, 2018, p. 64). This means the excitation is controlling reactive power production according to the generator terminal voltage. Exceptions should be agreed separately with Fingrid and relevant network operator when using other controller type than constant voltage regulation (Fingrid b, 2018, p. 64). Other controller types are constant reactive power control and constant power factor control.

Parallel reactors and capacitors are the other key resources for voltage control in transmission networks. Reactors are needed to compensate reactive power produced by the capacitance of transmission lines. This occurs in such operating conditions when load demand is low. Without reactors this effect would boost the system voltage to unacceptable levels. Capacitors are controlled when load demand is high. Capacitors are used to compensate reactive power consumption and to minimize the transmission of reactive power. These above mentioned capacitors and reactors are switchable. (Partanen, 2020)

In Finland on-load tap changers (OLTC) are used to keep 110 kV voltage in specific level. In practise this is kept as high as possible, typically 118 kV. On-load tap changers are known to have risk to cause problems in cases when reactive power demand is high and the power system reactive power reserves are running out. On-load tap changers will increase the demand of reactive power as the voltage decreases. This phenomenon comes later up more detailed in this work. (Partanen, 2020)

As a conclusion of transmission network voltage control: tap changers, capacitors and reactors are controlling the voltage during normal voltage variations. Synchronous generators will also actively adjust the reactive power production according to the voltage level, but the aim is to maintain its reactive power capability for reserve because of their fast response. When the reactive power capacity of synchronous generator is used, other resources with slower response times are used to restore this faster reactive power capacity again for reserve use.

2.2.2 Voltage control in distribution networks

In distribution networks (DN) one common problem has typically been unacceptable voltage drop at the end of long cable lines. Limits for voltage levels according to power quality standard EN 50160 are 0.90-1.10 pu during certain period. As a result of increasing amount of residential solar power photovoltaic (PV) systems, the power flow might no longer be unidirectional and certain solutions are required to prevent over voltages at end users in PV-rich distribution networks. (Procopiou et al., 2021) (Kulmala, 2014, s. 12)

Typically DN-side voltages are adjusted with OLTC at HV/MV transformer. MV/LV transformer can also have tap changer, but typically it can be only controlled in off-line. In primary substation where the HV/MV transformer is located, OLTC can be equipped with line drop compensation control. In this control the voltage drop is estimated according to secondary voltage and current, and thereby unacceptable voltage drop at the end of line is prevented. This control might fail in PV-rich or generally DGU-rich networks when the power flow is not unidirectional thereby estimation of voltage drop according to the current is incorrect. (Kulmala, 2014, s. 15)

Transmission of reactive power is intended to be minimized because of the losses. Most of the reactive power demand is located inside distribution networks and thereby also compensation is taking place in distribution networks. These are typically in use to avoid reactive power charges from the TSO. This also means that even if there are capacitor banks, they might not be possible to be used in voltage emergency support because they are already in use.

Above described distribution network is also known as passive distribution network (Kulmala, 2014, s. 17). In this context is meant that voltage is controlled mainly at the substation. Passive distribution networks are not sufficient for reliable and cost-effective use when distributed energy resources (DERs) are increasing.

2.2.3 Voltage support between DSO and TSO

TSOs can support distribution grid voltages with HV/MV transformer by adjusting on-load tap changer. HV/MV transformer tap changer has typically operation time in tens of seconds which makes it insufficient for voltage emergency situations as it has slow response. DSOs can support transmission grid voltages by using its flexibility with compensators, DERs and different ways of load curtailments.

DSO can provide fast voltage support to TSO by controlling DNs reactive power flow or by controlling loads. To control reactive power flow, DGUs can increase their reactive power production e.g. if DGUs are driven with constant power factor and reactive power capacity is left as reserve. Also if capacitor banks can provide fast voltage support if they are left as reserve and not used for compensation. Reactive power flow between TSO/DSO can be decreased or even DSO can transfer reactive power to transmission grid. (Ospina et al. b, 2021)

Transmission of real and reactive power between from TSO to DSO can be decreased by decreasing DN voltage. As the voltage decreases, also transmission of real and reactive power decreases according to the load characteristics. Voltages at DN side can be lowered with OLTC of substation transformer. In extreme situation loads can be disconnected. This is also known as load shedding which is intrusive but effective way to provide voltage support. (Zhang, 2009)

In some countries HV/MV substation is equipped with capacitor banks at MV side for reserve use. In these cases TSO has access to control these for reactive power support. (Zegers, 2014, pp. 19-21)

2.2.4 Load Shedding for Voltage Emergency Support

Load shedding is typically divided into two different parts: under frequency load shedding (UFLS) and under voltage load shedding (UVLS). These are the last actions to prevent voltage or frequency instability in power systems. (Jianjun et al., 2018, p. 1)

UVLS are used as distributed load-shedding and as centralized load-shedding. DFistributed load-shedding is also known as local load-shedding scheme. This means that a single load can be disconnected separately according to its protection and its measurement point, also the loads can be chosen accordingly their importance or sensitivity for voltage disturbances. In centralized load-shedding the loads in certain area are disconnected.

There are certain advantages in distributed load-shedding scheme than in centralized load-shedding scheme (Zhang, 2009, s. 3):

- More adaptability can be achieved since load shedding can be limited to minimal amounts of load disconnections. Load-shedding occurs only if the voltage at that point is decreasing. This can also be restrictive compared to central load-shedding which can operate before voltage instability is presented in some part of the grid.
- Loads are not dependent on each other's since every load has own protection. This is important in case of protection failure during voltage instability situations.
- Load-shedding is acting on areas where the voltage instability is the most strong since it has independent measurement to detect voltage instability.
- At simplest distributed load-shedding does not require communication facilities to operate.

There are certain advantages in centralized load-shedding scheme than in distributed load-shedding scheme (Zhang, 2009, s. 3):

- Voltage measurement can be taken from most critical locations of the power system and effectively operate centralized load-shedding around this area.
- Only few measurement point can be enough for reliable protection, this saves equipment costs.
- Also different indicators can be measured to help identifying voltage instability such as loss of important line or zero sequence voltages.

When implementing load-shedding strategies in power systems a certain factors should be taken into account. Load types needs to be identified e.g. as the constant power loads are most crucial in voltage instability situations because the natural effect of voltage reduction is not affecting the load. Also it is necessary to sort out which are less important loads

(Zhang, 2009, s. 5). Power factor of the load has also an effect, since lower the power factor is, more reactive power is needed. This leads a system specific under voltage load-shedding logic which should be implemented for correct load-shedding strategies.

In this work UVLS is considered as last option to recover voltage. UFLS is not taken into account in the simulations since the aim is to focus on voltage emergency control.

2.2.5 Power Factor Improvement for Voltage Emergency Support

The aim of this schematic is based on power factor adjustment in the point of common coupling between transmission and distribution system. Power factor is being adjusted by DGU's reactive power capacity together with OLTC. This method also identifies and tries to eliminate the counterproductive effects which emerges when DGU's reactive power production increases also the voltage in distribution network increases. Depending on load characteristics, loads will also increase which should be avoided in voltage emergency situations. (Ospina et al. a, 2020)

Proposed control relies on DGU's reactive power capacity and OLTC set point changes during emergency situations. As mentioned the aim is to have power factor as high as possible during emergency situation by minimizing reactive power flow from transmission side. Study was made using simple 5-bus schematic as seen in Figure 2.5. (Ospina et al. a, 2020)

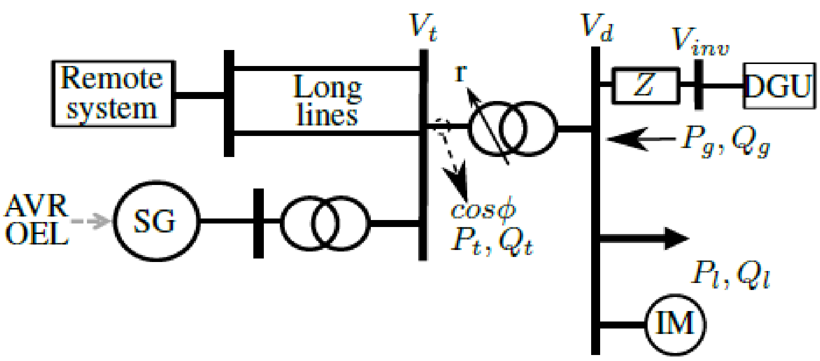

Figure 2.5 Power factor adjustment schematic in 5-bus system. (Ospina et al. a, 2020)

Transmission-generation system can be expressed as Thevens equivalent where in equation E is voltage source over the reactance X. This points out that the system can operate in steady state if following equation (12) is true:

$$-\left(\frac{P_t X}{E^2}\right)^2 - \frac{Q_t X}{E^2} + \frac{1}{4} = 0$$

where (12)

$$P_t = P_l - P_g \qquad Q_t = Q_l - Q_g$$

and (13)

P_l = Real power of Load

P_g = Real power of GU

Q_l = Reactive power of Load

Q_g = Reactive power of GU

This is attractive driver for ADN's since by adjusting Q_g the required real power P_g can be delivered with decreased risk of instability (Ospina et al. a, 2020).

The control scheme operates simply as follow: during emergency situation DGU's reactive power reserve is activated in synchronization of OLTC tap position decrease. This means that after the disturbance in the grid when transmission side generator has reached it's OEL, DGU's reactive power reserve is activated. DGU's reactive power is increased as long as certain value of V_d^{DGU} is reached (now 0.975 pu). Then DGU's reactive power production idles, and tap changer operates towards its set point V_d^{LTC} which here is 0.95 pu. Now DGU's reactive power production is activated again since $V_d < V_d^{DGU}$ and OLTC is locked until $V_d > V_d^{LTC}$. OLTC has time delay which means that V_d^{DGU} is typically already reached before OLTC acts.

This control logic prevents V_d to increase and eliminates the counterproductive effects of DGU's reactive power production by decreasing V_d with the tap changer operation. The effect of this synchronized control is depending on load's relation to voltage.

2.2.6 A Non-Intrusive Scheme for Voltage Emergency Support

The target in Non-Intrusive Scheme is to have voltage emergency control which will avoid previously presented load shedding's or conservative load reductions. This method thereby should be activated before voltage instability reaches critical levels, because load shedding is probably the last action and the most intrusive method to maintain the voltage levels.

Non-Intrusive Scheme presented in source (Ospina et al. b, 2021) is based on controlling the distribution transformer on-load tap changers together with DGU's reactive power capacity. Only two variables are driving this control scheme which are transmission side voltage V_t and distribution side voltage V_d. In this study the real power of DGU's are uncontrollable, because mostly DGUs are running on full power or accordingly to the weather.

The proposed method implemented by Opsina & Cutlem, (Ospina et al. b, 2021) has design criteria with six different features such as:

1. Non-intrusive
2. Adaptive
3. Local
4. Minimal input data
5. Effective control regardless system characteristics
6. Effective control regardless of load characteristics¨

For more details of the criteria's;

1. Non-intrusive –criteria means that the control should not affect DN voltages in the way that voltage limits (e.g. 0.95-1.05) are exceed or the assets would go overloaded (production of P or Q). 2. Adaptive –criteria means that the control should not over react or react in the same way depend less if the variation small or big. 3. Local, which is one of the key criteria and means that the control scheme should not require information from all over the grid. 4. Minimal input data which supports the previous criteria since the aim is to have less inputs to make it more practical. 5. and 6. stands for the scheme more sovereign of the system characteristics such as short circuit power or load characteristics such as load dependency of voltage.

Operation of Non-Intrusive scheme starts from alarm when voltage V_t or V_d exceeds the limits. If transmission side voltage drops below the limit the first action is to read out the voltages V_t and V_d and turn these as a set values for the incoming control. Thereby the value of V_d will became maximum value for distribution side voltage, and V_t will became the minimum value for the transmission side voltage. The control aims to keep the values under and below these limits. The control follows the scheme depending on the area where the grid voltages are as presented in Figure 2.6.

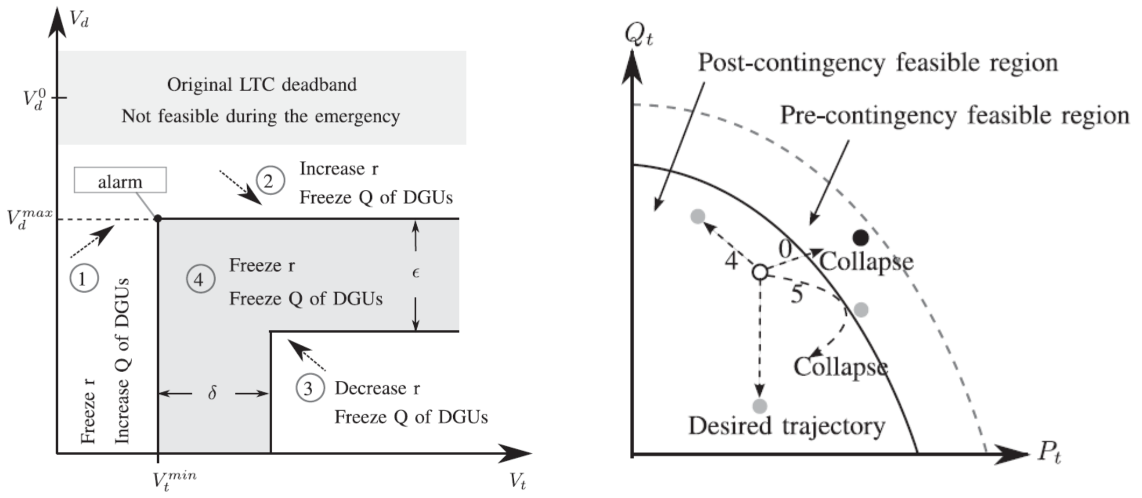

Figure 2.6 Non-intrusive control schematic. Desired trajectory points out the target of operation point during emergency situation. (Ospina et al. b, 2021)

In this case, voltage emergency in transmission side, first action is to lock the on-load tap changer of distribution transformer. As it is well known that operation of tap changer can worsen the situation in voltage emergencies. After that in area 1, reactive power of DGU's are increased to minimize the reactive power drained from the transmission side or even to produce reactive power to the transmission side. This will lead up to area 2 or 3. In case of area 2, distribution side voltage V_d is at maximum level, to prevent load increase because of voltage increase, reactive power production of DGUs are stopped. Then on-load tap changer is released to decrease V_d for suitable level (area 4). If the operation point is in area 3, where the transmission side voltage V_t is inacceptable level, the reactive power production of DGU's are stopped (if already aren't) and then the voltage of V_d is regulated to area 4. Area 4 is so called dead zone, no regulation is taking place here. It is important to drive the system to area 4 to have maximal range in every direction (to voltage limits) in case of new voltage emergency situation.

Figure 2.7 points out the correct operation of the schematic where the reactive power transmission from TSO is decreased while the real power is remaining still.

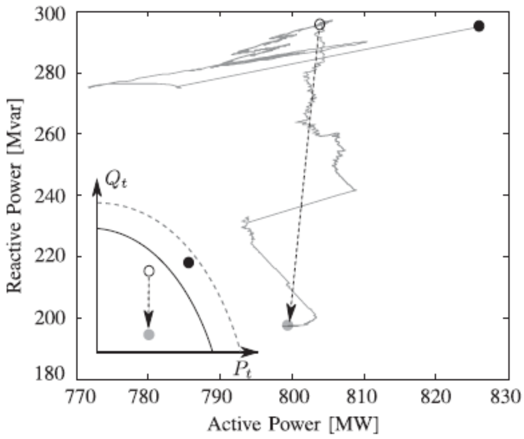

Figure 2.7 Non-Intrusive scheme trajectory in power space. (Ospina et al. b, 2021)

In Figure 2.8 is shown the effect of Non-Intrusive emergency control with and without load shedding. Without emergency control system voltage will collapse.

Case	Description
C0	No emergency control
C1	Non-intrusive emergency control
C2	Undervoltage load shedding
C3	Non-intrusive emergency control with back-up load shedding

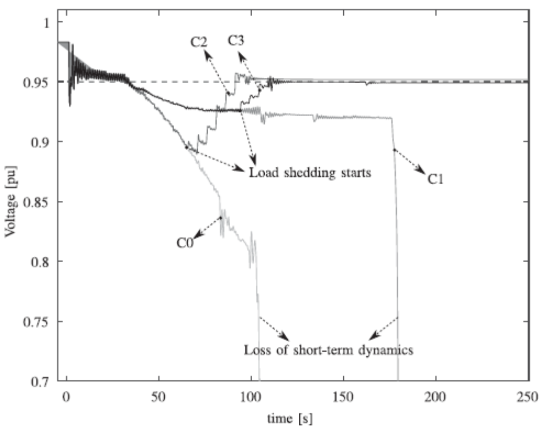

Figure 2.8 Results of several scenarios in the control developed by Ospina and Van Cutsem. (Ospina et al. b, 2021)

2.3 Conclusion of Voltage Emergency Support functions in TSO/DSO collaboration

Typical voltage emergency support concept focuses on compensating reactive power demand from TSO by utilizing reactive power resources located in distribution networks. This means that DGU's reactive power production capacities are activated during TSO voltage emergency situations. Different methods to boost reactive power production are developed. One common method is so called power factor improvement, which aims to increase power factor measured at TSO/DSO interface by decreasing reactive power flow from transmission side, simply by increasing DN side reactive power production. (Adewuyi et al., 2019) (Ospina et al. a, 2020) (Ospina, 2021) (Tang et al., 2019)

Load shedding is one of the most efficient method in voltage emergency situations to stabilise power system. Loads can be disconnected immediately by controlling the breakers. This is also the most intrusive method to provide voltage support and therefore should be the last action, because end-users will face out a black out. (Zhang, 2009)

Voltage reduction is less-intrusive method to decrease loads. Depending on load characteristics, load voltage might have significant effect on load powers or not. By decreasing DN voltages with HV/MV transformer tap changer, loads are decreased and also the power flow from transmission network to distribution network is decreased. In this way DSO will provide voltage support to TSO. Voltage reduction is sufficient method also to decrease power losses in DN. (Aristidou et al., 2017)

Capacitor banks can be used as reserve reactive power banks. Capacitor banks can be controlled as above described DGU's power factor improvement or they can be connected directly to provide reactive power to TSO side (Zegers, 2014). Capacitor banks are still uncommon solutions in this context. Importance of the location and size should be determined to obtain sufficient support in voltage emergency situation. (Kamel et al., 2019)

Battery Energy Storage Systems (BESS) located in DSO side can provide support in voltage emergency situations (Astapov et al., 2022). Connection of BESS systems will lower the real power transmission from TSO and therefore provides voltage support for TSO. BESS are typically taken into account in PV rich distribution networks. PV rich distribution networks might also suffer over voltages which requires better power factor control also (Kraiczy et al, 2017).

Conclusion of different methods for voltage emergency support between TSO/DSO is presented in Table 2. In this thesis all facilities except BESS are included in the implementation.

Table 2 Taxonomy of the voltage control functions referred in the thesis

Reference	Reactive power Support (DGU)	Load Shedding	Voltage Reduction / Tap Changer Operation	Capacitor Bank	BESS
(Ospina et al. a, 2020)	Y	N	Y	N	N
(Ospina et al. b, 2021)	Y	(N/Y)	Y	N	N
(Zhang, 2009)	N	Y	N	N	N
(Ali et al., 2017)	Y	N	N	N	N
(Astapov et al., 2022)	Y	N	N	N	Y
(Kraiczy et al, 2017)	Y	N	N	N	N
(Adewuyi et al., 2019)	Y	N	N	N	Y
(Aristidou et al., 2017)	Y	N	Y	N	N
(Tang et al., 2019)	Y	N	N	N	N
(Kamel et al., 2019)	N	N	N	Y	N
Thesis	Y	Y	Y	Y	N

(N/Y) function included in some simulations

3 Problem Statement and Solution Strategy

3.1 Research Gap

Several studies were researched where DGU's reactive power capability was used for voltage emergency support. Also load shedding and voltage reduction were common ways to provide voltage support between TSO/DSO.

According to Ospina's and Cutsem's study (Ospina et al. a, 2020) of voltage support between DSO and TSO is achieved by adjusting the power factor in the interface between TSO/DSO. In this study DSO is supporting TSO by activating reactive power resources in DN to have as high power factor as possible. Ospina and Cutsem has made another study of "Non-intrusive scheme" (Ospina et al. b, 2021) for voltage support between DSO and TSO. In this study reactive power resources such as DGU's are activated for reactive power production in synchronization with HV/MV transformer tap changer control.

Capacitor banks for voltage support are not included in the studies presented above. According to ISGAN report (Zegers, 2014) based on interviews of different TSOs and DSOs there are possibilities for TSO to activate DSO side capacitor banks which are reserved for emergency control. According to Kamel et al. (Kamel et al., 2019) study of voltage stability increase with shut capacitor, location and size of the capacitor has significant role to prevent voltage collapse. In the study made by Kamel et al. capacitor is installed in the weakest bus which is determined by voltage stability index (VSI).

Therefore in this work a model is created where power factor improvement, a non-intrusive scheme, distributed reserve capacitor banks and backup load shedding are combined to provide voltage emergency support between TSO and DSO. Also the effect of different load characteristics are studied further. Ospina's and Cutsem's (Ospina et al. b, 2021) study included two different load characteristics (constant current and constant impedance). In this study constant current, constant impedance, constant power and also one characteristics between constant load and impedance are studied and the impact of the proposed control logic is evaluated.

3.2 Problem statement and Objectives

Main objective of the thesis is to study voltage emergency control and its possibilities between DSO and TSO. In the practical study is made with simulations using PSCAD simulation software. Main applications used in voltage emergency support are studied from literature research. From literature researches several protocols and possible methods are taken into account in the simulations. Appropriate simulation environmental for voltage stability studies and emergency control strategies is built by developing IEEE 39 transmission grid in PSCAD with the inspiration gained from the literature research.

1) The major aim is to implement schematic for non-intrusive and adaptive voltage support from DSO to TSO in voltage emergency situations, without the need for load shedding. However the under voltage load shedding is taken into account as last option. When TSO-side voltage decreases below emergency limit, ADN's objective is to prevent voltage collapse of the power system using its utilities. Key resources in ADN's are DGU's, capacitor banks, distribution transformer's tap-changers (voltage reduction) and at the last load shedding. DGUs in ADNs are supposed to be operating at nominal real power load with power factor nearly 1 before failure, therefore real power production cannot be increased at DN side or TN side during emergency situation.

2) By adaptive control is meant that less critical changes requires less critical actions and in significant changes more significant actions are required. Aim is to limit the reactive power flow from TSO side to DSO side by using ADN's reactive power production capabilities together with conservative voltage reduction. The last option is load shedding where the loads are disconnected in a steps until voltage is in acceptable level.

3) ADN's voltage indexes to reactive and real power are playing significant role in the critical situations since it determines the demand of reactive power of the load and transmission. These factors and their effects are studied in the simulations also.

3.3 Solution Strategy

The solution strategy in this thesis was to perform literature survey on topics relating to TSO and DSO collaboration in voltage emergency situations. From literature survey several solutions for voltage emergency support between TSO and DSO are studied. The solution for identified research gap is implemented by utilizing these solutions studied from literature survey.

The control logic which was developed for the studies is presented in Figure 3.1. Load shedding was not used in most of the studies since the aim was to focus non-intrusive schematic without load shedding. Anyhow when the load characteristics where near or at constant power mode, load shedding was also taken into use to secure system stability. The proposed control logic was tested with different time constants. Load shedding should always to be planned as a backup protection for voltage stability since its effectiveness.

Time constants were changed during the simulations to study the effects. As previously mentioned tap changer operation time was set to 5 seconds when in realistic system it would be around 20-30 seconds. Voltage limits and time constants used in the simulations were as in Table 3.

Table 3 Voltage variants and time variants used in the proposed control logic.

Voltage limits	[pu]	time constants	[s]
V_{dmin}	0.90	t_c	10-15
V_{dmax}	1.10	t_{rev}	0-30
V_{tmin1}	0.95	t_{L1}	1-5
V_{tmin2}	0.90	t_{L2-L4}	1-5
δ	0.03		

Developed solution was tested by performing simulations with PSCAD to verify the implementation in IEEE 39 Bus system. PSCAD is common and plausible simulation software used by different network operators to perform accurate simulations of their networks.

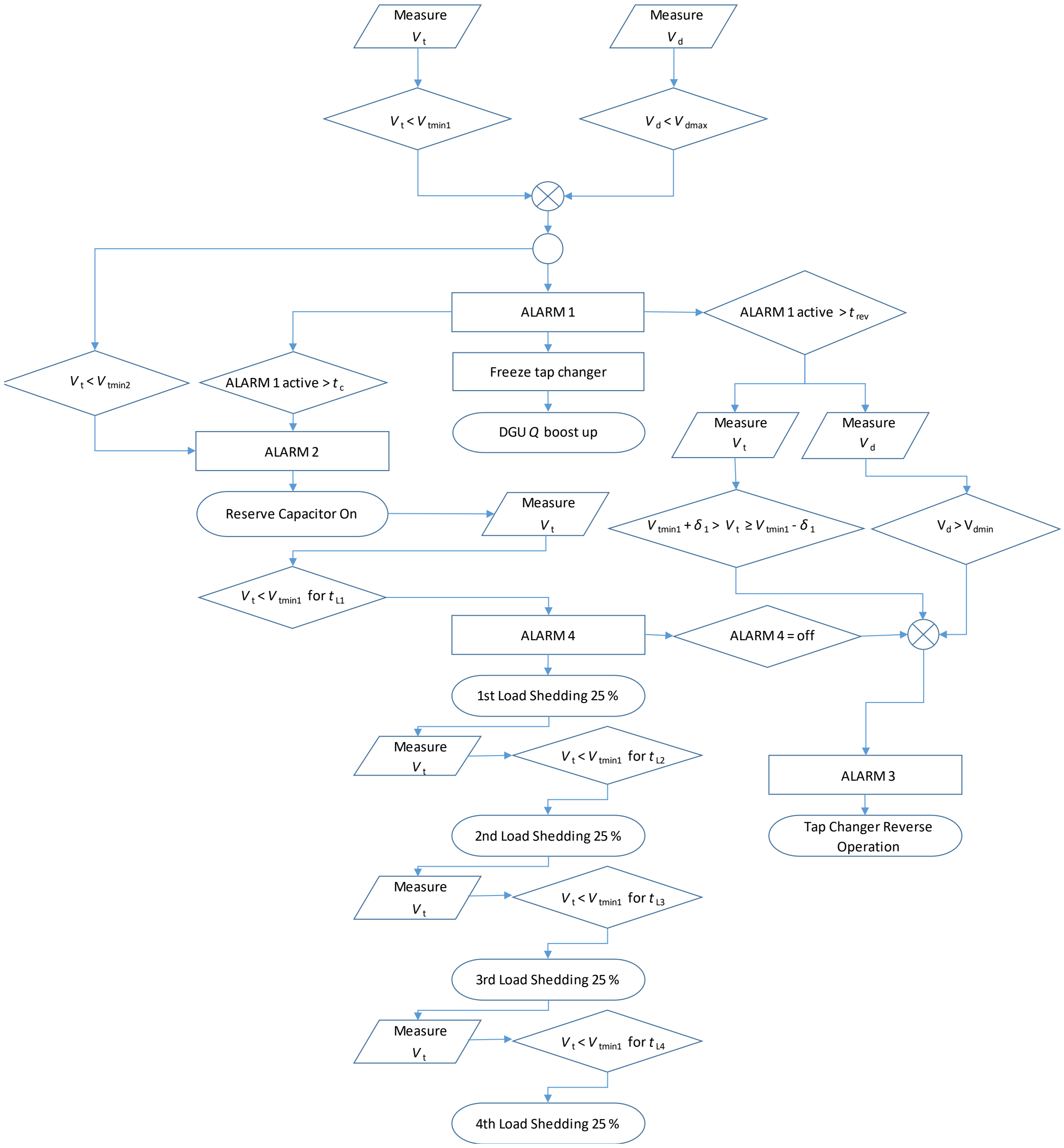

Figure 3.1 Proposed control logic for different alarm levels to activate different resources in Active Distribution Networks (ADN) during voltage emergency situations at transmission networks.

3.4 Limitations

Some limitations were done in the simulation itself according to its components and voltage controls. Aim was to limit the study of voltage emergency support between TSO/DSO to the interface of TSO and DSO and also to avoid too heavy simulation.

TN side transformers OLTC's were set with fixed values, meaning that TN-side transformers had fixed ratio during simulations, unlike ADN's. Also transmission side generator's excitations were equipped with OEL's without ceiling voltage functions. Used OEL's are however sufficient for long term stability study even if the short term over-excitation capacity was not taken into account.

Only four central loads were replaced with ADN's meaning that the rest of the loads in the power system remained unchanged. ADN's were represented only in the medium voltage (MV) level, meaning that all DGU's and loads were in MV level and connected to the same bus with a short cable. Congestion of DN side transformers or voltage rise at the end users was not studied. All different voltage index studies for reactive and real power are performed inside these four ADN's only. All ADN's tap changers are in operation time of 5 seconds to fasten the simulation when in real power systems would be around 25-30 seconds. Even though this was taken into account when analyzing the results.

4 Simulation in PSCAD using IEEE 39 Bus System

Voltage emergency support functions were implemented and tested in IEEE 39 Bus System model. This system is also known as “New England system” which is used for implementing new concepts or testing new protocols by many researchers. Validated IEEE 39-bus system was already found from PSCAD Manitoba by their developers (PSCAD c, 2018). The load flow of the model has been validated and compared to PSS/E model according to PSCAD.

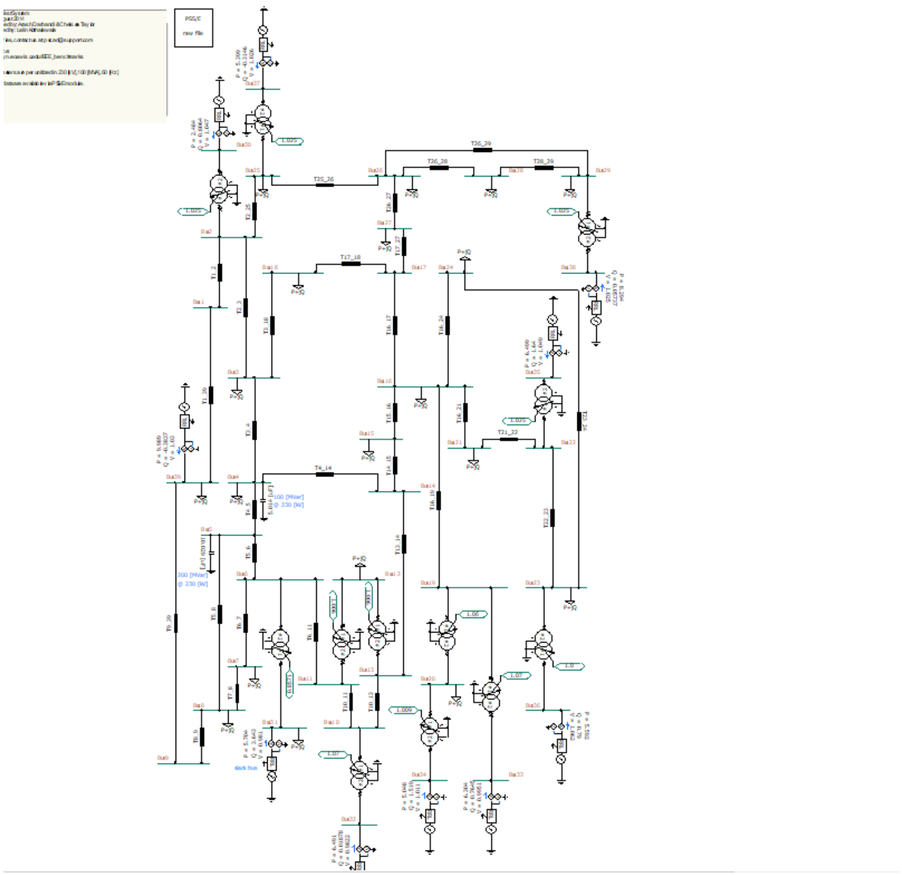

Figure 4.1 Original PSCAD model for IEEE 39 Bus system

This IEEE 39 Bus System in PSCAD consists of 10 generators, 48 transmission lines, 19 loads, 12 transformers and 2 capacitor banks. Every component in the model is rated 230 kV and transformers are with ratio 1:1 with certain set point values. Generators are modelled as three-phase voltage sources and loads are fixed loads. Transmission lines are modelled with Bergeron Model using different per unit (pu) values for positive sequence resistance, positive inductive reactance and positive capacitive susceptance. Length of the lines are fixed to one meter but the pu values are determining the distances. System frequency is 60 Hz.

Several components and parts were needed to be modified to get the voltage stability and voltage emergency support studies done in proper way. Three phase voltage sources are not usable for the study. One reason is because the output power or reactive power is not limited by the nominal values of the machine. Therefore three-phase voltage sources were replaced with dynamic models of synchronous machines including excitation and turbine control and with breakers and protection functions. Distribution networks were missing in the model since everything was built in 230 kV level. ADN's were implemented and built in the model for the voltage emergency support studies between TSO and DSO interface.

4.1 Implementation in PSCAD

Original PSCAD IEEE 39 (PSCAD c, 2018) bus system was developed for the voltage emergency studies. Original model had limitations for dynamic studies. All power system parameters are presented in Appendix 1.

4.1.1 Transmission lines

Transmission lines are modelled with Bergeron Model in original PSCAD IEEE 39 bus system. Bergeron model is typically used in long lines and in studies which are done in the fundamental frequencies, such as load flows or protection relay testing's. Bergeron model takes the propagation delay into account and is therefore more realistic compared to PI-model (also called π–section). To approximate the system losses this Bergeron model includes a lumped resistance. (PSCAD a)

Even though these advantages of are turning also disadvantages for these studies. PSCAD requires the solution time step to be 1/10 th of the shortest travel time when the simulation includes Bergeron models. Practically this means that the simulation solution time step would had to be chosen to be 28 µs. This would make simulations to be very time consuming since duration of the run would be in couple minutes to study voltage stability and emergency control schematics. Travel times are not relevant for these studies, therefore Bergeron models were replaced with coupled π–models.

Typically π–section is used in very short overhead transmission lines or cable lines. Disadvantage of π–section is that it does not provide an accurate full-frequency transient response. This doesn't affect the study here because the study is about long term stability and reactive power balance and it's relation to voltage which is slow phenomenon compared to transient stability. (PSCAD a)

Coupled π–section was chosen to replace all the transmission lines. Data (*R*, *X*, *B*) were entered in per units as in original model. Representation of coupled π–section is shown in picture Figure 4.2. System voltage remained the same 230 kV.

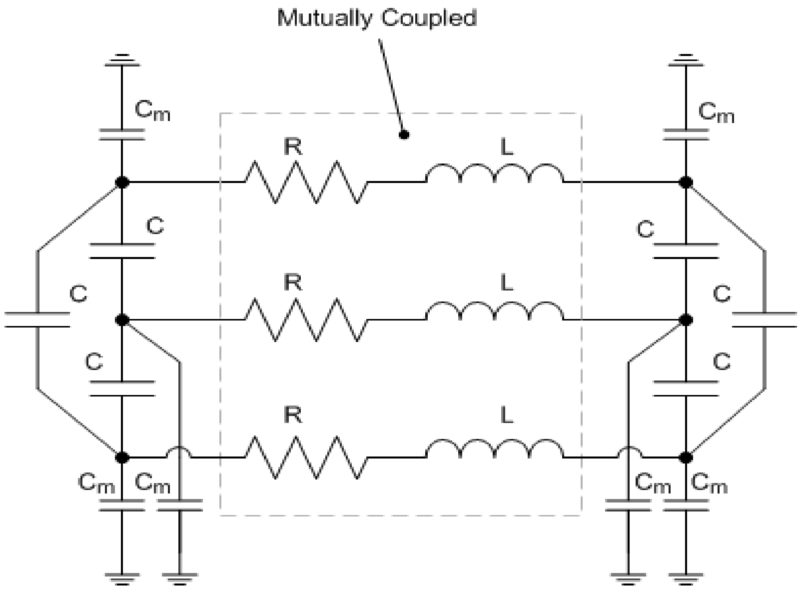

Figure 4.2 Coupled π–section used to model transmission lines in PSCAD simulation. (PSCAD d)

4.1.2 Generators at transmission network TN

The original three-phase sources were replaced with synchronous machines (Figure 4.3) together with excitation systems, turbine governors and multi-mass torsional shaft interfaces. Original sources had no nominal data, therefore each generator nominal power was chosen according to their operation point in the original model.

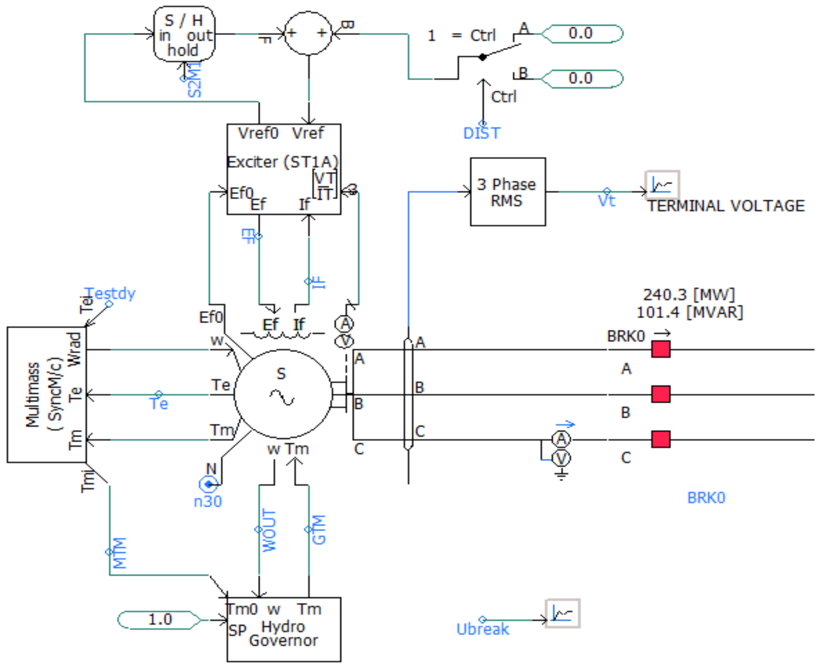

Figure 4.3 Generator model used in PSCAD simulation.

Nominal voltage of all generators was chosen to be 15,75 kV, nominal speed 3600 rpm (60 Hz), and inertia H = 3,14 seconds, except G31 H = 6,12 seconds. Transformers whose secondary side was connected to generator bus was set also to this same voltage level.

For the dynamic simulations saturation characteristic of the generators were set according to the Figure 4.4 below. The relationship between magnetomotive force (mmf) and air gap flux is linear when the iron path is unsaturated as the air-cap curve represents. When the generator iron path is saturating (mmf increases), the curve starts to act non-linear as the saturation curve represents. Every generator has identical saturation characteristic in the implemented model.

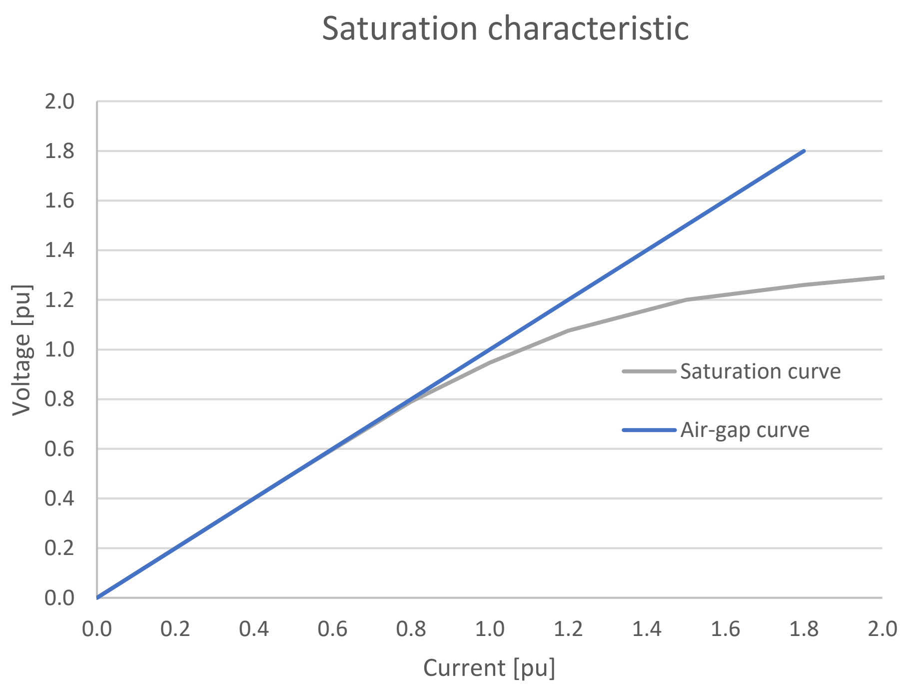

Figure 4.4 Generator saturation characteristic in PSCAD-model.

Governors are modelled as Compatible Hydro Governors (HGOV18) and mechanical shafts are modelled with Multi-mass Torsional Shaft Interface.

4.1.3 Excitation system and over excitation limiter

Excitation system was modelled using "IEEE Static Excitation System #1" ST1A (IEEE, 2005). This excitation system is simple one but suitable for this work. Most of the time constants and variables were chosen to be standard values (pre-set from PSCAD example) but some of the variables were tuned to have stable operation and some for the studies e.g over excitation limiter OEL. ST1A is a static excitation model and a potential-source with controlled rectifier exciter which is typically used to model excitation systems which are fed from transformers directly connected to the generator bus. Block diagram of the ST1A is presented below in picture Figure 4.5

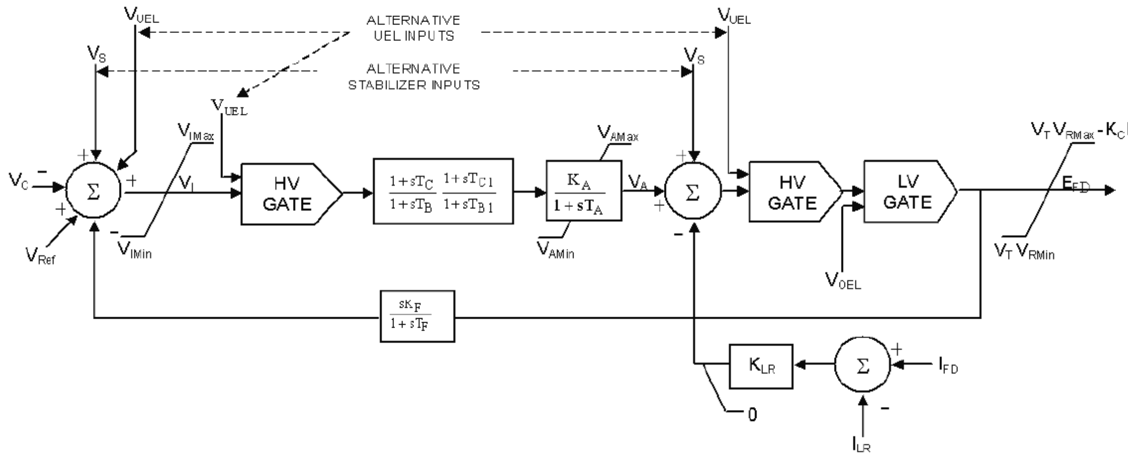

Figure 4.5 Generator excitation system block diagram used in PSCAD-model.

OEL is limiting the excitation voltage and current. For this study, the OEL is playing important role to keep the reactive power production of transmission side generators in realistic limits. The limit value for OEL was determined according to the nominal power *S* of the generator and the generator operation point (*P* and *Q*) in the simulation. As described early, the real power production of all generators during the simulations are kept constant. For example generator G30 OEL was calculated and determined as follow:

- G30 nominal power *S* is 300 MVA
- Real power *P* in the operation point is 250 MW
- Maximum reactive power capacity Q_c at power 250 MW calculated as:

$$Q_c = \sqrt{S^2 - P^2}\ MVar = \sqrt{300^2 - 250^2}\ MVar = 167\ MVar$$

Then simulation was run with high temporary reactive power load near the generator to determine the excitation values for OEL when reaching this specified reactive power. E.g G30 OEL values was chosen to be 1.89, this prevents overloading the generator stator during the tests and therefore is more realistic. Every generator OEL was determined in the same way. Presented in Figure 4.6.

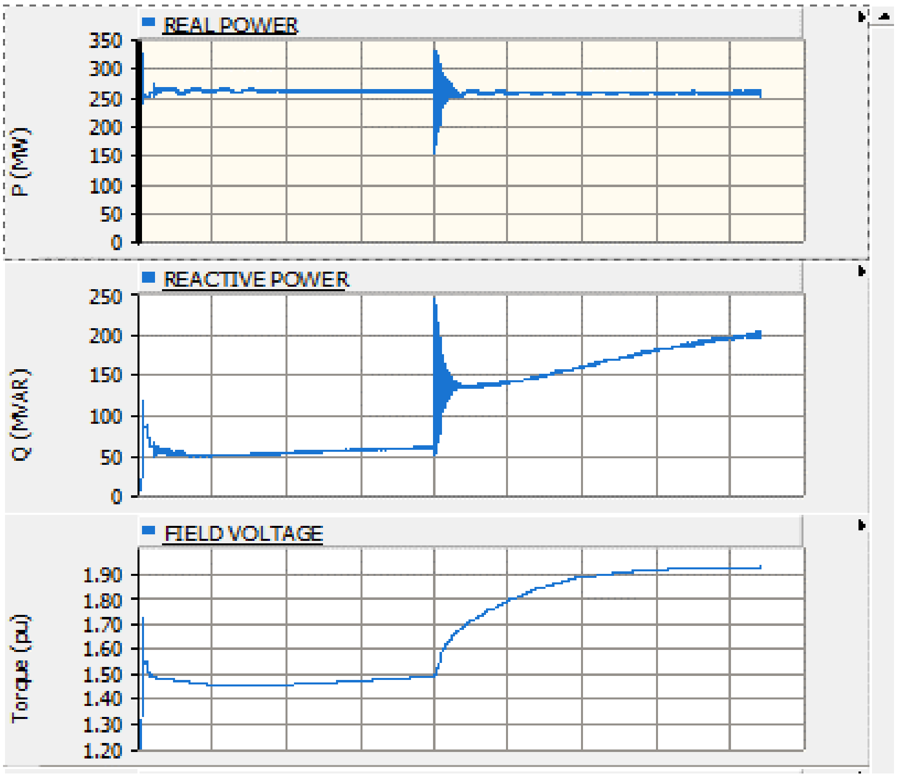

Figure 4.6 Determining the field current and field voltage limits for OEL according to generator nominal power.

4.1.4 Under voltage protection

Generator models were equipped with under voltage protection to protect generators in emergency cases when OEL is reached and the system voltage starts to decrease. Set point values was chosen to be as following:

– set point 1: $0.85 < V_g < 0.9$ $t_{uvp1} = 20$ s

– set point 2: $0.84 < V_g$ 0.85 $t_{uvp2} = 10$ s

– set point 3: $0.84 > V_g$ $t_{uvp3} = 1$ s

Where V_g is the generator voltage measured from terminals and $t_{uvp1\text{-}3}$ are the delays for under voltage protection to open the breaker. This is rigid and simple protection but enough for the studies to determine how long TN side generators would be able to support the grid during emergency situations before trip. Set point 2 is chosen according to Fingrid's grid code (VJV18). VJV18 requires generators to be able to operate even if the voltage drops 0.85 pu for 10 s. But this voltage 0.85 pu in VJV18 is actually the voltage at point of common coupling (PCC) which is often the point after step up transformer. Therefore the voltage could be higher at generator because the voltage drop of transformer. Under excitation limiters (UEL) were not used in the generator models.

4.1.5 TSO transformers and on-load tap changers

Transmission network transformers were not modified except the transformers which were connected to the generator busses, their secondary voltage was changed to match generator nominal voltage. Transmission side transformers tap positions could be modified with fixed values. Some values were changed to achieve acceptable voltage limits in the busses. Transmission side voltages are controlled only with generator reactive power productions and additional ADN's.

4.1.6 Active distribution network

Total of four fixed loads at the center of the transmission system were replaced with ADN's. Those loads were Bus 4, Bus 15, Bus 16 and Bus 21. Figure 4.7 points out the location in implemented IEEE 39 bus model.

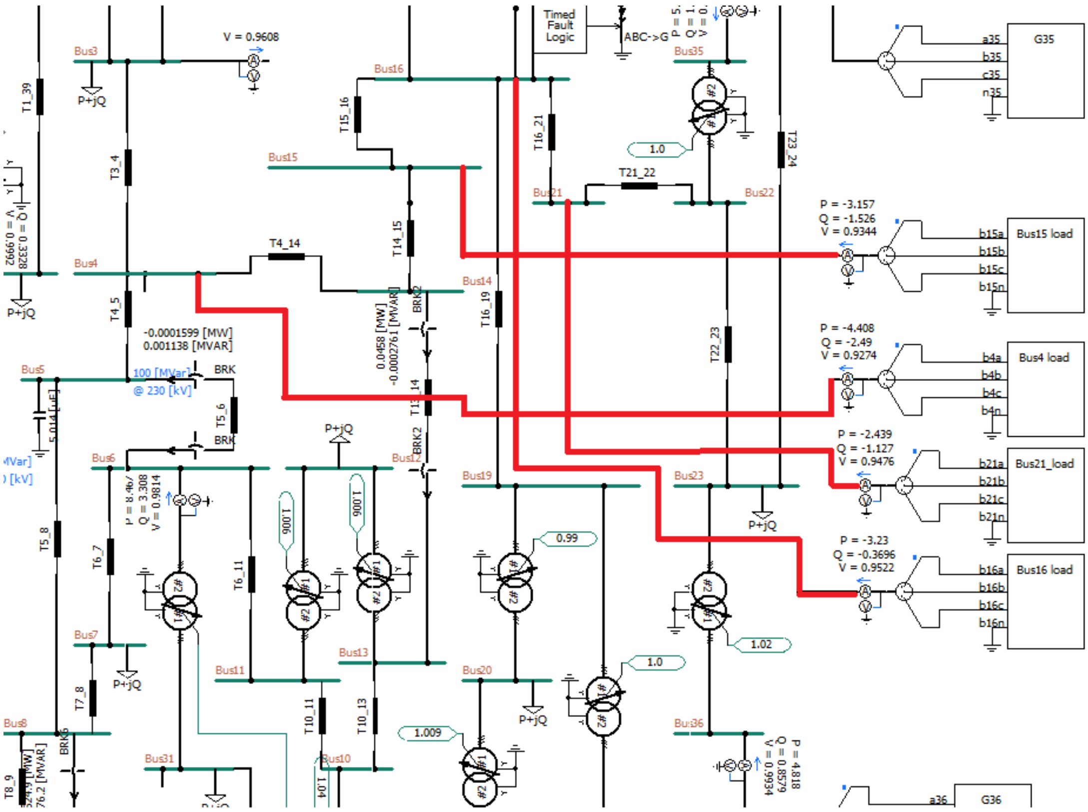

Figure 4.7 Central area of the implemented PSCAD-model. Original loads are replaced with active distribution networks ADN's. Red lines are connecting new ADN's to the busses.

Transmission side loads are fixed loads where different volt to reactive or real power indexes can be determined and also frequency to reactive or real power indexes can be determined as described in chapter 3.2. Below in Figure 4.8 is the single line diagram (SLD) from ADN side. DGU model is not shown, but it is as already presented transmission grid side generator model.

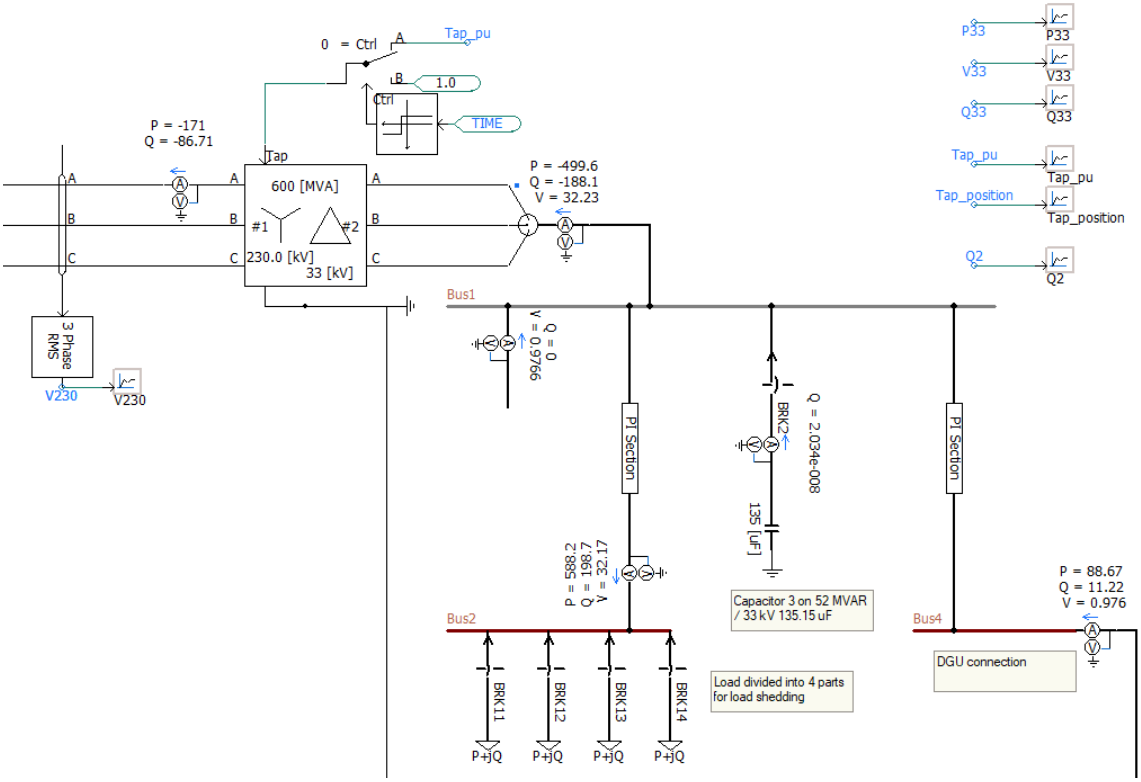

Figure 4.8 ADN’s main components presented. ADN includes HV/MV transformer with OLTC. ADN’s load is divided into four different section for load shedding, DGU and cable lines.

Loads of ADN’s are supplied through distribution transformers which are equipped with on-load tap changers (OLTC). This transformer represents the substation HV/MV transformer which has already described in first chapters of this work. OLTC has total of 20 positions, 10 in each direction from nominal value. OLTC is located at 230 kV side and it is adjusting the tap position according to 33 kV side voltage. All distribution transformers were 600 MVA and 230/33 kV regardless of load, however loads were not higher than transformers nominal power.

33 kV bus was equipped with controllable capacitor banks equal to 8,5 % of distribution transformer rated power (52 MVAr at 33 kV). Capacitor banks were modelled simply with capacitance to the ground.

Distributed generation was added with cable connection (π-section). The amount of distributed generation (DGU) was determined according to the paper “a Non-intrusive scheme” (Ospina et al. b, 2021) covering 20 % of the load with DGU. The original load was placed behind cable connection (π -section), and multiplied by 120 %. This is how the power transmission from transmission network remains the quite same, since the DGU covers the increase in load power. DGU's were determined to be cosφ -controlled meaning that DGU's were producing mainly real power, not reactive power. Therefore reactive power is left for emergency support. DGU's were modelled as transmission side generators including OEL and under voltage protection with an exception that set point 1 was not used.

4.2 Emergency Control System

As inspired of chapter 2.2.6 control logic, the main input for emergency control is simply the transmission side voltage V_t. Compared to the presented "*A Non-intrusive Scheme*" all ADN's have one reserve capacitor to be used as described early. Also load shedding is added into the main logic. The aim was to develop control logic with minimal inputs and keep the logic also adaptive, meaning less effect on less disturbances as presented in Figure 3.1.

Four different logics were built to control DGU's reactive power production, activation of reserve capacitor bank, on-load tap changer by locking it or/and activation of reverse operation and load shedding. Outputs of these four alarm signals were named as ALARM 1, ALARM 2, ALAMR 3 and ALARM 4 as in Figure 3.1.

4.2.1 ALARM 1 - boost the DGU reactive power reserves

ALARM 1 logic was built to boost DGU's reactive power (Figure 4.9). Purpose of the first alarm is to force DGU's to produce more reactive power even if the voltage level is in feasible level at DN side. This can be achieved by injecting additional signal which multiplies the V_{ref} –signal in the excitation when the transmission side voltage drops below limit (0.95 pu) if the DN side voltage is lower than the upper limit V_{dmax} of the DN system. Larger the dip at transmission side voltage, larger the injected excitation boost is. The reactive power production is limited by OEL of the DGU and DN-side voltage V_{dmax} which upper limit is defined to be 1.10 pu. OEL limit is based on DGU's rated power as previously described.

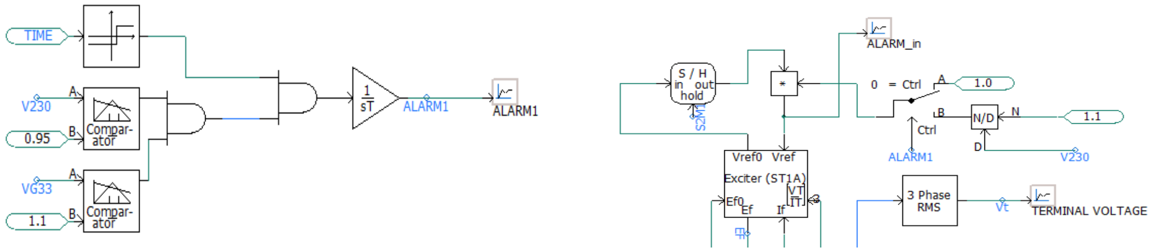

Figure 4.9 Block diagram for ALARM 1. Signal “V230” is the voltage from TN side in pu and signal “VG33” is the voltage from DN side in pu.

For example if excitation input would be in normal operation 1.0 pu, and when an ALARM 1 is presented, this excitation input 1.0 pu is multiplied by 1.1 divided by transmission side voltage, which would be less than 1, actually less than 0.95. This will give immediately boost to increase excitation. More transmission side voltage fells for example during voltage dips, more powerful the boost is. At ALARM 1 stage also OLTC is blocked to prevent its normal action. OLTC logic is presented more specific later.

4.2.2 ALARM 2 – activation of reserve capacitor bank

ALARM 2 is used to activate capacitor banks in the DN side (Figure 4.10). This has two requirements which only one has to be active to connect the capacitor bank. If ALARM 1 has been activated for specific time t_c, meaning that V_d or V_t are still below the limits or if the voltage starts to collapse more below specific value (e.g 0.90), the capacitor bank breaker is operated.

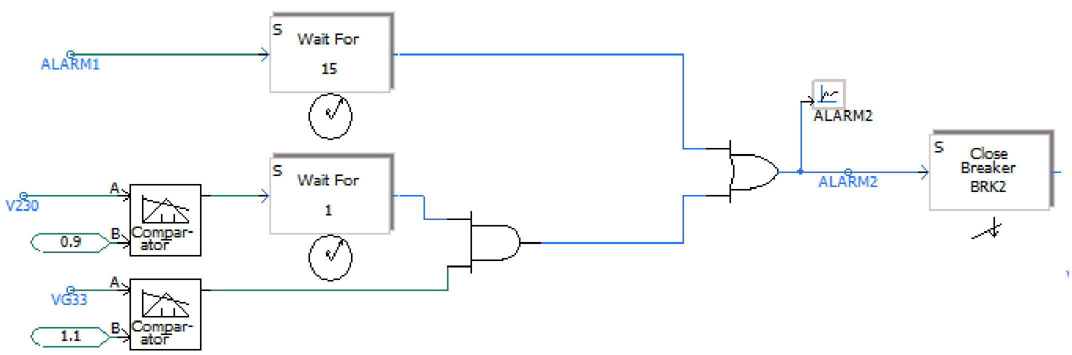

Figure 4.10 Block diagram for ALARM 2. Signal “V230” is the voltage from TN side in pu and signal “VG33” is the voltage from DN side in pu.

4.2.3 ALARM 3 – reverse operation of on-load tap changer

This stage can be activated after ALARM 1 or ALARM 2. To activate ALARM 3 after ALARM 1 or ALARM 2, a specific time must pass, e.g. in Figure 4.11 it is 30 seconds. Requirements are that DGU's reactive power boost must have been on for specific time t_{rev} and the voltage V_t is between the level in transmission side of $V_t + \delta$ and $V_t - \delta$ and also V_d must be higher than V_{dmin}. Logic shown in Figure 4.11.

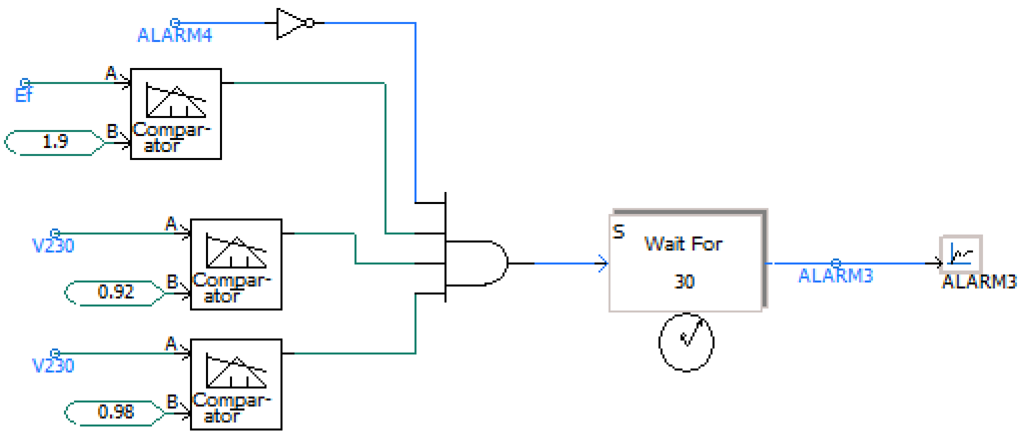

Figure 4.11 Block diagram for ALARM 3. ALARM 3 activates reverse operation of on-load tap changer which aims to decrease DN voltage according to the voltage difference in TN.

ALARM 3 signal releases the tap changer when it was locked in ALARM 1 section. ALARM 3 signal also changes the voltage measurement from DN-side to TN-side and reverses tap changer control signal by changing the multiplier from 1 to -1. This is how the tap changer will now decrease the secondary voltage (DN) if the voltage at primary side (TN) and/or at secondary side (DN) are lower than nominal value. Tap changer logic presented in Figure 4.12.

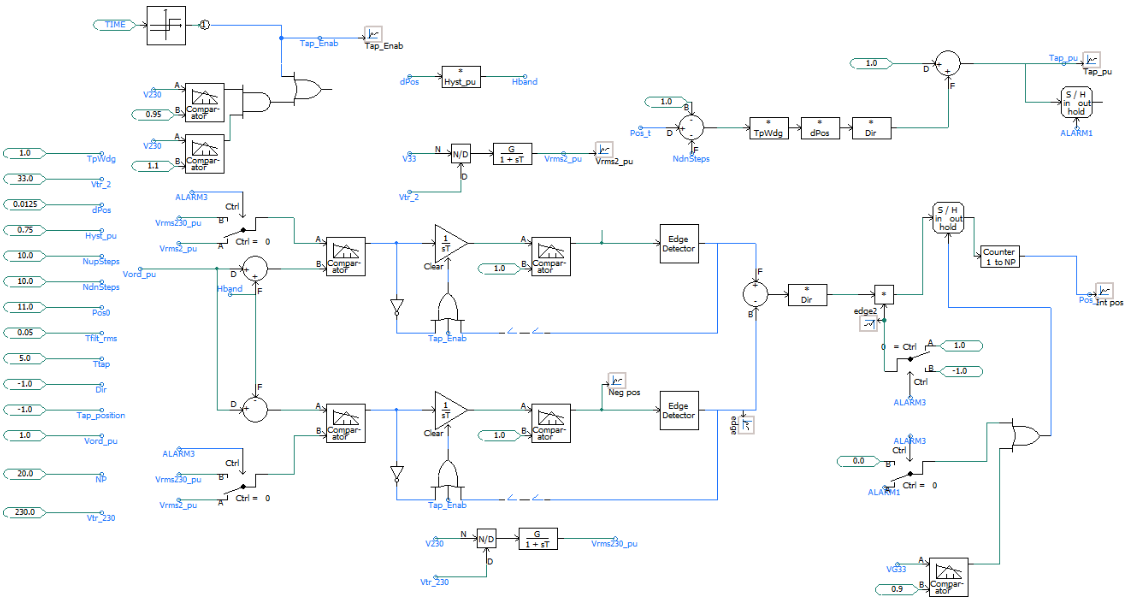

Figure 4.12 HV/MV transformer tap-changer control logic. ALARM 1 locks the tap changer. ALARM 3 activates the reserve operation of tap changer.

If load shedding is active (ALAMR 4), the tap changer is again locked because ALARM 3 will be deactivated. Load shedding is logic is presented in next chapter.

4.2.4 ALARM 4 – load shedding

Most intrusive method for voltage support from DSO to TSO is the load shedding which is the last action to recover voltage levels. For the load shedding function each AND's load is divided into four different parts which are equal to each other's. Logic for load shedding is that capacitor bank must be activated and the voltage V_t is still below V_{tmin1} for specific time t_{L1}. If these requirements are met, then 25 % of the load is disconnected and after a specific time t_{L2} if V_t will not recover up to V_{tmin1} another 25 % is disconnected etc. This logic actually requires DGU's to be at full reactive production, capacitor bank connected and if feasible, tap changer has tried to lower the secondary voltage to lower the loads or this load shedding can occur really fast without tap changer reverse operation.

Below in Figure 4.13 is presented how these alarm stages are affecting to the reactive power flow from TN side to DN side. In this case TN side is presented as infinite source and the ADN's control logic is implemented.

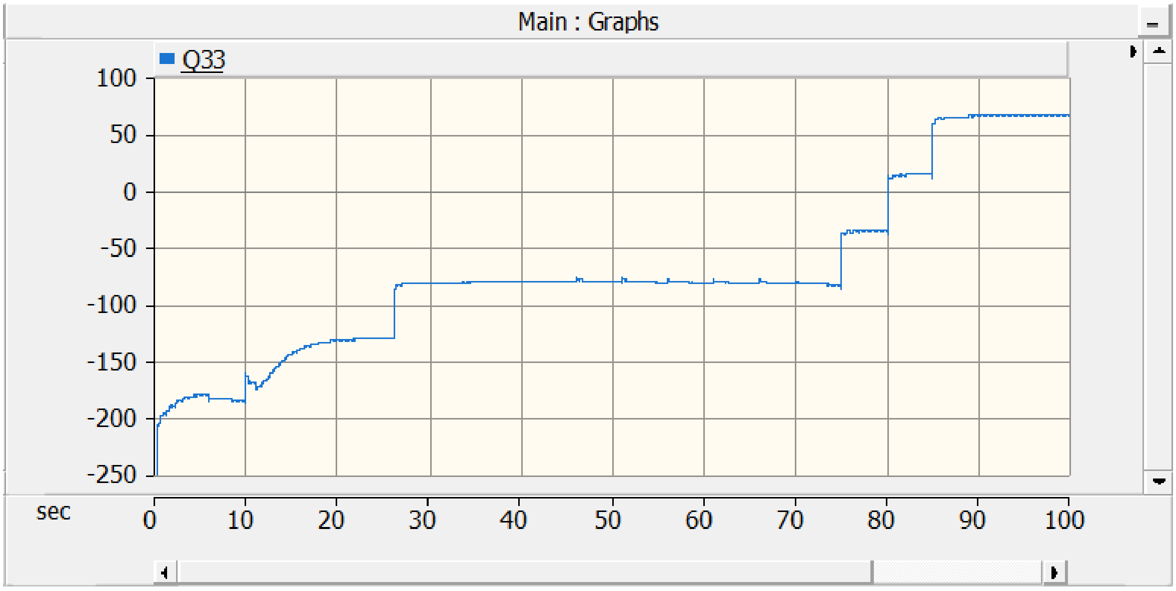

Figure 4.13 ADN's ALARM-logics activated to support TN side voltages by lowering the reactive power transmission from TN to DN.

Q33 represents the reactive power [MVAr] transfer from TN-side. At t = 10 s ALARM 1 is activated and DGU reactive power production is boosted. At t = ~28 s ALARM 1 has been active for 15 seconds and DGU reactive power capacity is reached (80 MVAr). At that time ALARM 2 control logic connects the capacitor bank (ALARM 1 activated $\geq t_c$ = 15 s,). After 45 seconds ALARM 3 comes active and OLTC reverse operation is trying to decrease DN side voltage to lower the reactive power flow. In this case OLTC reverse operation is insufficient because the load characteristics (see chapter 2.1.2 $NQ = NP = 0.5$). Finally at 75 seconds load shedding starts and total of 75 % loads are disconnected in 5 second steps. The DN network is now actually importing reactive power to the TN side with its reactive power production by DGU and capacitor bank. Terminal voltage of DGU is presented in Figure 4.14.

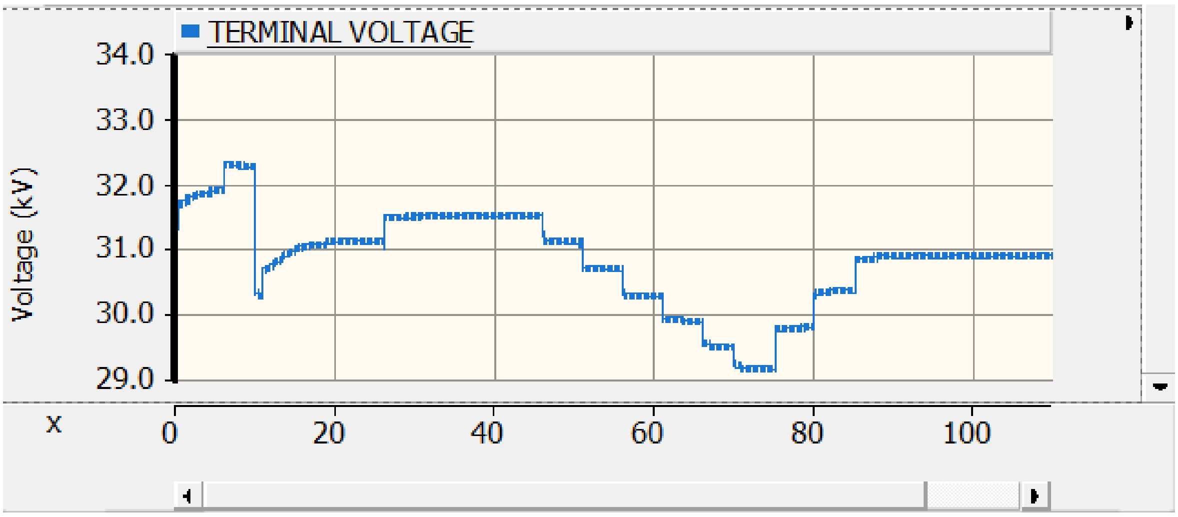

Figure 4.14 DGU's voltage variation during emergency control. Failure occurs after 10 seconds followed by DGU's reactive power production boost up to 25 seconds. After 28 seconds capacitor bank is connected. After 45 seconds tap changer reverse operation decreases the DN-side voltage to lower power. After 75 seconds load shedding starts.

Tap changer control logic can be seen in the Figure 4.15. At time t = 0 - 10 s tap changer control logic is normal and OLTC aim is to adjust the DN side voltage until nominal voltage. At 10 s ALARM 1 is activated and the tap changer is locked. At t = 45 s tap changer reverse operation is active and the voltage at DN side is being decreased. At t = 75 s operation is again locked because load shedding starts. Load shedding stops at 90 seconds after 3 of 4 loads are disconnected and TN side voltage has increased enough up to 0.95 pu. Then ALARM 4 decays and ALARM 3 becomes active again and tap changer reverse operation continues.

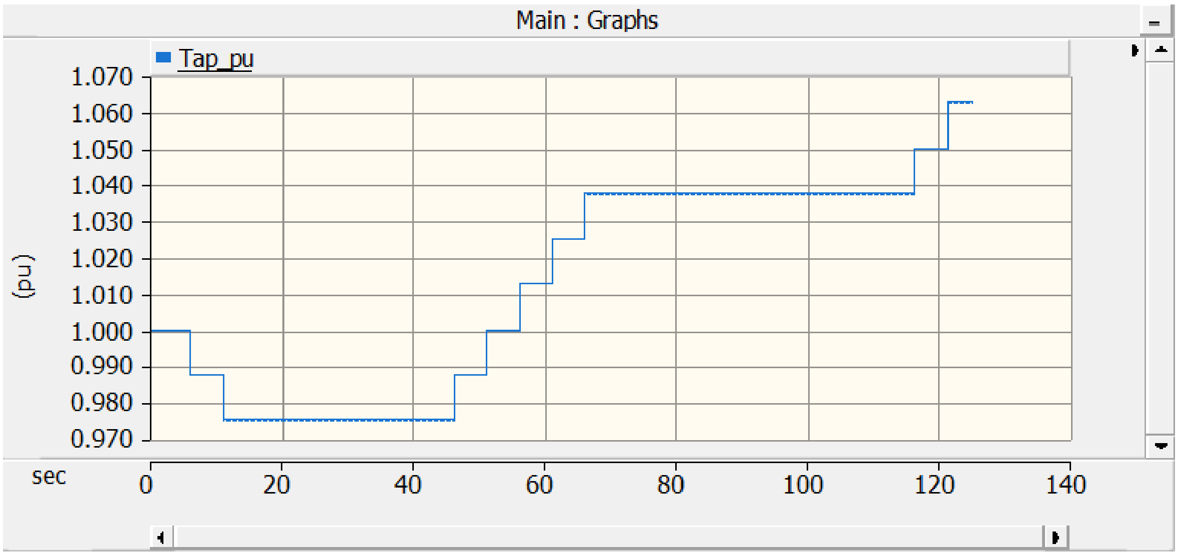

Figure 4.15 ADN's tap changer operation during emergency situation. Normal operation during t = 0 – 10 s, locked because of ALARM 1 at t = 10 – 40 s, reverse operation (ALARM 3) t = 40 – 70 s, locked (ALARM 4 active) t = 75 – 110 s and reverse operation t = 75 – 110 s.

PQ-curve (Figure 4.16) points out the function of proposed emergency control. As the aim was to move more feasible region in PQ-diagram to ensure stability (Figure 2.3), this can be observed to be successfully reached and in proper order. First the trajectory moves directly down, decreasing the reactive power but maintaining the real power, not affecting the loads. In the worst case (Figure 4.16) the stability was not reached and load shedding starts to act bringing the PQ in feasible region to maintain stability. Stability is reached when delivery from transmission network is P = 55 MW and Q = –65 MVAr, meaning that ADN's nominal load is decreased down to 25 % meaning total of 450 MW and 150 MVAr load shedded. DN is transferring reactive power to the TSO.

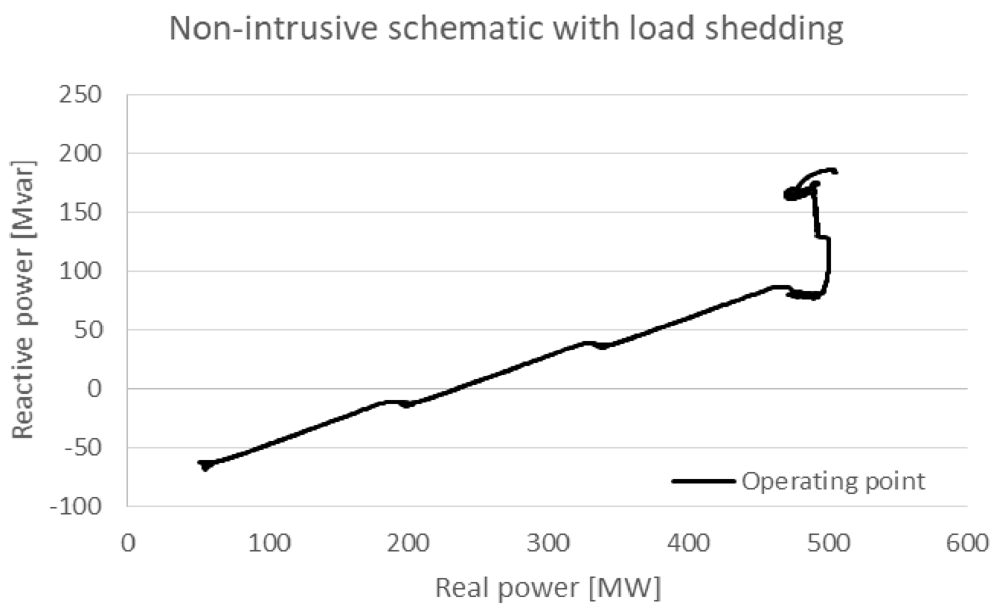

Figure 4.16 PQ-diagram of proposed control system in simplified model. At the beginning of the event trajectory is on maximum point where real and reactive power transfer from TN is at highest. First proposed control system maintains real power transmission and decreases reactive power transmission. At last load shedding starts and real power transmission from TS is reduced as the loads are decreased.

5 Simulation Results and Discussions

Previously presented control logics for voltage emergency support was tested in previously presented and implemented IEEE 39 bus system. Before the studies the system was run to confirm that every generator, ADN's and the system itself were stable. All voltages at TN side generator buses were in range of 0.98-1.01 pu as seen in Figure 5.1. When changes were made to the load characteristics, a small adjustments needed to be made to keep the voltages on limits at TN side.

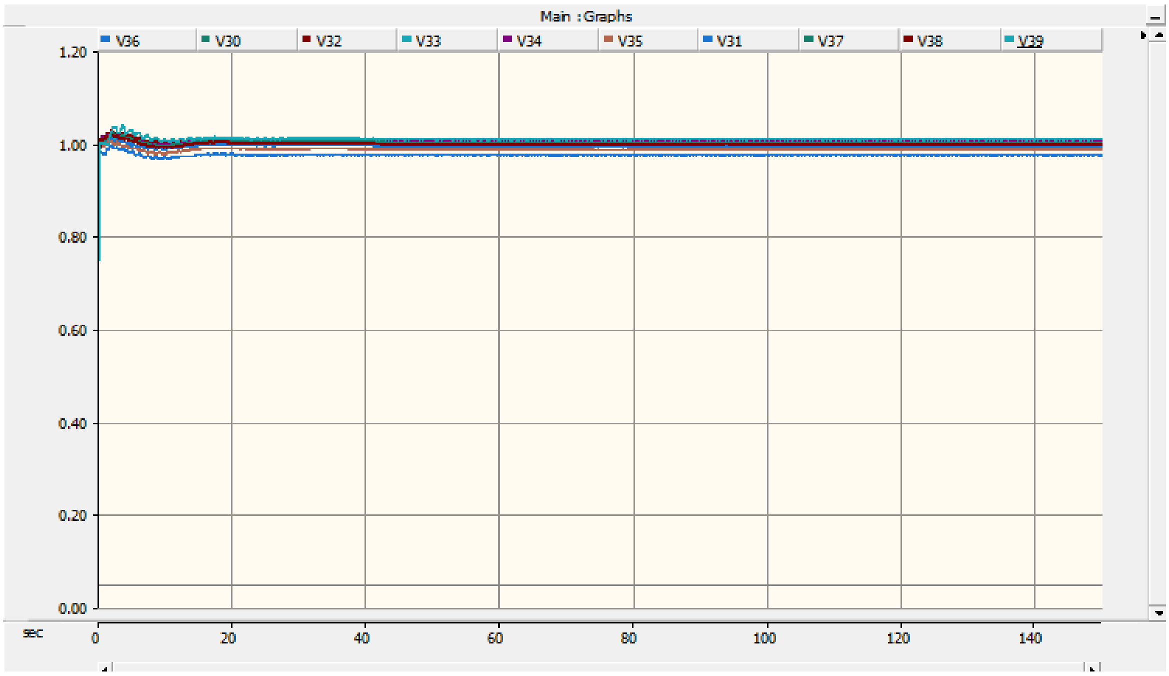

Figure 5.1 Testing the simulation without any faults. All voltage levels are in feasible level and between ranges of 0.98-1.01 pu.

Voltage emergency situation was simulated by tripping the line T5_6 between the bus 5 and bus 6 at 20 seconds. At 30 seconds line T12_14 was tripped also (see Figure 4.7). A three phase short circuit was not simulated to cause the trip, as usually done, to prevent unnecessary system oscillations.

Simulations were run with different alarm functions activated and with different load characteristics used. All ADN's had same load characteristics per simulation and other loads in the simulation were fixed constant power loads. Load characteristics were determined with exponential model which was explained in chapter 2.1.2. Exponents *NQ* and *NP* were changed to simulate constant power, constant current, constant impedance and also loads between these.

Table 4 Scenarios simulated with different control logics and load characteristics.

Scenario	DGU's increased Q production	Capacitor banks	OLTC reverse operation	Load shedding	Volt-Var index	Volt-W index
	Alarm 1	*Alarm 2*	*Alarm 3*	*Alarm 4*	*NQ*	*NP*
1	on	on	on	off	2	2
2	off	off	off	off	1	0,8
3	on	off	on	off	1	0,8
4	on	on	on	off	1	0,8
5	on	on	disabled	off	1	0,8
6 *	on	on	on	off	0,5	0,5
7	on	on	on	off	0	0
8	on	on	on	on	0	0
9 **	on	on	on	on	0	0

* Also alarm functions off and interactive collaboration between ADN's simulated.

** Different time constants used

5.1 Scenario 1

This scenario was run with all alarms activated expect load shedding. Load characteristics were chosen to model constant impedance. Figure 5.2 shows sufficient operation of emergency control. Also reverse operation of tap changer shows high impact on transmission side voltages.

At *t* = 20 s first line T5_T6 trips, 10 s later T12_14 trips, this is the basic emergency situation in transmission side in all scenarios.

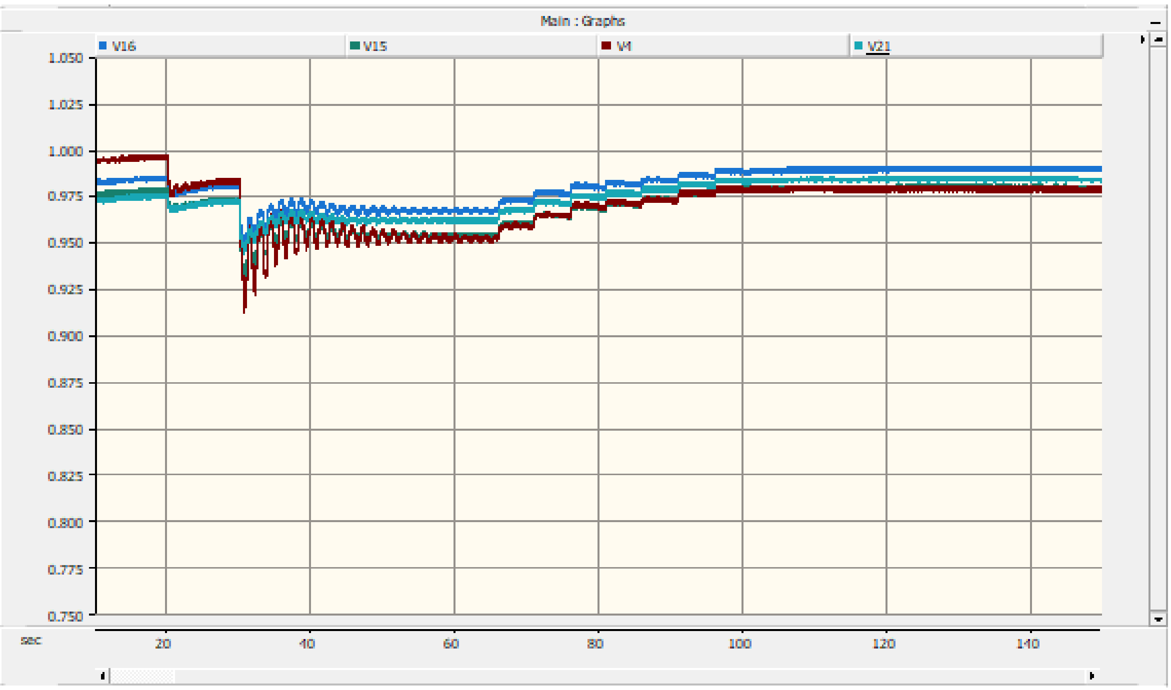

Figure 5.2 Scenario 1: Voltages at transmission side in pu during emergency situation. Trend of transmission side load voltages. Scale 1.00 pu = 230 kV.

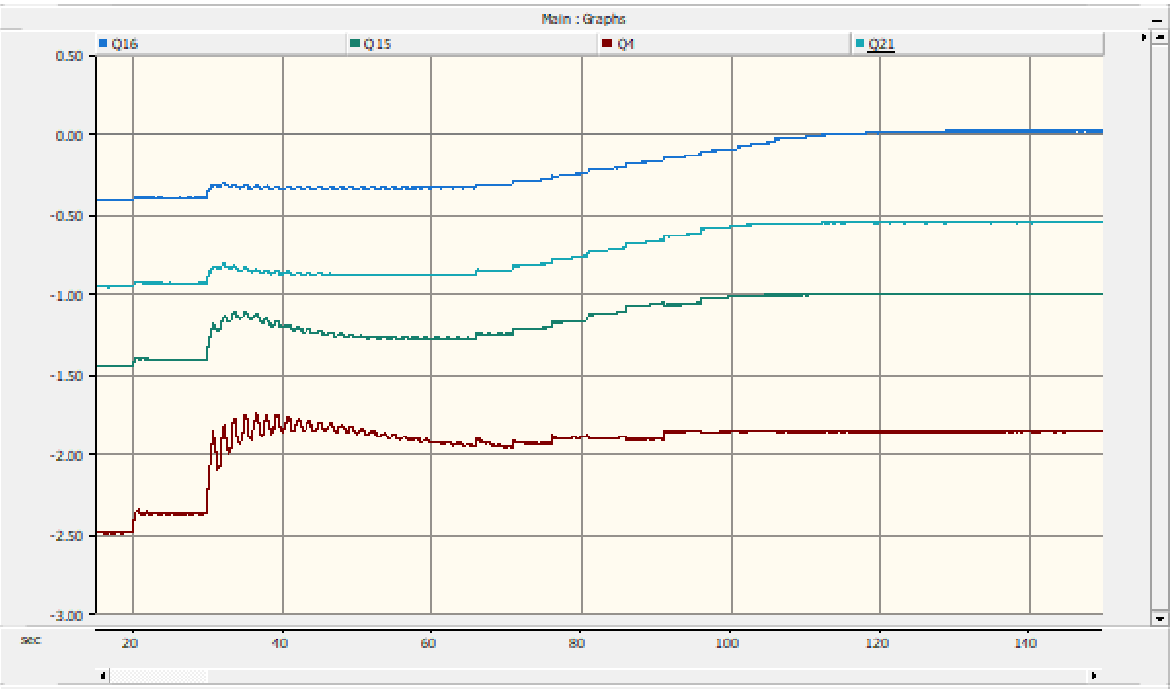

Figure 5.3 Scenario 1: Reactive power transfer between ADN's and TN's during emergency situation. Scale 1.00 pu = 100 MVAR.

According to Figure 5.3 natural reduction of reactive power consumption can be detected at 20 seconds in all ADN's when transmission side voltage decreases suddenly after the first line trips. TSO voltage has direct impact on DSO voltage, and therefore according to load characteristics, decreases the load demand. During the emergency situation, OLTC is locked, DGU's are producing more reactive power depending on how large is the voltage dip in TN side. Load voltage reduction has high impact in constant impedance model to transmission side voltages. Tap changer reverse operation is lifting the transmission voltage effectively up. Reserve capacitors in ADN's 4, 15, 16 and 21 are not activated because the voltage dip did not reach limit in their TN side. This is an example about adaptability, less critical change requires less critical actions. ADN's 16 and 21 are not affected as strong as ADN's 4 and 15.

5.2 Scenario 2

Scenario 2 load characteristics are chosen according to the study "A Non-intrusive scheme" (Ospina et al. b, 2021). Reactive powers of the loads are modelled as constant current and real powers nearly at same. Also now all the alarm functions are blocked to see the effect.

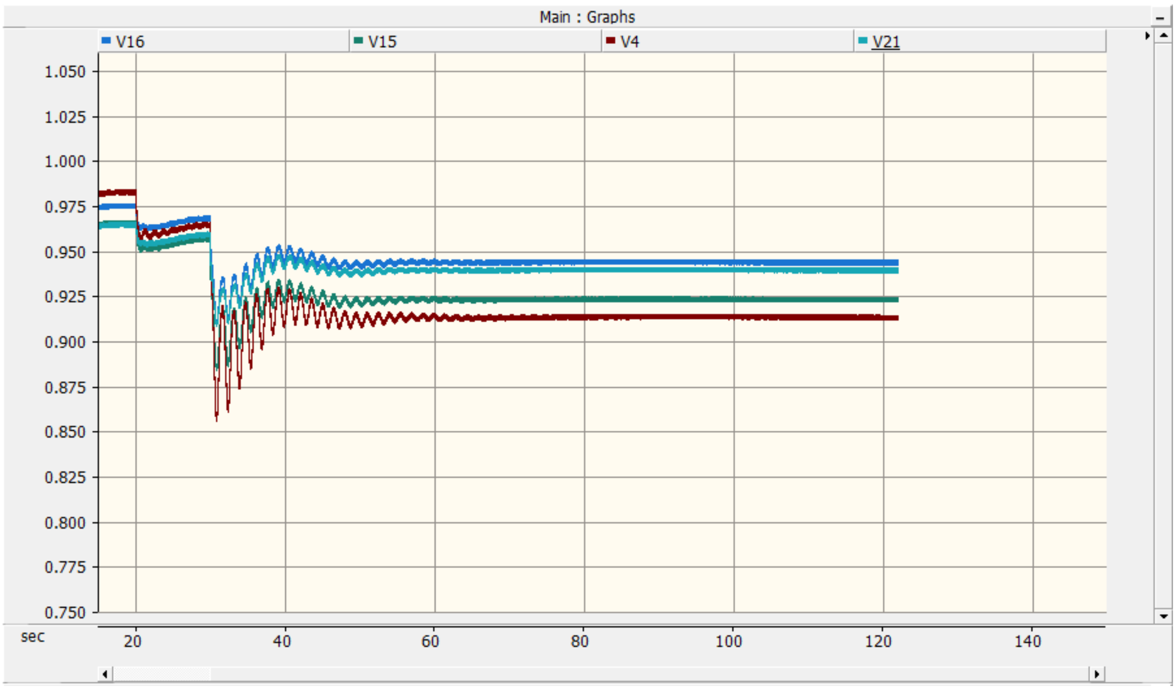

Figure 5.4 Scenario 2: No alarm functions activated during emergency situation. Trend of transmission side load voltages. Scale 1.00 pu = 230 kV.

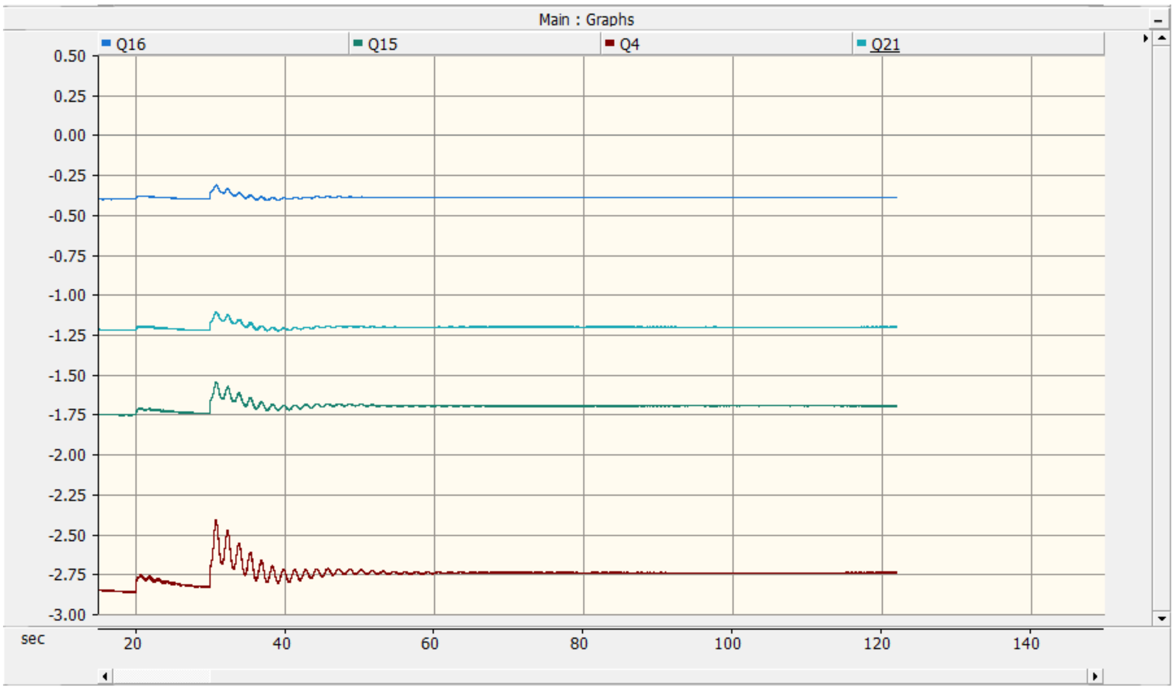

Figure 5.5 Scenario 2: No alarm functions activated. Reactive power transfer between ADN's and TN's during emergency situation. Scale 1.00 pu = 100 MVAR.

As Figure 5.4 and Figure 5.5 explains only natural reactive power decrease according to load characteristics is shown. Voltages are transmissions side remains too low < 0.95 pu, but the power system remains stable, since no voltage collapse is seen.

5.3 Scenario 3

In Scenario 3 all alarm functions except load shedding and capacitor banks are blocked (Figure 5.6 and Figure 5.7).

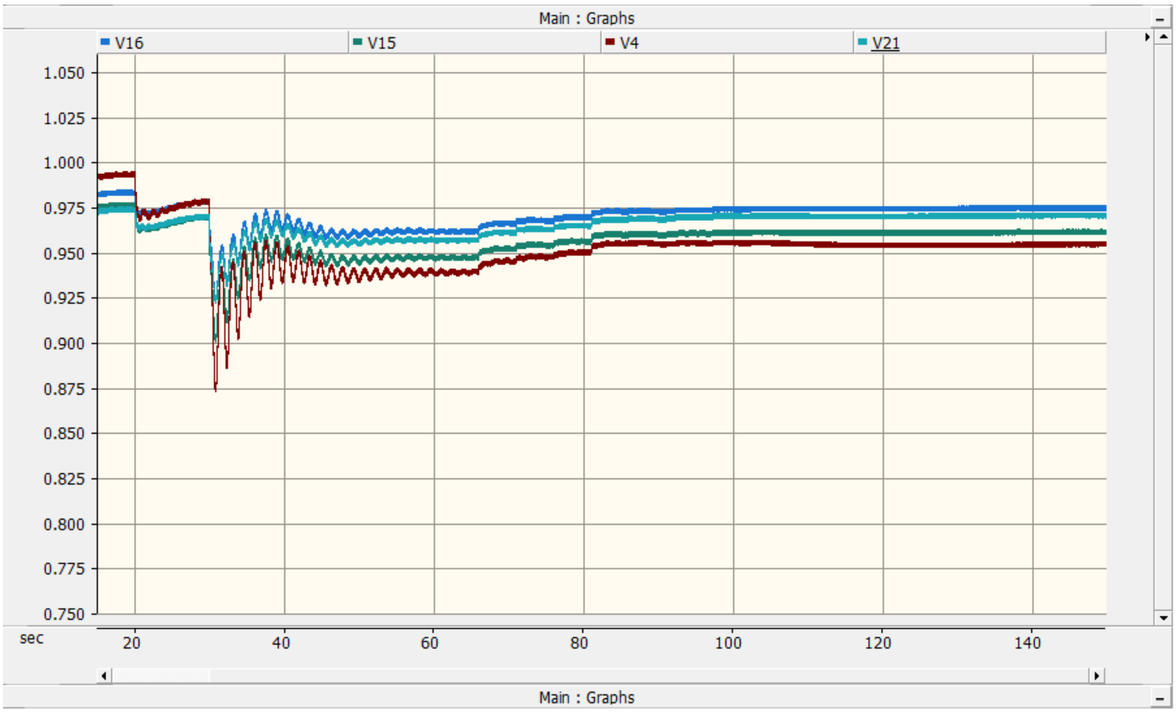

Figure 5.6 Scenario 3: Alarm functions activated except load shedding or reserve capacitor banks. Trend of transmission side load voltages. Scale 1.00 pu = 230 kV.

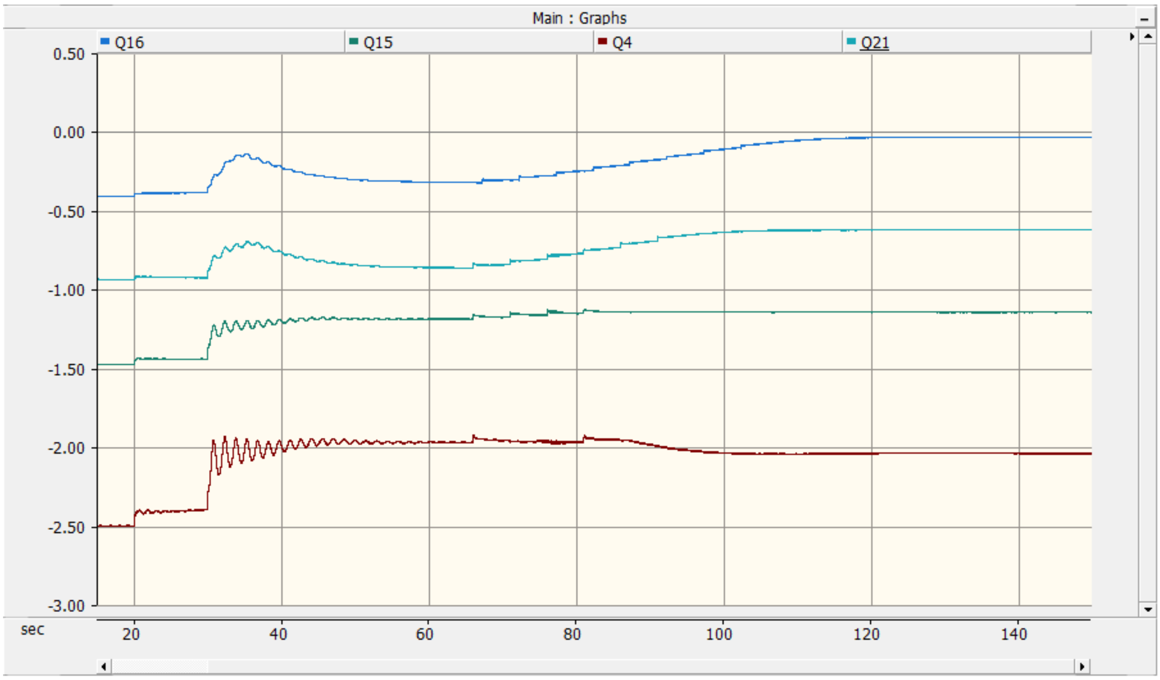

Figure 5.7 Scenario 3: Alarm functions activated except load shedding and reserve capacitor banks. Reactive power transfer between ADN's and TN's during emergency situation. Scale 1.00 pu = 100 MVAR.

When comparing Scenario 2 without any alarm control and Scenario 3 with partial alarm control, it is obvious that alarm functions will bring the transmission side voltage to feasible level > 0.95 pu, but still remains significantly low. All DGU's are activating reactive power boost depending of the voltage dip at TN side. Tap changer reverse operation is decreasing DN voltage to lower the reactive power transfer from TN, which can be seen also in increase of TN side voltage.

5.4 Scenario 4

Scenario 4 is done according to Scenario 3 but reserve capacitor banks are not blocked. Figure 5.8 and Figure 5.9 points out that even better transmission side voltage is reached. Only two ADN connected their reserve capacitor from alarm functions.

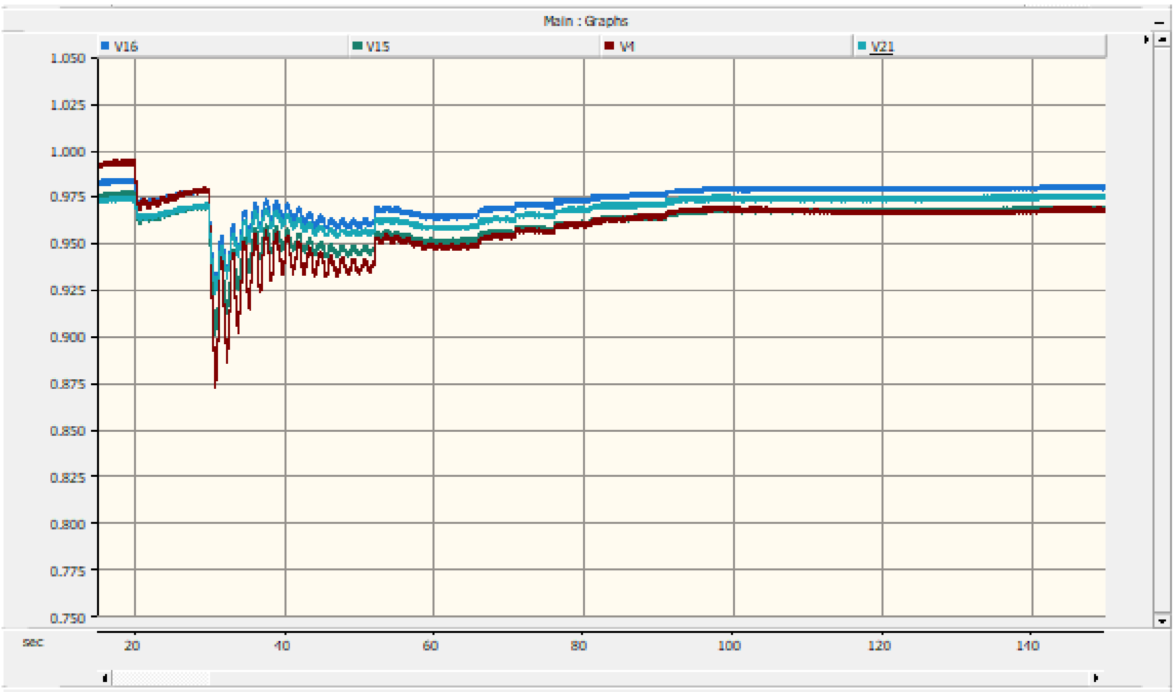

Figure 5.8 Scenario 4: All alarm functions except load shedding used. Trend of transmission side load voltages. Scale 1.00 pu = 230 kV.

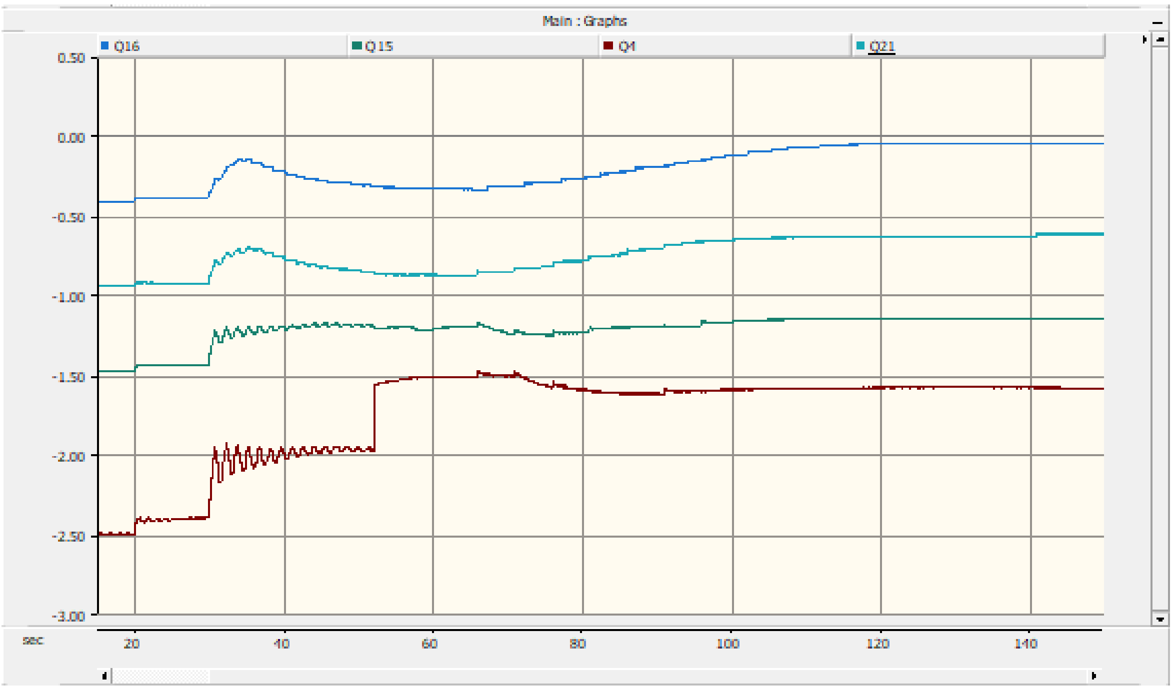

Figure 5.9 Scenario 4: All alarm functions except load shedding used. Reactive power transfer between ADN's and TN's during emergency situation. Scale 1.00 pu = 100 MVAR.

DGU's are boosting significantly reactive power to the load at t = 30 s, which can be seen as decrease of reactive power transmission from TN. Reserve capacitor bank is connected in ADN 4 at t = 55 s. According to TN voltage graphs, reverse operation of tap changer brings the TN side voltage nearly on feasible level.

5.5 Scenario 5

Scenario 5 was done to illustrate what would happen if the tap changer control is not reversed. In this case tap changer is on original control and it aims to maintain nominal voltage at DN-side. Tap changer is locked until 65 seconds and released then to normal operation. Figure 5.10 and Figure 5.11 points out total power system collapse. At loads 15 and 16 reactive power consumption is increasing, while in 4 and 21 it's also slightly increasing. Capacitor banks at loads 15 and 16 are activated near the system collapse. Cascading voltage collapse starts when first TN side generator is tripped by OEL and UVP. Cascading voltage collapse is analysed in later chapter more detailed.

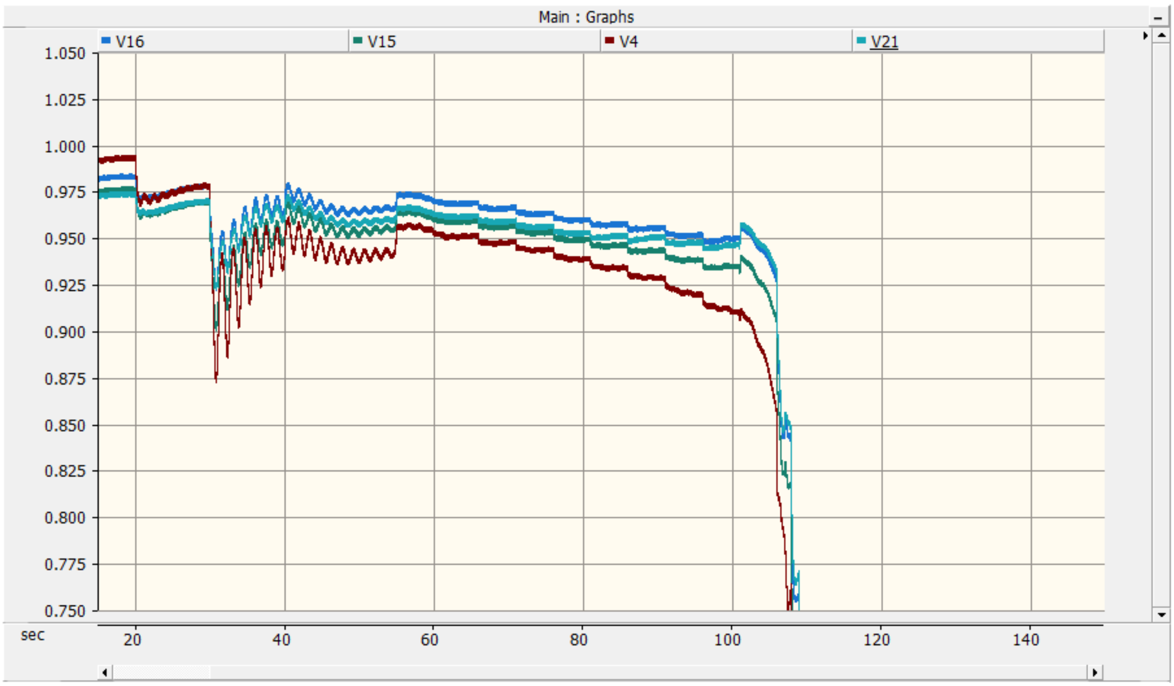

Figure 5.10 Transmission side voltages at connection points of ADNs during emergency control in Scenario 4. Scale 1.00 pu = 230 kV. Tap changer is released at *t* = 65 s and reverse operation is not used. Power system collapses due to the operation of tap changer.

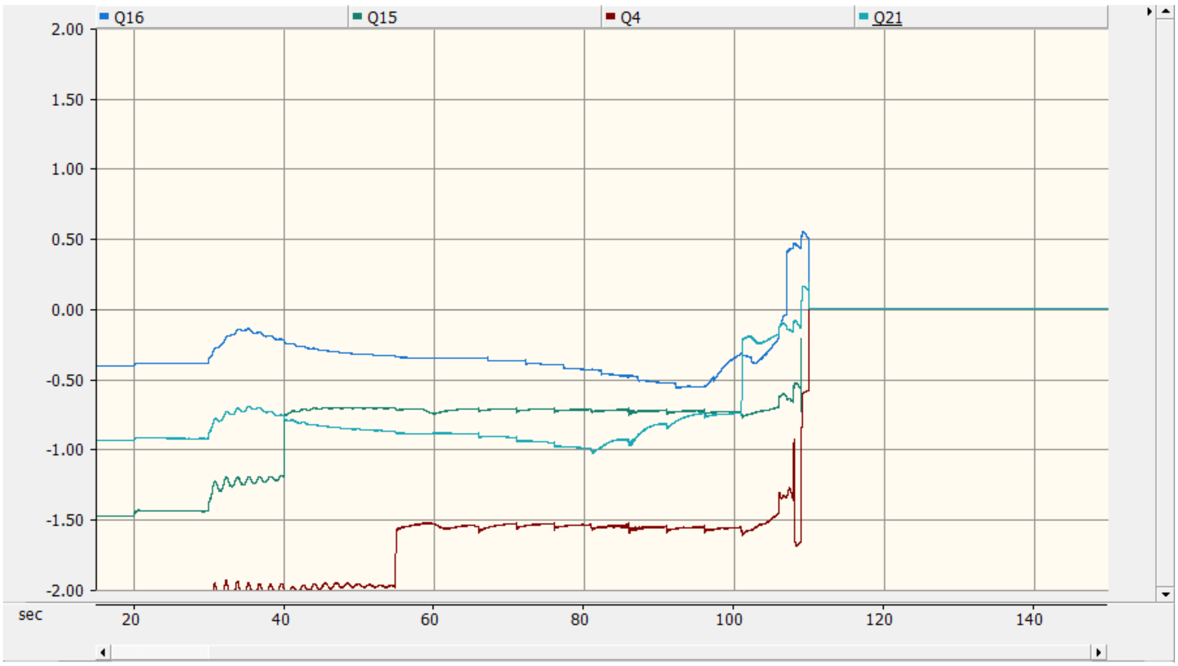

Figure 5.11 Reactive power flow between ADNs and TN in Scenario 4, 1.00 pu = 100 MVAR. Tap changer is released at *t* = 65 s but reverse operation is not used. System voltage will collapse.

5.6 Scenario 6

Load characteristics were changed to be between constant power and constant current. Without any alarm functions system would collapse as shown in Figure 5.12. The power system collapses after the transmission side generators are on their limits of reactive power production. First OEL's are reached, then when the reactive power demand is still higher than production, voltages starts to collapse at generator terminals (as described in Chapter 2.1). This leads at first to a single generator trip, which even increases the demand for reactive power (and real power) even more from the rest of generators, and then leads to a second generator trip. This is typical cascading effect and can be seen to happen in seconds when the power system is already in emergency situation.

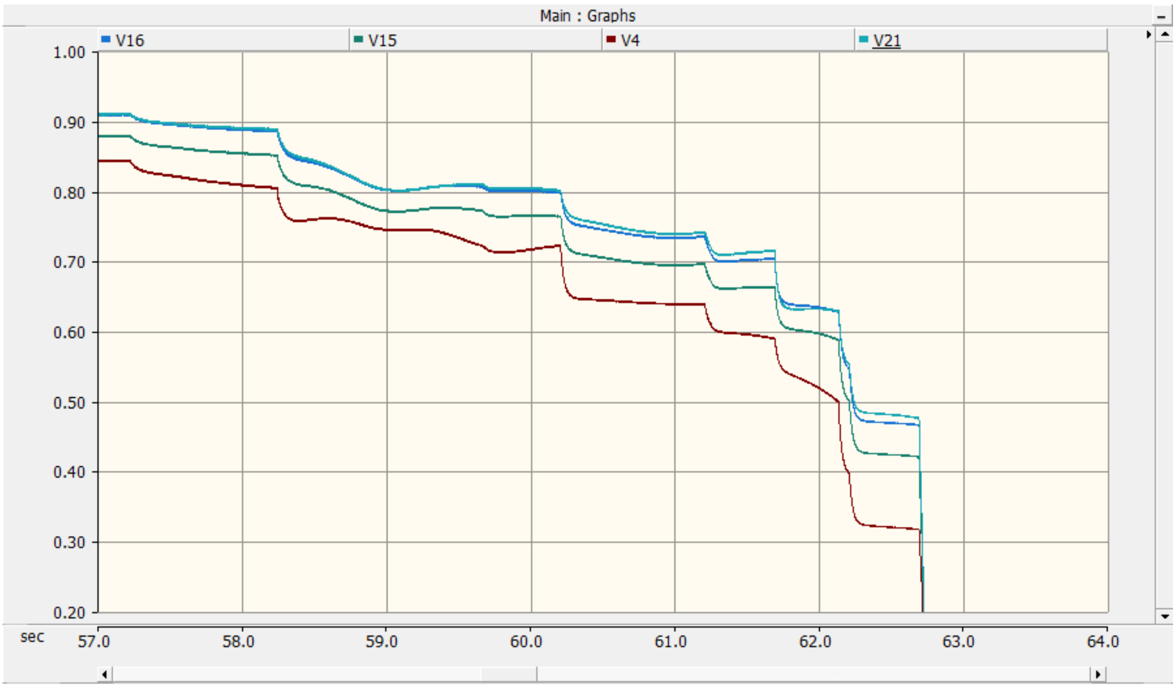

Figure 5.12 Transmission side voltages at connection points of ADNs during emergency control in Scenario 6 without alarm functions. Whole power system collapses.

If all alarm functions expect load shedding is used, the following situation is reached as shown in Figure 5.13.

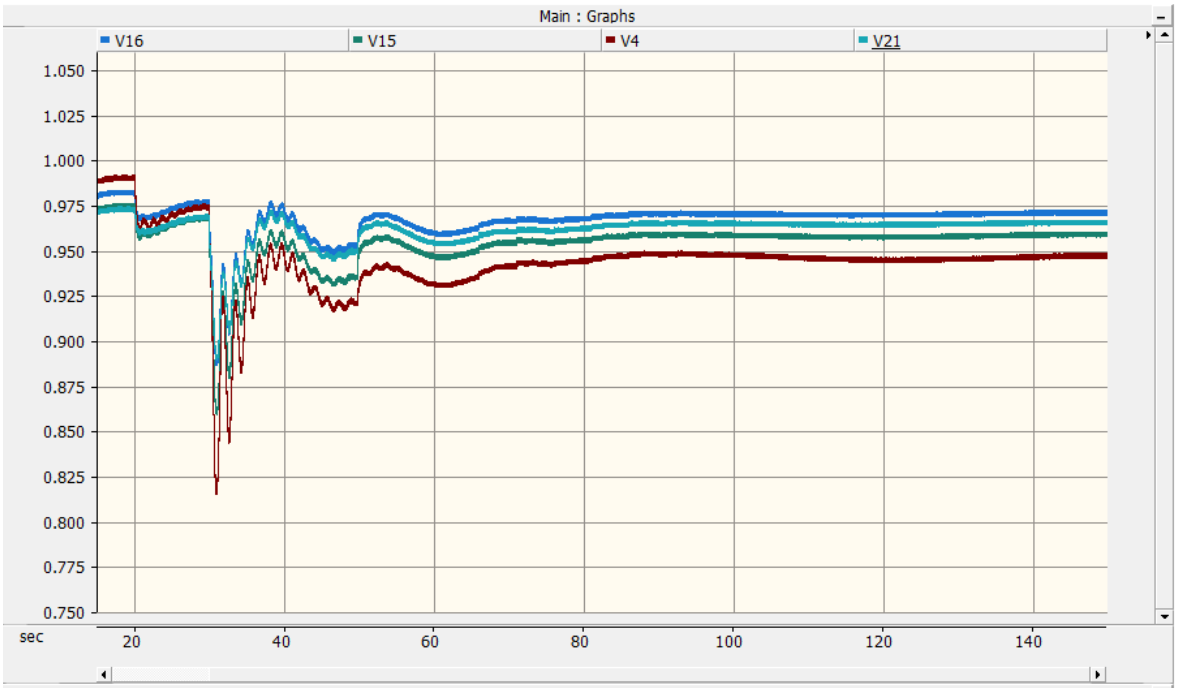

Figure 5.13 Transmission side voltages at connection points of ADNs during emergency control in Scenario 6 with alarm functions. Voltage levels are maintained in correct level.

As seen in Figure 5.13 voltage at load 4 is slightly at 0.95 pu, which is the minimum for transmission voltage. If looking the ADN's data, reserve capacitors at load 15 and 16 were not activated since their limits were not reached as the voltages of these parts are not heavily affected compared to loads 4 and 21. This leads to the demand of interactive collaboration between ADN's. ADN's could share this information and request reserves from other ADN's located in the region. As a result it would give better transmission side voltage as seen in Figure 5.14 and Figure 5.15.

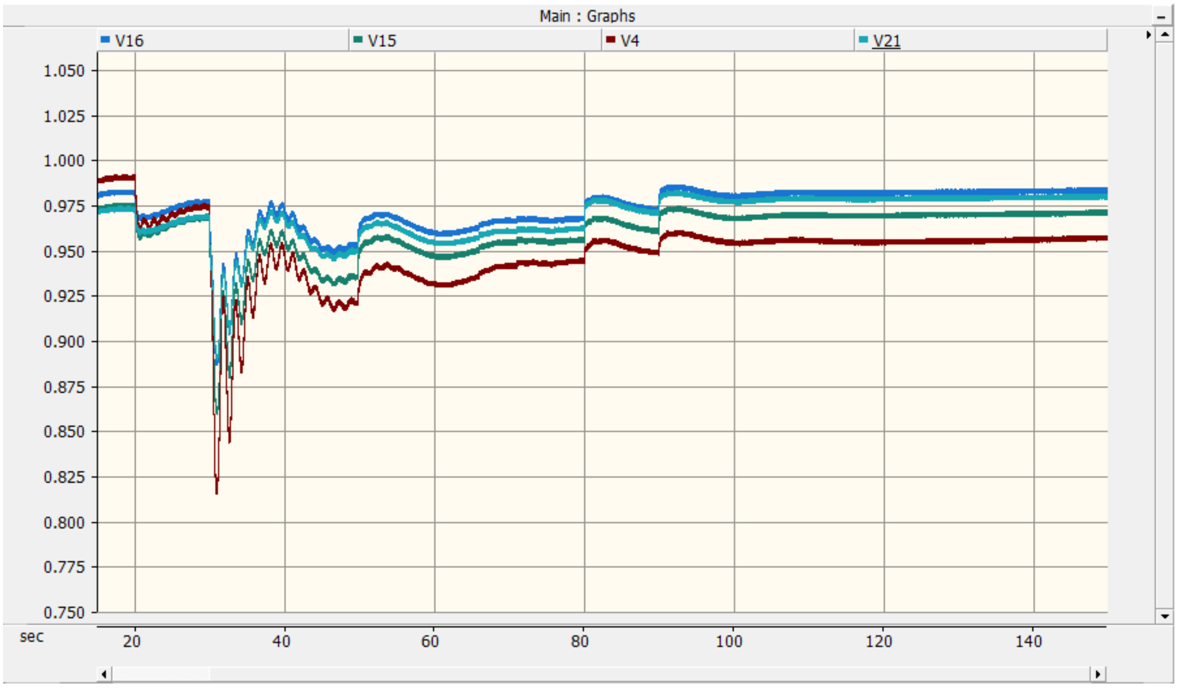

Figure 5.14 Interactive collaboration between ADN's to support voltages of weak busses has sufficiently recovered the voltage levels at transmission side.

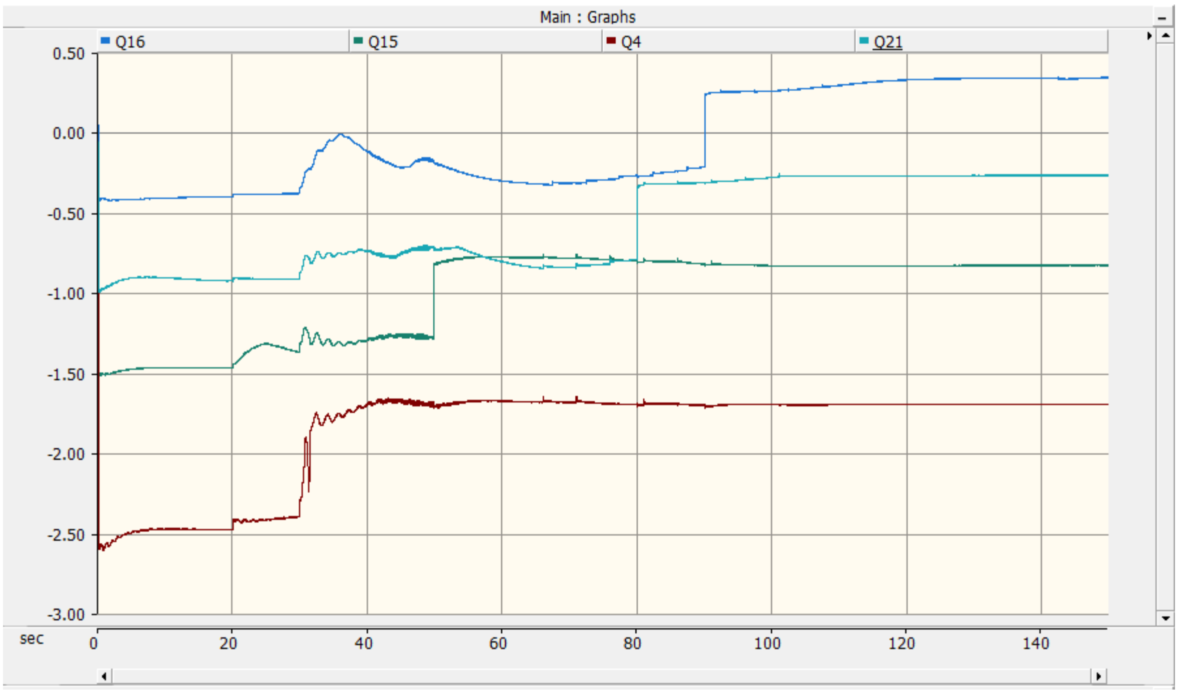

Figure 5.15 Interactive collaboration between ADN's to support voltages of weak buses. Reactive power transfer between ADN's and TN's during emergency situation, 1.00 pu = 100 MVAR. All reserve capacitors are connected.

5.7 Scenario 7

Scenario 7 is modelled as constant load. With all alarm functions expect shedding activated, system collapses after 5 seconds of the second line failure as seen in Figure 5.16.

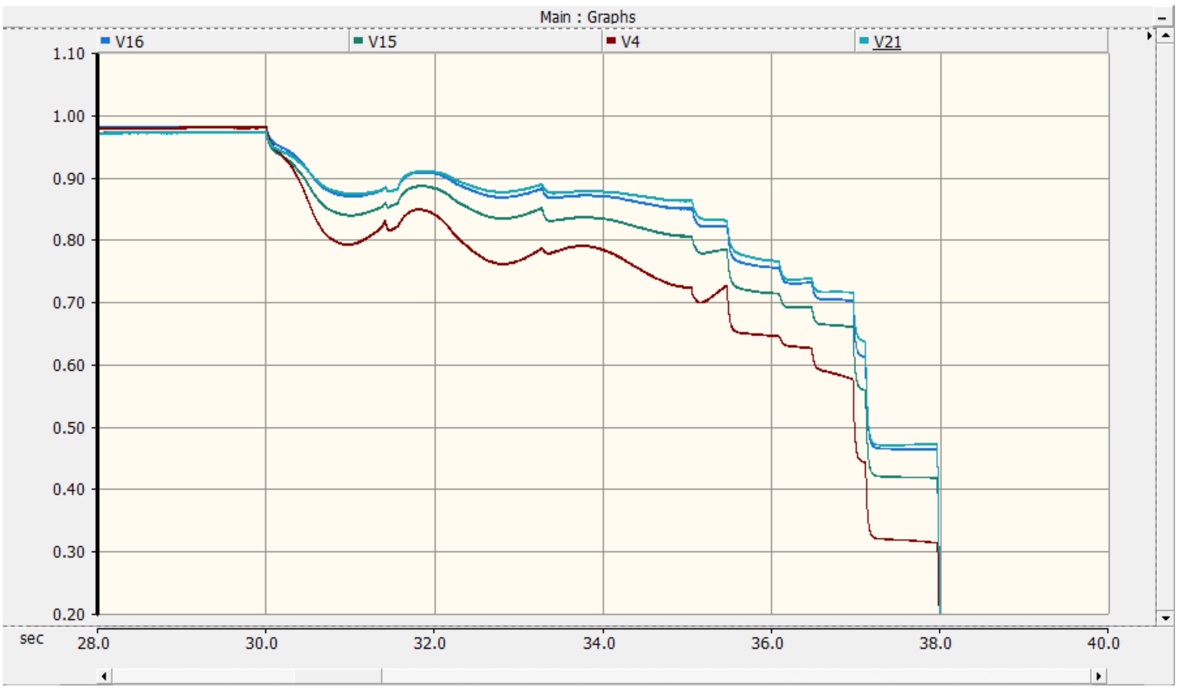

Figure 5.16 Scenario 7: Emergency support fails to recover voltage without load shedding in constant load model. Cascading voltage collapse in the power system occurs.

In this scenario the request of real and reactive power are not decreasing as the voltage decreases, therefore the natural effect is not shown as in previous scenarios at all. In constant load models DN voltage reduction is also insignificant tool for voltage support, since the load will not change. Constant load models are the most challenging load characteristics in this case.

5.8 Scenario 8

In scenario 8 load shedding is taken into use. Every load has constant power model and the loads are split into 4 equal parts for load shedding. Time constants presented in the proposed control logic in Figure 3.1 are set to values t_{L1} = 3 s and t_{L2} = t_{L3} = t_{L4} = 1 s. Load shedding is insufficient and the power system collapses as seen in Figure 5.17.

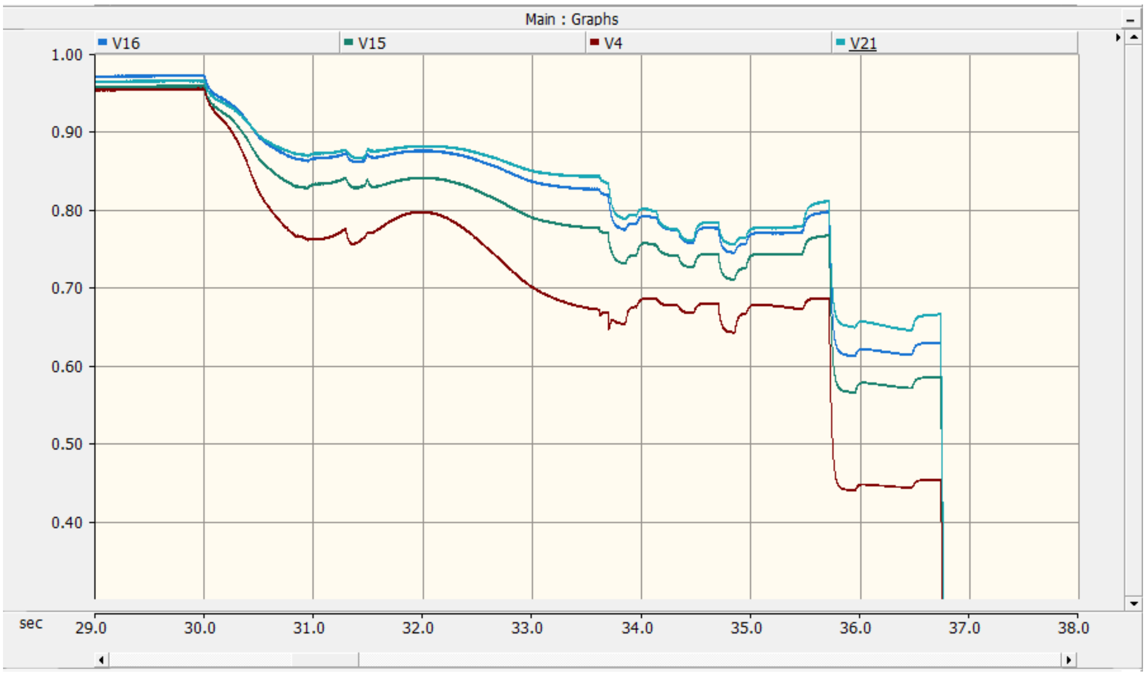

Figure 5.17 Scenario 8 cascading voltage collapse in constant power model.

Figure 5.18 represents ADN's operation. Reserve capacitors have been activated, but after *t* = 31 s, DGU of ADN 4 trips, and slightly after that DGU of ADN 15 trips also. Load shedding starts at *t* = ~34 s but is insufficient to prevent system level voltage collapse.

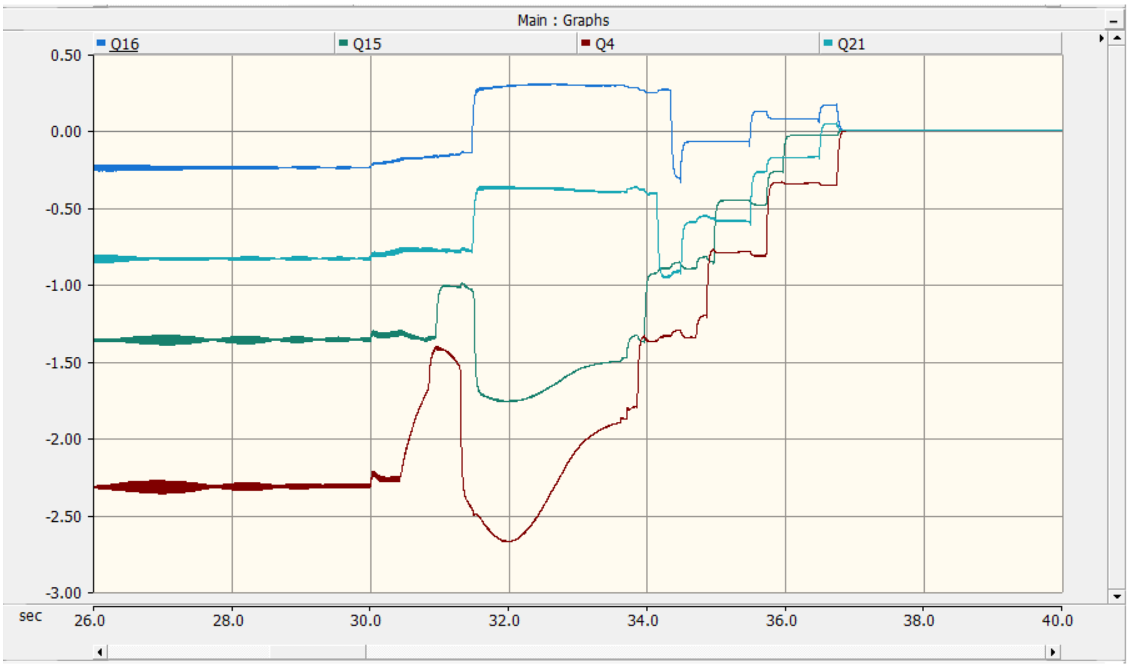

Figure 5.18 Scenario 8 power system collapse in constant power model. Reactive power transmission between TN and ADN's. 1.00 pu = 100 MVAr.

5.9 Scenario 9

In Scenario 9 (Figure 5.19) time constants presented in the proposed logic for emergency control are set to t_{L1} = 2 s and t_{L2} = t_{L3} = t_{L4} = 1 s, which means that load shedding will begin 1 second earlier compared to Scenario 8 where the system collapsed. Proposed load shedding prevents system collapse as seen in long term trend of ADN's transmission voltages in Figure 5.19.

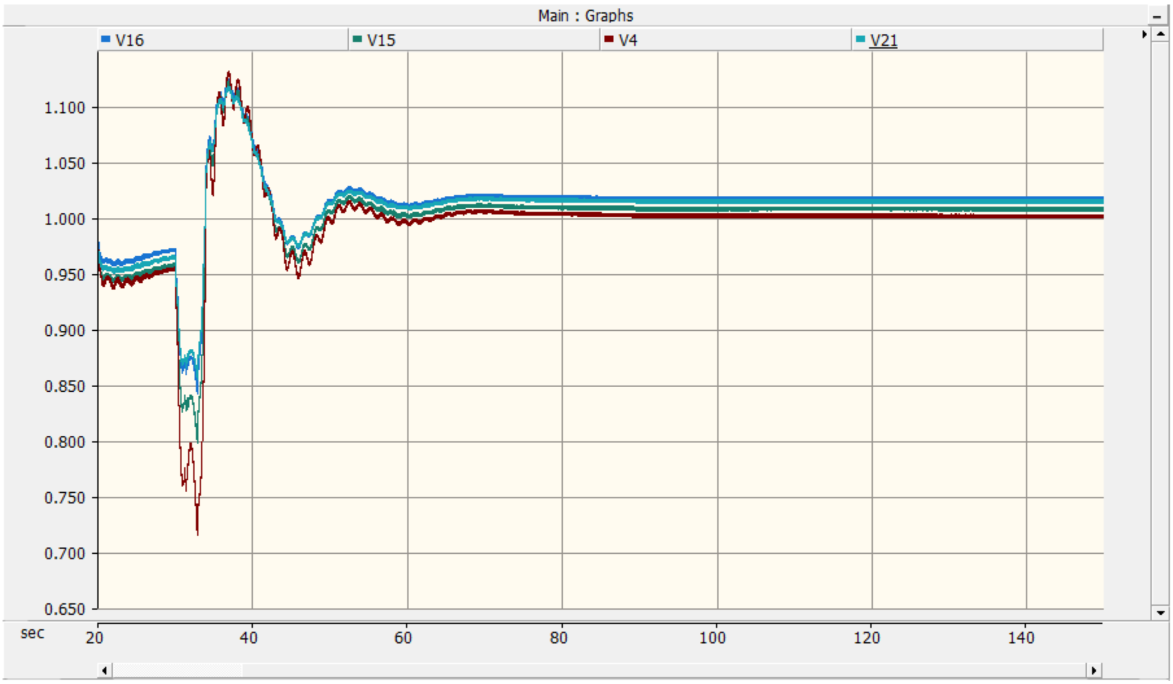

Figure 5.19 Scenario 9 load shedding prevents voltage collapsion. Load voltages from different ADN's. Load drops approximately 0.72 pu but recovers within 30 seconds to nominal range.

In Figure 5.20 is presented closer look of load voltages and in Figure 5.21 reactive powers transferred between transmission and distribution system. At first DGUs reactive power boosts are activated after voltage is less than 0.95 pu. Capacitor banks are connected in every ADN between t = 30 - 32 s. At t = 31 – 31.5 s DGUs at loads 4 and 15 trips. Load shedding starts by disconnecting first load at t = 32.8 s. Several other loads are disconnected to recover the voltage level at TN side. Even though two DGU's were lost due to over excitation and under voltage trip, load shedding is sufficient to recover the power system in stable situation.

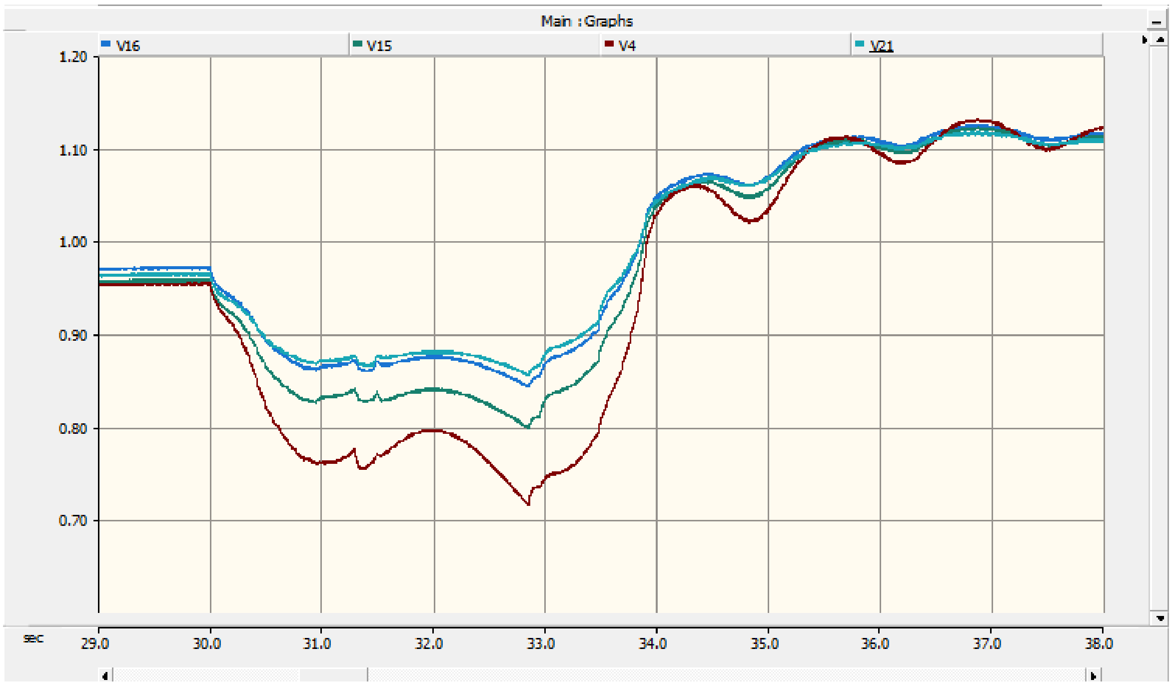

Figure 5.20 Scenario 9 load shedding prevents voltage collapsion. Load voltages from different ADN's. Load drops approximately 0.72 pu but recovers within 30 seconds to nominal range.

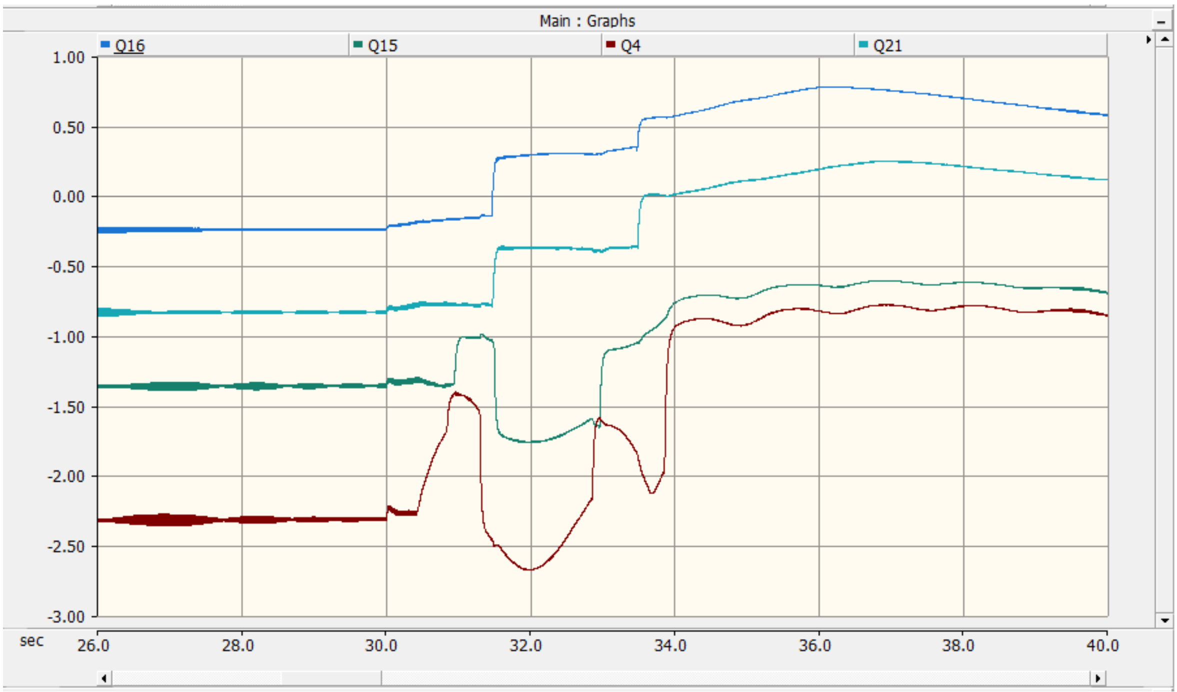

Figure 5.21 Scenario 9 reactive power flow between ADNs and TN. DGU's of load 4 and load 15 are tripped at t = 31 s. Load shedding in every ADN prevents the voltage collapsion.

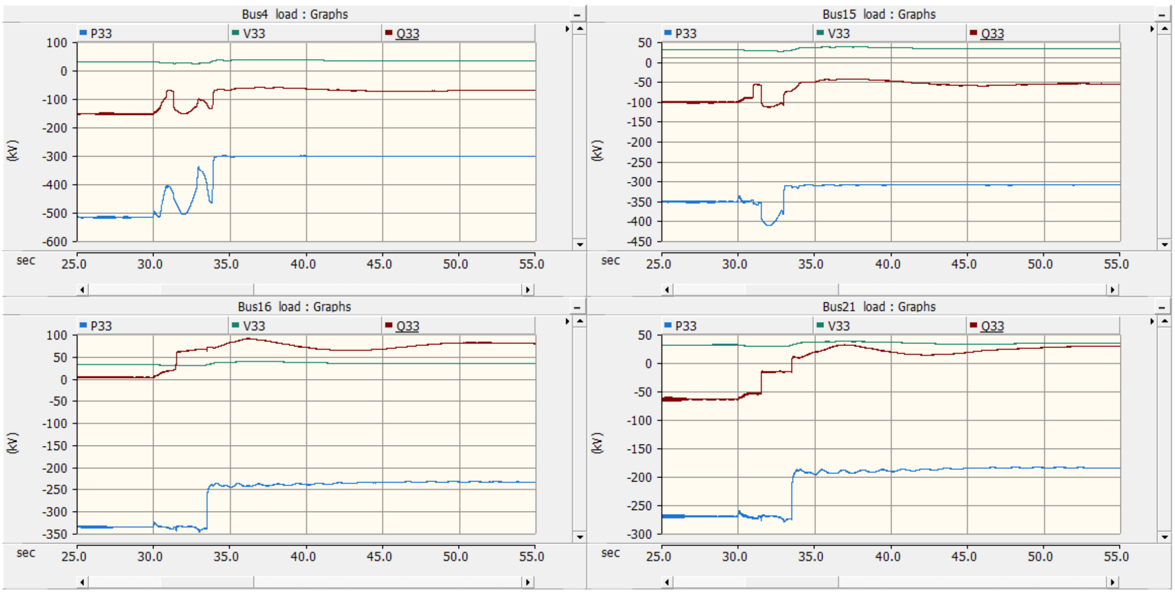

Figure 5.22 Scenario 9 ADNs real power (P33) and reactive power (Q33) and DN-side voltage (V33) during emergency control.

All four ADN's effectively supported TN side voltage during emergency situation (Figure 5.22). Every ADN connected their reserve capacitor on, activated their DGU's (two DGU's tripped), and started load shedding. None of the ADN's did activate tap changer reserve operation as it was planned to be used if the transmission voltage would remain in specific value for a certain time. Tap changers were locked during this fast emergency situation as planned. Load shedding was also operating adaptively. Most affected ADNs during the emergency situation were 4 and 15. The proposed control logic showed high adaptability as the loads where disconnected first from the most affected locations. It must be noted that at the moment when DGUs tripped at ADNs 4 and 15, the other ADNs 16 and 21 connected the reserve capacitors immediately and later on activated one step of load shedding. In real case two DGU's which tripped would have remained on no-load situation (circuit breaker open) and resynchronized back when the load shedding would have brought the DN voltage back in acceptable level. PQ-curves of all ADNs presented in Figure 5.23. Activation of emergency control in each ADN listed in Table 5.

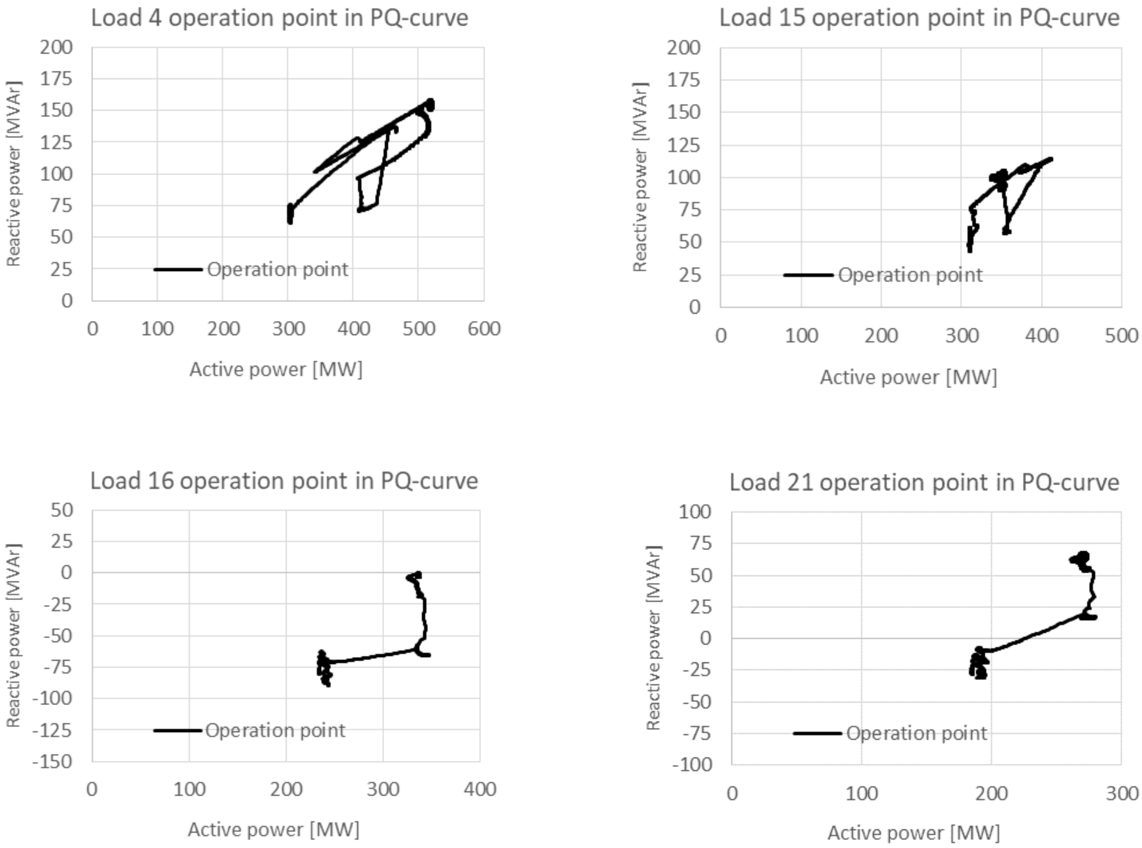

Figure 5.23 PQ-curves of all ADNs during Scenario 9. Power system stability is maintained.

Figure 5.23 points out the PQ curves of all ADNs. Loads 16 and 21 are acting as recommended: first reactive power transmission from TN is reduced, and after that active power is reduced with load shedding (compare to Figure 2.6). For loads 4 and 15 the trip of DGU causes an increase of reactive power consumption and mixes the trajectory. In the end stable state is reached after load shedding as the active and reactive power demand is decreased.

Table 5: ADNs voltage support functions to TSO during voltage emergency situation.

Active Distribution Network	DGU operation	Capacitor bank	Load shedding
ADN 4	OEL reached and trip	Activated	2 of 4 used -300 MW, -90 MVAr
ADN 15	OEL reached and trip	Activated	1 of 4 used -100 MW, -37 MVAr
ADN 16	OEL not reached	Activated	1 of 4 used -100 MW, -3 MVAr
ADN 21	OEL reached	Activated	1 of 4 used -110 MW, -25 MVAr

6 Conclusions and Suggestions

Voltage emergency support between TSO and DSO will become more important when renewable energy recourses are increasing. The reason is not only increasing RES, but also decreasing amount large scale power plants which have so far been carrying all the responsibility for voltage control in large power systems. As the power generation is partly moving from TSO under DSO and become more decentralized, several challenges have been identified to secure system stability. The importance of collaboration between TSO and DSO has been highlighted by many researchers and by global organizations for the past years, but still the regulation and solutions have not been developed for example in national use or even in practical use.

6.1 Concluding remarks

In this work the known concepts was studied and further developed and integrated to a new control model. This new control model for voltage emergency support uses the key resources located in DSO to support TSO side voltage. Those resources are DGU’s, capacitor banks, voltage reduction and at last load shedding. Design criteria for the implemented control scheme was to have minimal inputs, local, adaptive and non-intrusive. To achieve minimal inputs for the control scheme, only transmission side voltage level together with distribution side voltage level were used as an input for voltage emergency support. The emergency support scheme used only measurements around TN/DN transformer which made it local control. High adaptability was achieved by implementing different alarm functions to act depending on how critical the voltage emergency situation is in transmission network. Also the proposed control is non-intrusive unless the emergency situation is enough hazard to start load shedding.

Developed control logic for voltage emergency support between TSO and DSO was implemented and verified in the simulations with PSCAD. Developed ADNs are decreasing reactive power transmission from TN by activating reactive power resources located inside DN such as DGU’s and capacitor banks. Transmission of real and reactive power are decreased by performing voltage reduction using tap changer reverse operation function.

Intensity of this function is heavily depending on the voltage characteristics of the load. If these are not enough to prevent voltage collapse, load shedding was implemented to be used.

Simulations showed different results with different load characteristics. Load characteristics have high impact during voltage emergency situations. If the load characteristics are close to constant impedance model, the natural decrease of real power and reactive power demand of the load is significant as the voltage decreases. This supports transmission system since the power transmissions from TN to DN will decrease also. As the load is reduced, also transmission of power inside transmission system is reduced and therefore reactive power demand of the transmission system is reduced. Reverse operation of on-load tap changer, which can also be called as load voltage reduction, is efficient and non-intrusive way to provide support in systems where loads are close to constant impedance model. Simulations performed near constant load showed opposite results. Reverse operation of on-load tap changer did not have as significant impact as in constant impedance model, since the loads are not reduced with the voltage. Even though this supports to lower the currents in TN side and therefore slightly supports transmission network. Load shedding was found to be effective way to maintain voltage stability in constant load model. Even if load shedding is intrusive method, it should be considered always to be a part of emergency support.

In this work typical cascading voltage collapses were simulated to occur without any emergency functions. Simulations were performed by taking different alarm functions into use one by one and evaluating the results. In the end, proposed control logic for voltage emergency support between TSO/DSO were able to maintain the voltage stability of whole power system and maintain voltage levels in acceptable level (~1.00 pu) even in the most challenging load profiles (constant power) in ADNs. In this case load shedding was needed to maintain voltage stability. Two DGU’s tripped after their excitation capacity was reached and voltage decreased to critical level. In this case load shedding control logic (time constants) should be developed further to avoid DGU’s trip. In other hand also DGU’s should be controlled in a way that DGU is resynchronized back immediately when voltage reaches allowable level after load shedding. But in other hand this proved that the proposed load shedding logic is sufficient even if one or two DGU fails (Scenario 9). If the load profile is near constant impedance or constant current, load shedding is not needed and transmission system voltage is reaching acceptable levels with non-intrusive methods such as DGU’s reactive power boost and/or capacitor banks and/or reverse operation of tap changer (e.g. Scenarios 1, 3, 4, 6).

6.2 Further Studies

As shown in Scenario 6, interactive collaboration between different DSOs or in this case ADNs can be effective way to support TN voltages. In that case the control system is not anymore local and thereby it doesn't full fill the design criteria of proposed control scheme, but shows high potential. Interactive collaboration of DSO's could be developed in the way that depending on the DSO's location, size and importance for the power system, groups of DSO's could be formed. These groups could share reactive power resources in situations where one or more are affected to voltage emergency situations even if the rest are not affected. This should be studied and evaluated by the TSO with simulations how this formed group would harness it reactive power capacities and how would it provide voltage support in different scenarios. Groups would be formed in a way that each DSO has own specific group as shown in Figure 6.1. This kind of implementation would require advanced collaboration between TSO and DSO and basically TSO would be the main operator in this system.

For future work, interactive collaboration of DSOs could be studied using the proposed control logic presented in this work. Also distribution grid could be implemented in more realistic way including different types of DGU's and longer and more realistic distribution lines. In this work losses, voltage drops or voltage increases inside DNs were not playing significant role. Also operation of transmission system tap changers were not taken into account. The control logic for activation of DGU's reactive power production was presented in this thesis, but in practical use it would require centralized control system. This centralized control system could control all DGUs attached to this DSO network. In future systems DSOs could offer a market of emergency voltage support for DGUs. But like described in the introduction, clear regulations and markets are required to start taking new innovations into use.

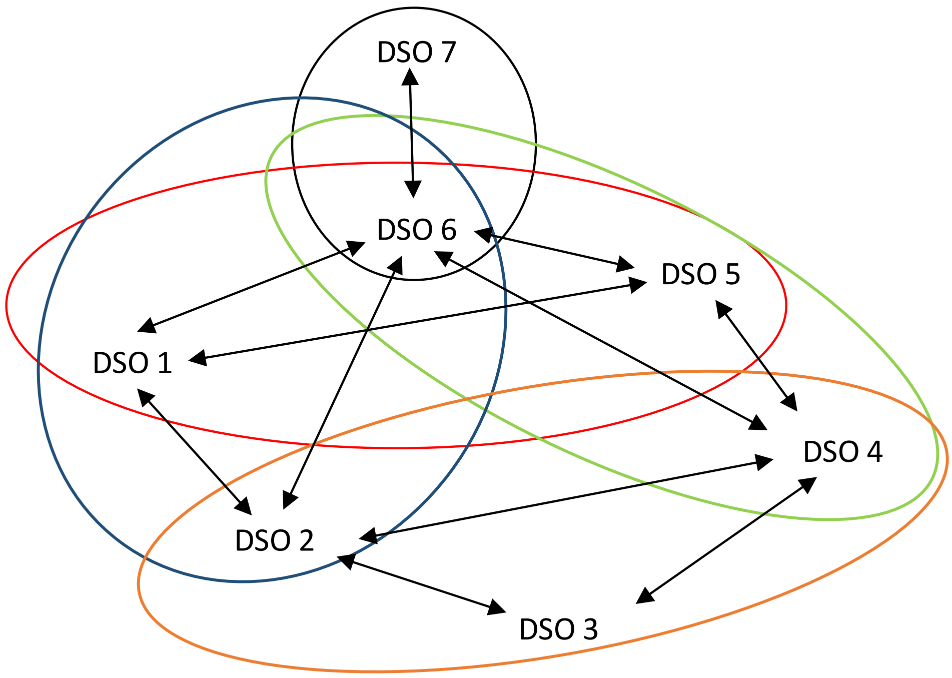

Figure 6.1 Interactive collaboration between groups of different DSOs in large transmission system. Groups are formed according to their physical location, size and impact on power system during voltage emergency situations. TSO controls DSO in voltage emergency situation.

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APPENDIX 1: Power System parameters and models

Table A1. Transmission system generators.

Generator		Operating values					Max values		Starting values	
Name	Sn [MVA]	P [MW]	Q [Mvar]	S [MVA]	Load %	cosp	Qcalc [MVAr]	OEL [p.u]	Phase [rad]	Voltage [p.u]
G30	300	249	72	260	87 %	0.96	166.7	1.89	-0.196	1.040
G31	1250	700	200	728	58 %	0.96	1035.6	1.61	-0.100	0.985
G32	680	512	117	525	77 %	0.97	447.5	1.78	-0.130	1.020
G33	700	620	167	642	92 %	0.97	325.0	1.73	-0.120	1.020
G34	550	486	119	500	91 %	0.97	257.5	1.81	-0.150	1.015
G35	700	546	129	561	80 %	0.97	438.0	1.81	-0.100	1.030
G36	600	511	78	517	86 %	0.99	314.5	1.81	-0.050	1.050
G37	600	515	-30	516	86 %	1.00	307.9	1.71	-0.098	1.025
G38	900	795	16	795	88 %	1.00	421.9	1.76	-0.030	1.031
G39	1400	1248	172	1260	90 %	0.99	634.4	1.78	-0.050	1.025

Table A2. DGUs in ADNs.

DGU		Operating values	Max values	
Name	Sn [MVA]	P [MW]	Qcalc [Mvar]	OEL [p.u]
DGU 16	70	60	42.3	1.92
DGU 15	70	60	36.1	1.92
DGU 4	100	80	60.0	1.92
DGU 21	70	56	42.0	1.92

Table A3. Loads in ADNs.

ADN	P_ph [MW]	Q_ph [MVAr]	Ptot [MW]	Qtot [MVAr]	cos φ
Bus 16	109.8	10.8	329.4	32.3	1.00
Bus 15	106.7	51.0	320.0	153.0	0.90
Bus 4	166.7	61.3	500.0	184.0	0.94
Bus 21	91.3	38.3	274.0	115.0	0.92

Table A4. Transformers in ADNs.

Name	*Sn* [MVA]	*X* [pu]	*U1* [kV]	*U2* [kV]
ADN 16	600	0.13	230.0	33
ADN 15	600	0.13	230.0	33
ADN 4	600	0.13	230.0	33
ADN 21	600	0.13	230.0	33

Table A5. Capacitors.

230 kV	
Bus	*C* [uF]
9	10.029
5	5.014

33 kV	
ADN	*C* [uF]
15	135
16	135
4	135
21	135

Table A6. Other loads (PQ) are modelled as constant load (PSCAD c, 2018).

Bus	*P* [pu]	*Q* [pu]
3	3.22	0.024
7	2.338	0.840
8	5.220	1.760
12	0.075	0.880
18	1.580	0.300
20	6.800	1.030
23	2.475	0.846
24	3.086	-0.922
25	2.240	0.472
26	1.390	0.170
27	2.810	0.755
28	2.060	0.276
29	2.835	0.269
31	0.092	0.046
39	11.040	2.500

Table A7. Transformers in 230 kV side. All are 100 MVA base. If generator is connected, then secondary is 15 kV, otherwise 230 kV.

From	To	*X* [pu]	U_{set}
30	2	0.018	1.025
37	25	0.028	1.025
29	38	0.016	1.025
39X	39	0.018	1.040
35	22	0.014	1.000
6	31	0.025	0.950
11	12	0.044	1.006
12	13	0.044	1.006
10	32	0.020	1.040
34	20	0.018	1.009
19	33	0.014	1.000
19	20	0.014	0.990
23	36	0.027	1.020

Table A8. Transmission lines (PSCAD c, 2018):

Start	To	*R* [pu/m]	*X* [pu/m]	*B* [pu/m]
1	2	0.0035	0.0411	0.6987
1	39	0.0010	0.025	0.7500
2	3	0.0013	0.0151	0.2572
2	25	0.0070	0.0086	0.1460
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.1130
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.0780
8	9	0.0023	0.0363	0.3804
9	39	0.0010	0.0250	1.2000
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.3660
15	16	0.0009	0.0094	0.1710
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.3040
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.0680
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.0140	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.0350	0.3610
25	26	0.0032	0.0323	0.5130
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.0290
28	29	0.0014	0.0151	0.0249

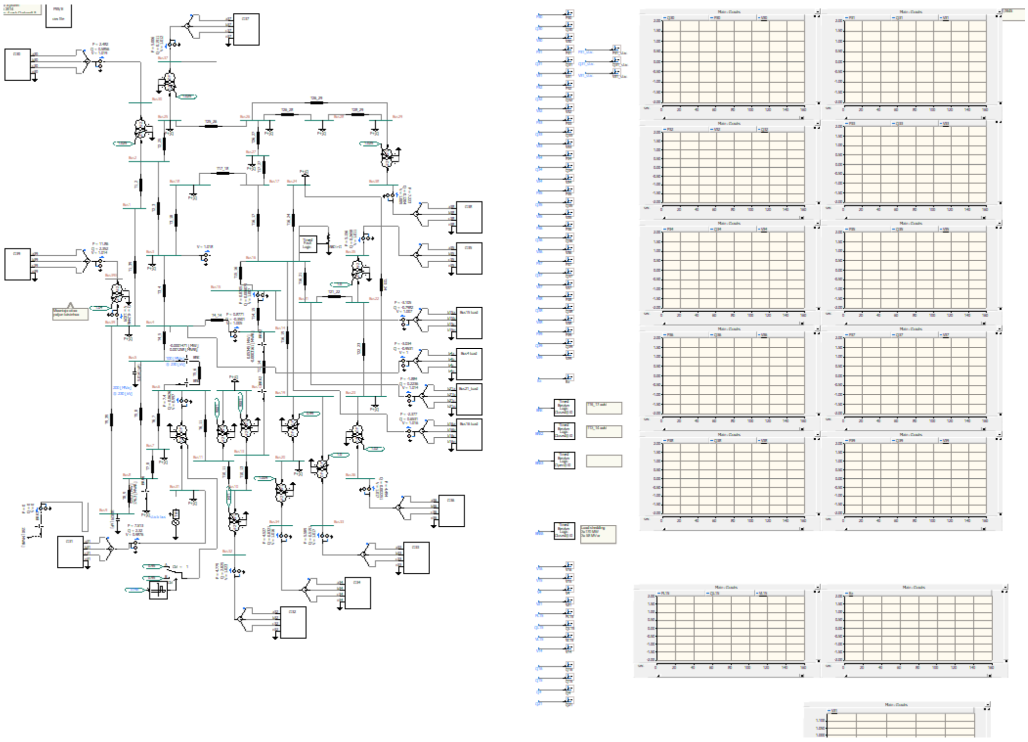

Figure A1 Modified IEEE 39 Bus System

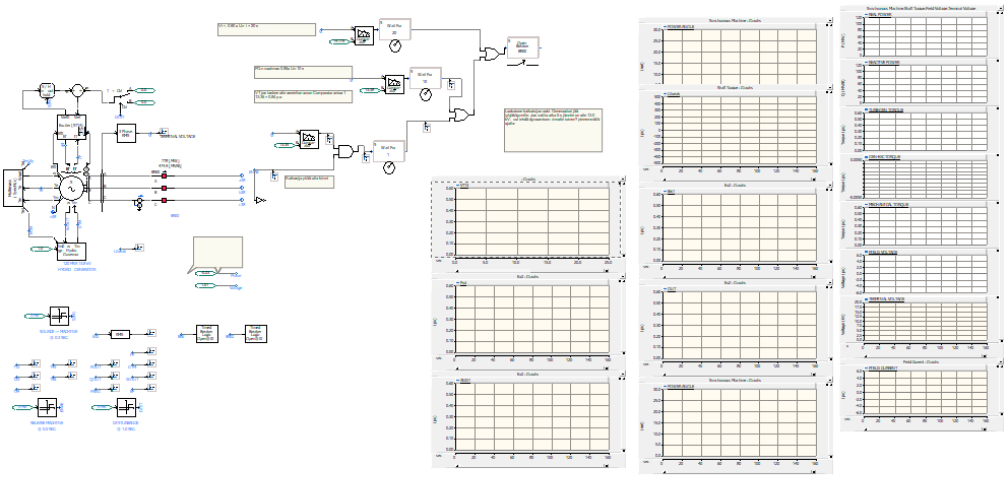

Figure A2 Transmission network generator model in modified IEEE 39 Bus System

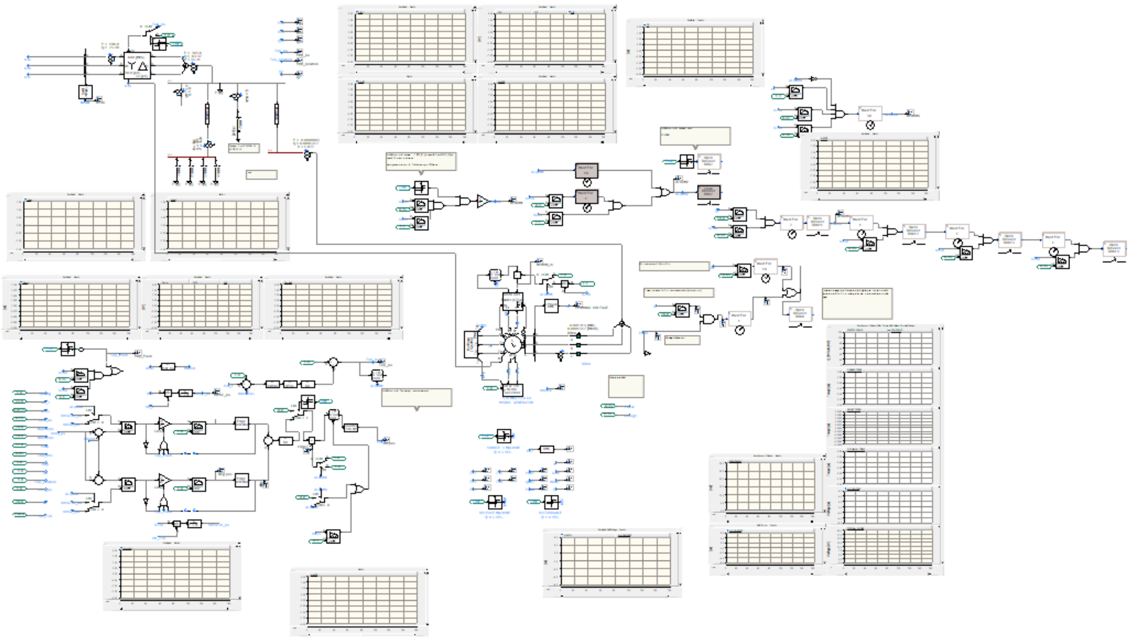

Figure A3 ADN model in modified IEEE 39 Bus System