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VOLTAGE QUALITY ENHANCEMENT BY COORDINATED OPERATION OF CASCADED TAP CHANGER TRANSFORMERS IN BI-DIRECTIONAL POWER FLOW ENVIRONMENT

Master of Science thesis

Examiner: Professor Sami Repo
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ABSTRACT

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Existing voltage control methods have been developed considering unidirectional power flow, and the power flow direction has been assumed to be from substation toward consumption points. In unidirectional power flow environment, undervoltage is considered to be the main voltage quality problem. However, increasing trend of integration of distributed generation (DG) such as solar and wind power to the grid has created possibility for bidirectional power flow and also emerging voltage rise as another voltage quality problem. Therefore, the previous control methods are not capable of efficient handling of the voltage problems and there is a need for development of new control methods.

Since transformers are the main voltage control resources and are owned by the system operator, the main focus in this thesis is on the voltage control using on-load tap changer (OLTC) transformers and especially on the coordinated operation of cascaded transformers. A centralized unit (algorithm) called Block OLTCs of Transformers (BOT) is defined for this purpose. The system operator can use the BOT in two different control schemes. In the first scheme, the BOT acts as a standalone unit that enhances the voltage quality by coordinating the cascaded transformers. In the second control scheme, the BOT unit acts as a supplementary algorithm for other voltage control algorithms (integrated operation) which again aims to improve the voltage quality by coordinating the cascaded OLTCs. The standalone operation of the BOT is the integral part of this thesis. However, integrated operation is also explained.

Performance of the BOT in standalone operation is widely tested and compared with the local control methods of cascaded OLTCs. The obtained results indicate that the BOT is able to prevent unnecessary tap actions of the cascaded OLTCs. This leads to a reduction in total number of tap operations and as a result an improvement in the supply quality regardless of power flow direction is achieved.

PREFACE

This M.Sc. thesis was done at the Department of Electrical Engineering of Tampere University of Technology, Finland. The thesis is a part of “Ideal Grid For All” (IDE4L) project work package 5 (congestion management in distribution networks) funded by the European Commission.

First, I would like to express my most sincere appreciation to my supervisor Professor Sami Repo for his superb supervision and friendly guidance during the thesis. Many thanks to my colleagues at the Department, especially Ph.D. Anna Kulmala and M.Sc. Antti Mutanen for their great support and replies to all my questions. I also want to thank M.Sc. Jasmin Mehmedalic and M.Sc. Zaid Al-Jassim both from Dansk Energi for their constructive comments in different phases of the IDE4L project.

Last but not least, my deep gratitude to my parents, my brother and sister for their endless support, encouragement and unconditional love. I am indebted to you. This M.Sc. thesis is dedicated to my family.

Tampere, November 2015

Farzad Azimzadeh Moghaddam

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TERMS AND DEFINITIONS

AVC	Automatic Voltage Control
BOT	Block OLTCs of Transformers
CVC	Coordinated Voltage Control
DB	Deadband
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operator
GT	Graded Time
HV	High Voltage
IDE4L	Ideal Grid For All
LDC	Line Drop Compensation
LV	Low Voltage
MV	Medium Voltage
OLTC	On Load Tap Changer
OPF	Optimal Power Flow
PC	Power Controller
PSAU	Primary Substation Automation Unit
PSAU.DB	Primary Substation Automation Unit Database
PV	Photovoltaic
SE	State Estimation
SSAU	Secondary Substation Automation Unit
SSAU.DB	Secondary Substation Automation Unit Database

1. INTRODUCTION

The lack of capacity in the power system for the power flow leads to the congestion. Congestion can be caused either by voltage exceeding the allowed limits or overload of components [1]. Considering the deregulated power system and future of the power grid, especially medium voltage (MV) and low voltage (LV) distribution networks, most of the customers will have their own production units such as photovoltaic (PV) and Wind. Since the amount of generation of these customer-owned units is not usually controlled by the distribution system operator (DSO), customers and also natural factors such as solar radiation and wind speed will define the output amount of these units [2]. Having maximum generation by these units, if network capacity is not enough for injected power, congestion will occur which can affect the voltage quality in the network [2]. In this thesis, congestion due to violation of voltage limits is the main concern.

Connection of distributed generation (DG) units to the present distribution networks usually causes voltage rise problems. The voltage rise limits the hosting capacity of the network. An acceptable voltage profile can be achieved by passive voltage control methods such as increasing the conductor size, connecting generation on a dedicated feeder and moving the connection point of DG toward substation. However, using active voltage control methods, voltage can be controlled in a more cost-effective way. Active voltage control methods utilize the controllable network resources in the voltage regulation. These controllable resources include transformers equipped with on-load tap changers (OLTCs), active and reactive power capability of DG units and other controllable devices connected to the network. Depending on the network structure and availability of controllable resources, a combination of active and passive methods can be utilized to achieve the voltage control in distribution network. [3]

In this thesis, the main focus is on voltage control using on-load tap changer transformers. Thesis is concentrated on coordination of the cascaded HV/MV and MV/LV transformers. It has been assumed that the MV/LV transformer is equipped with OLTC as well as the HV/MV transformer. This is a valid assumption, because high integration rate of renewables to the LV grids will result in deployment of OLTCs for the MV/LV transformers.

Being a part of work package 5 of “Ideal Grid For All” (IDE4L) project, thesis has had the following contributions to the project:

- A detailed state of the art survey of congestion management in distribution networks utilizing voltage control has been developed [1]

- Participation in development of the use cases for the medium and low voltage network power controllers [4][5]
- Development of the use case for managing the cascaded OLTCs [6]
- Participation in writing the deliverable document (D 5.2/3) of the project with the title “Congestion Management in Distribution networks” [7]

The thesis has been structured as follows:

In chapter 2, congestion management using active voltage control methods with an emphasis on operation of the cascaded OLTCs is presented.

In chapter 3, design specifications for the developed algorithm in this thesis in two different control schemes are provided.

Chapters 4 and 5 are dedicated to explanation of the developed algorithm and use cases in this thesis, respectively.

In chapter 6, simulation results are presented and finally the thesis is concluded in chapter 7.

2. CONGESTION MANAGEMENT USING ACTIVE VOLTAGE CONTROL METHODS

Active voltage control methods are divided into two categories, control based on local measurements and control based on information of the entire power system. Control based on local measurements means that controllable resources like DG units are controlled considering only local measurements, for instance, local voltage. If information of the entire system is utilized, a combination of active voltage control methods can be used for voltage regulation meaning that voltage control is achieved by taking all controllable resources into consideration at the same time. The latter case is called coordinated voltage control (CVC). The required network state data can be obtained either from state estimation (SE) or can be directly measured. Most of the CVC algorithms use a centralized unit for control purposes. [3]

Different methods in articles have been proposed for the congestion management. For example, in [2], feeder reconfiguration has been suggested. In [8], coordinated voltage control is done by controlling the substation voltage. In [9], coordinated voltage control utilizes the substation voltage and reactive power of DG.

In section 2.1, first voltage rise effect is explained, and then in section 2.2 mitigation of the voltage rise is presented. Section 2.3 presents the congestion management utilizing the CVC. In section 2.4, operation of the cascaded OLTCs is presented.

2.1 Voltage rise effect

The voltage rise effect is considered to be the main consequence of DG connection to the power grid. In [10], using an excellent example which is presented also in here, all parameters which are affecting the voltage rise magnitude have been extracted.

Let's assume a DG unit (here a typical embedded induction machine), as it has been depicted in Figure 2.1, is connected to an MV network where the real and reactive power of the wind turbine are P_g and Q_g. The real and reactive loads presenting the consumer load are P_L and Q_L, respectively. The feeder current is I_R and the feeder impedance is Z (real and reactive parts of impedance are denoted by R and X, respectively). The substation and DG connection point voltages are V_S and V_g, respectively. Also, the complex power is S_R.

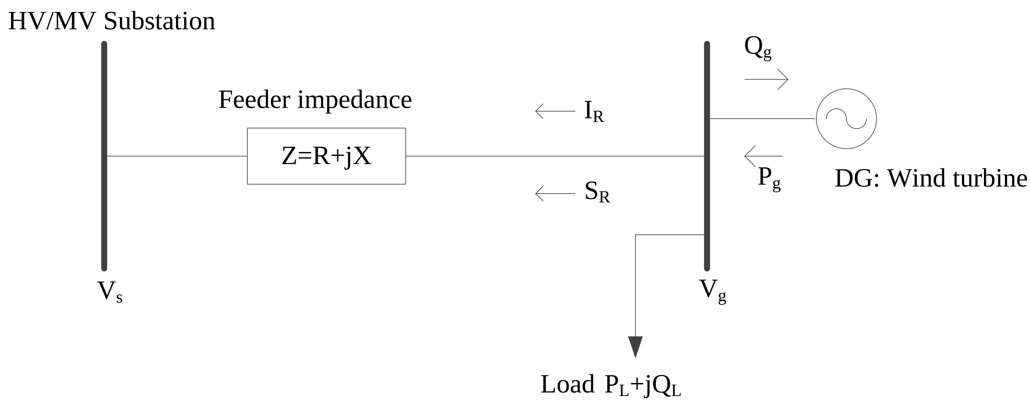


Figure 2.1 *A wind turbine connected to an MV network [10]*

Connection of the DG unit will result in bidirectional power flow in the network which is totally in contrast to assumptions of unidirectional power flow in the traditional power grid. In order to find out the effective parameters on voltage rise, complex power and also voltage difference between two ends of the depicted line in Figure 2.1 can be utilized as following:

$$S_R = P_R + jQ_R \tag{2.1}$$

where

$$P_R = P_g - P_L \tag{2.2}$$

$$Q_R = -(Q_g + Q_L) \tag{2.3}$$

Plugging (2.2) and (2.3) in (2.1) results in the following equation:

$$S_R = P_R + jQ_R = P_g - P_L - j\left(Q_g + Q_L\right) \tag{2.4}$$

The complex power can also be written as a function of voltage and current as following:

$$S_R = V_g \, . \, I_R^* \tag{2.5}$$

where

$$I_R = \frac{P_R - jQ_R}{V_g^*} \tag{2.6}$$

and the sign * determines the conjugate operator.

Voltage difference between two ends of the line (feeder) is a function of line current and impedance as following:

$$V_g = V_S + I_R \, . \, Z \tag{2.7}$$

Plugging (2.6) in (2.7):

$$V_g = V_S + \frac{P_R.R + X.Q_R}{V_g^*} + \frac{j(P_R.X - Q_R.R)}{V_g^*} \tag{2.8}$$

According to the phasor diagram shown in Figure 2.2:

$$V_g \,.\sin\delta = \frac{P_R \,.\, X - Q_R \,.R}{V_S} \tag{2.9}$$

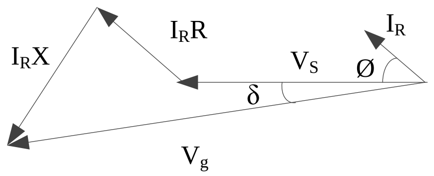


Figure 2.2 *Phasor diagram [10]*

Assuming a small voltage angle between V_S and V_g (i.e. $\delta \approx 0$), the third term in (2.8), $\frac{j(P_R.X-Q_R.R)}{V_g^*}$, is also very small and can be neglected. Plugging the value of the P_R and Q_R in (2.8), the magnitude of the voltage rise can be approximated as following:

$$\Delta V = \frac{\left(P_g - P_L\right)R - X\left(Q_g + Q_L\right)}{V_g^*} \tag{2.10}$$

Equation (2.10) presents all possible elements which can be utilized for voltage control purpose. Active and reactive power of DG unit and load, as well as feeder impedance, will define the magnitude of voltage rise.

2.2 Mitigation of voltage rise

In the case of voltage rise, the active power output of DG unit can be curtailed in order to reduce the voltage. In addition, DG unit can lower the voltage by absorption of the reactive power. Active power curtailment is not desirable from an economic standpoint. Reactive power absorption increases the possibility of the high reactive power flow over the network. Increase in reactive power flow leads to high current flow and as a consequence high loss in the network. [11] Besides active and reactive power capabilities of DG unit, transformers equipped with OLTCs can also be used for voltage regulation. In distribution networks, the HV/MV transformers are equipped with OLTCs and the MV/LV transformers are usually using an off-load tap changer. However, due to high penetration rate of renewables in LV networks, it is expected that OLTCs will also be deployed for the MV/LV transformers. Using the MV/LV OLTC, the system operator will have more control over the voltage in the LV networks.

From network planning point of view maximum acceptable active power output of the DG units is usually defined by the worst case scenario meaning maximum DG output, maximum substation voltage and minimum loading all at the same time. However, probability of simultaneous occurrence of all these events is very low and due to defined limits for maximum injected active power using the worst case scenario, production units will not utilize the entire capacity of the units which is not suitable from economical point of view. [10]

In order to utilize the entire capacity of the DG units, load control can be utilized. In traditional networks, peak load reduction is one possible approach but in today's grid, load control can have a quite different concept meaning that in the worst case scenario (i.e. having maximum DG output, maximum substation voltage and minimum loading condition), loads are encouraged to be connected to the grid. In this way, voltage rise can be efficiently mitigated. Energy storage loads are the best options to be switched on since they do not cause inconvenience to the customers. [10] In general, correlation of DG output and load demand should be increased. For instance, load control can be done by production following [12].

Using the loads for the voltage control is called utilizing Demand Response (DR). The DR has considerable role in voltage control and it can be divided into two categories. One is dispatchable which means the DSO can directly control the load (e.g. energy storage devices). The other one is non-dispatchable which means the DSO will introduce specific prices for the specific times of the day which will affect the customer's consumption behaviour (indirect load control).

In [10], a comparison of different control methods from economical point of view for mitigating the voltage rise is presented. Although using load control for voltage regulation has high costs, it is more cost effective than the existing traditional voltage regulation methods such as reinforcement and change of the DG connection point. Requiring more capital investments, load control has higher costs compared to reduction of output power of DG at severe times and also power factor control method. [10] It should be noted that this is very much case dependent. For instance, in some countries (e.g. Finland) smart meters which are capable of load control already exist resulting in less cost for load control.

Voltage control using controllable resources might not always completely mitigate the congestion. For example, having a high DG penetration rate may make the construction of new lines a necessity.

2.3 Coordinated voltage control

CVC methods can be divided into two categories, one is based on rule based algorithms and the other is based on optimization algorithms. [3]

2.3.1 Rule based methods

Having a simple network structure and few controllable resources, rule based methods can be suitable options. In the simplest rule based CVC method, substation voltage is controlled based on the network maximum and minimum voltages to keep all network voltages in the allowed range. Substation voltage is lowered if the network maximum voltage exceeds its limit and increased if the network minimum voltage falls below its limit. When both network maximum and minimum voltage limits are violated this method stops execution. [8][13]

It is also possible to combine the coordinated operation of substation voltage with local active and reactive power control of, for instance, DG units. In this case, the local control will operate faster than substation control, because the transformer automatic voltage control (AVC) relay and tap changer delays are much larger than the delays of the local active and reactive power controllers. This means that substation voltage is used as the last control option. [3]

Control sequences have been differently selected in the papers. For example, in [14], transformer OLTC is the primary control variable and then the reactive power control of DG utilized only when the substation voltage control is not able to bring the voltage back into acceptable range. [3]

2.3.2 Methods utilizing optimization

The CVC can be taken as an optimization problem. In the power system, any optimization problem which contains a set of power flow equations in the constraints can be treated as an optimal power flow (OPF) problem [15]. Hence, the CVC algorithm is a form of OPF problem. In general, OPF problems are nonlinear and non-convex which can contain both continuous and discrete variables [16].

The OPF problem can be presented on the following standard form [17][18]:

$$\text{minimize} \quad f(u,x) \tag{2.11}$$

$$\text{subject to} \quad g(u,x) = 0 \tag{2.12}$$

$$h(u,x) \leq 0 \tag{2.13}$$

where

u is the vector of controllable system variables
x is the vector of dependent or state variables
$f(u,x)$ is the objective function which determines the optimization goals
Vector function $g(u,x) = 0$ determines the equality constraints
Vector function $h(u,x) \leq 0$ determines the inequality constraints

Based on the requirements, different objectives can be considered in an OPF problem. Some possible objectives for an OPF algorithm, running at distribution level, are as follows [1]:

- Reduction of the network losses
- Reduction of the production curtailment
- Minimizing the load control actions
- Reducing the cost of changing the normally open disconnectors
- Reducing the cost of the reactive power flow supplied by the transmission network
- Reducing the cost of the active power flow supplied by the transmission network
- Reducing the voltage variation at each node (difference between current and reference value of the voltage)

Variables involved in OPF problems are divided into two categories, state (dependent) variables and controllable variables. Usually, bus voltage magnitude, bus voltage angle and real and reactive power injections at each node of the network are taken as state variables. State variables all are continuous. On the other hand, controllable variables are a subset of state variables (e.g. real and reactive power injections at generation buses of the network). In addition, switching device settings (e.g. capacitor bank status and OLTC ratios) are considered as controllable variables. Controllable variables can be continuous or discrete. [15]

OPF Constraints can be divided into two categories, equality constraints and inequality constraints. All balance equations are taken as equality constraint [15]. The technical limits and limits for controllable resource capabilities define inequality constraints [3].

2.4 Operation of cascaded OLTCs

In this section, the operation of cascaded OLTCs is discussed. First in subsection 2.4.1, some necessary background information is presented and then the most common control methods used in practice or in articles are briefly explained in subsection 2.4.2.

2.4.1 Operational principle of AVC relay

Since the AVC relay of transformer provides commands for the OLTC, the operational principles of the AVC relay should be well-understood. This controller constantly reads the voltage value at the secondary side (lower voltage side) of the transformer and whenever the voltage is out of the permitted margin (also called AVC relay deadband) it sends a command to tap changer to adjust its tap position for the voltage regulation [19]. The main purpose is to keep the voltage at consumption points (loads) as close as possible to its reference value.

In order to explain the AVC relay operation, from a mathematical perspective, Figure 2.3, which shows a transformer connected to a single load, can be considered. Having the load far away from the transformer, the AVC relay can apply line drop compensation (LDC) to take the voltage drop over the line into account while computing the load voltage. [20] The AVC relay uses the following two equations in its algorithm to calculate the voltage variation at the load point [20]:

$$V_{eff} = V_{VT} - I_{CT}(R_{line} + j \cdot X_{line}) \tag{2.14}$$

$$V_{dev} = V_{eff} - V_{target} \tag{2.15}$$

where V_{eff} is the effective voltage at load point. The variables V_{VT} and I_{CT} are the measured voltage and current, respectively. The model for the line impedance is presented by $(R_{line} + j \cdot X_{line})$. The variable V_{dev} is the voltage deviation from target (reference) voltage, and V_{target} is the target voltage. The AVC relay calculates the voltage variation at the load point and sends commands to OLTC to compensate for the voltage drop over the feeder by boosting the voltage at the output of transformer [19].

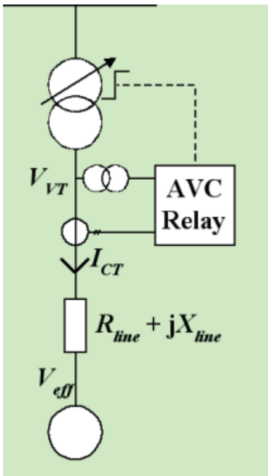


Figure 2.3 *Transformer connected to single load [20]*

In practice, there are several loads located at different distances from transformer making the line model a compromise [20]. In addition, transformers are usually supplying several feeders which means characteristics of each line (feeder) should be taking into consideration in the LDC settings [21]. Some system operators tend to deactivate the LDC (i.e. R_{line} and X_{line} both are set to zero) which means that the secondary bus bar (substation bus) voltage of the transformer is regulated instead of the load voltage [21].

Besides the line characteristics, connection of the DG units has also a significant effect on the control scheme using LDC. Figure 2.4, that shows a transformer with multiple feeder connections, can be used as an example case to see one of the possible effects of the DG connection on the LDC control scheme. The customer load is 500 ampere (A) in total and normally this should be supplied by the utility through the transformer, however, connection of a DG unit with the output of 150 (A) reduces the current flow through the transformer to 350 (A). The measured current (I_{CT}) in equation (2.14) now is 350 (A) and the transformer applies compensation to 350 (A), but 500 (A) current is flowing from substation toward the loads. Therefore, low voltage can occur in the network due to compensation for 350 (A) instead of 500 (A). [22]

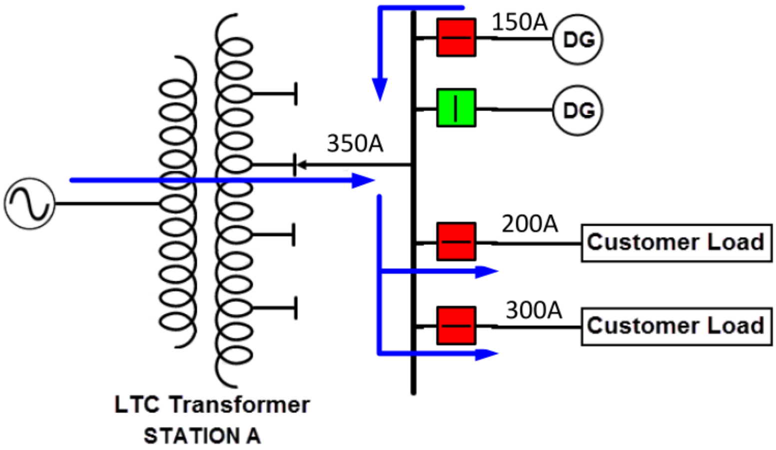


Figure 2.4 A transformer with multiple feeder connections *[22]*

Having several feeders with different voltage profiles connected to a single transformer, the voltage reference should be carefully set to have the voltage within the admissible range all over the network.

It should be noted that due to the discrete nature of the tap changer, it can regulate the voltage only in steps [19]. A deadband (DB) is defined to prevent hunting (continuous back and forth operation) of the tap changer. Also, a time delay known as the AVC relay time delay is considered to avoid the tap changer operation in case of voltage transients. The delay counter is started when difference between the measured voltage by the AVC relay and the reference (target) voltage becomes more than the AVC relay deadband. [3] There is also a hysteresis band defined inside the AVC relay deadband, the counter stops when the voltage is restored within this inner band otherwise, a tap changer operation is initiated after expiration of the AVC relay time delay [3] [23].The time delay can be either definite or inversely proportional to the difference between the measured and the reference voltages [3]. In addition to the AVC relay time delay, tap action is also accompanied by a mechanical time delay related to the tap changer mechanism [24]. After these two time delays, tap action is done. The time domain operation of the AVC relay is shown in Figure 2.5.

If a single tap action is not able to bring the voltage back within the hysteresis band, there are two possible AVC relay settings for the next tap actions. One is that counter starts again and tap action is done after the AVC relay time delay. Another one is that no AVC relay time delay is considered and tap action is done immediately (also called sequential operation mode). [23]

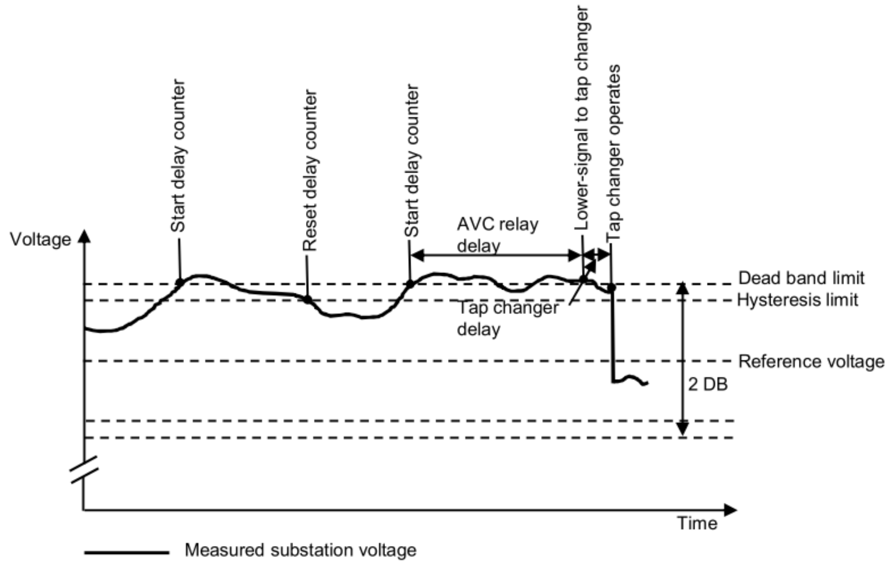


Figure 2.5 *Time domain operation of an AVC relay with definite time delay [3]*

2.4.2 The most common control methods of cascaded OLTCs

This subsection is dedicated to the most common control methods of the cascaded OLTCs that have already been used in real world by the power system operators or tested in articles.

Some control methods of the cascaded OLTCs are local meaning that no communication is required and the AVC relays take care of voltage regulation locally. On the other hand, some methods consider a centralized unit for coordination of the OLTCs. The centralized methods are dependent on communication. [25]

LOCAL CONTROL METHODS:

In local control methods, the AVC relay time delays can be set to be either identical or different. Assigning the same time delay for the cascaded transformers, voltage deviation can lead to simultaneous operation of the OLTCs. For instance in [25], connection of capacitor banks at bus 1 of the network, shown in Figure 2.6, has led to simultaneous operation of the OLTCs. Since the highest level OLTC is capable of regulating the voltage, the lower level OLTCs have done reverse tap actions in order to adjust the voltage in their respective downward networks. These extra tap actions are not desirable, since they lead to customer voltage fluctuations or in other words degrade the supplied voltage quality [24].

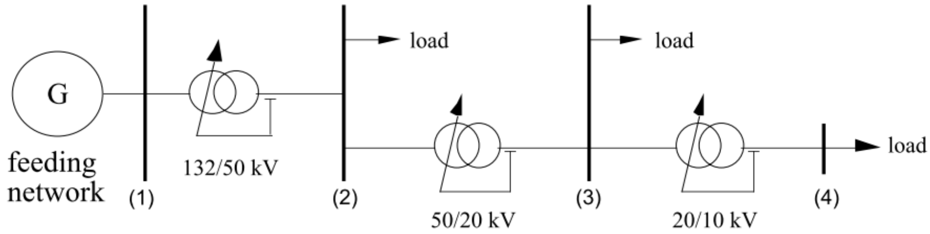


Figure 2.6 *Network model [25]*

In order to reduce the number of unnecessary tap operations, different time delays can be assigned for the AVC relays. The most commonly used approach for this purpose is called the graded time (GT) method. In this method, the initial time delay of the upper level OLTCs is set to be shorter than the lower level OLTCs. This is to ensure that the upper level OLTC operates first and then the lower level OLTCs act if required. The GT method considers the worst case scenario for voltage regulation time. [19] [26] This is the main disadvantage of the GT method which leads to delay in customer voltage restoration time [24].

CENTRALIZED CONTROL METHODS:

It is also possible to use a communication-based approach to coordinate the operation of the cascaded OLTCs.

In [25], an optimization based approach has been used. The problem has been formulated similar to an OPF problem. The main difference is in the objectives considered for this case. In the OPF problems, the main objective is the reduction of network power losses; however, here the objectives are reduction of voltage deviations from setpoints and minimizing the number of tap actions.

As another example for the centralized method, in [27] a fuzzy-rule-based controller that coordinates the operation of the cascaded OLTCs has been proposed. Fuzzy control is an approach for handling the problems where the information is incomplete or some heuristic knowledge is known about the problem [27][28]. Author in [27] has defined the following general rules for the operation of cascaded OLTCs:

1. *If the (local) voltage is high, order a downward tap operation.*
2. *If the (local) voltage is low, order an upward tap operation.*
3. *Cancel an upward tap operation if any tap changer higher in the network is about to order an upward operation.*
4. *Cancel a downward tap operation if any tap changer higher up in the network is about to order a downward operation.*
5. *If voltage deviation is very large, order an operation regardless of rules 3 and 4.*

2.4.3 Some recommendations in regard to selection of the control method for the cascaded OLTCs

In general, local control methods are more reliable than centralized methods, since they do not require communication between the substations. However, local control methods lead to slow customer voltage restoration [25]. The centralized methods such as optimal control and fuzzy-rule-based provide better selectivity compared to local methods (selectivity means that controller is able to select the correct OLTCs to compensate for the voltage disturbances) [25][27].

Deciding on using a centralized approach, it should be noted that optimization-based centralized control method needs accurate network model and usually requires extensive measurements and is computationally challenging. [25] On the other hand, the fuzzy-rule-based method is simple and does not require network model [27].

Regarding the number of the OLTC operations, in [27] a fuzzy-rule-based control method has been compared with the local controls and a centralized optimal control. The results indicate that the fuzzy-rule-based and optimal control methods are capable of reducing the number of tap operations by 36% and 45%, respectively in comparison to a GT method.

Tap actions lead to maintenance and replacement costs of tap changer component. However, tap actions are needed in order to maintain an acceptable voltage in the network. Therefore, a compromise should be done to achieve an acceptable voltage in the network with a minimum number of tap actions. [19]

The control scheme used for the coordination should be able to take the bidirectional power flow due to DG connections into consideration.

3. DESIGN SPECIFICATION OF THE DEVELOPED ALGORITHM

This chapter is dedicated to the design specification of the developed algorithm in this thesis that is called the BOT unit (Block OLTCs of Transformers). The BOT unit is a centralized unit in a sense that it is located at primary (HV/MV) substation and requires communication between substations. However, the BOT does not change the basic principles of the local automatic voltage controllers of the transformers. The BOT unit can be utilized by the system operator in two different control schemes. One is named standalone operation of the BOT and the other is named integrated operation of the BOT.

In standalone operation, the BOT unit acts as an independent unit that coordinates the operation of the cascaded OLTCs. In integrated operation, however, it acts as a supplementary algorithm for other CVC algorithms. The primary purpose of the BOT unit in both control schemes is to enhance the voltage quality by coordinating the operation of distribution transformers that are equipped with OLTCs. Basically, the goal is to prevent unnecessary operation of the cascaded transformers. For instance, in case where only the HV/MV tap changer operation can regulate the voltage in the network, operation of its downward MV/LV OLTC is blocked by the BOT. It should be noted that this study is conducted in a distribution network and it assumes that the MV/LV transformer is also equipped with OLTC as well as the HV/MV transformer. As mentioned in previous chapters, high integration rate of DGs such as wind and solar power to the LV networks will result in deployment of OLTCs for the MV/LV transformers.

Since the HV/MV and MV/LV OLTCs are located in series, lack of coordination between these OLTCs can lead to unnecessary tap changer actions and voltage fluctuations at consumption points [24]. The BOT unit is assigned to manage the cascaded HV/MV and MV/LV OLTCs so that coordination is achieved. Coordination is realized by sending OLTC block signals and block validity time/unblock signals to the AVC relays of HV/MV and MV/LV transformers. When OLTC is blocked, transformer cannot do tap action and it has to wait for the expiration of block validity time or receiving unblock signal. The main purpose of the BOT is to [24]:

- solve the voltage problem as locally as possible
- reduce the voltage fluctuations at consumption points
- minimize the total number of tap actions
- prevent hunting phenomenon of OLTCs

In order to understand the applicability of the BOT unit to both control schemes, two separate design specifications for standalone and integrated operations of the BOT are presented in sections 3.1 and 3.2, respectively.

First, it is necessary to introduce some naming conventions which have been used in IDE4L project. From now on, the thesis will follow the same conventions. For instance, the PSAU.BOT represents the BOT unit. The first part (before .) is indicator of location of the BOT that is primary substation automation unit (PSAU) and the second part (after .) is indicator of the name of the unit that is BOT. All the required data transfers between different units/devices are realized via databases (DBs) located at corresponding voltage levels. There are two DBs. The DB located at PSAU is called PSAU.DB, and the DB located at the secondary substation automation unit (SSAU) is called SSAU.DB. Data transfer between the PSAU.DB and SSAU.DB is also predicted in case there is, for example, need for the LV data in a unit located at the primary substation.

3.1 Standalone operation of the BOT unit

As mentioned at the beginning of this chapter, the PSAU.BOT in standalone operation acts as an independent unit that coordinated the operation of the cascaded HV/MV and MV/LV OLTCs. In chapter 4, the PSAU.BOT algorithm is explained in a detailed manner.

3.1.1 BOT dependencies

The PSAU.BOT unit is dependent on the meters that provide active and reactive power flow values through the distribution transformers. These measured power values are inputs of the PSAU.BOT (the complete list of PASU.BOT inputs and outputs is presented in section 4.3). The PSAU.BOT outputs are sent to the AVC relay of HV/MV transformer (PSAU.AVC) and the AVC relay of MV/LV transformer (SSAU.AVC). Figure 3.1 depicts a general view of the PSAU.BOT interactions in standalone operation. The detailed interface diagram (sequence diagram) is presented in section 5.1.

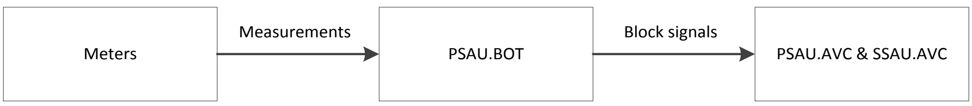


Figure 3.1 *BOT interactions in standalone operation*

It is important to notice that power flow information of the MV/LV transformer first is stored in SSAU.DB. Afterwards, to make this info accessible to the PSAU.BOT, data is transferred from SSAU.DB to PSAU.DB. The inverse data transfer is done for sending the PSAU.BOT outputs to SSAU.AVC.

3.1.2 Development and simulation platforms

The PSAU.BOT algorithm has been implemented in MATLAB and the physical network model has been constructed in PSCAD. Also, PSCAD/MATLAB interface is utilized in simulations. The development and simulation platforms are as follows:

- Windows 7, 64-bit
- MATLAB R2013a, 32-bit
- PSCAD, version 4.5.4, 64-bit, professional edition

3.2 Integrated operation of the BOT unit

Although the main focus of this thesis is on the standalone operation of the PSAU.BOT, the design specification for integrated operation is also presented. In integrated operation, the PSAU.BOT coordinates the operation of the two OPF-based CVC algorithms that are working at two different voltage levels. These CVC algorithms are basically identical and the only difference is their operational level.

This OPF-based CVC algorithm has already been developed by Anna Kulmala [3] at Electrical Engineering Department of Tampere University of Technology. Since the CVC algorithm is an OPF-based algorithm, from now on the term “power controller” is used instead of the CVC algorithm in this thesis and the CVC is considered to be the most integral part of the power controller.

In subsection 3.2.1, at first developed power controller in [3] is briefly presented, and then its connection with the PSAU.BOT is described in subsection 3.2.2.

3.2.1 Power controller

There are two power controllers (PCs); one is located at PSAU which is responsible for the power flow and voltage control in the MV network, and the other is located at SSAU which is responsible for the power flow and voltage control in the LV network. Both power controllers are optimizing their networks to have an efficient and cost-effective network operation while respecting all the constraints.

The objectives of the PSAU.PC and the SSAU.PC algorithms are as follows:

- Reduction of the network losses
- Reduction of production curtailment

The PSAU.PC and the SSAU.PC algorithms have been implemented in MATLAB. The $fmincon$ function, which is available in optimization toolbox of the MATLAB, has been used to minimize the above-mentioned objectives. Table 3.1 presents the outputs generated by the power controllers.

Table 3.1 *Outputs generated by the power controllers*

Outputs of the PSAU. PC	**Outputs of the SSAU. PC**
reference voltage for the PSAU.AVC	reference voltage for the SSAU.AVC
reference active power for the MV network controllable resources	reference active power for the LV network controllable resources
reference reactive power for the MV network controllable resources	reference reactive power for the LV network controllable resources

3.2.2 Connection of the power controllers with the BOT (integrated operation)

It is possible to consider one single power controller which optimizes the entire distribution network (i.e. the MV and LV networks combined), but in order to make the computation time of the algorithms feasible and more attractive for the real-time implementation, power controllers have been implemented separately. This means that the PSAU.PC is responsible for control of only MV network controllable resources and the SSAU.PC is responsible for control of the LV network controllable resources. The coordination part of the PSAU.PC and the SSAU.PC is realized by the PSAU.BOT that is developed in this thesis.

The need for coordination is due to the fact that the PSAU.PC and SSAU.PC are controlling controllable resources located at their own respective voltage levels i.e. the PSAU.PC does not take the MV/LV transformer operation into account and similarly the SSAU.PC does not consider the HV/MV transformer operation in its algorithm. This uncoordinated operation can lead to extra tap changer actions and also additional actions by other controllable resources that are controlled by the power controllers. The PSAU.BOT here acts as a supplementary algorithm that coordinates the operation of the PSAU.PC and SSAU.PC by managing their OLTCs.

The main difference between the integrated and standalone operation of the PSAU.BOT is that in integrated operation, coordination is realized not only by sending OLTC block signals and block validity time/unblock signals to the PSAU.AVC and SSAU.AVC, but also to the PSAU.PC and SSAU.PC.

3.2.3 BOT dependencies

In addition to the PSAU.BOT, PSAU.PC and SSAU.PC, in integrated operation, two SE units are present. The SE units are responsible to provide the best possible estimated values of the network parameters such as nodal voltages, power flows and load value of each node. The inputs of the PSAU.PC are provided by the medium voltage network state estimation (PSAU.SE), and the inputs of the SSAU.PC are provided by the low voltage network state estimation (SSAU.SE). Also, input data related to the coordination of the PSAU.PC and SSAU.PC is obtained from the PSAU.BOT. Using received data; the power controllers compute and send the control setpoints to the AVC relay of transformers and other controllable resources in the network. Figure 3.2 depicts a general view of the PSAU.BOT interactions in integrated operation. The detailed interface diagram (sequence diagram) is presented in section 5.2.

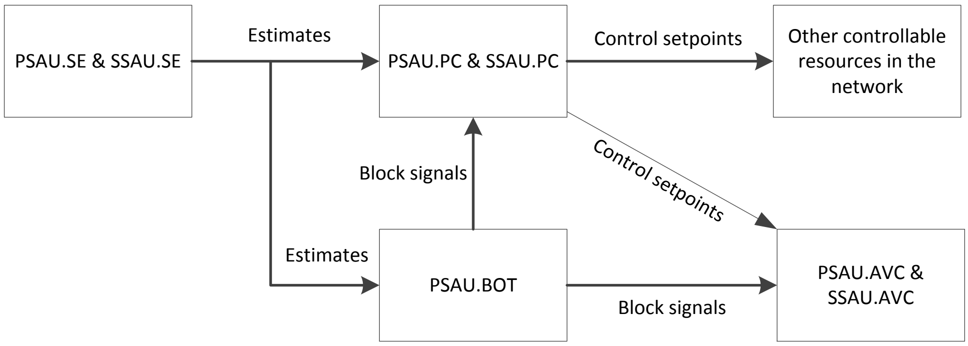


Figure 3.2 *BOT interactions in integrated operation [7]*

All data transfer between different units stated in Figure 3.2, are via the PSAU.DB or SSAU.DB. The data transfers at the MV level are via the PSAU.DB, and the data transfers at the LV level are via SSAU.DB.

The PSAU.BOT in integrated operation is dependent on SE units, since its inputs (active and reactive power flows through HV/MV and MV/LV transformers) are provided by the PSAU.SE and SSAU.SE. It is important to notice that power flow through the MV/LV transformer is calculated by the SSAU.SE then it is stored in SSAU.DB. Afterwards, to make this info accessible to the PSAU.BOT, data has to be transferred from SSAU.DB to PSAU.DB. The inverse data transfer is done for sending the PSAU.BOT outputs to the SSAU.AVC and the SSAU.PC.

4. BOT UNIT ALGORITHM DEVELOPMENT

In this chapter, the developed algorithm in this thesis is presented. As it has been mentioned in chapter 3, the PSAU.BOT unit is responsible for managing the transformers operating in series in a way that coordination of transformers in bidirectional power flow environment is realized. The main focus is on standalone operation of the PSAU.BOT. However, the PSAU.BOT use in integrated operation which aims to coordinate the operation of the PSAU.PC and SSAU.PC by managing their OLTCs is shortly explained in section 4.4.

4.1 Need for the BOT

In this thesis, a communication based approach is utilized for managing the OLTCs. As already stated in chapter 3, the PSAU.BOT unit is located at the primary substation. The PSAU.BOT utilizes the communication platforms to send the OLTC block signals and block validity time/unblock signals to AVC relays. The main motivation for the development of the PSAU.BOT is deficiency of the local AVC relay of transformers.

Usually, the OLTCs are used to adjust the voltage on the secondary side (lower voltage side) of the transformers. In order to adjust the secondary side voltage of the transformer, the AVC relay should provide commands for the OLTC. The AVC relay is not able to determine whether the voltage change has originated from the primary or secondary side of the transformer and it reacts based on the voltage change at the secondary side. For instance, when there is a load increase in the MV network, the HV/MV transformer should do tap action to compensate for the voltage drop; however, the AVC relay of the MV/LV transformer will also sense a voltage drop which will result in simultaneous actions by both transformers. Since only the HV/MV transformer operation is necessary for voltage restoration, the MV/LV transformer will do a reverse action resulting in more voltage fluctuations at the load point. Therefore, finding the origin of voltage change (voltage level) is a momentous task for proper coordination of cascaded OLTCs. The PSAU.BOT unit is capable of finding the origin of voltage variations in the network by tracking the active and reactive power flow changes through the distribution transformers. This unit is specifically designed for a bidirectional power flow environment. Hence, it is able to consider reverse power flow through the transformers due to integration of distributed generation. [24]

The main advantage of the PSAU.BOT over the local control methods, mentioned in subsection 2.4.2, is that it provides more selectivity; however, it does not alter the operational principles of the AVC relays that regulate the voltage locally. In comparison to the local control where the time delays of cascaded OLTCs are set to the same value, the PSAU.BOT is able to reduce the number of unnecessary tap actions [24]. Also, compared to the GT method where the time delays are set based on the worst case scenario for the voltage regulation, the PSAU.BOT leads to reduction in customer's voltage restoration time, since it allows assigning the same time delay for the cascaded OLTCs [24]. Compared to other centralized methods, for example, the optimal control, mentioned in subsection 2.4.2, the PSAU.BOT is a quite simple method that makes it more approachable for the system operators.

4.2 BOT unit operational logic

The internal operation of the PSAU.BOT unit has been divided into two steps. At first, the origin of the voltage change is located. Afterwards, an OLTC block signal is sent to the AVC relay of the transformer whose operation should be delayed or avoided [24]. The developed control scheme for the PSAU.BOT is depicted in Figure 4.1. The variables P and Q in the figure are active and reactive powers, respectively. In chapter 5, detailed sequence diagrams representing the communication between the different devices/units have been drawn and explained step by step.

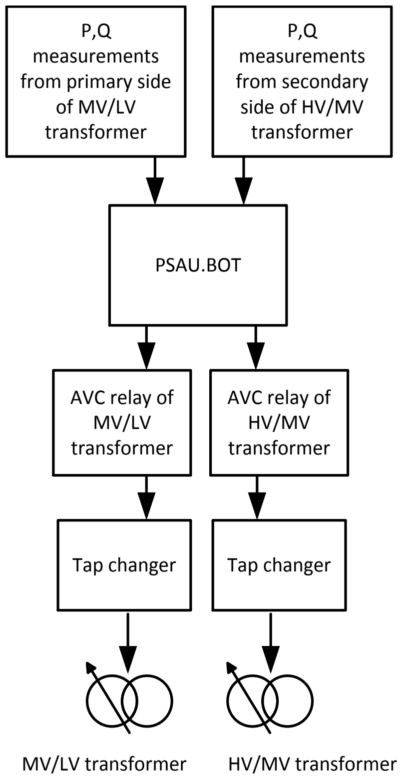


Figure 4.1 *Developed PSAU.BOT control scheme [24]*

The main assumption in the Figure 4.1 is that the active and reactive powers of the MV/LV transformer are measured at the MV side (primary side) of the transformer. However, due to the fact that metering devices are usually located at the lower voltage side (secondary side) of the transformers, these measurements can also be collected from the LV side. This has no effect on the developed control logic and only the power losses over transformer should be considered.

In order to determine the operational principle of the PSAU.BOT, an example distribution network model is used. The network model is shown in Figure 4.2. As already stated in previous chapters, a valid assumption is that the MV/LV transformer is also equipped with OLTC (see section 2.2).

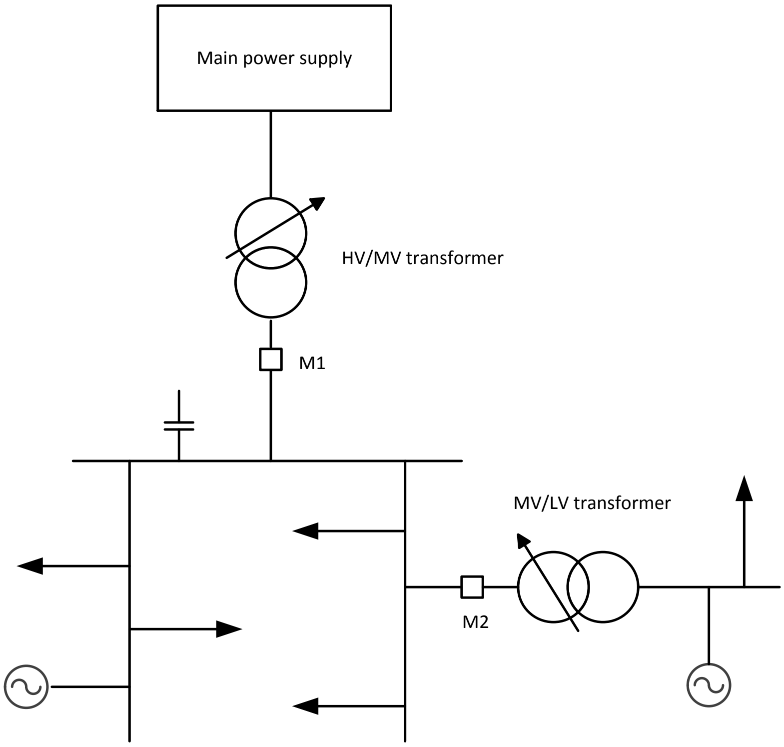


Figure 4.2 *An example distribution network model*

4.2.1 Locating the origin of voltage variation

Meters M1 and M2 in Figure 4.2 are providing the active and reactive power flow information. Power flow recorded by M1 indicates the power flow to/from the whole MV network including LV networks. However, M2 presents the power flow to/from the LV network. Since the system has a cascaded nature, changes in power flow recorded at M2 are also sensed by M1. This means that power changes in the LV network are also visible at M1 in the same direction. Of course, there is some difference in power variations at M1 and M2 due to the network power losses and physical parameters which should be considered. On the other hand, power variation elsewhere in the MV network is not affecting the power flow at M2. The power flow measured by M2 is dependent on the LV network loading and generation unless there are some outages or critical problems in the higher voltage levels. Using the active and reactive power changes recorded by M1 and M2, the PSAU.BOT detects the origin of voltage variations in the network. [24]

It is important to notice that changes in the LV network may not be always visible at M1. The reason for this can be changes elsewhere in the MV network in opposite direction. General rules developed for the PSAU.BOT based on the power variations are presented in subsection 4.2.3.

4.2.2 Ordering OLTC block signals

The principle, used inside the PSAU.BOT algorithm, for generating the block signals is quite simple. Having voltage changes originating from the MV network, the PSAU.BOT sends a block signal to the AVC relay of the MV/LV transformer that prevents the MV/LV OLTC operation. Similarly, voltage changes caused by the LV network lead to blocking of the HV/MV OLTC (usually this is not the case, and the HV/MV OLTC is blocked only in case of voltage disturbance in HV network). The OLTC block signals are generated along with block validity time. This is to make sure that in the case of communication failure between the PSAU.BOT and the AVC relays, the blocked OLTC will not stay blocked for an indefinite and possibly very long period of time. [24]

The PSAU.BOT is also capable of generating unblock signals for the blocked OLTCs, however, it is more reliable to use block validity time since it decreases the need for additional number of data transfer between the PSAU.BOT and the AVC relays.

4.2.3 General rules defined for the BOT operation

Based on explanations presented in subsections 4.2.1 and 4.2.2, the following set of rules is defined for the PSAU.BOT unit:

1. If power changes recorded by M1 are (considerably) bigger than power changes recorded by M2, send a block signal and a block validity time to AVC relay of MV/LV transformer (selection criteria for the block validity time have been presented in subsection 4.2.4).

2. If power changes are not considerable at M1, there are two possibilities:
   2.1. Changes in the MV and LV networks are neutralizing each other
   2.2. There is no change in the entire MV network which includes also the LV network

   In either case, no block signal is generated and the AVC relays of transformers take care of voltage control locally.

As it can be inferred from rules 1 and 2, the HV/MV OLTC has higher operational priority. There is also a case where both of the HV/MV and MV/LV transformer OLTCs should be blocked. This happens when the origin of the voltage disturbances is in the feeding (HV) network.

4.2.4 Important settings related to the BOT unit

The time delay of the AVC relays should be set equal for all cascaded transformers, which will result in fast restoration of voltage at consumption points [24]. Block validity time should be carefully selected. This time should not be very small as that can weaken the coordination of cascaded transformers. Also, it should not be set to a high value as that can lead to blocking the OLTC for a long period of time. In general, the block validity time might be in the following interval:

$$T_m < T_{block} < T_{AVC} \quad (4.1)$$

where T_m and T_{AVC} present the mechanical time delay of tap action and time delay of the AVC relay, respectively. T_{block} is the block validity time. It is recommended to set the T_{block} value slightly more than T_m. In this way, it is more likely that tap action has already been done by the unblocked transformer. The AVC relay delay counter of the blocked transformer starts after expiration of the block validity time.

4.3 Detailed list of the BOT inputs and outputs

The PSAU.BOT inputs are listed in Table 4.1. In the first column, the inputs are mentioned. The second column determines the data which have been exchanged. The third column shows the source of the input data. The forth column indicates whether the exchanged data are received from local or remote sources. If data are received from the devices or units located at the same voltage level (substation), data transfer is local, otherwise, remote. The data update schedule (update frequency) is mentioned in the fifth column.

Table 4.1 *Inputs of the PSAU.BOT unit*

Input	**Data exchanged**	**Source**	**Local / Remote**	**Update schedule**
Measured active power at secondary side (MV side) of HV/MV transformer	Value of active power	Metering device	Local	On a fixed schedule
Measured reactive power at secondary side (MV side) of HV/MV transformer	Value of reactive power	Metering device	Local	On a fixed schedule
Measured active power at primary side (MV side) of MV/LV transformer	Value of active power	Metering device	remote (since the metering device is at the LV side)	On a fixed schedule

Measured reactive power at primary side (MV side) of MV/LV transformer	Value of reactive power	Metering device	remote (since the metering device is at the LV side)	On a fixed schedule
Network topology	1. Lines from node # to node # 2. Substations from node # to node # 3. Location of meters that provide active and reactive power values (i.e. which transformer)	Network company	remote from control center	On request (quite rarely)

The PSAU.BOT outputs are listed in Table 4.2. In the first column, the outputs are mentioned. The second column determines the data which have been exchanged. The third column shows the destination of the output data. The forth column indicates whether the exchanged data are sent to local or remote destinations. If data are sent to the devices or units located at the same voltage level, data transfer is local, otherwise, remote. The data update schedule (update frequency) is mentioned in the fifth column.

Table 4.2 *Outputs generated by the PSAU.BOT unit*

Output	**Data exchanged**	**Destination**	**Local / Remote**	**Update schedule**
Block signal (for the AVC relays of the HV/MV and MV/LV transformers)	Block signal which prevents the OLTC operation	AVC relay of transformers	Local for the HV/MV transformer relay Remote for the MV/LV transformer relay	After each run of the PSAU.BOT unit. Default value of the block signal is 0 (unblocked) unless the PSAU.BOT unit changes it to 1 (blocked)
Unblock signal (for the AVC relays of the HV/MV and MV/LV transformers)	Unblock signal (this is used when block validity time is not considered)	AVC relay of transformers	Local for the HV/MV transformer relay Remote for the MV/LV transformer relay	After each run of the PSAU.BOT

Block validity time If the value of the block signal is 1, then block validity time is sent along with it	Validity time of block signal	AVC relay of trans-formers	Local for the HV/MV trans-former relay Remote for the MV/LV trans-former relay	After each run of the PSAU.BOT

4.4 Bot unit operation in the presence of power controllers (integrated operation)

The operational principle of the PSAU.BOT in the presence of power controllers (i.e. in integrated operation) is the same as what has been stated in section 4.2. However, the active and reactive power inputs of the PSAU.BOT are assumed to be received from the PSAU.SE and SSAU.SE and not directly from the metering devices. The PSAU.BOT inputs all are available at the PSAU.DB. Besides the inputs mentioned in section 4.3, there is also an input flag which is called SE ready flag. This flag is indicator of the new data update by the PSAU.SE and SSAU.SE. The PSAU.BOT first checks if the PSAU.DB contains new data from both PSAU.SE and SSAU.SE. If no new data is available, the PSAU.BOT returns to a waiting state. If new data is available, it is read and the PSAU.BOT algorithm is run and its outputs are generated.

In addition to the outputs mentioned in section 4.3, in integrated operation, there is an output flag called BOT ready flag. This flag is used to inform the PSAU.PC and SSAU.PC that the PSAU.BOT outputs have been generated. The outputs of the PSAU.BOT are saved in the PSAU.DB. Then these outputs are used as inputs by the PSAU.PC, the SSAU.PC and the PSAU.AVC and SSAU.AVC relays. Figure 4.3 presents the PSAU.BOT unit interaction with the PSAU.DB. In section 5.2, a detailed description of the PSAU.BOT interactions with the power controllers, PSAU.DB and SSAU.DB is presented.

Regarding the PSAU.BOT effect on the power controllers, the following points should be considered:

- If “block signal” is zero in a power controller, tap variable will be considered as an unknown control variable which means the OPF algorithm can use the OLTC as a controllable resource.

- If “block signal” is one in a power controller, tap variable is constant and cannot be changed which means the OPF algorithm cannot use the OLTC as a controllable resource. The blocked OLTC will be unblocked after expiration of the block validity time.

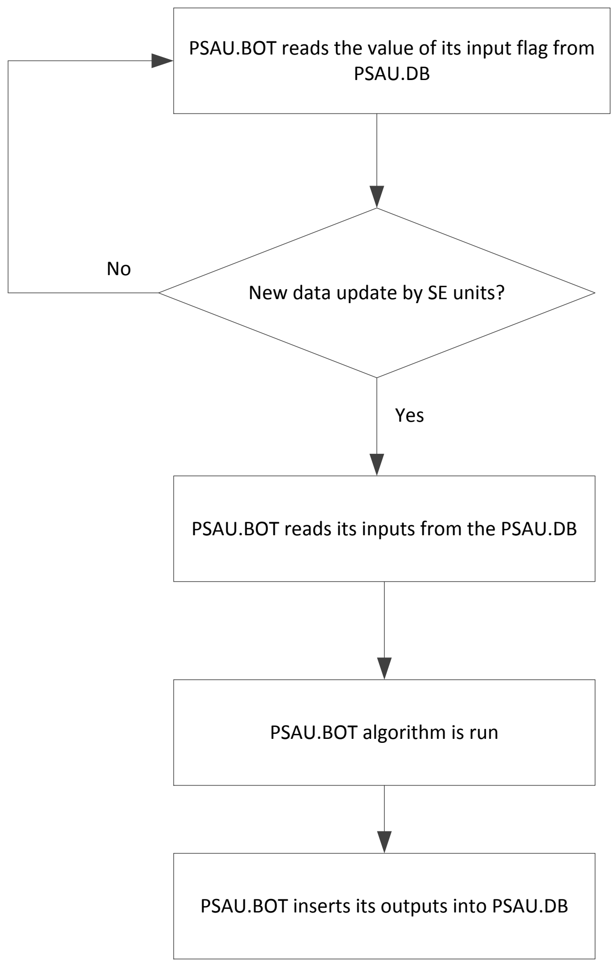


Figure 4.3 *PSAU.BOT interaction with the PSAU.DB*

5. USE CASES FOR THE DEVELOPED ALGORITHM

“A use case describes a way in which a real-world actor interacts with the system” [29]. In order to show the functionality of the PSAU.BOT unit and also define its interactions with other units or devices, two use cases are defined in this chapter. The first use case is for the standalone operation of the PSAU.BOT and the second for the integrated operation of it.

The required information regarding the components/signs used in the sequence diagrams are explained as they appear in the diagrams for the first time. In order to fully understand the PSAU.BOT integrated use case, it is recommended to start first with the standalone use case.

5.1 Use case for the standalone operation of the BOT

5.1.1 Scope and objective of the use case

The PSAU.BOT is an input provider of the AVC relays of the HV/MV and MV/LV OLTCs. It sends block and unblock signal/block validity time to the HV/MV and MV/LV OLTC AVC relays. The objective of the PSAU.BOT is to prevent unnecessary tap operations and enhance the voltage quality at consumption points.

5.1.2 Narrative of the use case

The main functionality of the PSAU.BOT is to coordinate the operation of the cascaded OLTCs. In order to make the PSAU.BOT unit functional some actors are required. Actors are units that somehow have interaction with the system to achieve some specific goal. Here that specific goal is to control the voltage level in the distribution network using on-load tap changers. Table 5.1 presents the actors used in standalone operation of the PSAU.BOT. The PSAU and SSAU in the table refer to the primary substation automation unit and secondary substation automation unit, respectively.

Table 5.1 *Actors used in standalone operation of the PSAU.BOT*

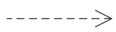
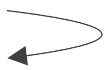
Actor name	**Actor type**	**Description of the actor**
PSAU.BOT	Application	Block OLTC’s of transformers unit

PSAU.AVC	Device	Automatic voltage controller of HV/MV transformer
PSAU.DB	System	Primary substation automation unit database
SSAU.AVC	Device	Automatic voltage controller of the MV/LV transformer
SSAU.DB	System	Secondary substation automation unit database
M1	Device	Meter located at MV side of the HV/MV transformer
M2	Device	Meter located at MV side of the MV/LV transformer

5.1.3 Sequence diagram

Figure 5.1 presents the PSAU.BOT standalone sequence diagram. The actions (or data transfer) start from the upper left corner and next actions appear below the previous action. The boxes at the top of the diagram are representing the actors. Below the actors, there are also some boxes (connected to actors by dashed lines) that indicate when the actors are active. Depending on the availability and frequency of active and reactive power measurements; the process in the figure is repeated. Here it has been assumed that the frequency of measurements is one minute (**loop** [every 1 minute] in the diagram). Term **parallel** is indicator of simultaneous actions (simultaneous actions have been separated by a dashed line). Term **if** is used when some conditions (inside the bracket) should be fulfilled for taking an action. Table 5.2 shows the signs present in the sequence diagram. Microsoft Visio has been used for drawing the sequence diagram.

Table 5.2 *Signs used in the sequence diagram*

Sign	**Sign description**
	Message
	Return message
	Asynchronous message
	Internal calculations
	Termination of actor activation

All the above-mentioned statements/signs are true also in the integrated sequence diagram of the PSAU.BOT.

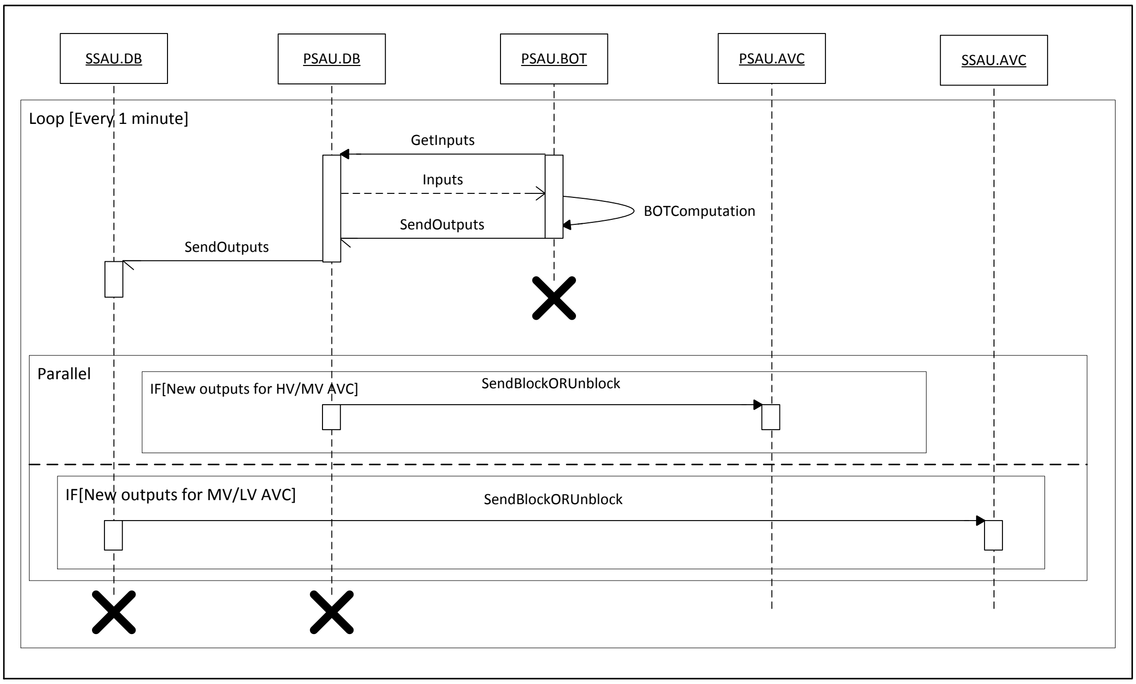


Figure 5.1 *Sequence diagram of the PSAU.BOT in standalone operation*

5.1.4 Step by step analysis of the sequence diagram

Table 5.3 presents the step by step analysis of the PSAU.BOT standalone sequence diagram. It should be noticed that each arrow in the sequence diagram is presented by a row in the table. The network topology info is assumed to be known for the PSAU.BOT at the beginning of the process. Also, all the active and reactive power measurements are assumed to be available in the PSAU.DB (the main source of the power measurements are actors M1 and M2). Block and unblock signals have been used as outputs of the PSAU.BOT, however, it is also possible to use block validity time instead of the unblock signal.

Table 5.3 *Step by step analysis of the PSAU.BOT standalone sequence diagram*

Step #	Event	Description	Information producer	Information receiver	Information exchanged
1	PSAU.BOT input data request	PSAU.BOT asks inputs from PSAU.DB	PSAU.BOT	PSAU.DB	Request for data import
2	PSAU.BOT data import	PSAU.BOT receives its inputs from PSAU.DB	PSAU.DB	PSAU.BOT	Active and reactive power measurements
3	PSAU.BOT calculations	PSAU.BOT algorithm runs to generate	Internal calculation	Internal calculations	No information exchange

		outputs			
4	PSAU.BOT result export to PSAU.DB	PSAU.BOT sends its outputs to PSAU.DB	PSAU.BOT	PSAU.DB	OLTC block or unblock commands for PSAU.AVC and SSAU.AVC
5	PSAU.BOT result export to SSAU.DB	PSAU.BOT sends its outputs to SSAU.DB via PSAU.DB	PSAU.BOT	SSAU.DB	OLTC block or unblock commands for SSAU.AVC
6	Steps 6.1 and 6.2 are in parallel operation				
6.1	PSAU.DB sends commands to PSAU.AVC when new outputs are generated	PSAU.BOT sends block or unblock signal to PSAU.AVC	PSAU.DB	PSAU.AVC	OLTC block and unblock commands
6.2	SSAU.DB sends commands to SSAU.AVC when new outputs are generated	SSAU.BOT sends block or unblock signal to SSAU.AVC	SSAU.DB	SSAU.AVC	OLTC block or unblock commands

5.2 Use case for the integrated operation of the BOT

5.2.1 Scope and objective of the use case

The PSAU.BOT unit is an input provider of the PSAU.PC, PSAU.AVC, the SSAU.PC and SSAU.AVC. It sends block and unblock signal/block validity time to the PSAU.PC, SSAU.PC, PSAU.AVC and SSAU.AVC. The objective of the PSAU.BOT unit is to prevent unnecessary tap operations, reduce the voltage fluctuations at consumption points and avoid the additional utilization of other controllable resources such as DG units and capacitor banks.

5.2.2 Narrative of the use case

The main functionality of the PSAU.BOT unit is to coordinate the operation of the PSAU.PC and SSAU.PC by managing the cascaded HV/MV and MV/LV OLTCs. As standalone operation, in integrated operation the goal is to control the voltage level in the distribution network using on-load tap changers. Table 5.4 presents the actors used in integrated operation of the PSAU.BOT.

***Table 5.4** Actors used in integrated operation of the PSAU.BOT*

Actor name	**Actor type**	**Description of the actor**
PSAU.BOT	Application	Block OLTC's of transformers unit
PSAU.DB	System	Medium voltage network data exchange platform
PSAU.PC	Application	Medium voltage network power controller
PSAU.SE	Application	Medium voltage state estimation
PSAU.AVC	Device	Automatic voltage controller of the HV/MV transformer
SSAU.DB	System	Low voltage network data ex-change platform
SSAU.PC	Application	Low voltage network power controller
SSAU.SE	Application	Low voltage network state esti-mation
SSAU.AVC	Device	Automatic voltage controller of the MV/LV transformer

5.2.3 Sequence diagram

Figure 5.2 presents the PSAU.BOT integrated sequence diagram.

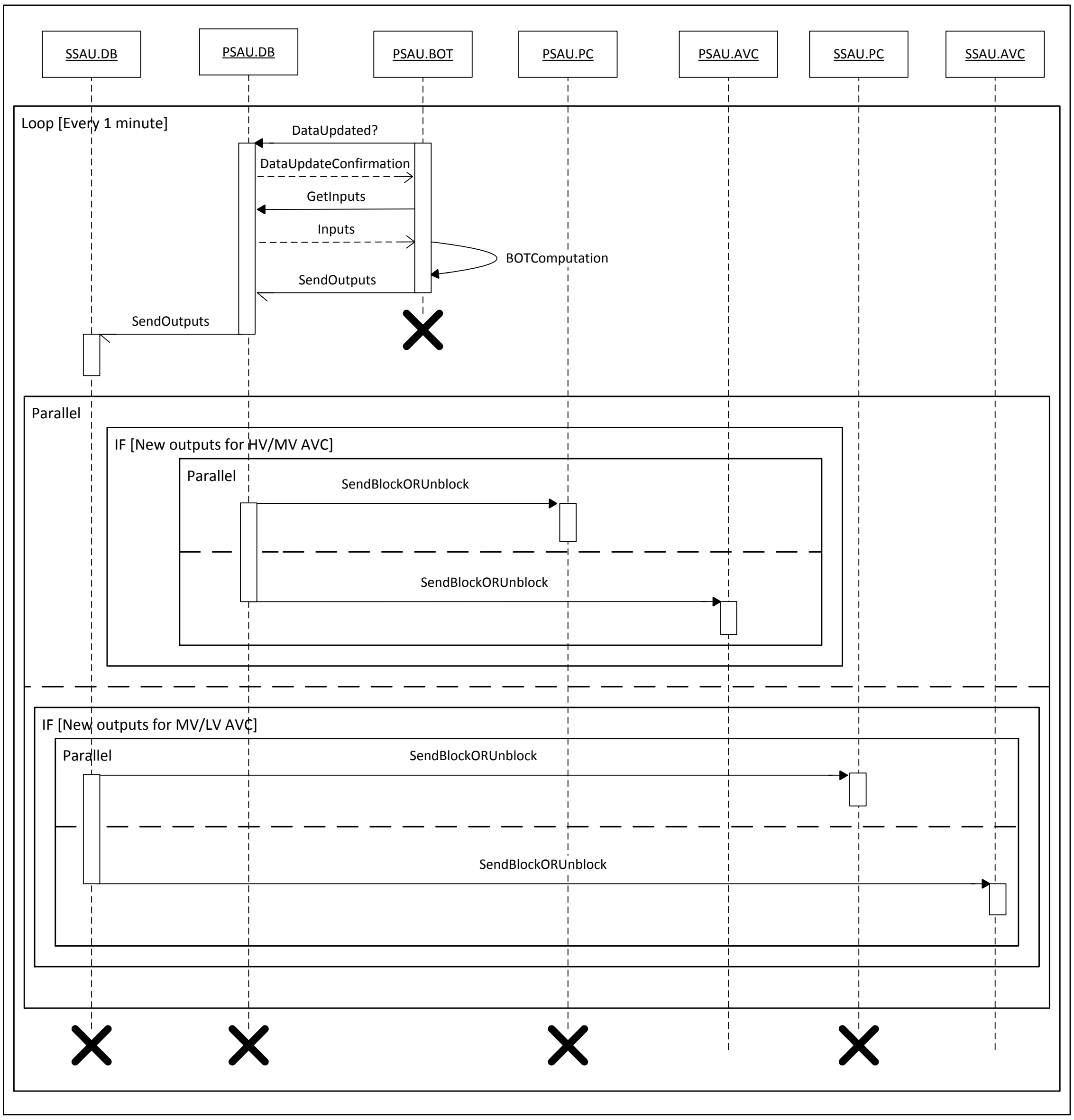


Figure 5.2 *Sequence diagram of the PSAU.BOT in integrated operation*

5.2.4 Step by step analysis of the sequence diagram

Table 5.5 presents the step by step analysis of the PSAU.BOT integrated sequence diagram. Similar to the standalone operation, it has been assumed that the network topology is known at the beginning of the process. Also, the PSAU.BOT inputs are assumed to be available in the PSAU.DB. The Active and reactive powers measurements are reserved by the PSAU.SE and SSAU.SE and then inserted into the PSAU.DB. Each arrow in the sequence diagram is presented by a row in the table. As standalone operation, block and unblock signals have been used as outputs of the PSAU.BOT, however, it is also possible to use block validity time instead of the unblock signal.

Table 5.5 *Step by step analysis of the PSAU.BOT integrated sequence diagram*

Step #	Event	Description	Information producer	Information receiver	Information exchanged
1	PSAU.BOT checks the new input data update	PSAU.BOT checks if new data has been updated into PSAU.DB	PSAU.BOT	PSAU.DB	Signal checking the data update
2	Data update confirmation	PSAU.DB confirms the data update	PSAU.DB	PSAU.BOT	Signal confirming the data update
3	PSAU.BOT input data request	PSAU.BOT asks inputs from the PSAU.DB	PSAU.BOT	PSAU.DB	Request for data import
4	PSAU.BOT data import	PSAU.BOT receives its inputs from PSAU.DB	PSAU.DB	PSAU.BOT	Active and reactive power values
5	PSAU.BOT calculations	PSAU.BOT algorithm is run to generate outputs	Internal calculations	Internal calculations	No information exchange
6	PSAU.BOT result export to PSAU.DB	PSAU.BOT sends all its outputs to PSAU.DB	PSAU.BOT	PSAU.DB	OLTC block or unblock commands for the PSAU.PC, PSAU.AVC, SSAU.PC and SSAU.AVC
7	PSAU.BOT result export to SSAU.DB	PSAU.BOT sends its outputs to SSAU.DB via PSAU.DB	PSAU.BOT	SSAU.DB (via PSAU.DB)	OLTC block or unblock commands for the SSAU.PC and SSAU.AVC
8	Steps 8.1 and 8.2 are in parallel operation				
8.1 If new outputs for PSAU.AVC and PSAU.PC: PSAU.DB sends the PSAU.BOT outputs to PSAU.PC and PSAU.AVC (steps 8.1.1 and 8.1.2 are in parallel operation)					
8.1.1	PSAU.DB sends new outputs to PSAU.PC	New outputs are sent to PSAU.PC by PSAU.DB	PSAU.DB	PSAU.PC	OLTC block and unblock commands

8.1.2	PSAU.DB sends new outputs to PSAU.AVC	New outputs are sent to PSAU.AVC by PSAU.DB	PSAU.DB	PSAU.AVC	OLTC block and unblock commands
8.2 If new outputs for SSAU.AVC and SSAU.PC: SSAU.DB sends the PSAU.BOT outputs to SSAU.PC and SSAU.AVC (steps 8.2.1 and 8.2.2 are in parallel operation)					
8.2.1	SSAU.DB sends new outputs to SSAU.PC	New outputs are sent to SSAU.PC by SSAU.DB	SSAU.DB	SSAU.PC	OLTC block and unblock commands
8.2.2	SSAU.DB sends new outputs to SSAU.AVC	New outputs are sent to SSAU.AVC by SSAU.DB	SSAU.DB	SSAU.AVC	OLTC block and unblock commands

6. SIMULATION AND TESTING

In this chapter functionality of the PSAU.BOT unit in standalone operation is tested. The chapter is divided into two sections. In section 6.1, the network model, used in simulations, is briefly described. In section 6.2, the performance of the PSAU.BOT in different network conditions is analyzed and compared with the local control methods of cascaded OLTCs.

6.1 The network model

The network model consists of an MV and an LV network. The MV network model has been presented in [30]. In this thesis, there is only one generation unit (a current source) in the MV network which is connected to the primary (HV/MV) substation. In addition, thesis considers a capacitor bank which is also connected to the primary substation. The MV network is supplied by an HV network via an HV/MV transformer. The used LV network is the same as the one in [31] and contains DG units in the form of current sources (the same current source model has been used also for the MV network generation unit). The LV network is connected to the MV network via an MV/LV transformer. The simplified network model, used in simulations, is shown in Figure 6.1.

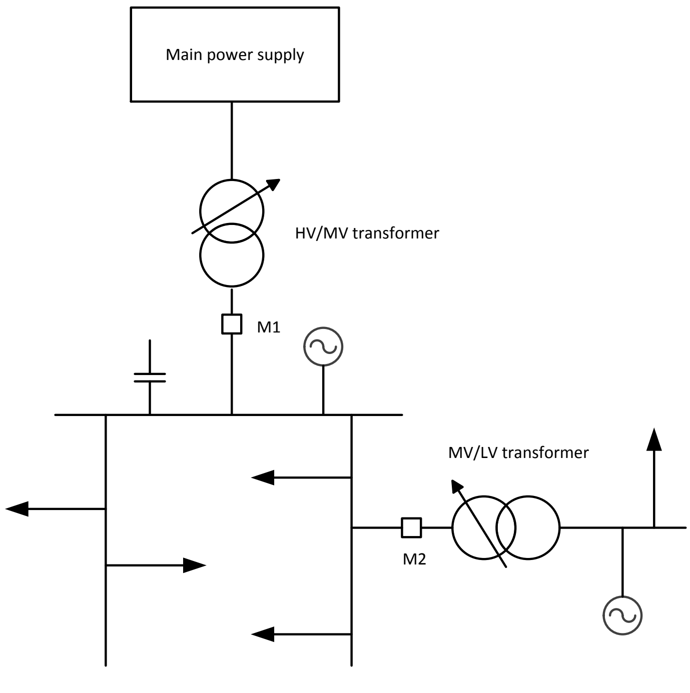


Figure 6.1 *Simplified distribution network model in PSCAD*

6.2 BOT unit performance test

In this section performance of the PSAU.BOT unit in two test cases (A and B) is tested. In the Test case A, the PSAU.BOT is compared with the local control method where the same time delays have been assigned for the AVC relays of cascaded transformers. In the Test case B, the PSAU.BOT performance is compared with a GT method where the AVC relay time delay of the MV/LV transformer is set based on the worst case scenario for the voltage regulation. First some parameters that are common for both test cases are presented.

Table 6.1 presents the initial loading of transformers (beginning of simulations) for both test cases.

Table 6.1 *Initial Loading condition in the network for both test cases*

Load at HV/MV transformer at minimum loading case	323.933 kW -83.213 kVAr
Load at MV/LV transformer at minimum loading case	4.71 kW 1.7 kVAr

Table 6.2 presents the test sequence used in both test cases. The test sequence has been created in a way that it tries to push the network beyond its limits by high loading of the transformers and pushing the voltage toward the network voltage limits, and it causes both voltage rise and voltage drop problems in the network. In addition, it leads to bidirectional power flow in both MV and LV networks.

Table 6.2 *Test sequence for both test cases*

Time of change	Change level	Type of change	Value of change
4 s	MV	Power plant connection	12 MW
15 s	LV	Active and reactive load increase	20 kW, 5 kVAr
23 s	MV	Active load increase	8 MW
33 s	LV	Power production by DG units	20 kW
50 s	MV	Inductive load increase	6 MVAr
75 s	MV	Capacitor bank connection	3 MVAr
100 s	LV	Reactive power generation by DG units	20 kVAr
108 s	MV	Power plant disconnection	12 MW
120 s	LV	Active and reactive load decrease	20 kW, 5 kVAr

127 s	MV	Active load decrease	8 MW
138 s	LV	Disconnection of DG units	20 kW
146 s	MV	Inductive load decrease	6 MVAr
173 s	MV	Capacitor bank disconnection	3 MVAr

The voltage reference is set to 1.01 per unit (pu) for the HV/MV transformer (primary substation) and 1 pu for the MV/LV transformer (secondary substation) in both test cases. The voltage references should be set in a way that there are minimum voltage deviations from no-loading to full-loading of the transformers. Line drop compensation is set to zero meaning that the AVC relays are controlling the transformer secondary bus voltages. Also, the block validity time has been set based on the recommendation presented in subsection 4.2.4 (block validity time is set to 1.1 s in all simulations with PSAU.BOT). Simulations are conducted and the results are recorded.

6.2.1 Test case A

Test case A itself is further divided into two sections (A.1 and A.2). In test A.1, the same AVC relay deadbands and tap steps are considered for both HV/MV and MV/LV transformers. In test A.2, however, the deadband of the MV/LV AVC relay is expanded and tap steps are bigger than test A.1.

Table 6.3 shows the used time delays for tap operations for both PSAU.BOT and local method (with the same AVC time delays). The applied time delays are much more in reality. In practice, time delay of AVC relays can be in the range of 30-120 s, and the mechanical time delay is in the range of 1-5 s [27]. As using this time delays will lead to a very long simulation time, they have been reduced in both Test case A andTest case B.

Table 6.3 *Time delays used in simulations for test case A*

Control approach	**Time delay of first tap operation**	**Time delay of consecutive tap operation**	**Mechanical time delay**
Coordinated using PSAU.BOT	3 s	2 s	1 s
Local method with same time delays	3 s	2 s	1 s

Time delays presented in Table 6.3, are the same for both HV/MV and MV/LV transformers.

TEST A.1:

The transformer parameters in test A.1 are presented in Table 6.4.

Table 6.4 *Transformer parameters for test A.1*

Transform-er	Voltage ratio	Full capacity	Deadband	Initial tap position	Tap steps	Number of avail-able taps
HV/MV	110/20 kV	16 MVA	1.5 %	1.0334	1.67 %	9 up 9 down (central position:1)
MV/LV	20/0.4 kV	0.1 MVA	1.5 %	1.0167	1.67 %	9 up 9 down (central position:1)

Figure 6.2 presents the operation of HV/MV and MV/LV OLTCs when the local control method (with the same time delays) is used. There are some extra tap actions (6 extra in total) by the MV/LV OLTC. The reason for these extra actions is the uncoordinated operation of the HV/MV and MV/LV OLTCs in response to changes at times 4 s, 50 s and 146 s. Since the HV/MV OLTC restores the voltage, the MV/LV OLTC has done reverse tap actions to restore the voltage in the LV network.

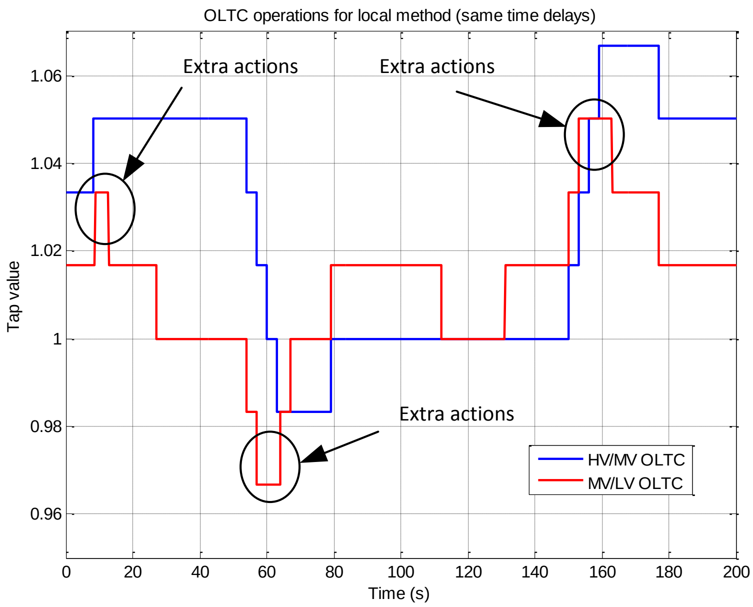


Figure 6.2 *HV/MV and MV/LV OLTC operations for the local method with the same time delays*

Figure 6.3 shows the operation of OLTCs when the PSAU.BOT is in use. The results indicate that extra tap actions occurred in the previous case have been eliminated. The reason for this is the blocking of the MV/LV OLTC by the PSAU.BOT at around times 4.1 s, 55 s and 150.5 s. At time 4 s, there is a power plant connection at the MV network which causes reverse power flow from the MV network to HV network, the PSAU.BOT detects the voltage disturbance level (i.e. MV network) and sends a block signal to

MV/LV OLTC. The MV/LV OLTC blocking at around time 55 s is due to operation of HV/MV OLTC in response to change in time 50 s (inductive load increase at the MV network). The MV/LV OLTC blocking at time 150.5 s is also because of operation of the HV/MV OLTC in response to the load decrease at the MV network at time 146 s.

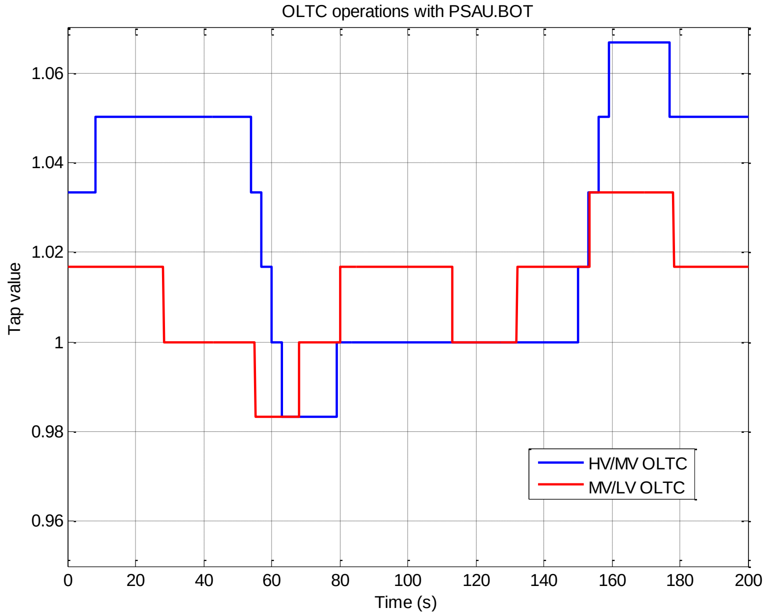


Figure 6.3 *HV/MV and MV/LV OLTC operations using PSAU.BOT*

Figure 6.4 shows the recorded voltages at the primary substation using both local method (with the same time delays) and PSAU.BOT. As expected, voltages are exactly the same, and the reason is the HV/MV OLTC operation, that is the same for both methods.

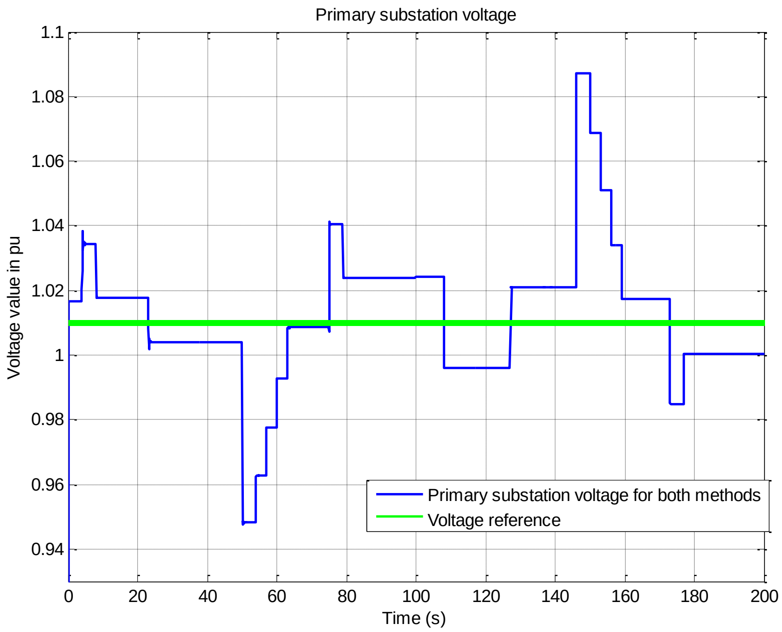


Figure 6.4 *Recorded voltage at primary substation*

Figure 6.5 presents the recorded voltage at the secondary substation using both local method (with the same time delays) and PSAU.BOT. The voltage fluctuations are more using the local method (marked with arrows in the figure), and the reason is the extra tap actions occurred using this method. The local control method is doing a faster tap action most of the time; however, it leads to unnecessary tap actions and sudden voltage changes that are not desirable.

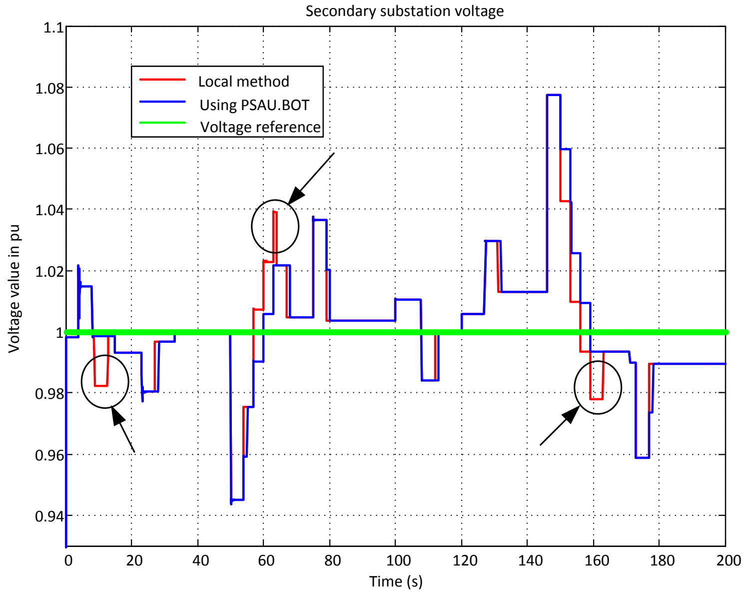


Figure 6.5 *Recorded voltage at secondary substation*

TEST A.2:

The transformer parameters in the test A.2 are presented in Table 6.5.

Table 6.5 *Transformer parameters for test A.2*

Transform-er	Voltage ratio	Full capacity	Deadband	Initial tap position	Tap steps	Number of avail-able taps
HV/MV	110/20 kV	16 MVA	1.5 %	1.0334	1.67 %	9 up 9 down (central position:1)
MV/LV	20/0.4 kV	0.1 MVA	2.25 %	1	2.5 %	4 up 4 down (central position:1)

Figure 6.6 presents the operation of HV/MV and MV/LV OLTCs when the local control method (with the same time delays) is used. An important point is that, assigning a bigger tap step and a bigger (expanded) deadband for the MV/LV tap changer and AVC relay, number of tap actions has been reduced by 3 compared to the local control method in test A.1 (compare Figure 6.2 and Figure 6.6). Having a bigger deadband, the AVC relay allows the voltage to deviate more in secondary substation and therefore less tap actions are required for restoring the voltage within permitted margin in the LV net-

work. In addition, having a bigger tap step size plays a key role in reducing the number of tap action i.e. less tap actions are required for restoring the voltage.

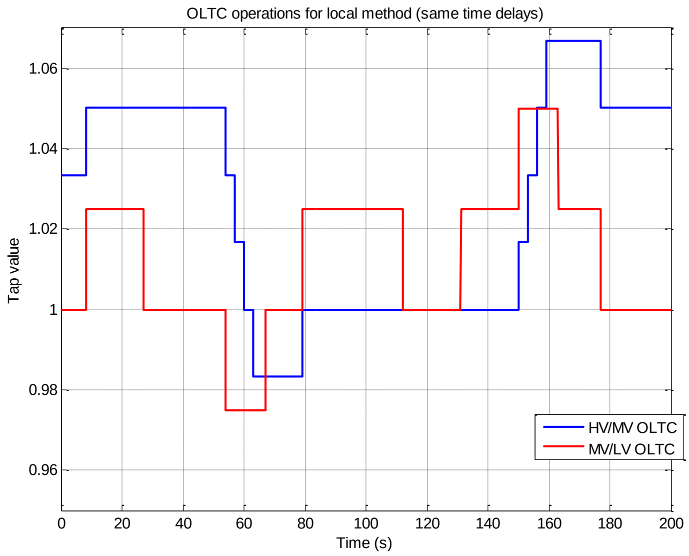


Figure 6.6 *HV/MV and MV/LV OLTC operations for the local method (with bigger deadband for MV/LV relay)*

Figure 6.7 shows the operation of OLTCs when the PSAU.BOT is in use. The results indicate that the number of tap actions present in the previous case has been reduced. The reason for this is blocking of the MV/LV OLTC by the PSAU.BOT at around times 4.1 s and 173.5 s in response to the changes at the MV network.

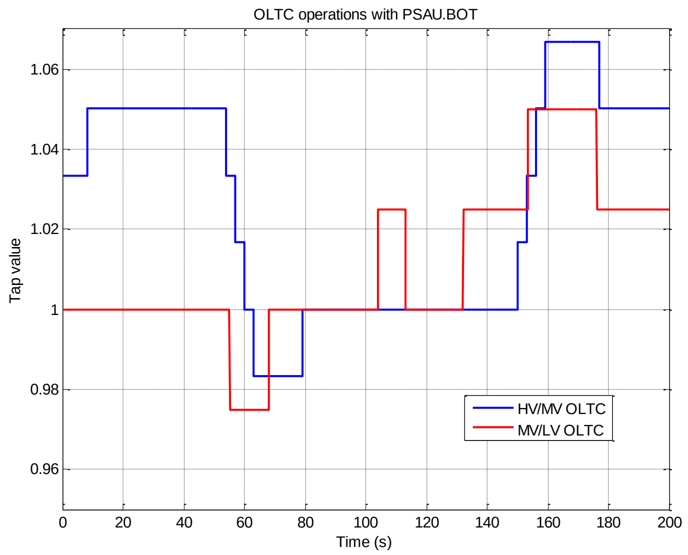


Figure 6.7 *HV/MV and MV/LV OLTC operations using PSAU.BOT (with expanded MV/LV AVC relay deadband)*

The recorded voltage at the primary substation using both local method and PSAU.BOT is identical to Figure 6.4. The difference is in the secondary substation voltage, as shown in Figure 6.8.

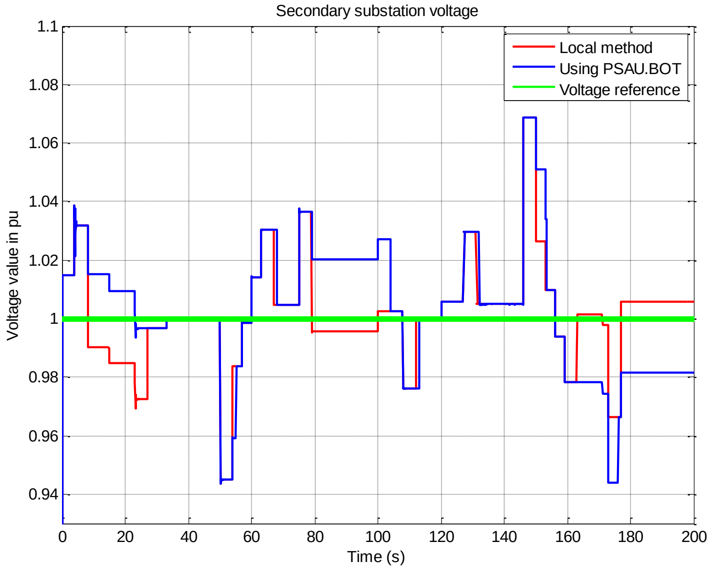


***Figure 6.8** Recorded voltage at secondary substation for local method and PSAU.BOT (with expanded MV/LV AVC relay deadband)*

Similar to test A.1, the PSAU.BOT has minimized the total number of the MV/LV OLTC actions; however, voltage restoration is accompanied with some delay in comparison to the local method.

It should be noticed that due to assigning a bigger tap size for the MV/LV OLTC in test A.2 and in order to avoid tap action when there is no change in the network, initial position of the MV/LV tap has been set to 1 resulting in a rather different initial (before changes in the network) secondary substation voltage compared to test A.1.

6.2.2 Test case B

Similar to Test case A, test case B is also divided into two sections. In test B.1, the same AVC relay deadbands and tap steps are considered for both HV/MV and MV/LV transformers. In test B.2, the deadband of the MV/LV AVC relay is expanded and tap steps are bigger than test B.1.

Table 6.6 and Table 6.7 present the used time delays for tap operation for the HV/MV and MV/LV transformers, respectively.

Table 6.6 *The HV/MV transformer time delays used in simulations for test case B*

Control approach	Time delay of first tap operation	Time delay of consecutive tap operation	Mechanical time delay
Coordinated using PSAU.BOT	3 s	2 s	1 s
The GT method	3 s	2 s	1 s

Table 6.7 *The MV/LV transformer time delays used in simulations for test case B*

Control approach	Time delay of first tap operation	Time delay of consecutive tap operation	Mechanical time delay
Coordinated using PSAU.BOT	3 s	2 s	1 s
The GT method	7 s	2 s	1 s

TEST B.1:

The transformer parameters in the test B.1 are presented in Table 6.8.

Table 6.8 *Transformer parameters for test B.1*

Transform-er	Voltage ratio	Full capacity	Deadband	Initial tap position	Tap steps	Number of avail-able taps
HV/MV	110/20 kV	16 MVA	1.5 %	1.0334	1.67 %	9 up 9 down (central position:1)
MV/LV	20/0.4 kV	0.1 MVA	1.5 %	1.0167	1.67 %	9 up 9 down (central position:1)

Figure 6.9 depicts the operation of HV/MV and MV/LV OLTCs when the GT method is used.

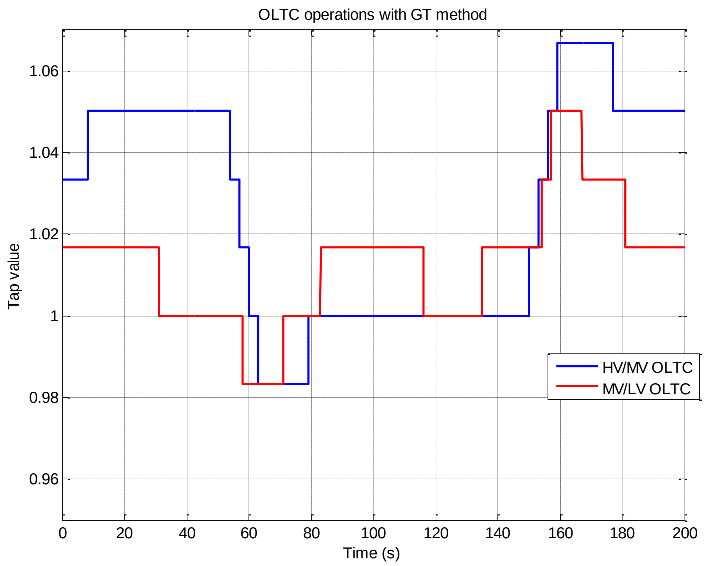


Figure 6.9 *OLTC operations with GT method*

The HV/MV OLTC operations using both GT and PSAU.BOT methods are exactly the same. However, the main difference is in the MV/LV OLTC operations. Figure 6.10 can be used to compare the MV/LV OLTC operation for both methods. As it is visible from figure, using the GT method all tap actions are accompanied with more delay in comparison to the PSAU.BOT. In addition, two extra tap actions are recorded using the GT method. These tap actions are considered extra because the HV/MV OLTC has regulated the voltage and the MV/LV OLTC has done reverse tap action to adjust the voltage at secondary substation. The extra tap actions can be eliminated by assigning a higher delay for the MV/LV AVC relay; however, it will lead to a very slow customer voltage restoration.

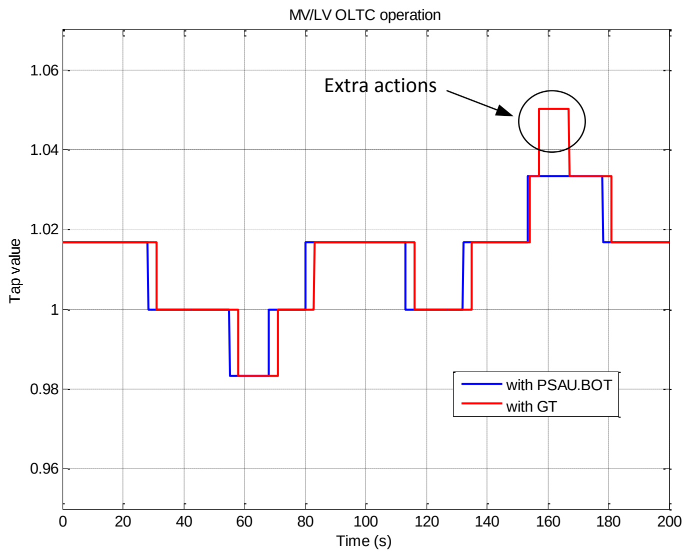


Figure 6.10 *MV/LV OLTC operation for both methods*

Recorded voltage at primary substation indicates the exactly same behavior for both GT and PSAU.BOT methods. On the other hand, based on operation of MV/LV OLTC, it is expected to have a better voltage quality at secondary substation when the PSAU.BOT is in use. Figure 6.11 proves this fact. Since the PSAU.BOT allows assigning the same time delay for AVC relay of cascaded OLTCs, It is capable of much faster voltage restoration in comparison to the GT method where the time delay of the MV/LV AVC relay is set to a value higher than HV/MV AVC relay.

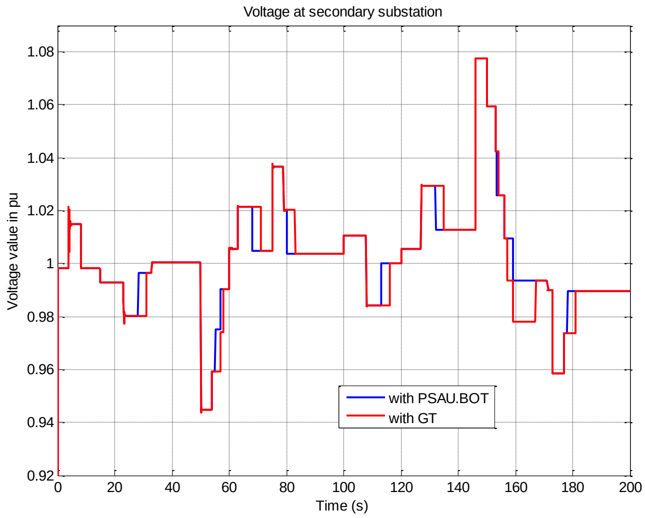


Figure 6.11 *Voltage at secondary substation*

TEST B.2:

The transformer parameters in the test B.2 are presented in Table 6.9.

Table 6.9 *Transformer parameters for test B.2*

Transformer	Voltage ratio	Full capacity	Deadband	Initial tap position	Tap steps	Number of available taps
HV/MV	110/20 kV	16 MVA	1.5 %	1.0334	1.67 %	9 up 9 down (central position:1)
MV/LV	20/0.4 kV	0.1 MVA	2.25 %	1	2.5 %	4 up 4 down (central position:1)

The operation of the HV/MV OLTC is the same for both GT and PSAU.BOT methods and as a result recorded voltage at primary substation is the same. In order to observe the effect of expanded deadband of MV/LV relay on coordination of the HV/MV and MV/LV OLTCs using the GT method, these two OLTC actions are depicted together in Figure 6.12.

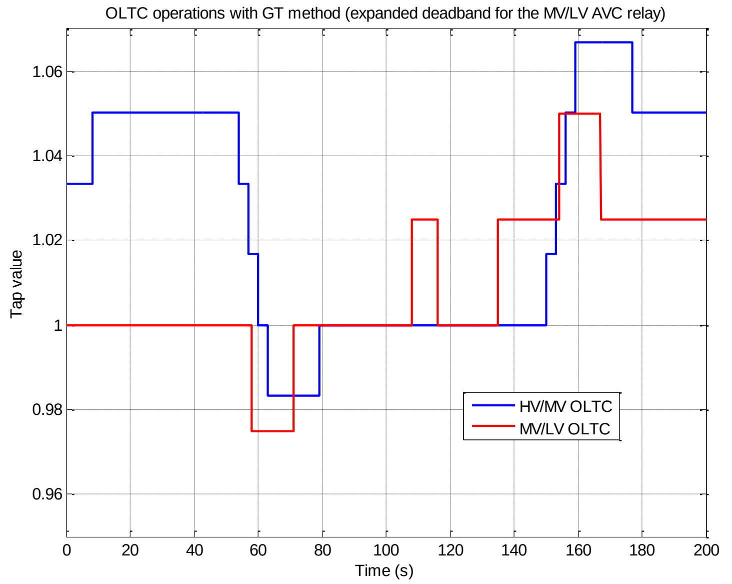


Figure 6.12 *HV/MV and MV/LV OLTC operations using GT method (with expanded deadband for MV/LV relay)*

Figure 6.13 presents the operation of the MV/LV OLTCs for both GT and PSAU.BOT methods. Using expanded deadband for MV/LV transformer AVC relay, there is no any extra action with the GT method. However, using the PSAU.BOT, tap actions are done faster most of the time.

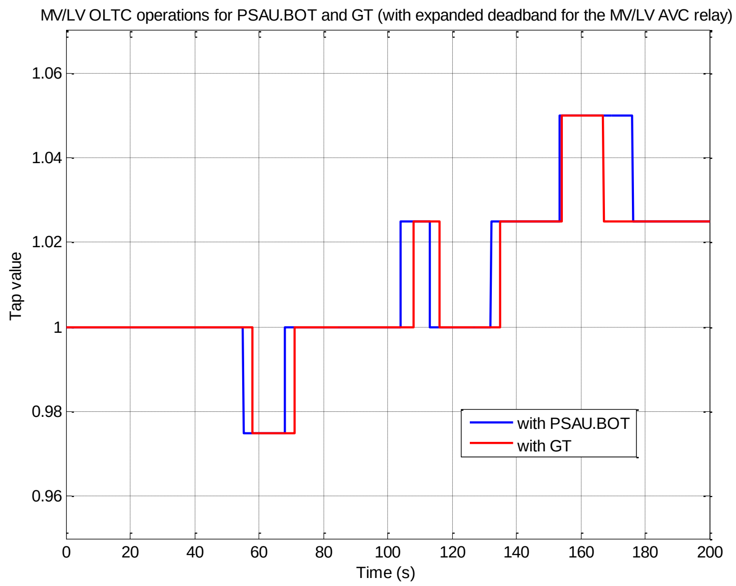


Figure 6.13 *MV/LV OLTC operations for PSAU.BOT and GT methods (with expanded deadband for MV/LV relay)*

Figure 6.14 depicts the recorded voltage at secondary substation using both methods. Using the PSAU.BOT voltage is restored faster most of the time. However, there is also a case where the GT method has led to a faster voltage restoration (marked with an arrow). The main reason for this is the capacitor bank disconnection at the MV network which has led to blocking the MV/LV OLTC by the PSAU.BOT. After expiration of the block validity time, the tap action is done.

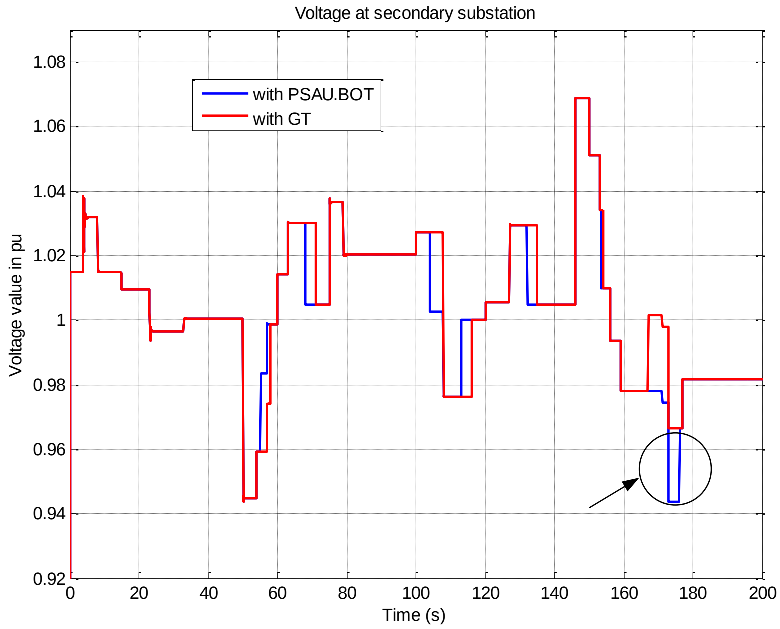


Figure 6.14 *Voltage at secondary substation for both methods (with expanded MV/LV AVC relay deadband)*

It should be noticed that due to assigning a bigger tap size for the MV/LV OLTC in test B.2 and in order to avoid tap action when there is no change in the network, initial position of the MV/LV tap has been set to 1 resulting in a rather different initial (before changes in the network) secondary substation voltage compared to test B.1.

6.3 Summary of simulation results

A summary of recorded tap actions in all test cases is presented in the following tables.

Table 6.10 *Number of tap actions recorded in test A.1*

Test A.1		
Control approach	**Number of HV/MV OLTC operations**	**Number of MV/LV OLTC operations**
PSAU.BOT	11	8
Local (same time delays)	11	14

Table 6.11 *Number of tap actions recorded in test A.2*

Test A.2 (expanded MV/LV AVC relay deadband)		
Control approach	**Number of HV/MV OLTC operations**	**Number of MV/LV OLTC operations**
PSAU.BOT	11	7
Local (same time delays)	11	10

Table 6.12 *Number of tap actions recorded in test B.1*

Test B.1		
Control approach	**Number of HV/MV OLTC operations**	**Number of MV/LV OLTC operations**
PSAU.BOT	11	8
Local (GT method)	11	10

Table 6.13 *Number of tap actions recorded in test B.2*

Test B.2 (expanded MV/LV AVC relay deadband)		
Control approach	**Number of HV/MV OLTC operations**	**Number of MV/LV OLTC operations**
PSAU.BOT	11	7
Local (GT method)	11	7

According to the tables the total number of tap actions by the HV/MV OLTC is the same for all control methods. However, the main difference is in the total number of tap actions by the MV/LV OLTC. The local control (with the same time delay for the AVC relays) has the highest MV/LV OLTC operations. The GT method has the second rank, and finally the PSAU.BOT has the minimal number of MV/LV OLTC operations.

As expected, assigning a bigger deadband for the MV/LV transformer AVC relay and bigger tap step sizes, the number of MV/LV OLTC actions has been reduced for all methods. The reason for this is that voltage is allowed to deviate within a bigger deadband resulting in less need for tap actions. The following tables can be used to observe how the voltage deviation (from setpoint) is affected by different control methods.

Table 6.14 *Secondary substation voltage deviation recorded in test A.1*

Test A.1	
Control approach	**Total voltage deviation from setpoint at secondary substation in pu**
PSAU.BOT	27.5995
Local (same time delays)	27.1071

Table 6.15 *Secondary substation voltage deviation recorded in test A.2*

Test A.2 (expanded MV/LV AVC relay deadband)	
Control approach	**Total voltage deviation from setpoint at secondary substation in pu**
PSAU.BOT	35.3593
Local (same time delays)	24.5276

Table 6.16 *Secondary substation voltage deviation recorded in test B.1*

Test B.1	
Control approach	**Total voltage deviation from setpoint at secondary substation in pu**
PSAU.BOT	27.5995
Local (GT method)	32.2084

Table 6.17 *Secondary substation voltage deviation recorded in test B.2*

Test B.2 (expanded MV/LV AVC relay deadband)	
Control approach	**Total voltage deviation from setpoint at secondary substation in pu**
PSAU.BOT	35.3593
Local (GT method)	37.3787

The results from tables indicate that although using local control method (with the same AVC relay time delays) maximum number of MV/LV transformer tap actions occurs; the voltage deviations from setpoint (1 pu) are minimal. Using the PSAU.BOT, voltage deviation is more compared to the local method (with the same AVC relay time delays); however, the number of the tap actions is minimal. The GT method presents the worst performance regarding the voltage deviations, but the number of tap actions is less than local method (with the same time delays) and comparable with the PSAU.BOT.

In simulations with the PSAU.BOT, it has been assumed that its dynamic inputs (i.e. active and reactive powers) are available as changes happen in the network. In practice, this is not the case and measurement delays should also be considered.

7. CONCLUSION

In this thesis congestion management using active voltage control methods with a main focus on on-load tap changer transformers have been discussed. A centralized unit called PSAU.BOT (also called BOT) which aims to coordinate the operation of the cascaded OLTCs has been developed. The PSAU.BOT has capability of working as a standalone unit or as supplementary algorithm for other voltage control algorithms. The standalone operation of the PSAU.BOT has been tested and compared with the local control methods of cascaded OLTCs. In section 7.1, first a summary of the main results obtained from simulations in chapter 6 is provided. Afterwards, possible future developments are presented in section 7.2.

7.1 Main results

The main advantage of the PSAU.BOT is that it provides higher selectivity compared to local control methods. This means that using the PSAU.BOT usually the correct OLTC compensates for the voltage disturbance. High selectivity also leads to a reduction in total number of tap actions. In addition, the PSAU.BOT allows assigning the same time delay for the AVC relay of cascaded OLTCs which leads to fast voltage restoration at consumption points compared to GT methods. Another positive aspect of the developed control method is that it does not alter the basic principles of local control methods and it uses a block signal along with a block validity time to achieve the coordination of cascaded OLTCs.

Considering the simulation results presented in section 6.3, the following conclusions can be made:

- Having the same deadband for the AVC relays of cascaded OLTCs, the same tap step sizes and considering a reliable data transfer between substations, the PSAU.BOT is the most effective method, since it leads to minimum number of tap actions. Besides that, the total voltage deviation (from setpoint) is comparable with the local control method where the same time delay is assigned for the AVC relay of cascaded OLTCs.
- Having an expanded deadband for the AVC relay of lower level OLTC and an expanded tap step size for it, the local control method (with the same time delay for the AVC relays) is the superior method, since it leads to a reduction in total voltage deviation from setpoint. It should be noted that the number of tap actions by lower level OLTC is not minimal for this case.

7.2 Future development

In addition to standalone operation, the PSAU.BOT can also be used as a supplementary algorithm for other coordinated voltage control algorithms (integrated operation). The basic ideas regarding the integrated operation of the PSAU.BOT have been explained in sections 3.2 and 4.4. Also, a use case for integrated operation has been created in section 5.2. However, the integrated operation has not been tested in this thesis. In integrated operation, the entire system performance (the PSAU.BOT and power controllers combined) is more crucial than only the PSAU.BOT performance. Therefore, there is a need for further analysis of the PSAU.BOT in integrated operation.

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