QATAR UNIVERSITY

COLLEGE OF ENGINEERING

AUTOMATIC VOLTAGE REGULATION FOR SUBSTATION IN SMART GRID

BY

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Abstract

The recent developments of smart grids and their Advanced Metering Infrastructures have brought new possibilities of enhancing the system performance and quality of power delivery to diverse consumers. For instance, with the existence of smart meters that measure, in real time, the voltage, current and power factor at the consumer side, it is possible to automatically control the voltage at the load side in order to improve the efficiency of the power delivery and to avoid voltage drop or rise beyond the acceptable limits set by the relevant standards.

This research is intended to develop a new and simple technique for voltage regulation at the low-voltage side of power distribution network. The proposed technique uses the smart meters readings to regulate the minimum/maximum voltages within the standard limits. Meanwhile, it assures that all load voltages are set to their minimum possible values which reduce the energy consumption to the desired amount. This voltage control technique is implemented on a distribution transformer equipped with an On-Load Tap Changer (OLTC). The selection of the appropriate OLTC tap position is decided by a voltage control algorithm. The proposed OLTC uses Solid-State Relays (SSR) instead of the conventional mechanical relays. One of the advantages of the SSR is that it allows the OLTC to change more than one tap at a time.

The proposed control technique is applied on an actual residential compound electric system. Several scenarios are considered testing the power quality and determining the energy saving. The scenarios investigated on power quality include over-voltage, under-voltage and voltage unbalance. The energy saving is due to two reasons; the proposed voltage control method and the choice of the tap controller. The results show that we can obtain a fast response of the OLTC while maintaining the voltage profiles for all nodes at desired levels. In addition, the results ensure that significant amount of energy can be saved without compromising power quality. It has been proved that DG in radial network configuration has less impact on the system using the proposed voltage control method compared to the tree network.

Table of Contents

List of Figures

List of Tables

Abbreviations & Symbols

1ϕ	Single Phase
Δ	Variation/Deviation
AC	Air Condition
AMI	Advanced Metering Infrastructure
AVC	Automatic Voltage Control
CCC	Current Carrying Capacity
$cos\phi$	Power Factor
DF	Diversity Factor
DG	Distributed Generation
E	Energy
EHV	Extra High Voltage
GTO	Gate Turn-Off Thyristor
hr	Hour
HV	High Voltage
Hz	Hertz
i	Current
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
k	Tap position
Δk_p	Deviation of tap from zero-position
K_{tap}	Total number of transformer taps on the primary winding
kWh	Kilowatt-hour
LDC	Line Drop Compensation
LV	Low Voltage
min	minute
MV	Medium Voltage
MVA	Mega Volt-Ampere
N_p	The number of turns at the primary side of the transformer
ΔN_p	Absolute deviation of the number of turns form zero-position in the primary

	winding
N_s	The number of turns at the secondary side of the transformer
ΔN_{tap}	Tap minimum number of turns
OLTC	On-Load Tap Changer
P	Active Power
$p(t)$	Instantaneous power
P_{SW}	Power loss across the switch
pu	per unit
PV	Photo-Voltaic
Q	Reactive Power
QAR	Qatari Riyal
QGEWC	Qatar General Electric and Water Corporation – KAHRAMAA
R	Resistance
rms	root mean square
S	Apparent Power
SSR	Solid-State Relays
SSTC	Solid-State Tap Changer
SVR	Step Voltage Regulator
SW	Switch
t	time
TV	Tele Vision
ULTC	Under-Load Tap Changer
V	Voltage
V_{D_max}	Maximum stress voltage across the diode
V_{IGBT_max}	Maximum stress voltage across IGBT
V_{max}	Maximum Voltage
V_{min}	Minimum Voltage
V_{ref}	Maintained voltage reference level equals to 0.92pu
V_{refu}	Upper limit voltage reference equals to 1.1 pu
V_{sw_max}	Maximum stress voltage across the switch

VAR	Volt-Ampere Reactive
V_p	Transformer primary voltage
V_{pn}	Transformer primary winding nominal voltage
V_s	Transformer secondary voltage
V_{sn}	Transformer secondary winding nominal voltage
ΔV_s	The deviation of voltage at transformer secondary winding
X	Reactance
Z	Impedance

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Chapter 1: INTRODUCTION

1.1 Background

1.1.1 Need of this Research

The first question that comes into the mind: “what is the reason behind this research?” Simply, the regulation of the voltage improves the energy efficiency and maintains the power quality; therefore, it saves a significant amount of cost and provides more confidence in the electric system. In other words, as much as the voltage is controlled within specified limits, set by international standards and guidelines, as much as the power quality is not compromised and/or the energy saving is increased. This is directly reflecting on the cost of the electrical network within each country.

This research is intended to study the voltage regulation effects on power networks at Low Voltage (LV) distribution side. The voltage regulation on transmission side has gone far using several control techniques that grab information from High Voltage (HV) substation using communication cables. However, the regulation at LV distribution side will be more efficient due to two main reasons:

- More accurate control; the controllers are connected closer to the consumers.
- Local controls which are required due to the increase of distributed generations (DGs).

1.1.2 Motivation for this Research

The complexity of power systems and the change of demand load at the consumer level make it necessary to control the voltage to avoid any unnecessary voltage drop or rise beyond the acceptable limits set by the standards. Unlike voltage control at the transmission side, the voltage regulation at LV distribution side still requires ample of researching and studies in order to enhance the energy efficiency while maintaining power quality. Studies of voltage regulation at consumer level are essential in nowadays power systems due to the following reasons:

- The complication of the power systems at LV consumer level due to a variety of appliances including motive equipment like fridges, ACs, cooker units; in addition to lighting systems and electronic instruments like TVs, computers, and others.
- The increase in the use of DG at consumer levels (e.g. rooftop PV systems).
- The aids of smart meters which make it easier to obtain the information in real-time from each consumer and feed it back to the LV distribution substation.

Moreover, the evolution of switches in the tap-changers from mechanical contacts into solid-state relays makes it possible to provide a faster and reliable On-Load Tap Changer (OLTC) that provides more accurate regulation of the voltage even with frequent load fluctuations.

1.1.3 Significance of this Research

The automatic voltage regulation in Qatar is not applied at LV distribution level of the electric power network. In addition, the use of different configurations on the low voltage feeders makes it difficult to use the conventional methods of voltage regulation. Moreover, the insertion of smart meters that have started to be implemented in the residential area in Qatar in 2014 will play an important role in regulating the voltages at the consumer level. Therefore, the study made herein gives a clearer figure of the relation between the changes in load at each consumer to the way the voltage is regulated at the distribution level of the substation. This figure allows knowing the extent of the energy efficiency and saving accomplished by regulating the voltage at LV consumer level while maintaining the power quality up to the standard for all loads connected to the same substation.

1.2 **Thesis Scope**

This thesis is implemented within the requirements of the degree of Master of Science in Electrical Engineering. The scope of the thesis is to provide a proposal for a voltage regulation method to be applied at LV distribution side of the power network. The voltage regulation method uses an OLTC which is designed using power semiconductor switches. The thesis includes an analysis of a residential compound electric power system which is modeled and simulated with Matlab/Simulink. The applications of the proposed voltage control algorithm on the residential compound include several scenarios that tackle power quality and energy efficiency simultaneously.

Therefore, the scope of this thesis can be defined as a list of questions:

- What will be achieved from the thesis?
- Is the proposed method sufficient to regulate the voltage?
- Why voltage regulation at LV distribution side?
- How can the proposed control technique be applied in the power network?
- Who will gain from the proposed method?
- Where is the best place to implement this voltage control technique?

The answer to the above questions is the whole contents of the thesis which can be rewritten with one single statement as follows:

The proposed voltage regulation method and OLTC design can be applied at LV distribution level where smart meters are implemented to provide real-time information on voltages at consumers' side to permit direct, simple and fast voltage control in order to achieve more energy saving (more cost saving for utilities and society), while maintaining power quality (better network reliability).

1.3 **Thesis Aim and Objectives**

The main aim of the thesis is to provide a voltage regulation method and OLTC design that accounts for better energy efficiency and power quality at LV distribution level of the power network using the benefits of installed smart meters.

The objectives of this thesis can be listed below as follows:

- Provide a practical voltage regulation method at distribution side.
- Design an OLTC using the latest technologies that can provide faster and more accurate results.
- Demonstrate that the proposed system gives sufficient energy saving while the power quality is not violated.

1.4 **Thesis Layout and Organizational Overview**

The thesis is structured into six chapters as follows.

Chapter One: Introduction

In chapter one, the background of the thesis is introduced providing a clear explanation of its basis. The motivation to conduct this study, the need of the research and its significance is brought together highlighting the purpose of the thesis. A description of the research scope is identified and its objectives are set and listed giving a straight way towards the aim of the research. At the end of the chapter, the layout of the thesis is presented along with its organization.

Chapter Two: Literature Review

In chapter two, a literature review of existing voltage control methods and techniques is summarized and explained. Two branches of review are conducted; voltage regulation techniques and OLTC systems. The techniques used in voltage regulation at distribution level including line drop compensation, VAR compensation, and tap-changing transformers are introduced and summarized. Further in the chapter, the technologies of OLTCs are defined including mechanical, electronically assisted, and solid-state tap changers. At the end, the topologies of OLTCs are presented.

Chapter Three: Proposed Voltage Regulation Method and OLTC Design

In chapter three, the methodology of the research is presented. First, the proposed voltage regulation method and the assumptions considered are introduced including the algorithm of the system. Then, the selected structure of the power switch module and the OLTC are presented. This includes the choice of the tap-changer topology and the mathematical equations of determining the tap position. Finally, the three-phase architecture of the proposed transformer with OLTC and controller is described.

Chapter Four: Case Studies

In chapter four, a simple single-phase case study is used to validate the proposed method. The results of the voltage profiles are shown to ensure that the proposed system is practical. Then, an actual Qatari residential compound is modeled where all the electrical parameters are given. Two networks, radial and tree, are considered and investigated in order to cover the configurations of the low voltage networks designed in the gulf countries.

Chapter Five: Results and Discussion

In chapter five, the proposed voltage control system is implemented for the residential compound model. Several scenarios are analyzed. First, the results of the normal operation of the tree network are shown including the voltage profiles and the tap position for 24 hrs simulation. The power quality has been studied under different scenarios such as over-voltage, under-voltage, and voltage unbalance. It is shown that the proposed system is reacting to the power quality violations and resolving the issues very fast. Later, the energy saving from the application of the proposed system is determined. The results show that significant amount of energy is saved from the proposed method. At the end, a comparison between the tree and radial networks is presented where a distributed generation (DG) is inserted at one of the terminals of the system.

Chapter Six: Conclusion and Future Works

Chapter six concludes the thesis and presents some of the future works.

Chapter 2: : LITERATURE REVIEW

2.1 **Introduction**

The purpose of this chapter is to review the main researches conducted on voltage regulation techniques at the distribution level as well as the OLTC technologies.

In the studies of voltage regulation, the distribution level is considered both the medium voltage (MV) and low voltage (LV). The scope of this thesis is the LV side, hence, the researches tackled in this review are only those related to LV side of the power distribution network.

Studies conducted on voltage regulation at the LV side are relatively few compared to those published for the transmission level; high-voltage (HV) and extra-high-voltage (EHV). The main reasons are:

- The voltage drop at the transmission level impacts significantly the cost on the utilities including, but not limited to, capital cost, maintenance cost and operation cost;
- The methods applied at the distribution level depend mainly on the forecasted voltage profiles, which, in reality, don’t provide accurate control to the voltages delivered to the consumers.

The other part of the literature review is on the OLTCs. The types and topologies of tap-changers will be presented.

Nowadays, the move toward smart and intelligent grids and the implementation of smart meters make it helpful to obtain real-time voltage measurements at the consumer level which can be used for voltage regulation at the consumer side. In addition, the development of fully electronic power switches for the tap changes instead of the conventional mechanical contacts increases the possibility to have accurate regulation of voltage at the LV side of the power network.

2.2 **Voltage Regulation Techniques at Distribution Level**

The voltage control problems can be defined as the assurance of maintaining electric power quality for all consumers [1]. Disturbances like over-voltage, under-voltage, voltage unbalance, and voltage harmonic distortion affect the power quality which imposes to control the voltage to avoid such problems. The two approaches of voltage control are the off-line control that depends on a dispatch schedule ahead of time as a forecast of the voltage changes; and the on-line (automatic) that depends on real-time measurements of the voltage.

Moreover, the active network management of a power system may be categorized into coordinated control, semi-coordinated or decentralized control strategies. As mentioned in [2], centralized or coordinated control strategy provides voltage control from the substation towards the rest of the network. On the other hand, the semi-coordinated and decentralized control strategies must be able to control each unit locally in an active manner while coordinating it with a limited number of other network devices.

In a centralized or coordinated voltage control scheme, several techniques are implemented including distribution management system control, distribution system components (like VAR compensator and step voltage regulator [3]), intelligent centralized methods (like artificial neutral networking (ANN) [4] and fuzzy logic [5]), as well as multi-agent system.

On the other hand, the techniques implemented in the decentralized voltage control scheme are summarized into reactive power compensation, power factor voltage control, on-load tap changer, generation curtailment and intelligent decentralized systems.

By reviewing the researches conducted on voltage regulation at distribution side, it is concluded that tap-changing transformers, VAR compensation and line drop compensation are the techniques that are mostly studied and used in the literature which are presented hereafter.

2.2.1 Line Drop Compensation

Line drop compensation (LDC) is a traditional method of calculating the voltage drop along each line, hence calculating the voltage at the terminals and set the voltages accordingly. This method can be applied once by setting the voltage according to the calculated voltages at the consumer, or using a tap changer. This method doesn’t provide accurate results due to several reasons. For instance, the addition of distributed generation makes the line drop calculations not accurate.

As per [6], the voltage drop on a line between the source bus-bar and the load is calculated by Automatic Voltage Control (AVC) relay using the input current and the impedance value of the line. The relay adjusts the control parameter to increase or compensate the source bus-bar voltage by an amount equal to the calculated voltage drop.

The impedance of a line might not be accurate since there might be several branches extending from one feeder like in tree network arrangement. In addition, the AVC relay can have one feeder resistance (R) and reactance (X) setting although most substations have multiple feeders. In order to resolve these shortcomings, the R and X settings on the LDC is based on a hypothetical composite feeder model that has to cater for the worst combination of demands on each of the feeders [6].

As a result of the above, the LDC method is no more used by itself, rather in conjunction with other methods.

2.2.2 Tap-changing transformers

Tap-changing transformers technique uses an off-line or on-line tap changer to regulate the voltage to a reference level. The tap changer can be placed at the primary or secondary side of the transformer. It varies the number of turns in a transformer thereby adjusting the turns’ ratio in order to achieve the required voltage at the secondary side of the transformer.

In [7], the authors present an overview of the existing OLTC control schemes used to control the voltage at distribution network. The authors summarize the operations and coordination of the OLTCs in the full electric network from the transmission up to the distribution side.

An optimal control of distribution voltage, coordinated with distribution installations like load ratio control transformer, step voltage regulator, shunt capacitor, shunt reactor and static VAR compensator, is proposed in [8]. The problems arising in the step-voltage regulator are [8]:

- The complication of the voltage distribution of each feeder and the non-uniformity of the load distribution in the system;
- The time period and sensitivity voltage which are the main features of step-voltage regulator might not give exactly the optimal solution for the entire power system.

The authors in [8] proposed an algorithm to control the voltage of each node by determining the sending voltage of the substation in a certain time section, the tap location of the step-voltage regulator, the on-off states of the shunt capacitor, and the capacity of the static VAR compensator.

The authors in [9] tried to solve the issue of bi-directional power flow arising from the insertion of DG. The paper presents a new OLTC voltage control strategy for use on networks where DG is connected. The automatic compensation method has been proposed where the voltage setting point changes according to the direction of the transformer current.

Other methods, like fuzzy logic, have been correlated with OLTC to control the voltage. The authors in [10] proposed a new voltage control scheme for residential area networks in Saudi Arabia based on Fuzzy logic. An algorithm has been proposed to convert the linguistic control strategy provided by fuzzy logic, which is based on expert knowledge, into an automatic control strategy.

Even though the above literature provides several approaches to control the voltage using step-voltage regulators and OLTCs, the reviews depend on forecasted data or static power flow equations which mainly don’t give the accurate results due to load fluctuations at the distribution side.

In [11], an online voltage control strategy for a realistic distribution system is proposed. This strategy minimizes the operational conflicts while maximizing the voltage regulation support by DG. The proposed control system in this paper is based on updating the reference voltage of DG excitation control and blocking the simultaneous operations between DG voltage control module and step-voltage regulator (SVR) taps in real time. An algorithm is used to tune the control settings of DG voltage control module, control settings of SVR, and substation OLTC local controllers.

2.2.3 VAR Compensation

VAR compensation or reactive power control is a technique to regulate the voltage using reactive elements like static synchronous compensator (STATCOM), static VAR compensator, or switched fixed capacitors/inductors (for example shunt capacitors) [12]. The method is based on measuring the line voltage, comparing it with a reference level and connecting compensators (reactive or capacitive) to regulate it.

Since the VAR compensation is an old method of regulation, the latest researches are mostly studying the use of VAR compensation with DG. The authors in [13] are proposing a voltage control approach for distribution network with DG using reactive power compensation. The approach is based on the worst case scenario of distribution network with DG using active power flow equations.

In [14], voltage and reactive power control methods in distribution systems in the presence of DG is presented. A comparative analysis of different voltage control methods is shown. The study is based on power flow analysis of the system with OLTC, DG and shunt capacitors. The number of OLTC operations has been reduced with the use of the dispatch schedule of the shunt capacitors. Moreover, it has proved that coordinated voltage control involving DG will have potential benefit in increasing reactive power reverse for emergency purpose.

2.2.4 Comparison

The three techniques play an important role in regulating the voltage. However, several problems arise at distribution networks including, but not limited to, load fluctuations, voltage instability, line drops, network configuration, etc.

All the three techniques depend on forecasted voltages which are not real and accurate. In addition, they mostly depend on power flow analysis which can resolve static equations and cannot provide dynamic analysis.

The line drop compensation is simple; however it doesn’t provide accurate results due to the change in loads and the addition of feeders in the network.

The VAR compensation technique requires several capacitors at the feeders. A dispatch schedule of capacitors is required to control the system which is a disadvantage since this schedule still doesn’t provide real values.

The control in the tap-changing transformer is more complex. Even though OLTC can provide better values than line drop and VAR compensation due to the known load variations, however, the control still is based on forecasted and not real loads since the voltages at the end customers cannot be measured in the traditional distribution networks. The evolution towards advanced metering infrastructure (AMI) and the use of smart meters to measure the voltages in real time plays an important role in the enhancement of voltage control techniques. Hence, the OLTC becomes a more attractive and promising solution for much more accurate, faster and simple dynamic voltage control at LV distribution systems.

2.3 OLTC Technologies

2.3.1 Definition

A tap changer is a selection tool along a power transformer winding that permits a variable number of turns to be selected in discrete steps. A transformer with a variable primary to secondary turns' ratio is formed, allowing stepped voltage regulation of the output. The tap selection may be made via an automatic or manual tap changer mechanism. [15]

The mechanism of tap-changing can be made on-load or off-load. If there is no load connected to the transformer, the tool is called off-load tap changer or no-load tap changer. However, the tap-changer works during load is called under-load tap changer (ULTC) or on-load tap changer (OLTC).

OLTC is a mechanism to change the tap at the transformer in order to regulate the voltage at the output during running load and without interruption. Generally, OLTC is used to keep the voltage for all the end customers within the standard acceptable limits.

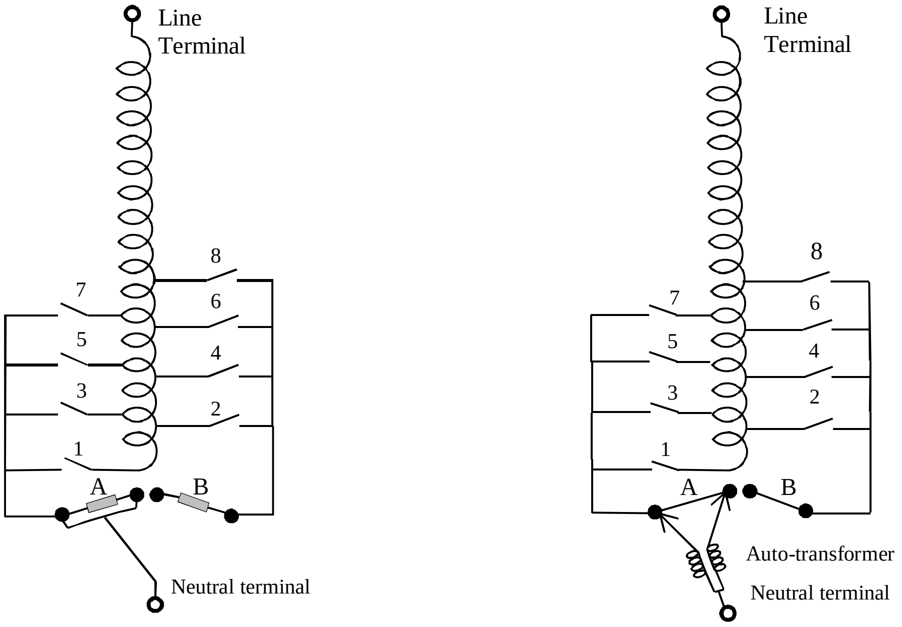
2.3.2 OLTC Categories

OLTCs may be classified into three different categories

- Mechanical tap changer
- Electronically-assisted tap changer
- Solid-state tap changer

A mechanical tap changer makes physically the new tap connection before releasing the old one, using multiple tap selector switches. It avoids creating high circulating currents by using a diverter switch to temporarily place large diverter impedance in series with the short-circuited turns (Figure 2-1a). This technique overcomes the problems with open or short circuit taps. In a resistance type tap changer, the changeover must be made rapidly to avoid overheating of the diverter.

A reactance type tap changer uses a dedicated preventive autotransformer winding to function as the diverter impedance. A reactance type tap changer is usually designed to sustain off-tap loading indefinitely (Figure 2-1b). [16]



(a) Resistance-Type (b) Reactance-Type

Figure 2-1: Mechanical Tap Changer with diverter

As mentioned in [17], the mechanical tap-changers have many disadvantages like arcing in the diverter switches during tap changing process, high maintenance cost, slow taps changing speed and high losses in the tap change.

As per [18] the arc in the contacts of diverter switches during the tap-changing process is an essential problem in the mechanical under-load tap changer. Electronically-assisted tap changers are developed to resolve this issue by reducing the arc with more controllability of the switches. One type of such tap changers uses thyristor to take the on-load current while the main contacts change over from one tap to the other [19]. A sample connection between contacts A and B of a certain tap is shown in Figure 2-2.

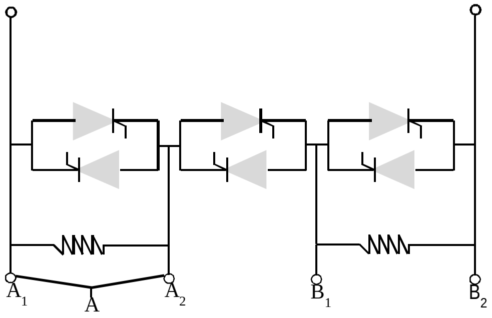


Figure 2-2: Electronically assisted tap contacts

An OLTC with electronically-assisted tap changers is designed in [20] and a lab setup illustrating its application is presented in [21]. The authors in [19] proposed to use hybrid configuration of mechanical and bidirectional electronic switches that switch between no-load and on-load situations.

Apart from mechanical and electronically assisted tap changers, a recent development of OLTC is solid state tap changer (SSTC). Solid-state tap changer uses bidirectional solid state relays (SSR) to switch the transformer winding taps and to pass the load current in the steady state. The design and implementation of SSTC are provided in [22]. SSR can be made from several configurations of power electronic devices including Insulated-Gate Bipolar transistor (IGBT) [23] or gate turn-off thyristor (GTO) [24].

The difference between conventional and electronic tap-changer are introduced in [15]. The performance comparison of mechanical and electronic tap-changers indicated that the following differences are required in goals and responsibilities of controllers of these two categories of tap-changers.

- A reduction of the tap-changing frequency in the controller of mechanical tap-changer is one of the design objectives, while this is not the case in an electronic tap-changer.
- In a mechanical tap-changers controller, taps must be changed step-by-step, while there is no such limitation in an electronic tap-changer.
- A complicated arrangement of taps and switches in the control system of an electronic tap-changer makes it necessary to have a look-up table for storing the position of each switch which corresponds to each of the output states. Such a look-up table is not required in mechanical tap-changer.
- The tap-changing process is very quick with an SSCT, so there is a need to use an algorithm for quick and accurate detection of the amplitude and phase of the sinusoidal variables (such as primary and secondary voltages and load current). In

contrast, the tap-changing process is much slower in a mechanical tap-changer, so averaging methods over several cycles to determine the rms voltage and current are sufficient.

- In electronic tap-changer controller, it is necessary to detect the zero-crossing of the load current in order to have soft switching of the tap-changer switches. The tap-changing commands are therefore issued at these instants. In a mechanical tap-changer, the tap-changing process is slower, so soft switching cannot be realized.

2.3.3 Topologies of OLTC

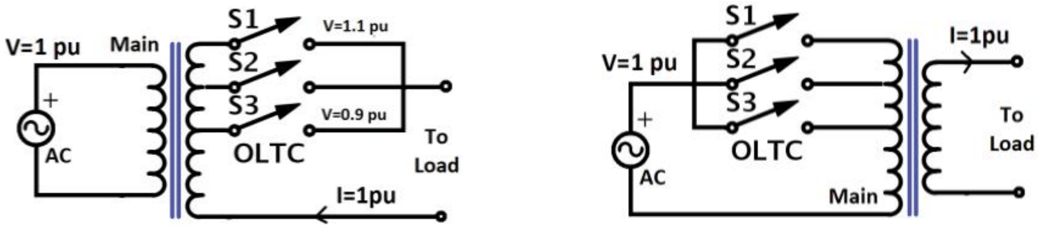
The main topologies of OLTC are discussed in [25]. An analysis to compare the different topologies for OLTC is presented. Eleven different topologies are compared on the basis of voltage and current rating of the transformer windings and tap switches. OLTC depends mainly on the following five factors:

- OLTC is built using a two-winding transformer or an autotransformer
- Nominal voltage and current rating of the transformer windings
- Number of taps/semiconductor switches
- Nominal voltage and current rating of the semiconductor switches
- Fault conditions in the network, protection, and control

The objective is to study the different topologies based on the first four factors considering the fault conditions are the same. Eleven topologies are designed providing both positive and negative compensation of the grid voltage.

2.3.3.1 ***Topologies 1 and 1a***

Those topologies (Figure 2-3) use a conventional two winding transformer of 1.1pu power rating with taps positioned either on the secondary (1) or on the primary (1a). The topology provides complete isolation between the input source and the output load. $2N+1$ taps are required for positive, negative and 0% compensation. Due to the asymmetry in the arrangement of taps, the maximum forward and reverse blocking voltages of the tap switches are not the same for all taps and differs based on the tap position.



(a) Topology 1

(b) Topology 1a

Figure 2-3: Topologies (1) and (1a) [25]

2.3.3.2 ***Topology 2***

Topology 2 (Figure 2-4) uses a three-winding transformer with two on the secondary side. One of the windings at secondary provides the load power and is rated 1pu voltage and 1pu current. The tertiary winding has taps and the compensating voltage is fed in series to the grid voltage using a series transformer of 1:1 turn ratio. Using two transformers is very expensive, however, such configuration ensures that the switches are isolated and so are the source and load.

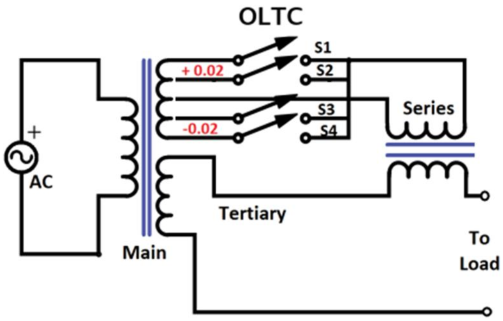
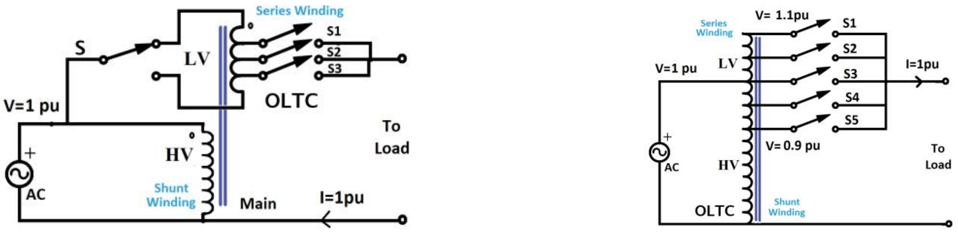


Figure 2-4: Topology 2 [25]

2.3.3.3 ***Topologies 3 and 3a***

Topology 3 (Figure 2-5) corresponds to the conventional voltage regulators that are utilized in the grid. It consists of an autotransformer with taps on the series winding at the secondary side. A selector switch connects either the top or the bottom of the series winding LV side to the primary HV side so as to provide negative or positive compensation respectively. Topology 3a does not have a selector switch and has a total of (2N+1) switch. The primary input winding is rated 0.9pu and is permanently connected to the series winding LV that has taps on it and is rated 0.9pu.



(a) Topology 3

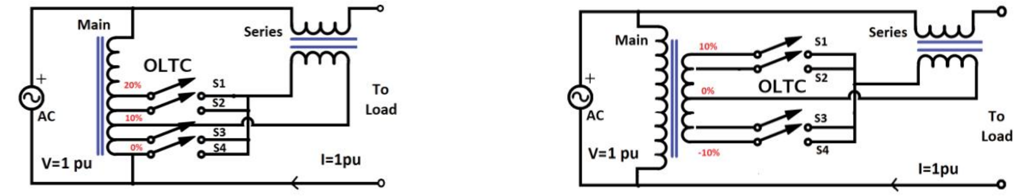
(b) Topology 3a

Figure 2-5: Topologies 3 and 3a [25]

2.3.3.4 ***Topologies 4 and 4a***

Topology 4 (Figure 2-6) combines the benefit of using an autotransformer in buck mode and the need to have isolation for switches through a series transformer. The compensation voltage is derived from the grid voltage through the use of an autotransformer tapped at 0% and 20% points and a center tap at 10%.

Topology 4a is similar to 4 with a two-winding transformer providing isolation of switches from the source side.



(a) Topology 4

(b) Topology 4a

Figure 2-6: Topologies 4 and 4a [25]

2.3.3.5 ***Topologies 5 and 5a***

Topologies 5 and 5a are the same as topology 4 and 4a respectively, however with the usage of selector switch as provided in topology 3 and 3a.

2.3.3.6 ***Topology 6***

Topology 6 (Figure 2-7) uses a single transformer for compensation that is rated only for the compensation power (0.1pu) where a step-down type centered-tapped transformer is used.

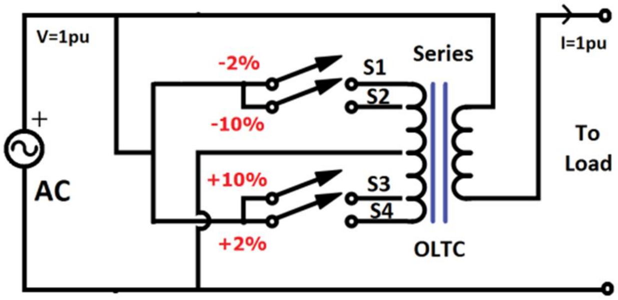


Figure 2-7: Topology 6 [25]

2.3.3.7 ***Topology 7***

Topology 7 uses the same technique as topology 6; however the switches are moved to the secondary side. The benefit beyond this is that the switch voltage ratings in OFF condition are reduced.

A new solid-state on-load tap changer topology is proposed, giving 53 voltage steps using 11 switches, which is an optimal solution as compared to the literature in [26].

Table 2-1: Summary of Topologies Ratings and Features

Topology	**No of switches**	**Rating of main transformer (Vpu)**		**Rating of series transformer (Vpu)**		**Blocking Voltage (V_{pu})**		**Isolation of source and load (Yes/No)**
		Pr	**Sec**	**Pr**	**Sec**	**Tap**	**SS**	
1	2N+1	1	1.1	-	-	0.2	-	Yes
1a	2N+1	1.22	1.1	-	-	0.2	-	Yes
2	2N+1	1	0.2	0.1	0.1	0.2	-	Yes
3	(N+1)+1SS	1	0.1	-	-	0.1	0.1	No
3a	2N+1	0.9	0.2	-	-	0.2	-	No
4	2N+1	0.8	0.2	0.1	0.1	0.2	-	No
4a	2N+1	1	0.2	0.1	0.1	0.2	-	No
5	(N+1)+1SS	0.9	0.1	0.1	0.1	0.1	0.1	No
5a	(N+1)+1SS	1	0.1	0.1	0.1	0.1	0.1	No
6	2N+1	-	-	10	0.1	6	-	No
7	(N+1)+1SS	-	-	2	0.1	0.1	2	No

2.3.3.8 Comparison between topologies

Based on the actual voltage, power level, and fault conditions, in addition to the type of semiconductor devices, the most suitable power electronic OLTC topology for voltage regulation can be chosen as concluded at the end of [25]. Table 2-1 provides a summary of the ratings and some of the features of the eleven topologies.

Hence based on the data provided in the table, the best topology can be chosen. For example, the selector switch rating is different from other switches when any of the topologies 3, 5, 5a or 7 is chosen. On the other hand, topologies 1, 1a and 2 provides isolation of source and load and can be chosen this feature is required.

2.4 Voltage Regulation using SSR

Voltage regulation at distribution side using SSR has been tackled by some researches. A new approach to solid-state tap changing transformers is introduced in [27]. The proposed system is able to offer up to 48 steps with the ability to do this with fewer transformer tap windings. In [28], the authors prove, using different case studies, that the voltage profiles at the MV distribution side are improved with fully electronic switches both in normal and emergency situations.

As mentioned earlier, OLTCs are used in voltage regulation to resolve power quality violations in the power network. Many studies have tried to resolve the over and under voltage problems. Nevertheless, in [29], the authors proved that the use of power electronic components in on-load voltage regulation will not generate harmonics. Moreover, the optimal tap setting of voltage regulation transformers in unbalanced distribution systems is determined in [30].

2.5 **Summary**

The literature review provided a wide range of voltage regulation methods and techniques which are mostly applied on HV-MV side of the power network. Those applied on the distribution side or, in other words, the LV side of the power network, are limited. Nevertheless, the provided voltage regulation methods and techniques still use forecasted instead of real-time load profiles. Hence, the proposed voltage regulation will not give the intended results and require analysis every while which is mostly dependent on the consumers usage that is unknown.

The other challenge is the architecture of the tap changer which uses mechanical contacts that have its drawbacks. One of these drawbacks is the inability to change more than one tap per step. The evolution towards solid-state power devices provides a better solution to changing the taps as required by the load variations.

In the next chapter, a simple voltage regulation method is proposed along with the design of power semiconductor switched based OLTC. The architecture of the three-phase OLTC is also introduced.

Chapter 3: PROPOSED VOLTAGE CONTROL METHOD

3.1 Introduction

The voltage regulation method proposed in this chapter uses smart meter readings at the consumer side to regulate the minimum/maximum voltages within the standard limits. According to IEC 60038 [31], in normal operating situations, the voltage control range is ±10% that is [0.9pu, 1.1pu]. The proposed method is simple and able to maintain all load voltages at their minimum possible values, which reduces the energy consumption to the desired amount while maintaining the required power quality.

This voltage control technique is implemented on a distribution transformer equipped with an On-Load Tap Changer (OLTC). The selection of the appropriate OLTC tap position is decided by the voltage control algorithm. The proposed OLTC uses Solid-State Relays (SSR) instead of the conventional mechanical relays. One of the advantages of the SSR is that it allows the taps to change more than one-step at a time without generating arcs and voltage spikes.

In this chapter, the proposed voltage control algorithm for the determination of the tap position is introduced. The design of the OLTC using power semiconductor switches is detailed whereas the pros and cons of such design are mentioned. The switch structure and the OLTC architecture are presented including the determination of the tap position. At the end of the chapter, the suggested three-phase system is introduced.

3.1 **Methodology**

3.1.1 Proposed Voltage Control System

The general network at the distribution side is shown in Figure 3-1. The voltage applied at each feeder is equal to the secondary voltage of the transformer. Assuming that the voltage at load node "*r*" is the regulated voltage (maximum or minimum), the equation between the voltage at the transformer secondary side and that at the regulated load node is:

$$V_s = V_{Lr} + i_r Z_r \tag{3.1}$$

Since the impedance Z_r of the line is directly proportional to the length of the cable, which is relatively short in the distribution system, then the term $i_r Z_r$, representing the voltage drop in feeder "*r*", can be assumed to be negligible. As a consequence, in this study, the regulated load voltage variation ΔV_{Lr} at node "*r*" is assumed to be the same as that at the secondary side of the transformer ΔV_{s}. Based on the measured voltages, the minimum and maximum are determined and the tap position is selected.

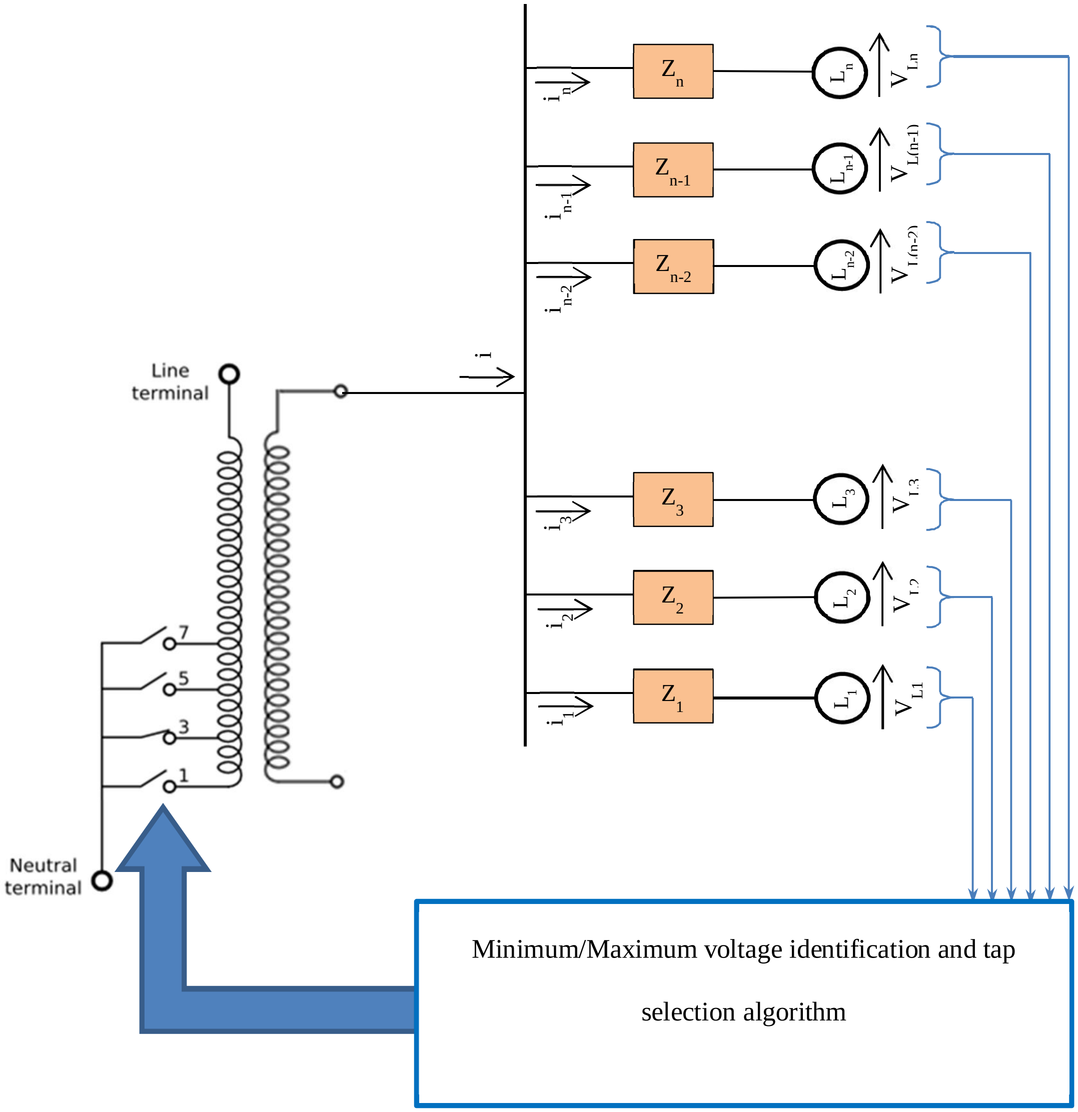


Figure 3-1: General configuration of a power distribution network with tap changer

3.1.2 Proposed Voltage Control Algorithm

The proposed method is based on controlling the number of taps within the OLTC of the transformer at the medium voltage (MV) side. The transformer tap-change controller determines the number of taps “k” based on the required voltage adjustment and the minimum tap step voltage. In other words, the tap position is controlled by determining the exact number of taps required to move from the current tap position to the next one that will maintain the reference voltage within the standard margin. This can be achieved without going through only one step tap change at a time, which makes the voltage regulation response much faster. This method can be applied to an endless number of terminals depending on the grid allowance and can estimate whatever tap steps and position required based also on the maximum number of taps that the OLTC is designed for.

The energy efficiency and the power quality of a system depend mainly on the potential difference applied to each device in the network. In smart grid, the voltage applied to each terminal on the distribution side of the network is usually measured using smart meters which provide real-time information and make it easier for automatic voltage regulation. The minimum voltage is maintained at a reference value (e.g. V_{ref}=0.92pu), or the maximum voltage is lowered to avoid exceeding the maximum allowable voltage limit (e.g. V_{refu}=1.1pu).

The flowchart in Figure 3-2 summarizes the algorithm followed to determine the number of taps. At first, the maximum voltage violation in any of the buses is checked by identifying the bus with maximum voltage. If the maximum voltage is greater than the allowed upper limit, the controller will determine the required value of k that will bring that maximum voltage to or below the allowed upper limit V_{refu}.

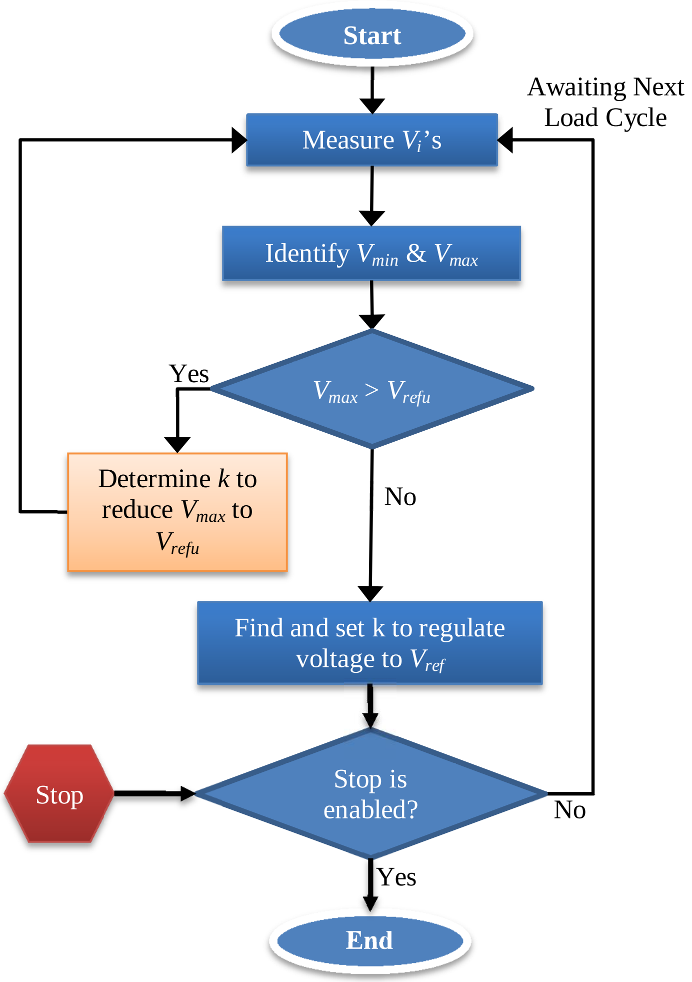


Figure 3-2: Voltage regulation algorithm flowchart

By determining the maximum voltage and its corresponding node, the value of this maximum voltage V_{max} is compared to the maximum allowed reference voltage V_{refu}. If the difference is positive, implying that the maximum voltage at that specific node is over the reference value, V_{max} must be reduced to a safer value. Therefore, the node voltage can be modified by changing the voltage at the secondary side, hence, controlling the voltage at the primary side of the transformer.

The next step is to check the minimum voltage violation following the same approach. The minimum voltage V_{min} and its corresponding bus are determined. The difference between this minimum voltage and the minimum reference voltage V_{ref} is calculated. If this value is positive, the voltage is in the safe range, otherwise, it has to be increased.

Finally, in order to improve the energy efficiency of the system, the same procedure can be followed by modifying the minimum bus voltage value close to the minimum allowed reference voltage.

The algorithm will await the next load cycle to determine if any of the violations occur and react accordingly.

3.2 **Power Semiconductor Switch-Based OLTC Design**

3.2.1 Tap Switch Design

The basic unit suggested for a solid-state tap-changer is a full electronic bidirectional switch as shown in Figure 3-3. Using this tap-switch configuration, it is clear that the stress on the power semiconductor switches is reduced because of the series connection of the two diodes with the IGBT. The authors in [18] compared three types of bidirectional switches:

- A switch with two anti-parallel thyristors
- Two unidirectional switches (IGBT) and two diodes
- A unidirectional switch (IGBT) with one diode.

There are other used switches but the above are the commonly used for tap changers. Among the above switches, the first one is uncontrollable and the second one has two IGBTs. However, the last one has only one IGBT which gives the advantage among others even though it has a voltage drop at the switch. Moreover, even though MOSFET may be used instead of IGBT, it has a higher voltage drop.

The maximum stress voltage across the switch (when open) is therefore divided almost equally among the three switching devices as shown in (3.2).

$$V_{D\_\max} = V_{IGBT\_\max} = \frac{V_{sw\_\max}}{3} \tag{3.2}$$

However, the on-voltage drop across one tap switch is determined by the characteristics of the diodes and the IGBT that are used. For instance, 1.6MVA three-phase transformer with 11kV at its primary would draw from the grid an rms current of about 84A during its rated operation. The approximate total voltage drop across the switch, when using normal silicon high power diodes and IGBT, would reach 6-9V during on state condition [32]. According to (3.2), the power loss in the whole switch would be around 756W, which is not negligible.

$$P_{SW} = (2V_{on\_Diode} + V_{on\_IGBT})I_{rated} = 9 \times 84 = 756W \tag{3.3}$$

These losses can be minimized in the future when high power Silicon Carbide switches are developed and commercialized.

Besides, when switching from SW_1 to SW_2 and both SW_1 and SW_2 are conducting simultaneously, a circulating current will flow in both switches which discharge the magnetic energy stored in the winding inductance. To avoid such a situation, switching between two taps should be made during the zero-current crossing.

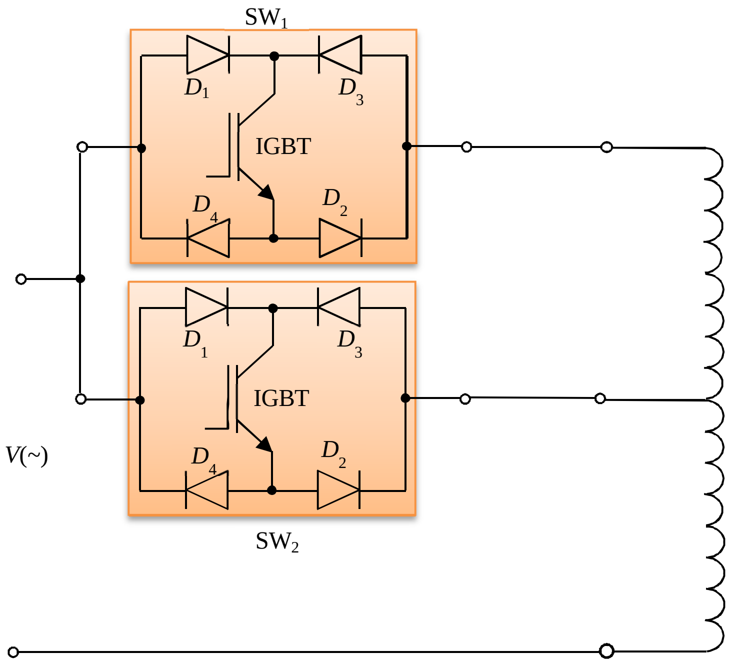


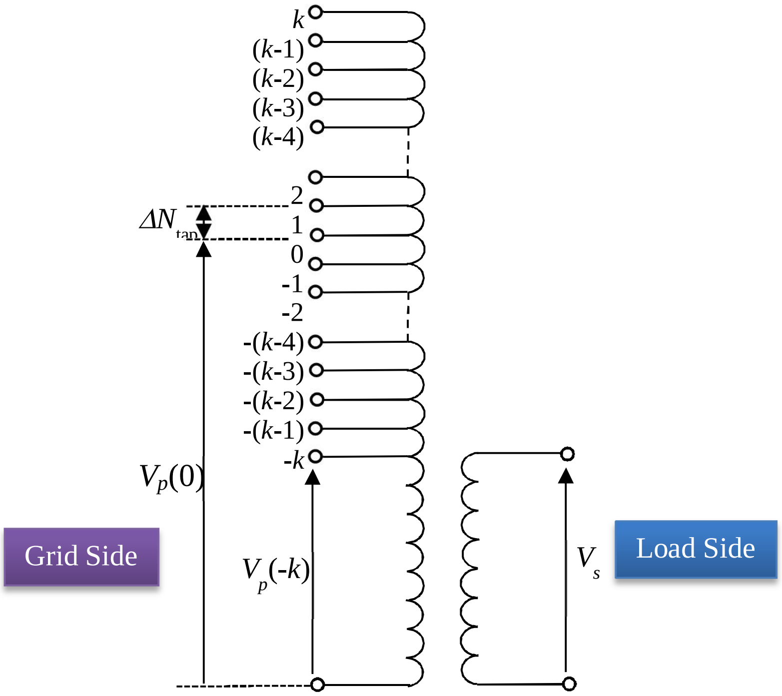
Figure 3-3: Tap switch configuration.

3.2.2 Tap Selection

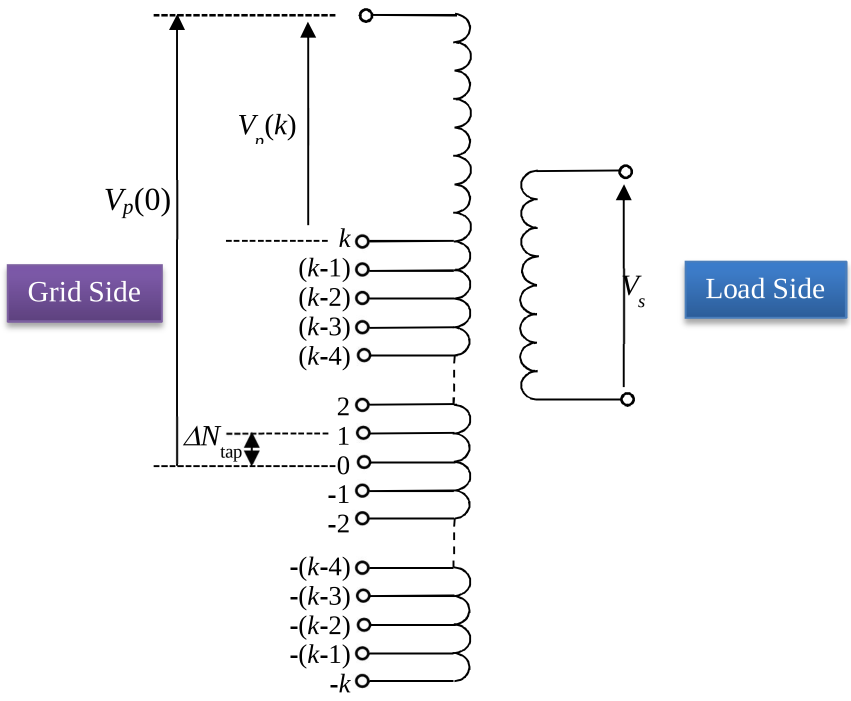
The configuration of a single-phase transformer with K_{tap} taps in its primary (MV) winding is shown in Figure 3-4. The parameters and variables used are defined in the list of Abbreviations and Symbols.

The OLTC may be placed on the primary or secondary winding of the transformer. For instance, for a distribution network with 1.6MVA 11kV/415V transformer at the substation, the current at the primary side of the transformer is about 84A compared to 2226A on the secondary side. Hence, with the availability of the power electronic switches in the market, it is preferable to place the tap changer at the primary side.

The tap changer on the primary side of the transformer can be placed on the hot wire (Figure 3-4a) or the neutral (Figure 3-4b). The author in [18] states that it is better to place the tap changers which are installed in star-connected windings on the neutral of the transformer because, in this case, only the line-to-neutral voltage part is insulated.



(a) Taps are on the hot wire side



(b) Taps are on the neutral wire side

Figure 3-4: Configuration of a 1ϕ transformer with K_{tap} taps in its primary (MV) winding.

3.2.3 Determination of Tap Position

The transformer winding voltages are related to the transformer winding numbers of turns as shown in (3.4).

$$\frac{V_p}{N_p} = \frac{V_s}{N_s} \tag{3.4}$$

In order to determine the required tap position for a voltage deviation ΔV_s at the minimum bus voltage, which is also reflected on the secondary side of the transformer, (3.5) is further developed into (3.4).

$$\frac{V_p}{N_p(0) + \Delta\mathrm{N}_p} = \frac{V_\mathrm{s}(0) + \Delta V_\mathrm{s}}{N_s} \tag{3.5}$$

Hence, the number of turns at the primary side of the transformer can be expressed as in (3.6).

$$\Delta N_p = \frac{N_\mathrm{s}.V_p}{V_s(0) + \Delta V_\mathrm{s}} - N_p(0) \tag{3.6}$$

Now, dividing both sides of (3.6) by $N_p(0)$, (3.6) it can be further simplified into (3.7).

$$\Delta N_{p\_pu} = \frac{N_\mathrm{s}.V_p/N_p(0)}{V_s(0) + \Delta V_\mathrm{s}} - 1 \tag{3.7}$$

Equation (3.7) can be rewritten as

$$\Delta N_{p\_pu} = \frac{N_\mathrm{s}.V_p/[N_p(0).V_s(0)]}{1 + \Delta V_{\mathrm{s\_pu}}} - 1 \tag{3.8}$$

According to (3.4), the term $N_\mathrm{s}.V_p/[N_p(0).V_s(0)]$ is equal to unity. As a result, the deviation in number of turns on the primary side from the zero-tap position is expressed as a function of the deviation of the voltage at the secondary side of the transformer as

$$\Delta N_{p\_pu} = \frac{-\Delta V_{\mathrm{s\_pu}}}{1 + \Delta V_{\mathrm{s\_pu}}} \tag{3.9}$$

The variation of the number of taps Δk_p from the tap position zero is a function of the variation of the number of turns ΔN_{p_pu} at the primary side and the tap minimum number of turns ΔN_{tap_pu}as given in (3.10).

$$\Delta k_{p=}\frac{\Delta N_{p\_pu}}{\Delta N_{tap\_pu}} \tag{3.10}$$

Substituting (3.9) into (3.10), the deviation of the number of taps is determined as a function of the deviation of voltage as in (3.11):

$$\Delta k_p = \frac{-\Delta V_{s\_pu}}{(1 + \Delta V_{s_{pu}})\Delta N_{tap\_pu}} \tag{3.11}$$

Finally, once Δk_p is determined, the controller turns off the switch of the previous tap position and turns on the switch at the new tap position Δk_p. The same calculations are repeated during each control cycle.

3.3 **Proposed Three-Phase Configuration**

The proposed three-phase configuration uses simply identical 3-single phase transformers and OLTCs. Each transformer winding is connected between one phase and the neutral. The importance of having 3-single phase system is the ability to control each phase separately. Thus, during voltage unbalance, the controller of each phase can react separately and regulate the voltage delivered to each customer more reliably with better power quality and efficiency. Figure 3-5 shows the architecture of the proposed three-phase system. Using the tap selection criteria presented above, the tap selector for each phase determines the required tap position, which might not be the same for each single-phase transformer in the case of phase voltage unbalance. Several switching configurations are studied in the literature as in [33]. Among the compared switching configurations, it is concluded that using dedicated winding for the tap changer is preferable. Same has been proposed in the three-phase system.

3.4 **Summary**

The proposed OLTC control method in this chapter considers measuring the voltages at the secondary side of the network. In cases, the maximum voltage is over the allowed limit or the minimum voltage is below the acceptable voltage, the tap selector identifies the required tap position to shift the voltages delivered to customers to the acceptable range as per IEC standards. However, if the voltages are within the acceptable range, the minimum voltage is shifted to a reference voltage of 0.92pu that is expected to improve the energy efficiency of the distribution system. This selection can provide a significant amount of energy saving to the system maintaining the required power quality. The designed tap selector is a full electronic bidirectional power switch. To avoid the magnetic energy to be discharged in the winding inductance, zero-current switching is assured during switching between two taps. The proposed three-phase system uses a 3-single phase transformers and relevant OLTCs. The main advantage of this system is its ability to control each phase independently. In the next chapter, validation case studies for the proposed voltage regulation algorithm are presented. The studied models are introduced along with their network parameters and load profiles.

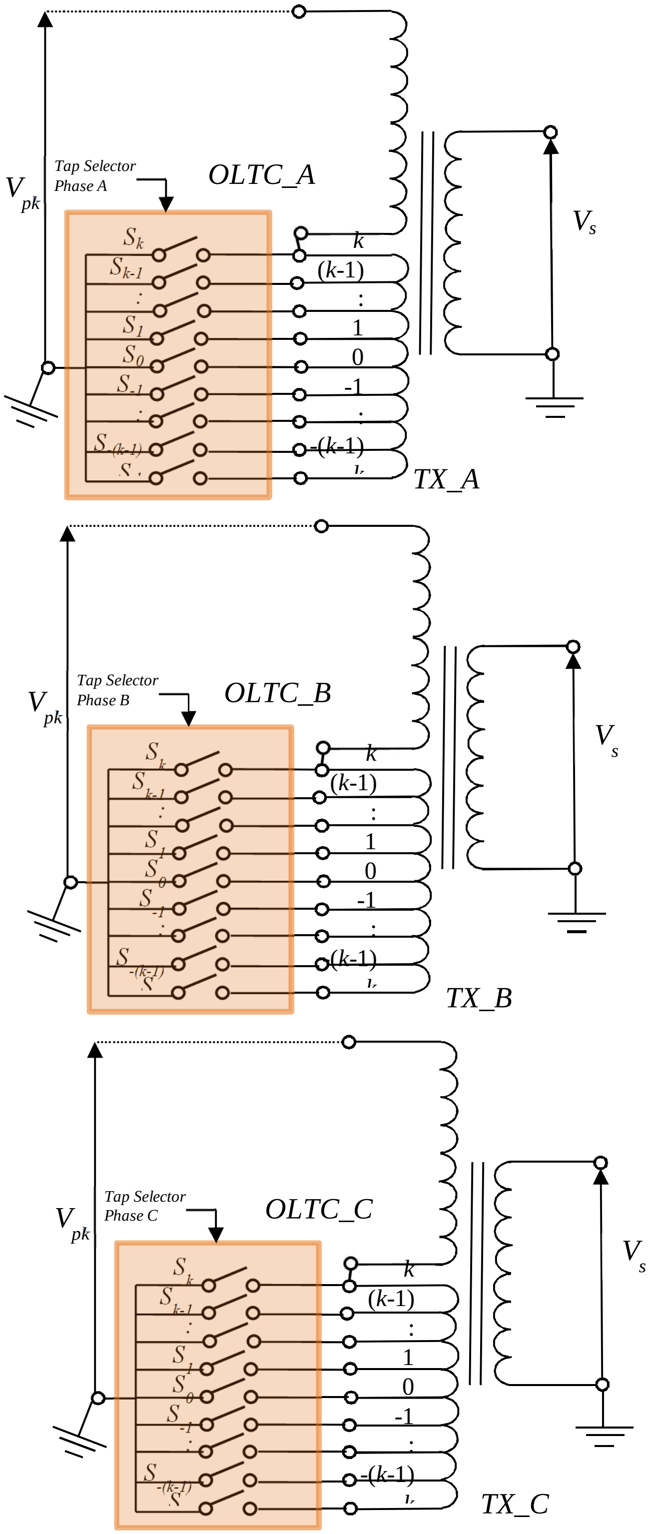


Figure 3-5: Proposed three-phase system architecture

Chapter 4: CASE STUDIES

4.1 **Introduction**

The proposed algorithm and controller introduced in the previous chapter are implemented and applied on modeled systems which are presented in this chapter.

First, a single-phase case study is proposed to validate that the method is feasible prior to implementing on a more complex model. The system is composed of a transformer along with an OLTC, a tap controller, the grid and three load terminals.

After validating the proposed algorithm on a single-phase case study, a residential compound model is introduced. The compound is a mock-up of a real model including the main features of a compound in the gulf region. The load usage of each plot of the compound is considered while setting the load profile of the whole compound. Moreover, the tree and radial systems are considered.

4.2 **Single Phase Case Study**

In this section, a single-phase case is studied as shown in Figure 4-1: Single Phase Studied Case. The parameters of the studied case are introduced in Table 4-1.

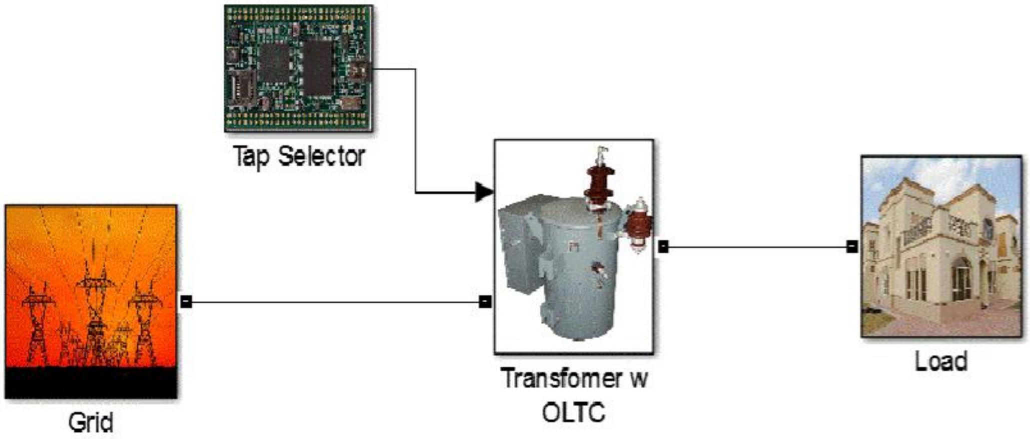


Figure 4-1: Single Phase Studied Case

Table 4-1: Parameters of single phase case study

Parameter	***Value***
Transformer Rating	1 MVA
Transformer Primary Nominal Voltage	6.35 kV
Transformer Secondary Nominal Voltage	240 V
OLTC Number of taps	21 (±10% with 1% step)
Frequency	50 Hz
Tap Selection Time	1 min

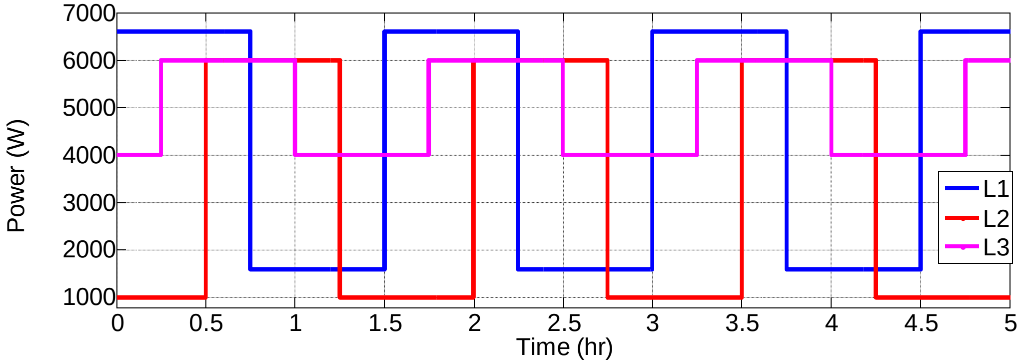
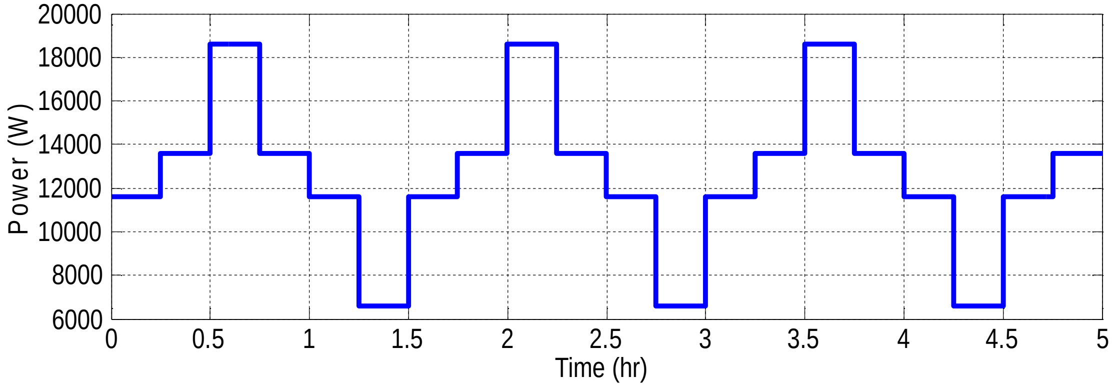


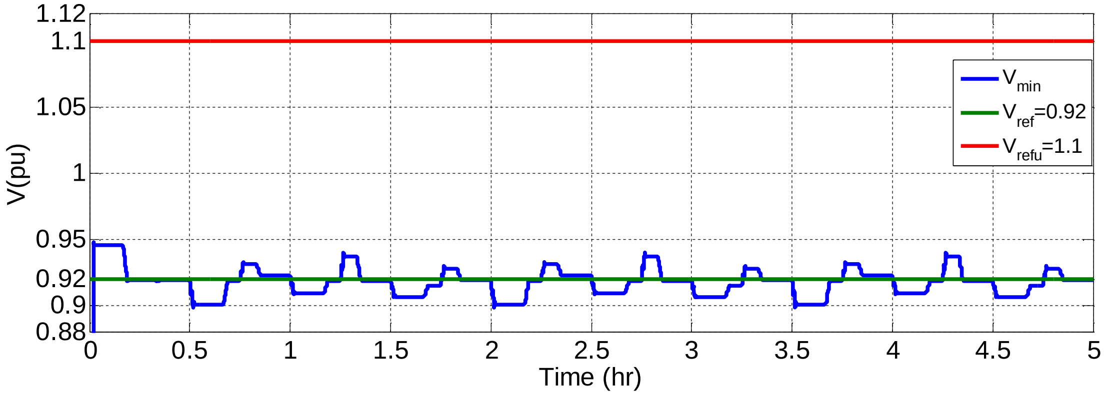
Figure 4-2: Load profile for each terminal of the single phase studied case

The proposed system consists of 1MVA, 6.35kV/240V transformer along with three load terminals. The load profile for the three terminals is shown in Figure 4-2. The number of taps/switches considered in the tap-changer is K_{tap}=21 (±10%) with a Δk_{tap_pu}=1% corresponding to the minimum tap change. The purpose of this case is to ensure that the proposed algorithm is feasible on a simple system prior to applying it to a more complicated system.

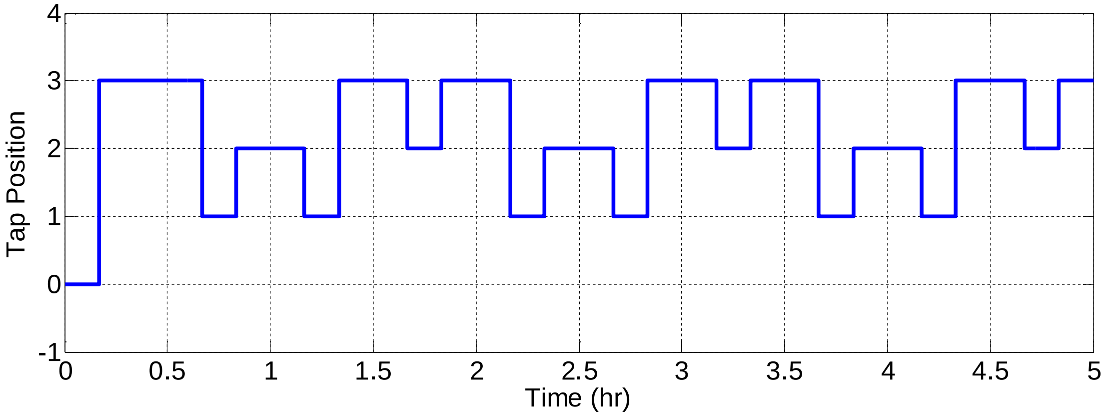
The total load profile is shown in Figure 4-3a, while Figure 4-3b shows the minimum voltage among the three terminals. It can be inferred that the minimum voltage is being regulated to the V_{ref}=0.92pu. At t=10min (0.5/3 hr), the voltage is decreased from about 0.94pu to 0.92pu. The voltage is further decreased to 0.9pu at t=30min due to the increase in load. After 10min, at t=40min, the OLTC reacts to this change in voltage and changes the tap so the voltage is increased again to about 0.92pu.



(a) Load profile



(b) Minimum voltage of the single-phase case study



(c) Positon

Figure 4-3: Single-phase case study results

The voltage profile of the minimum voltage continues to change in line with the change in power. Moreover, the tap changes smoothly without spikes. The required tap position for maintaining the minimum voltage at the reference voltage is shown in Figure 4-3c.

4.3 **Residential Compound Studied Case**

The proposed voltage regulation method is applied to a residential compound model to study the impact of a real and more complex system. The model is a mock-up of a residential compound including the main features of a compound in the gulf region. The compound consists of 21 villas, treatment plants including sewage, drainage, and irrigation pumping stations. The compound also includes a mosque, an amenity building, green areas and a guard room as shown in Figure 4-4.

The load for each of the plots is calculated using the demand loads used in Qatar. The total connected load for each plot along with the power factor is shown in Table 4-2. The required load for each plot is modeled for 24 hr. Each villa and other building have their dedicated load profile. The load usage of each plot is considered proportional of 10%, 25%, 50%, 75% and 100% of the full load. Figure 4-5 shows the full load profile of the whole compound. At time 16:00 (4:00 pm), the load reaches its maximum peak, while at time 4:00am the total load in the compound is at its minimum.

In order to study the impact of the proposed system on real cases, two different systems have been analyzed here; radial and tree networks as shown in Figure 4-6 and Figure 4-7, respectively.

Figure 4-4: Residential compound plan

In the tree system, each feeder is connected to more than one plot through loop connection, whereas, for the radial system, each plot has its dedicated feeder. The number of plots per feeder is calculated based on the current carrying capacity of the cable. In addition, the connections are through joints (tagged at “T” in the figures). For each plot, a kWh smart meter cabinet is proposed that is used to measure the voltage and communicate it back to the substation for controlling.

Table 4-2: Residential compound total connected load for each plot/building

Plot	***Load (kW)***	***Power Factor (cosϕ)***	***Reactive Power (kVAR)***
Villa	33.8	0.8	25.35
Amenity	46.6	0.75	41.097
Irrigation Pump	20.0	0.7	20.404
Drainage Pump	20.0	0.7	20.404
Sewage Pump	50.0	0.7	51.01
Mosque	4.0	0.8	3.0
Guard Room	1.6	0.8	1.2
Green Area	3.0	0.9	1.452
Street lighting	3.0	0.9	1.452
Grand Total	**858**	**0.78511**	**676.9**

The size of the cables differs depending on the load and maximum allowable voltage drop set by Qatar General Electrical and Water Corporation (QGEWC-KAHRAMAA) standard [34]. For tree system, the main cable is 4Cx300 mm^2 with a service cable of relevant size as per the current carrying capacity (CCC) values. For radial connection, the cable connected to the meter cabinet is directly running from the LV panel within the substation. It is to be noted that the mosque and guard room have been combined into one load and only one meter/connection has been assumed. Same has been assumed for the green area and the street lighting.

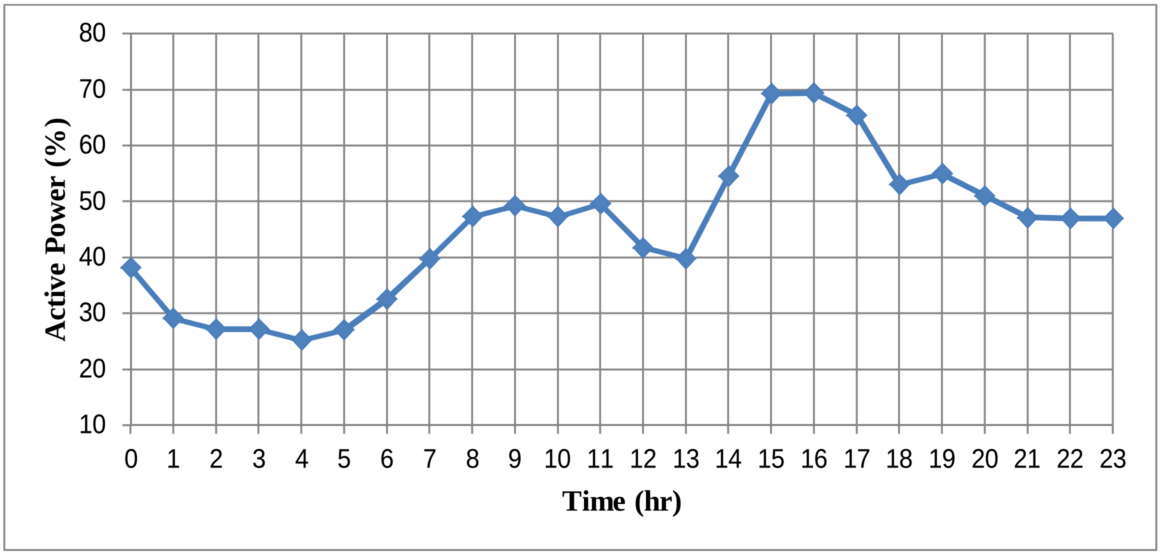


Figure 4-5: Residential compound full load profile

Based on the total connected load on the system and taking into consideration a diversity factor (DF) of 0.9, the transformer rating is calculated as follows:

$$S = \frac{P}{cos\emptyset * DF} = \frac{858}{0.78511 * 0.9} = 1.21427\ MVA$$

The available next-level transformer rating is 1.6 MVA which is chosen in this study.

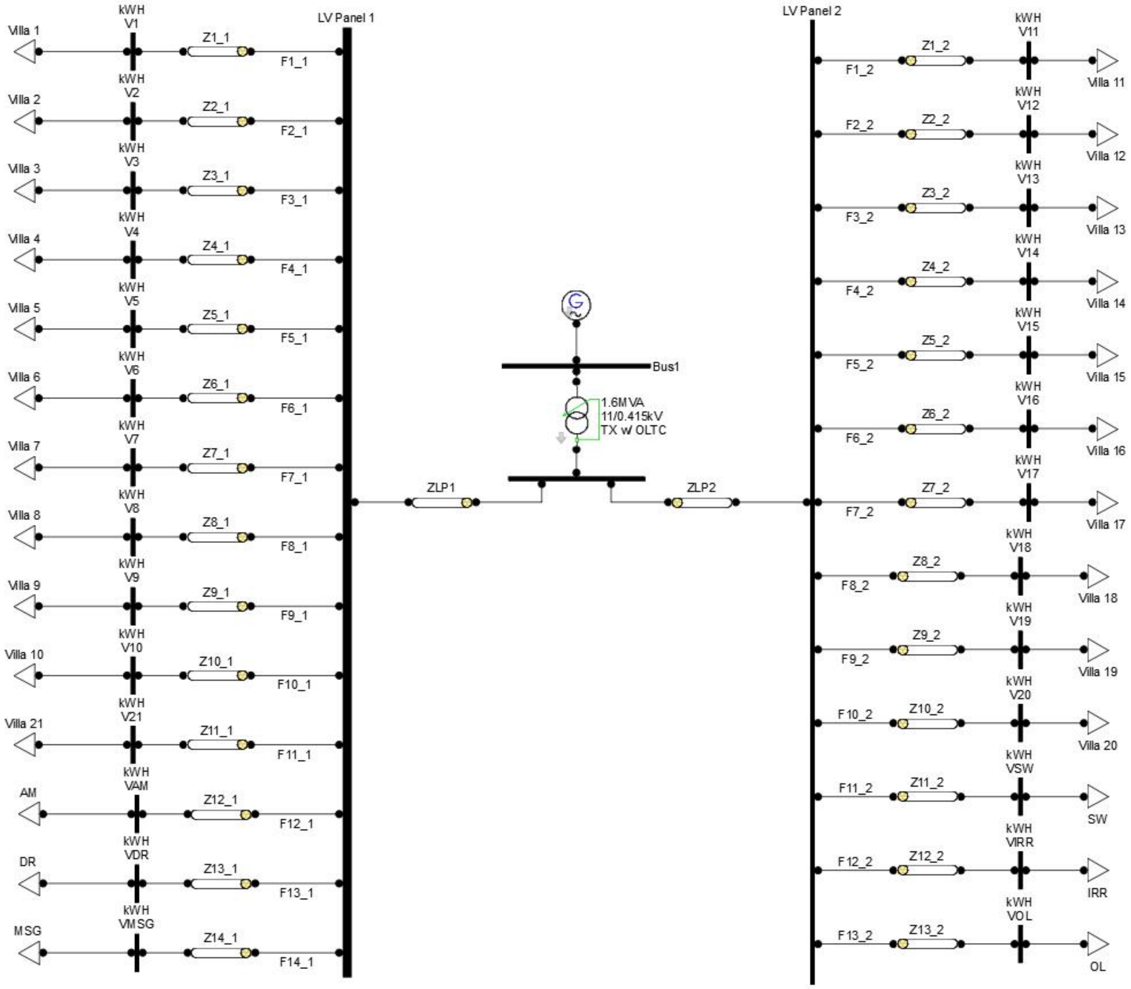


Figure 4-6: Residential compound model radial system

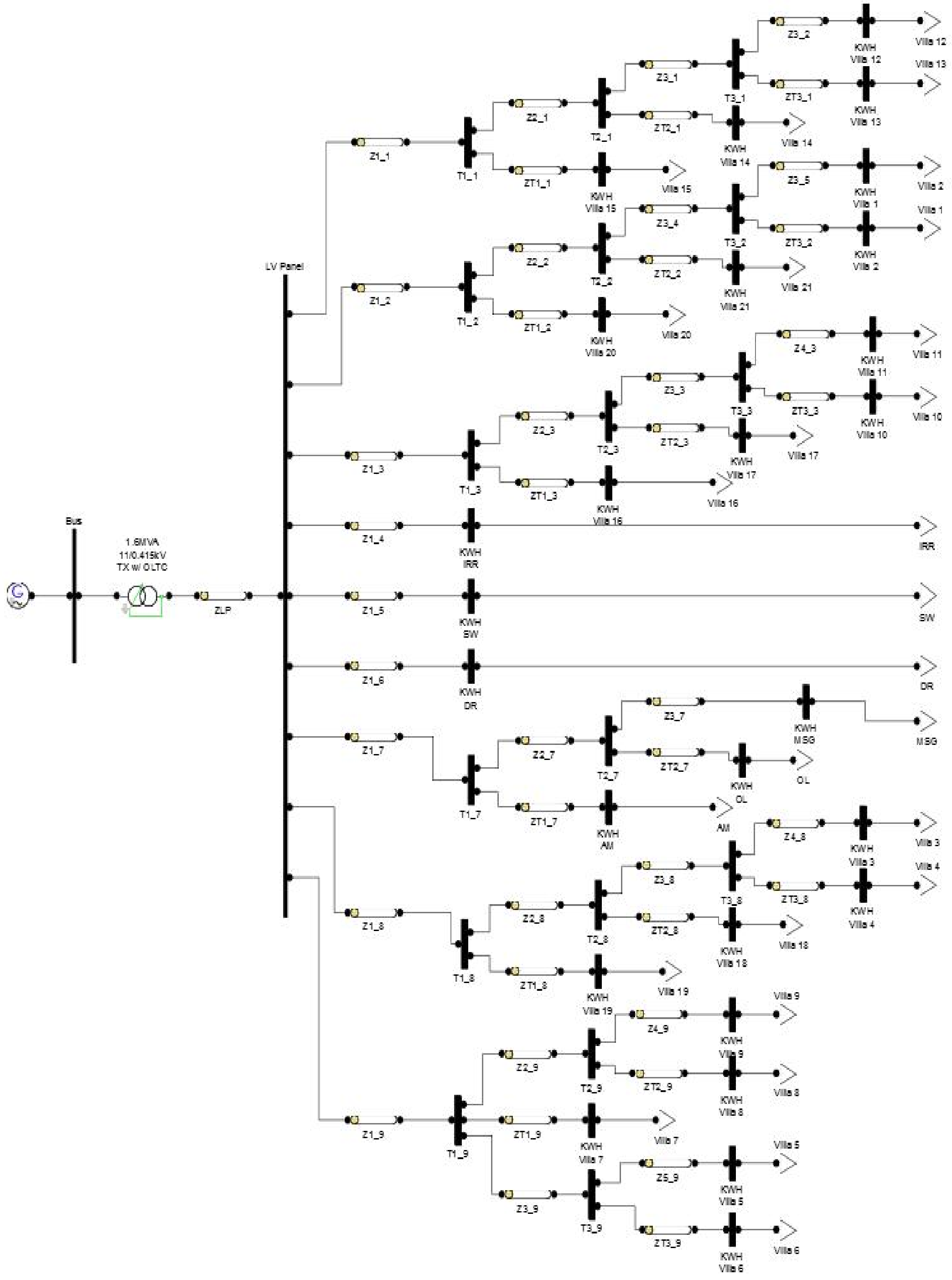


Figure 4-7: Residential compound model tree system

The MV grid voltage is 11kV and the impedances are calculated based on the length of each cable and the manufacturer’s data. The transformer parameters along with the OLTC parameters are listed in Table 4-3 and Table 4-4.

4.4 **Summary**

In this chapter, the two case studies which are used for testing and validating the proposed voltage regulation method are presented and described. A simple single-phase case study is proposed as a validation case to ensure that the method is feasible. Afterward, a more real and complex case of a residential compound model is presented, which is typical to Qatar the gulf region. The load profile for 24hr is modeled and the parameters of the main equipment of the electric network are defined. The tree and radial network systems are considered and configured. The single line diagrams of these two systems are presented.

These case studies are analyzed, in the next chapter, on different scenarios including heavily and lightly loaded operations. The results are presented, whereas, the power quality and energy saving for several load scenarios are discussed and evaluated.

Table 4-3: Parameters of three phase transformer

Parameter	***Value***
Voltage at Primary	11kV (phase-to-phase)
Voltage at Secondary	240V (phase-to-neutral)
R pu	1.027%
X pu	6.165%
Configuration	Δ / Y
Rating	1600 kVA

Table 4-4: Parameters of OLTC in three-phase system

Parameter	***Value***
Voltage Reference (pu)	0.92
Voltage step (pu)	0.01
Number of taps	21
Initial and Final tap position	-10 to 10
Tap change time (min)	5min

Chapter 5: RESULTS AND DISCUSSIONS

5.1 Introduction

The proposed voltage regulation method is implemented on a residential compound model which is a three-phase system. The residential compound model defined in the previous chapter consists of several terminals each equipped with a smart meter. The smart meters are used to measure the voltage at each node and feed it back to the substation where the controller reacts to those measurements and regulate the voltages according to the proposed algorithm.

The two important features of an electrical system are the power quality and energy saving. Power quality ensures the continuity of service to all consumers within the acceptable range set by standards, which, in the case of voltage, is [0.9, 1.1]pu as per the national and international standards. In the other hand, energy saving is important for the utilities and also for the society. By increasing the amount of energy saving, the operation and maintenance cost and the environmental impact are reduced.

In this chapter, the results of the normal operation of the tree configuration are shown. Then, some operation cases that violate power quality of the system are simulated and their results are presented. The amount of energy saving is estimated. Then, the tree and radial system configurations are compared when a DG is inserted at one terminal using the proposed technique. Finally, the results are discussed and summarized showing the positive impact of the proposed technique on a real model.

5.2 **Normal Operation**

The radial and tree systems are simulated in normal operation. Recall the load profile of the whole residential compound shown in Figure 5-1. Figure 5-2(a) shows the normal operation of the tree system of the modeled residential compound.

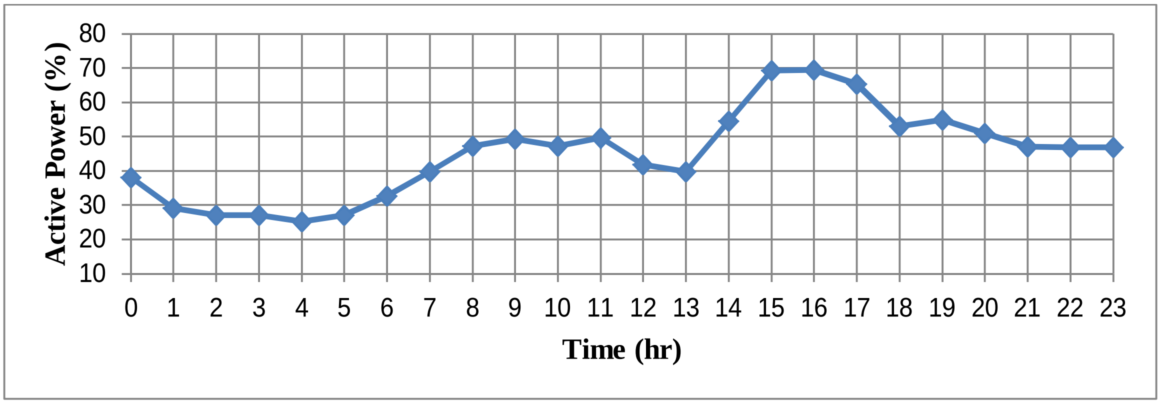
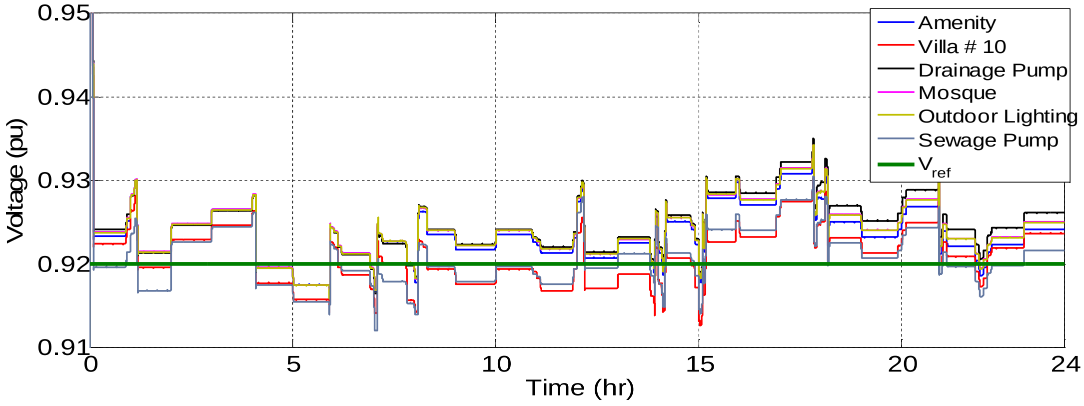


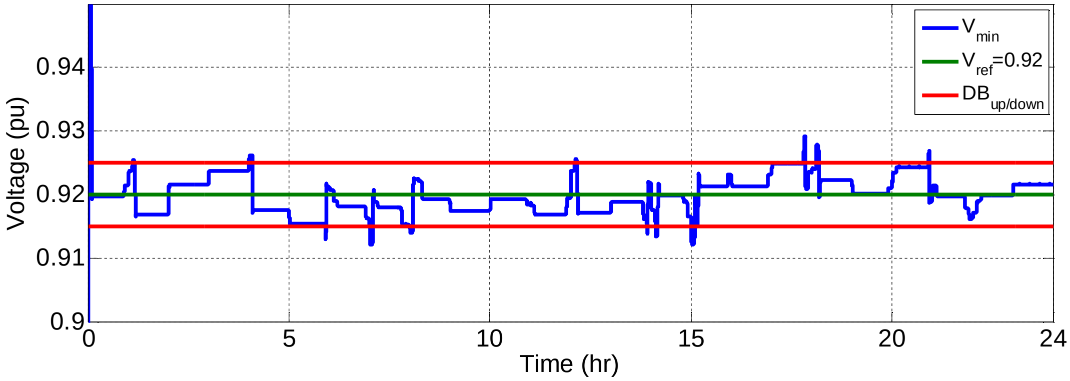
Figure 5-1: Residential compound load profile

In normal conditions, the system is balanced; hence, the voltages presented here are only for only phase-A of some of the loads which are the most severe cases. For example, Villa # 10 has the longest cable length, sewage pump is the highest mixed load, outdoor lighting has the highest power factor, amenity has the highest load and mosque and guard room are two different loads connected to one feeder.

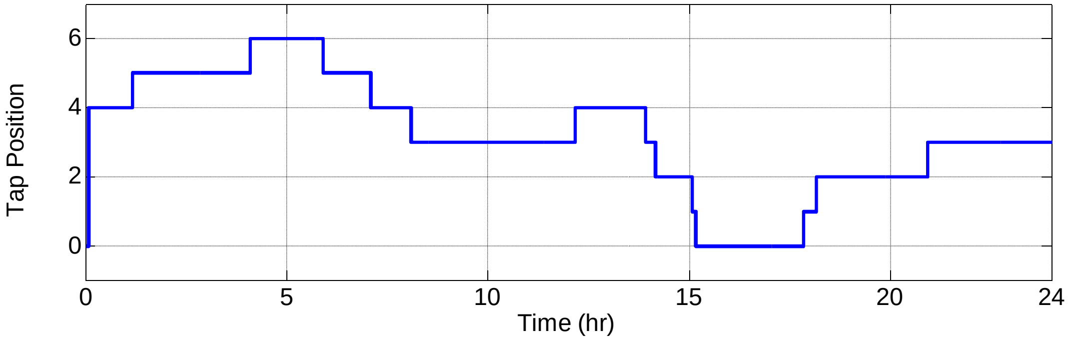
The minimum voltage of the tree network and the corresponding tap position for the normal operation are shown in Figure 5-2 (b) and (c) respectively.



(a) Voltage Profiles



(b) Minimum Voltage



(c) Position

Figure 5-2: Tree network normal operation profiles

When the power increases at t=6hr (equivalent to 6s actual simulation time in Matlab), the voltage across the load increases, hence the tap controller reacts to this increase by decreasing the tap position at the primary side in order to maintain approximately the same voltage delivered to the customers.

The systems are running normally where the voltage profiles are following the load profile within a specified dead-band of DB=±0.5% and the tap controller is reacting to the load voltage variation caused by the assumed change in load. However, at a certain time, unknown causes might occur without any indication, which would negatively impact the system and the continuity of service. Some of these causes are over-voltage, an increase of the line impedance, voltage unbalance, increase/decrease in load or disconnection of a feeder. In each case, the power quality of the system may become under severe situation which requires an action to ensure continuity of service.

5.3 **Results of Power Quality Control**

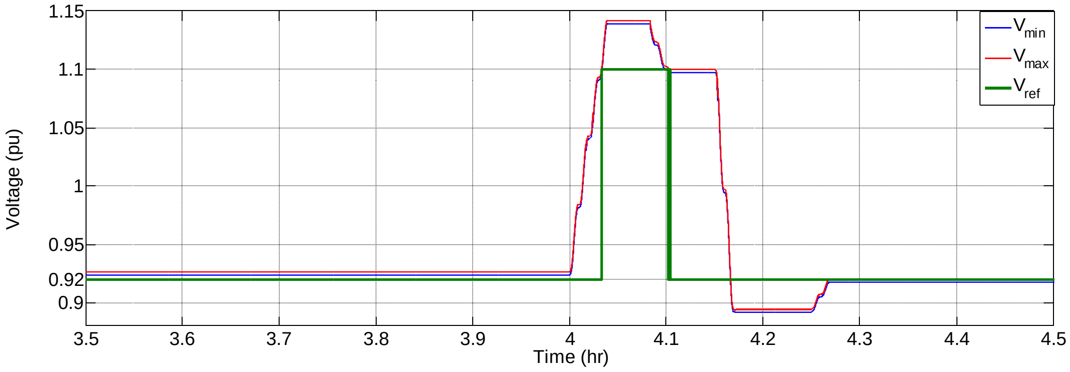
The power quality is, by no means, the most important value of an electric network. The variation of voltage is one of the parameters that impact the quality of power in a system. As set by IEC, the acceptable voltage range is within [0.9, 1.1]pu, therefore, the impact of over-voltage, under-voltage, and voltage unbalance is studied hereafter.

5.3.1 Over-Voltage

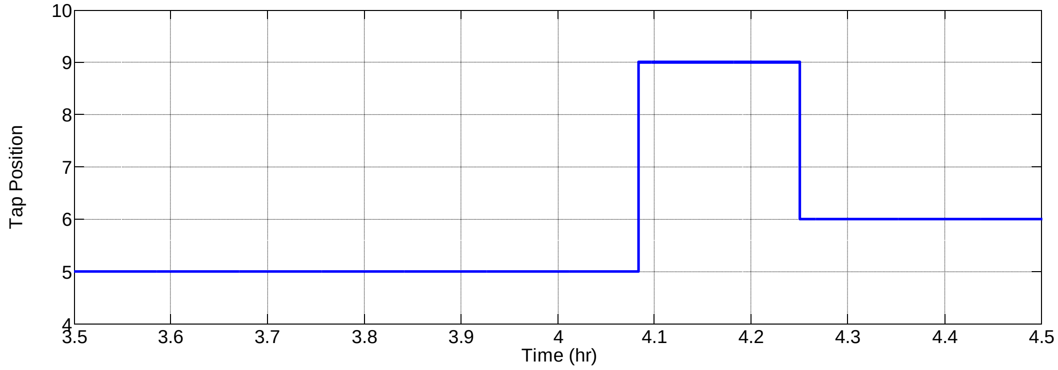
An over-voltage might occur due to several reasons; delivered voltage from upstream is over the required voltage, major loads from long-line are abruptly disconnected, induced voltages due to atmospheric changes, several loads become very low at the same time, etc. To simulate and test such a situation, it is considered that, at *t*=4hr, the delivered voltage from upstream in the tree system goes higher than the maximum voltage limit.

Figure 5-3 shows the results of the regulated voltage profile and the controlled tap positions for phase-A.

In case the maximum voltage in the system is less than 1.1pu, the regulated voltage considered is the minimum among all load voltages. However, when one of the voltages goes over the maximum allowable voltage, the regulated voltage becomes the maximum voltage (power quality is controlled first). As shown in Figure 5-3, the tap changer is initially at tap position 5 to regulate the minimum voltage to the 0.92pu reference used for energy saving. At *t*=4hr, the voltage increases and the reference increase to 1.1pu. After one tap selection period of 5min (adjustable), the controller senses this difference and regulates the maximum voltage to the 1.1pu by changing the tap to position 9. When this over-voltage is removed at *t*=4.16hr, the controller continues to regulate the minimum voltage to the 0.92pu and changes the tap again to position 6.



(a) Minimum and maximum voltage profiles



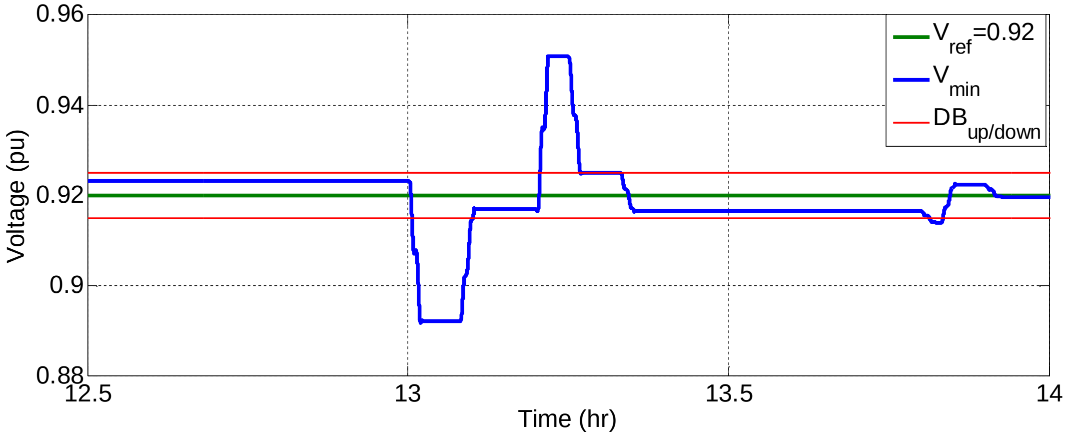
(b) Position

Figure 5-3: Over-voltage case; voltage profile and tap position

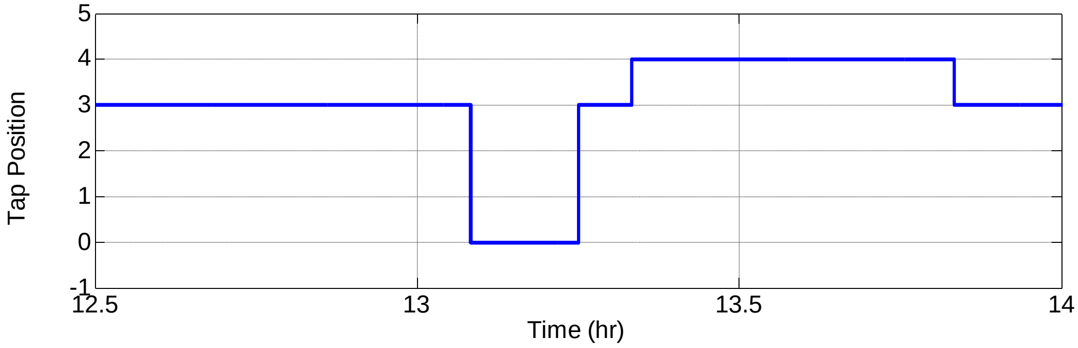
5.3.2 Under-Voltage

Under voltage situations can happen due to several reasons; heavily-loaded system, increase in line impedance, a decrease in the voltage required from the upstream, etc. In the studied case, it is considered that the impedance of line # 4 (connecting to Villa # 4) of the radial network at time *t*=13hr has increased. The increase in the impedance affects the voltage delivered to Villa # 4, which has reduced to 0.89pu as shown in Figure 5-4.

Immediately the controller reacts to this situation and the tap position at the primary side reduces from the position 3 to the required tap 0 (Figure 5-4b) so that the voltage at the secondary side increases to the reference level. At t=13.2hr, the impedance of the line has been assumed to be resolved, the voltage increases, the tap controller reacts and increases the tap position to 3 in order to return the voltage to the reference level.



(a) Minimum voltage profile



(b) Position

Figure 5-4: Under-voltage; voltage profile and tap position

5.3.3 Voltage Unbalance

Another power quality drawback is the voltage unbalance which has severe circumstances on home appliances and equipment. The proposed three-phase transformer equipped with separate single tap controllers has structured accordingly in order to solve this weakness in the power system.

In the studied case, the voltage on phase A at Villa # 4 at *t*=11hr changes and returns back to its initial state at *t*=12hr. Hence, a voltage unbalance occurs. Figure 5-5 shows the voltage at Villa # 4 for the three phases along with the tap positions of each phase

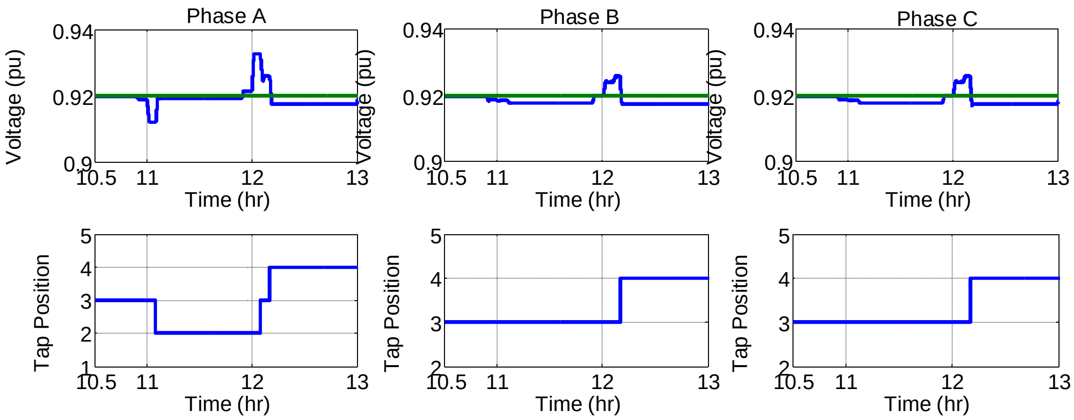


Figure 5-5: Voltage profiles and tap positions in case voltage unbalance

For phases B and C, the voltage doesn’t change, hence, the tap controller doesn’t react and it keeps the current tap position. However, due to the change in phase A voltage, the corresponding tap controller changes the tap to position 2. Notice that the three phases have different tap positions. However, the voltage for the three phases is maintained in the range of the reference voltage (0.92pu).

5.4 **Results of Energy Saving**

Apart from power quality which has been analyzed in the previous section, energy saving is one of the important features for utilities. Voltage regulation within the accepted range would impact significantly the energy saved at the MV/LV transformer level which consequently leads to a considerable amount of energy saved in the power system. In addition, the proposed controller provides better energy saving compared to the traditional mechanical tap changer. In this section, the energy saving in the proposed residential compound model is presented and analyzed.

5.4.1 Energy Saving by Voltage Regulation

The purpose of voltage regulation is to maintain the voltages delivered to the customers within the acceptable range where the minimum voltage across the whole terminal is kept at the reference voltage level (0.92pu). In the case where the voltages are increased, the energy saving is impractical and power quality of the system dominates. However, in the cases where the voltages are decreased, the required power to ensure continuity of service is maintained within the acceptable range and a considerable amount of energy is saved.

In Figure 5-6, the voltage across Villa # 10 in the tree configuration is shown with and without voltage control.

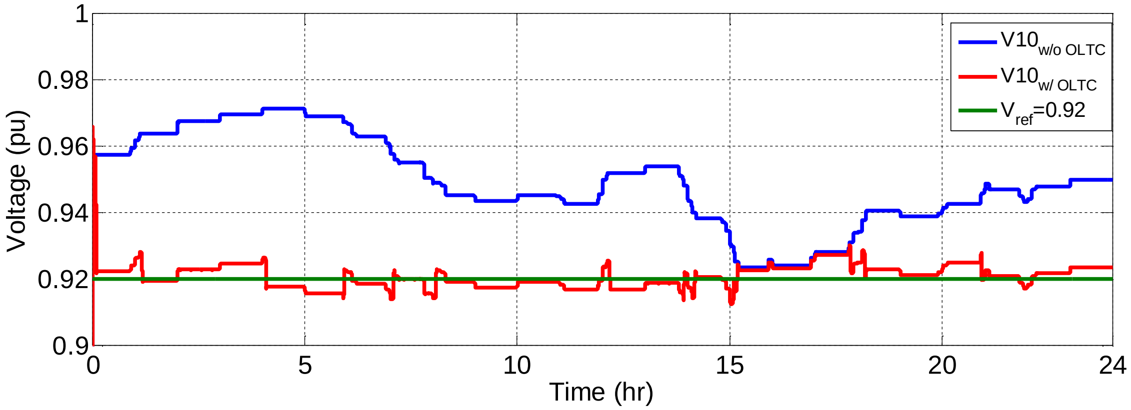


Figure 5-6: Voltage of Villa # 10 with and without tap controller

This voltage reduction, while using the proposed tap changer with fixed load impedance, gives a saving in power consumption, thus more saving in energy. Across the whole system, the voltage with tap controller under normal conditions is less than that without tap controller.

The relation between power, voltage and current in a three phase system is given by equation 5.1

$$P = \sqrt{3} V_{rms} I_{rms} cos\emptyset \tag{5.1}$$

Or in other words,

$$P = \sqrt{3} \frac{V_{rms}^2}{Z} cos\emptyset \tag{5.2}$$

Hence, the ratio between the power consumed with OLTC and that without OLTC is given in (5.3).

$$\frac{P_{w\ OLTC}}{P_{wo\ OLTC}} = \frac{V_{w\ OLTC}^2}{V_{wo\ OLTC}^2} \tag{5.3}$$

From Figure 5-10, at time t=8.4hr, the voltage with OLTC is $V_{w\ OLTC}$=0.92pu, while that without OLTC is $V_{wo\ OLTC}$=0.942pu.

Hence, the power ratio between the two systems is:

$$\frac{P_{w\ OLTC}}{P_{wo\ OLTC}} = \frac{0.92^2}{0.942^2} = 0.95384$$

At t=8.4hr, the required load for Villa # 10 as per the proposed load profile is:

$$P_{villa\ 10} = 0.5 * 33800 = 16900\ \mathrm{W}$$

Hence, the power consumed by Villa # 10 while maintaining the same quality service by using the proposed voltage regulation method by tap controller is:

$$P_{v10}{}' = P_{v10} * 0.95384 = 16120\ W$$

The power saving at t=8.4hr for Villa # 10 is:

$$\Delta P = P_{v10} - P_{v10}{}' = 16900 - 16120 = 780\ \mathrm{W}$$

As a percentage,

$$\Delta P\% = \frac{\Delta P}{P_{v10}} * 100 = \frac{780}{16900} * 100 = 4.62\%$$

This percentage is the power saving at a specific time, however, the power consumption with and without OLTC is not the same over the whole day. Figure 5-7 shows the power consumption for the whole tree system with and without OLTC.

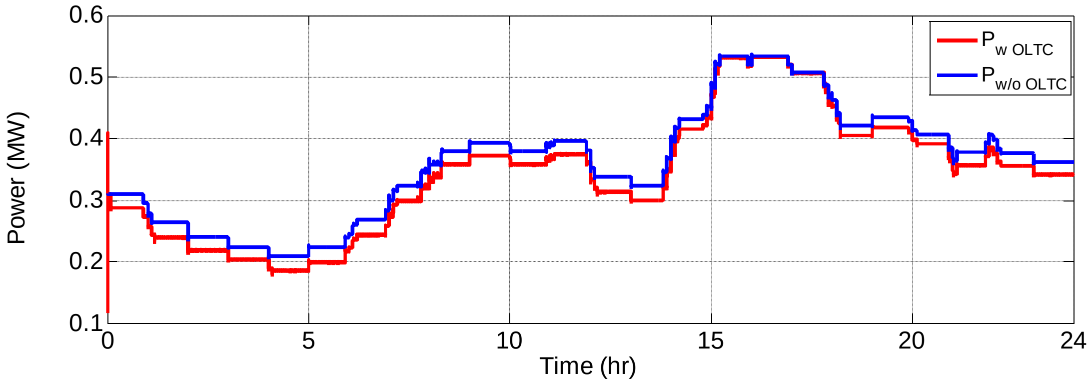


Figure 5-7: Power profile with and without tap controller

Hence, the term that would reflect the efficiency of the system is energy consumption and not instantaneous power. Determining the energy saving over the 24hr gives a better figure of the advantage of the proposed voltage regulation and control system.

$$E = \int_0^{24} p(t)dt \tag{5.4}$$

The amount of energy saving is determined by

$$\Delta E_{24hr} = \int_0^{24} (p(t)_{wo\ OLTC} - p(t)_{w\ OLTC})dt \tag{5.5}$$

$$\Delta E_{24hr} = 8159.1 - 7743.5 = 417.6 \text{ kWh}$$

The energy efficiency of a system is measured in percentage giving the following result:

$$\Delta E_{24hr}\% = \frac{417.6}{8159.1} * 100 = 5.12\%$$

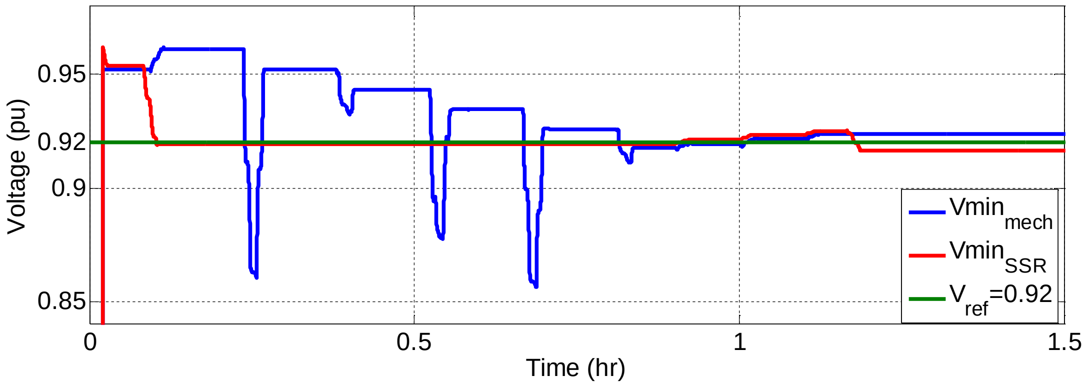
This amount is significant and provides a considerable saving in cost, maintenance and has a better environmental impact due to the reduction of generation.

5.4.2 Energy Saving by SSR-Based Tap Controller

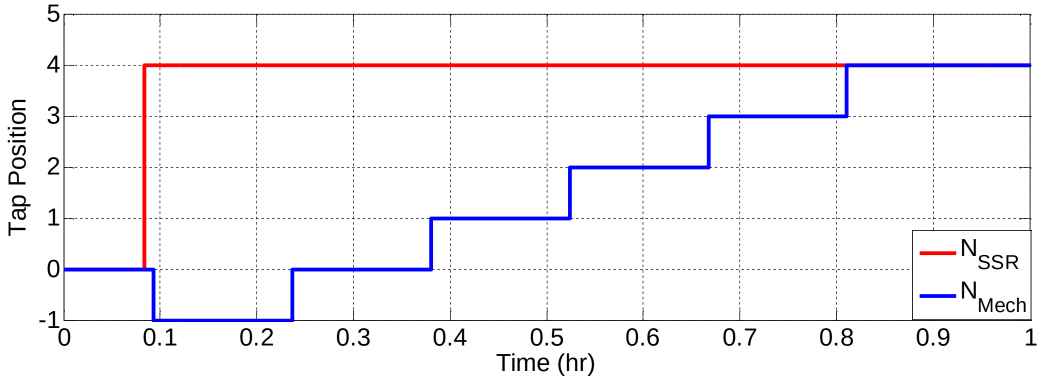
Apart from the energy saved due to the voltage regulation, an amount can be saved from using the proposed SSR-based tap controller which is faster and react immediately compared to the mechanical controller. The minimum voltages of the radial system with the proposed controller and with the mechanical controller are shown in Figure 5-8a, while the tap position for both systems is shown in Figure 5-8b.

Prior to determining the energy saved due to the proposed SSR-based tap controller, it is important to mention that the change in the mechanical OLTC generates spikes (as shown in Figure 5-8) at each time the tap moves to another position. Nevertheless, the tap controller with SSR changes smoothly and reaches the required tap position without any spikes. In addition, a mechanical delay is required by the controller from the time it receives the measured minimum voltage until the time the controller changes its tap which is reflected in Figure 5-8.

The energy saved due to the choice of SSR-based tap controller is defined by the time required for the tap to reach the required position. Considering the above case, at the first reading of the voltages, the tap controller using SSR reacts to the change of the voltage and moves the tap to position # 4. However, due to the mechanical relays and delay in reaction to the voltage change, the tap controller using mechanical relays requires 10 cycles of the controller (0.833 hr = 50min) to reach the required tap position. Hence, there is 45min delay in reaching the required tap position in the above case. This 45min time difference can be translated into energy saving also.



(a) Voltage Profiles



(b) Position

Figure 5-8: Voltage profiles and tap position of mechanical and SSR tap controllers

From Figure 5-8, the mechanical tap controller takes 5 steps from t=5min to reach the same tap position at t=50min. The calculated energy for each case for the period of 50min is measured:

$$E_{mech} = 236.5 \text{ kWh}$$

$$E_{SSR} = 228.6 \text{ kWh}$$

As a result, the proposed tap changer for one change during the day is giving an amount of *7.9*kWh as an energy saving. The energy efficiency of this choice of the tap controller is:

$$\Delta E\% = \frac{7.9}{236.5} * 100 = 3.34\%$$

5.5 **Distributed Generation**

In this section, a comparison between the tree and radial network is performed using the proposed tap controller and voltage regulation method. This comparison is done to study the impact of distributed generation (DG) on the proposed system. In both systems, a distributed generation is proposed at Villa # 4, which most probably is a roof-top PV system.

The distributed generation acts as a controlled voltage source in case it is injecting power to the grid or providing power to Villa # 4. Hence, the model is proposed in such a way, at t=10.3hr, the DG is providing sufficient power to the Villa and injecting power to the grid. For the sake of study only, the Villa is reconnecting to the network at t=11.2hr assuming that the power from the DG is not sufficient to energize the villa.

Voltages of the terminals connected to the same feeder with Villa # 4 on tree network are studied. Same has been considered for the radial system. Figure 5-9 shows an extract from the tree network of feeder 8 where the location of DG at Villa # 4 is highlighted.

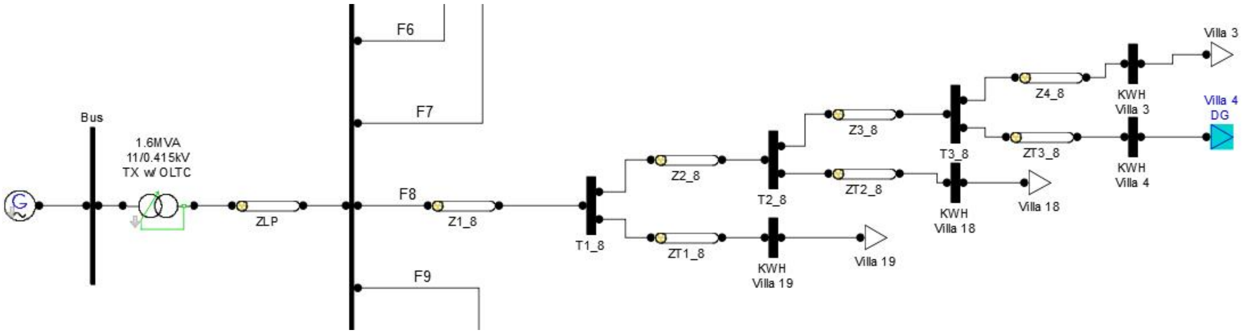
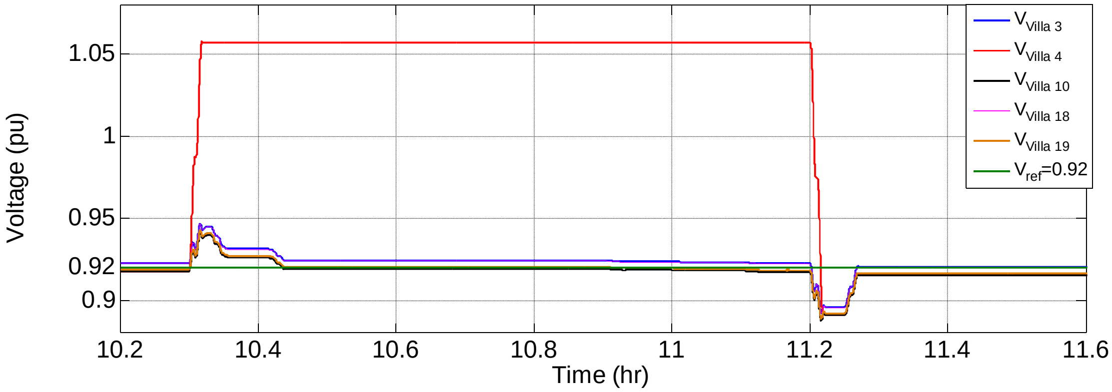


Figure 5-9: Extract from the tree network (Feeder # 8)

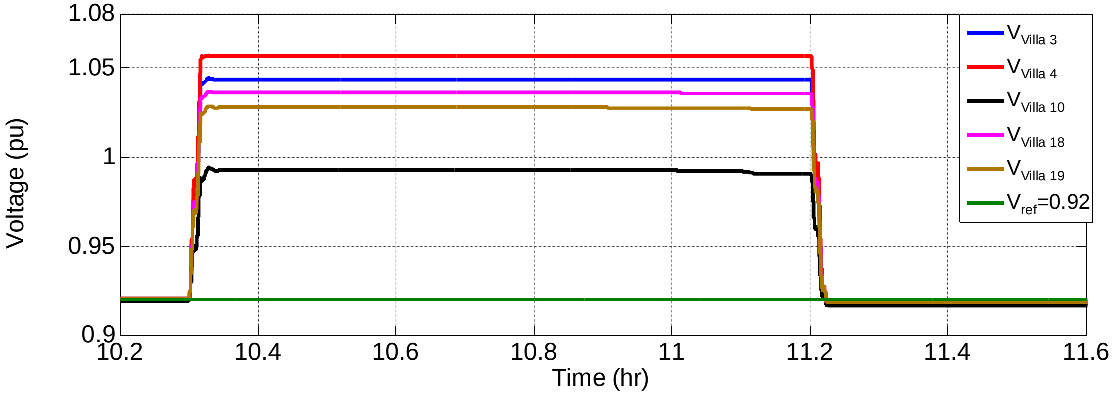
On the same feeder, Villas # 3, 18 and 19 are affected.

Figure 5-10shows the voltage of the villas # 3, 4, 18, 19 and also # 10 which has an independent connection.

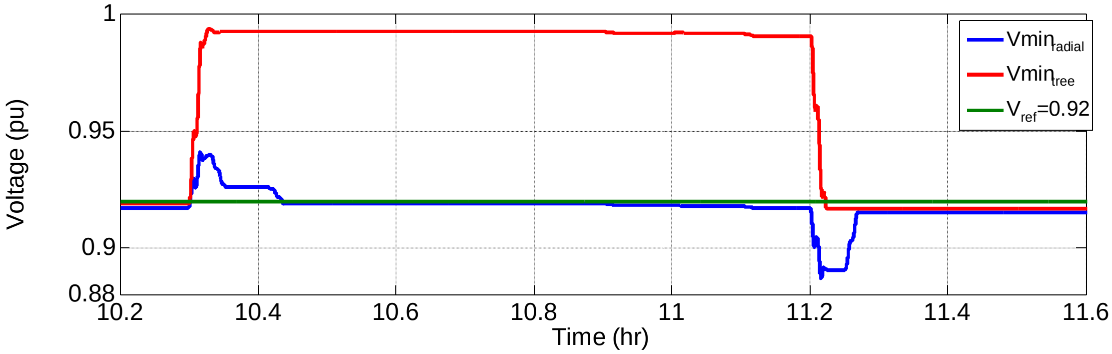
The voltage of the DG is assumed to be 1.06pu in order to analyze the reaction of the controller with this high voltage. It can be concluded, in the radial system, the DG doesn’t have a major impact in the controller. Even though, the voltages across the other terminals increase at *t*=10.3hr; the controller reacts to this increase and regulates all the other voltages (Figure 5-10a). On the other hand, the DG in the tree network has a major impact on the system. The minimum voltage cannot be regulated to the reference level since the required tap position to regulate it is 11, which is not reachable; hence, the current tap position of 3 is maintained (Figure 5-10d).



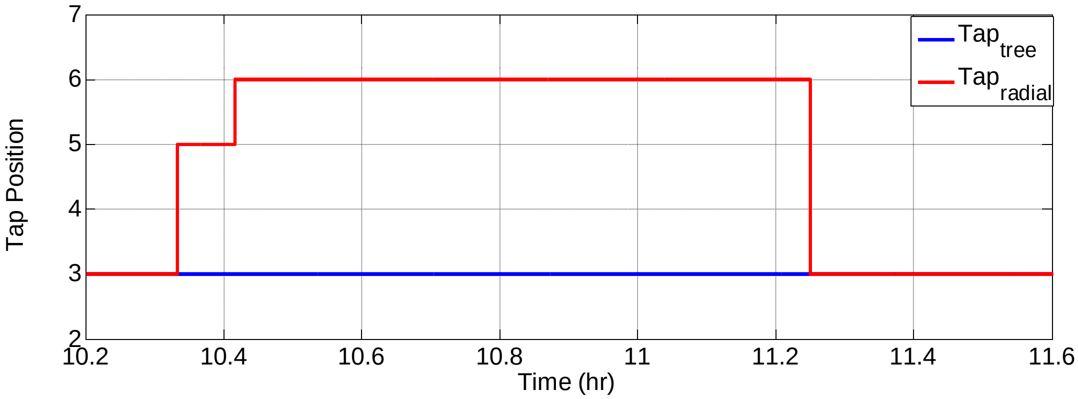
(a) Voltage profiles of radial system using DG



(b) Voltage profiles of tree network using DG

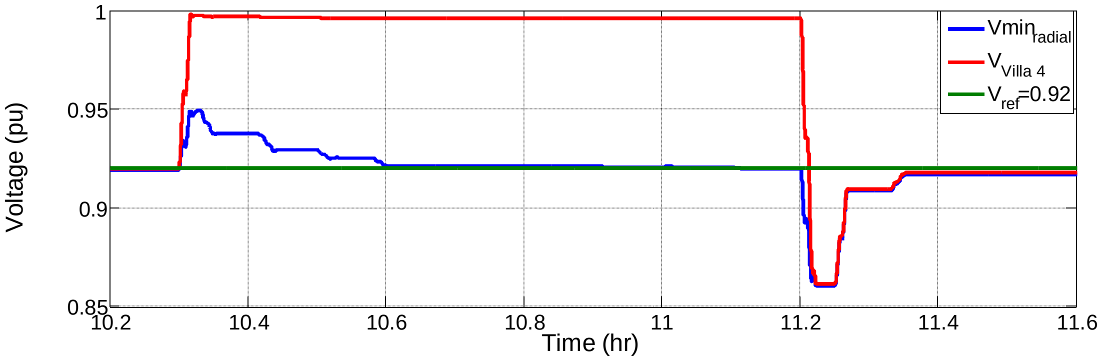


(c) Minimum voltages of tree and radial networks using DG

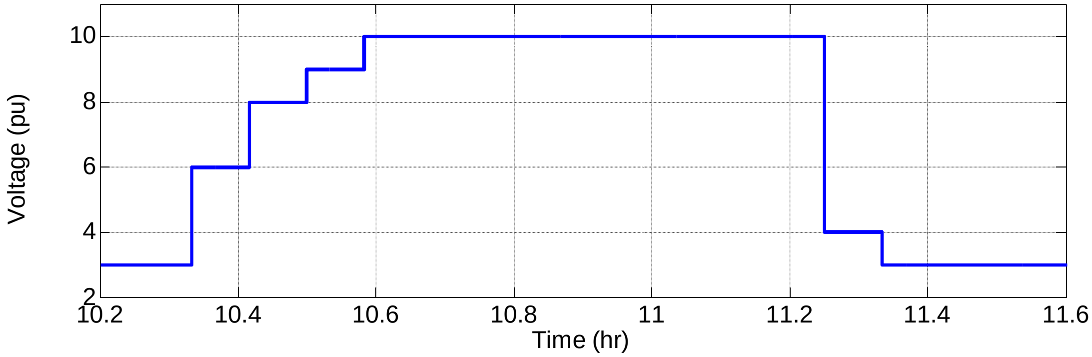


(d) Tap position of the tree and radial networks using DG

Figure 5-10: Profiles using DG in radial and tree systems



(a) Voltage profiles of tree network using DG



(b) Tap position of the tree network using DG

Figure 5-11: Profiles of tree network using DG with voltage at 1pu

Providing a controlled DG of voltage level below1pu gives a better control of the tree system as shown in Figure 5-11. Even in the case the voltage at Villa # 4 is about 1pu, the minimum voltage across the grid is regulated to the reference level. When the DG is not injecting power to the grid, the voltage reaches 0.86pu, however, the controller reacts to this under-voltage and changes the tap position to regulate the voltage again.

As a conclusion, the insertion of DG has more influence on the tree system compared to the tree system. Hence, the rules of insertion in the tree system must be more stringent. In all cases, the AMI provides a more robust communication between the terminals and the controller at the substation especially in the case where DGs are inserted.

5.6 **Summary**

The results of the power quality, energy saving and a comparison between the tree and radial system using distributed generation at one of the villas of the residential compound model are presented. The proposed voltage regulation method and tap controller play an important role to enhance the quality of power delivered to the load terminals. In addition, they provide a significant amount of energy saving which has a big influence on the capital cost, maintenance cost, and the environment. Finally, the proposed system has more stringent rules in case of tree system compared to radial system especially in the case where DGs are inserted in the system.

The obtained results show that during over-voltage where the delivered power from upstream exceeds the required voltage, the controller reacts very fast to this over-voltage and regulates the maximum voltage (instead of the minimum one) to the 1.1pu as set by IEC. When the over-voltage violation is removed, the controller reacts again to this change and changes the tap position accordingly. It also proved that during under-voltage operation scenario, where the voltage at one load has dropped to around 0.89pu due to the high impedance in the line, the tap controller reacted to this voltage drop and changed the position to 0 which returns the voltage back to the reference level of 0.92pu. Furthermore, voltage unbalance was studied and analyzed in a three phase system. Among the objectives of the proposed type of controller is to resolve also the problem of voltage unbalance. When the voltage at phase-A is changed, while that at phases B and C are kept in normal conditions, the tap controller dedicated for phase-A changes the tap position from 3 to 2 to compensate the voltage change and to return it back to its desirable reference level. It has also shown that the tap positions for the controllers at phases B and C have not changed.

The proposed voltage regulation system provides fast, accurate and real-time control in case the power quality is violated. Nevertheless, the power quality problems may exceed the regulated limits in this research. For example, lightning, earth fault, voltage sags and others are beyond the objectives of this research. Such violations have different protective devices and are tackled by several separate researches.

In addition to power quality, the energy saving in the system has been analyzed. The energy saving can be divided into two parts; one due to the proposed voltage regulation method and the other due to the proposed OLTC design using SSR instead of mechanical relays.

The results show that in the case of voltage regulation, the energy saved during one day for the considered case study is around 5% of the daily consumed energy. In addition, it was proved that using SSR for the power switching between taps in the controller compared to using mechanical relays provides an energy saving around 3% for only one example of a change in the tap position from 0 to 4.

The capital cost, maintenance cost, operation cost, and environment are affected positively by this energy saving. Considering that the cost of energy as per KAHRAMAA is 0.08 QAR for each consumed kWh. Hence, for this study case of the residential compound, for the same load profile, the equivalent saving in cost of consumption on the user side is more than 1,002QAR/month.

As per [35], the electricity generation in Qatar in 2012 is 32.7 billion kilowatt-hours, while the electricity consumption is 30.5 billion kilowatt-hours. The residential consumption in Qatar is approximately 33% of the total consumption. Hence, considering the same required consumption and applying the energy efficiency only on the residential areas, the required electricity generation is 32.15 billion kilowatt-hours with an energy saving of about 554 million kilowatt-hours.

At the last, a comparison between the radial and tree networks is studied using the proposed system. The results show that the tree system is more sensitive to the insertion of the DG and the controller has limited actions in such configuration. The reason is the influence of the DG on the nearby villas especially those connected to the same feeder. Nevertheless, the insertion of DG in the radial network doesn’t have the same influence on voltage fluctuations, and the voltages across other terminals are regulated by the tap changer. As a result, the insertion of DG in the tree network has to have stringent regulations in order to maintain the voltage in the acceptable range.

In the next chapter, the whole conclusion of the thesis is presented and the future works are listed ensuring that this thesis gives an outset to several studies at distribution level within the smart grids.

Chapter 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

This thesis proposes a simple and efficient voltage regulation technique at the LV electric power distribution network. The development of smart grids and Advanced Metering Infrastructure allows considering smart meters in reading the measurements of voltages, currents and other parameters which can be used for real-time analysis that was not well tackled in the literature for the distribution side of the power system.

The proposed voltage regulation method assumes that the voltage regulation at the consumer level is the same at the transformer level considering that, in short distance networks (as in low-voltage side), the voltage drop variation in the line is negligible. In other words, the percentage of voltage variation at the transformer side is considered the same as that on the consumer side. The proposed control algorithm checks first the violations of the maximum voltage within the standard limits to ensure that power quality is always respected and satisfied. Then, if the maximum voltage is not violated, the minimum voltage is regulated to an arbitrary reference voltage of 0.92pu. This voltage regulation is achieved by changing the tap position of OLTC connected on the primary winding side (MV) of the transformer.

The designed OLTC uses SSR instead of the conventional mechanical relays. Even though there is small power loss in the power semiconductor devices, unlike mechanical relays, SSRs provide faster response to the change in voltage without voltage or current spikes and sparks because they can switch at zero current, and therefore can change more than one tap each step. The proposed three-phase configuration of the proposed OLTC allows each phase tap changer to operate independently which can effectively regulate the voltages in case of voltage unbalance.

After validating the proposed method on a single phase case, a residential compound is modeled. The compound is a mock-up of a similar residential compound in Qatar and the gulf countries. The load profile of the compound is modeled for 24 hours taking into account the required consumption of each load terminal. The OLTC in the transformer considered for the residential compound case study has 1% voltage step per tap with arbitrary tap control time of 5min (adjustable).

It was proved that during normal operating conditions, the voltage profiles of the system are following the load profiles where the minimum voltage on the system is regulated at the minimum reference level. In this case, the tap position can change more than one tap per step giving a fast response to the change in load.

In order to offer more confidence in the proposed system, several cases where power quality is violated were tested. It is that the system is reacting to the over-voltage and under-voltage immediately as soon as the power quality is violated. Moreover, it is demonstrated that in the case of voltage unbalance, the OLTC is changing the tap of only one phase keeping the other phases in their current tap positions.

A distributed generation was also inserted at one of the villas for both the tree and radial configurations. The system was studied and it was shown that the distributed generation has more influence on the tree configuration rather than on the radial one.

Finally, the energy efficiency has been analyzed. The saving in energy is achieved by the proposed voltage regulation algorithm and also by the choice of the SSR-based OLTC. The proposed technique provides an approximate daily energy efficiency of 5% for the case studied. To illustrate and estimate the total energy saving that the proposed method can achieve for Qatar power system (if only the residential electricity consumptions are considered), the equivalent annual energy saving is approximately 554 million kilowatt-hours which equivalent to about 139 million QAR

As a conclusion, the proposed voltage regulation technique is able to regulate the voltage for any residential area where the power factor is not low as in industrial areas. The proposed simple voltage regulation technique is practical due to the use of smart meter readings where the voltage profiles follow the load fluctuations due to the ability of the OLTC to change more than one tap per step. Even in cases where the quality of power is violated, the proposed technique can react very fast to such scenarios and provide the required compensation of the voltage. Nevertheless, the severe situations of power quality like earth fault, short circuit, lightning, etc. cannot be resolved by such type of tap changer and the specific protective devices are still required to be used in the power network. The method works in scenarios where distributed generation is connected to the network, however, regulations must be set based on the type of configuration where the radial network is preferable. The proposed voltage regulations technique provides sufficient amount of energy saving, consequently it reduces the cost of the power system generation and the bill amounts on utilities and customers

6.2 **Future Work**

The future works which can be extended from this thesis can be listed as follows:

- Such type of OLTCs can be commercialized where the voltage regulation at distribution level is no more dependent on forecasted loads rather on real loads.
- In Qatar, KAHRAMAA has started to implement smart meters in residential areas in 2014. Hence, the proposed method can be applied on real areas after obtaining the real-time load profiles from KAHRAMAA.
- The development of high power Silicon Carbide switches can help reduce the power losses in the OLTCs. Hence, the proposed OLTC design can be replaced by those using high power Silicon Carbide switches.
- Cost Analysis can be studied including the benefits of DG for the residential areas and the amount of energy saved.
- A typical area where distributed generations from several sources are implemented can also be studied

References

[1] G. Fusco and M. Russo, Adaptive Voltage Control in Power Systems Modelling, Design and Applications, Berlin: Springers, Advances in Industrial Control, 2007.

[2] T. Hashim, A. Mohamed and H. Shareef, "A review on voltage control methods for active distribution networks," *Electrical Review,* vol. 88, no. 6, pp. 304-312, 2012.

[3] F. A. Viawan, Voltage Control and Voltage Stability of Power Distribution Systems in the Presence of Distributed Generation, Göteborg: Chalmers Univeristy of Technology, 2008.

[4] W. L. Xiao-Hu Yu and Taufik, *Design and Implementation of a neural network controller for real-time adaptive voltage regulation,* California: California Polytecnic State University, 2011.

[5] J. Akhtar and S. P.M, "Power Qaulity Improvement using Fuzzy Logic Control Static Var Compensator in Power System Network," *IOSRJEN,* vol. 2, no. 8, pp. 01-08, 2012.

[6] F. T. Dai, "Voltage Control of Distribution Networks with Distributed Generation," in *International Conference on Developments in Power Systems Protection*, Birmingham, 2012.

[7] C. Gao and M. A. Redferb, "A review of Voltage Control techniques of networks

with Distributed Generation using On-Load Tap Changer transformers," in *UPEC*, Cardiff, 2010.

[8] T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki and T. Funabashi, "Optimal Distribution Voltage Control and Coordination with Distributed Generation," *Power Delivery, IEEE transactions*, vol. 123, no. 2, pp. 1236, 1242, April 2008.

[9] C. Gao and M. A. Redfren, "Automatic Compensation Voltage Control Strategy for On-Load Tap Changer Transformers with Distributed Generations," in *The International Conference on Advanced Power System Automation and Protection*, Beijing, 2011.

[10] R. A. Shalwala and J. A. M. Blejis, "Voltage Control Scheme using Fuzzy Logic for Residential Area Networks with PV Generators in Saudia Arabia," in *Innovative Smart Grid Technologies*, Hilton Anaheim, CA, 2011.

[11] D. R. Rallage, A. Agalgaonkar and K. Muttaqi, "Online Voltage Control in Distribuion Systems with Multiple Voltage Regulating Devices," University of Wollongong, New south wales, 2014.

[12] D. S. Romero, Voltage Regulation in Distribution Systems - Tap Changer and Wind Power, Lund: Faculty of Engineering, Lund University, 2010.

[13] M. A. Mahmud, M. J. Hossain, H. R. Pota and A. B. M. Nasiruzzaman, "Voltage Control of Distribution Networks with Distributed Generation using Reactive Power Compensation," in *37th Annual Conference on IEEE Industrial Electronics Society*,

Mellbourne, 2011.

[14] F. A. Viawan and D. Karlsson, "Coordinated Voltage and Reactive Power Control in the Presence of Distributed Generation," *Power and Energy Society General Meeting,* pp. 1,6 20-24, July 2008.

[15] J. Faiz and B. Siahkolah, "Differences between conventional and electronic tap-changers and modifications of controller," *IEEE transactions on Power Delivery,* vol. 21, no. 3, pp. 1342-1349, 2006.

[16] Wikipedia, "Tap Changer," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Tap_changer. [Accessed 26 February 2016].

[17] D. Nadeem, H. ur-Rashid and M. Saeed, "Fully Electronic Tap Changer Control," in *2013 IEEE Conference on Clean Energy and Technology (CEAT)*, Langkawi, 2013.

[18] J. Faiz and B. Siahkolah, Electronic Tap-changer for Distribution Transformers, Berlin: Springer, 2011.

[19] E. Martinez, I. Fernandez and J. M. Canales, "Thyristor based solid state tap changer for distribution transformers," in *2013 IEEE 11th International Workshop of Electronics, Control , Measurements, Signals and their applications on Mechatronics*, Toulouse, 2013.

[20] G. Ram, C. Mouli, P. Bauer, T. Wijekoon, A. Panosyan and E.-M. Barthlein, "Design of a Power-Electronic-Assisted OLTC for Grid Voltage Regulation," *IEEE*

Transactions in Power Delivery, vol. 30, no. 3, pp. 1086-1095, 2015.

[21] D. Monroy-Berjillos, A. Gomez-Exposito and A. Bachiller-Soler, "A Lab Setup Illustrating Thyristor-Assitsed Under-Load Tap Changers," *IEEE Transactions on Power Delivery,* vol. 25, no. 3, pp. 1203-1210, 2010.

[22] J. Faiz and B. Siahkolah, "Solid-state tap-changer of transformers: Design, control and implementation," *Electrical Power and Energy Systems, ELSEVIER,* vol. 33, no. 1, pp. 210-218, 2011.

[23] R. Fourie and H. d. T. Mouton, "Development of a MV IGBT based Solid-State Tap Changer," in *IEEE AFRICON,* Nairobi, Kenya, 2009.

[24] H. Jiang, R. Shuttleworth, B. A. T. A. Zahawi, X. Tian and A. Power, "Fast Response GTO Assisted Novel Tap Changer," *IEEE Transactions on Power Delivery,* vol. 16, no. 1, pp. 111-115, 2001.

[25] G. Ram, V. Prasanth, P. Bauer and E.-M. Barthlein, "Comparative Analysis of On-Load Tap Changing (OLTC) transformer topologies," in *16th International Power Electronics and Motion Control Conference and Exposition*, Antalya, 2014.

[26] B. S. Jawad Faiz, "New Solid-State Onload Tap-Changers Topology for Distribution Transformers," *IEEE Transactions on Power Delivery,* vol. 18, no. 1, pp. 136-141, 2003.

[27] O. Demirci, D. A. Torrey, R. C. Degeneff, F. K. Schaeffer and R. H. Frazer, "A New

Approach to Solid-State On Load Tap Changing Transformers," *IEEE Transactions on Power Delivery,* vol. 13, no. 3, pp. 952-961, 1998.

[28] D. Monroy, A. Gomez-Exposito and E. Romero-Ramos, "Improving the Voltage Regulation of Secondary Feeders by Applying Solid-State Tap Changers to MV/LV Transformers," in *9th International Conference in Electrical Power Quality and Utilisation*, Barcelona, 2007.

[29] Zhao-Yulin, Dong-Shoutian, Li-Jiahu, Yao-Xin, Zheng-Na and Liu-Xueli, "Study on Non Contract Automatic on load voltage regulating distributing transformer based on solid state relay," in *5th International Conference in Power Electronics and Motion Control, IPEMC,* Shanghai, 2006.

[30] B. A. Robbins, H. Zhu and A. D. Dominguez-Garcia, "Optimal Tap Setting of Voltage Regulation Transformers in Unbalanced Distribution Systems," *IEEE Transactions on Power Delivery,* vol. 31, no. 1, pp. 256-267, 2016.

[31] IEC, *IEC standard voltages, IEC 60038,* Geneva: International Electrotechnical Commission, 2002.

[32] J. H. Jonathan Dodge, "IGBT Tutorial," Advanced Power Technology Application Note, 2002.

[33] V. Kanas, Condition Assessment of the Insulation of On-Load Tap Changers by Partial Discharge Measurements, Deft: Deft University of Technology, 2013.

[34] K. E. Department, Regulations for the Installation of Electrical Wiring, Electrical Equipment and Air Conditioning Equipment, State of Qatar: KAHRAMAA, December 2010.

[35] EIA, "International energy data and analysis, Qatar," U.S. Energy Information Administration, International, 2015.

[36] B. S. Jawad Faiz, "New Solid-State Onload Tap-Changers Topology for Distribution Transformers," *IEEE Transactions on Power Delivery,* vol. 18, no. 1, pp. 136-141, 2003.

[37] O. Demirci, D. A. Torrey, R. C. Degeneff, F. K. Schaeffer and R. H. Frazer, "A New Approach to Solid-State On Load Tap Changing Transformers," *IEEE Transactions on Power Delivery,* vol. 13, no. 3, pp. 952-961, 1998.

[38] T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki and T. Funabashi, "Optimal Distribution Voltage Control and Coordination with Distributed Generation," *IEEE transactions on Power Delivery,* vol. 123, no. 2, pp. 1236, 1242, April 2008.

[39] C. Gao and M. A. Redfren, "Automatic Compensation Voltage Control Strategy for On-Load Tap Changer Transformers with Distributed Generations," in *The International Conference on Advanced Power System Automation and Protection*, Beijing, 2011.

[40] D. S. Romero, Voltage Regulation in Distribution Systems - Tap Changer and Wind

Power, Lund: Faculty of Engineering, Lund University, 2010.

[41] F. A. Viawan, Voltage Control and Voltage Stability of Power Distribution Systems in the Presence of Distributed Generation, Göteborg: Chalmers Univeristy of Technology, 2008.

[42] F. T. Dai, "Voltage Control of Distribution Networks with Distributed Generation," in *International Conference on Developments in Power Systems Protection*, Birmingham, 2012.

[43] H. Jiang, R. Shuttleworth, B. A. T. A. Zahawi, X. Tian and A. Power, "Fast Response GTO Assisted Novel Tap Changer," *IEEE Transactions on Power Delivery*, vol. 16, no. 1, pp. 111-115, 2001.

[44] J. Faiz and B. Siahkolah, "Differences between conventional and electronic tap-changers and modifications of controller," *IEEE transactions on Power Delivery,* vol. 21, no. 3, pp. 1342-1349, 2006.

[45] J. Faiz and B. Siahkolah, "Solid-state tap-changer of transformers: Design, control and implementation," *Electrical Power and Energy Systems, ELSEVIER*, vol. 33, no. 1, pp. 210-218, 2011.

[46] R. A. Shalwala and J. A. M. Blejis, "Voltage Control Scheme using Fuzzy Logic for Residential Area Networks with PV Generators in Saudia Arabia," in *Innovative Smart Grid Technologies*, Hilton Anaheim, CA, 2011.

[47] R. Fourie and H. d. T. Mouton, "Development of a MV IGBT based Solid-State Tap Changer," in *IEEE AFRICON*, Nairobi, 2009.

[48] Wikipedia, "Tap Changer," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Tap_changer. [Accessed 26 February 2016].

[49] Zhao-Yulin, Dong-Shoutian, Li-Jiahu, Yao-Xin, Zheng-Na and Liu-Xueli, "Study on Non Contract Automatic on load voltage regulating distributing transformer based on solid state relay," in *5th International Conference in Power Electronics and Motion Control, IPEMC*, Shanghai, 2006.

[50] G. Fusco and M. Russo, Adaptive Voltage Control in Power Systems Modelling, Design and Applications, Berlin: Springers, Advances in Industrial Control, 2007.

[51] C. Gao and M. A. Redferb, "A review of Voltage Control techniques of networks with Distributed Generation using On-Load Tap Changer transformers," in *Universities Power Engineering Conference, UPEC*, Cardiff, 2010.

Appendix A – Matlab Scripts

The script herein determines the new tap position from the measured input voltages and the current tap position based on the tap selection equations described in chapter 3. Each step is defined inside the script by the green lines which are only for clarification.

```
function [y] = fcn(V, y0)
% Definition
% y is a vector of 1 and 0s where the 1 is the position of the tap
% y0 is the initial tap position
% V is the set of voltages of all customers

% Determination of the number of customers
n=length(V);

% Setting the total number of taps
p=21;

% Initiating the vector of per unit voltages
Vpu=zeros(n,1);

% Initiating the tap position vector
y=zeros(p,1);

% Initiating the primary nominal voltage
V1n=11000;

% Determining the voltage deviation of each tap
DVTap=2200/(V1n*(p-1));

% Calculating the per unit values of each voltage
for i=1:n
    Vpu(i)=V(i)*sqrt(3)/415;
end

% Determining the minimum voltage across the whole network
Vmin=Vpu(1);
for i=2:n
    if Vpu(i)<Vmin
        Vmin=Vpu(i);
    end
end

% Determining the maximum voltage across the whole network
Vmax=Vpu(1);
for i=2:n
    if Vpu(i)>Vmax
        Vmax=Vpu(i);
```

```
    end
end

% Calculating the difference between minimum and maximum voltages
DVu=Vmax-Vmin;

% Setting out the reference value (Vref) and regulated voltage (VV)
if Vmax>1.1 && DVu>0.2
    Vref=1.1;
    VV=Vmax;
else
    Vref=0.92;
    VV=Vmin;
end

% Determining the previous tap position
m=0;
s=0;
for i=1:p
    if y0(i)==1
        Nn=i;
        m=1;
        s=i;
    else
        Nn=11*(1-m)+s;
    end
end
Nn=11-Nn;

% Calculating the tap position
DV2pu=Vref-VV;
DNi=-DV2pu/((1+DV2pu)*DVTap);
N=round(DNi)+Nn;

% Checking if the required tap positon is within the tap controller
limits
if abs(N)<11
    No=abs(N);
else
    No=abs(Nn);
end

% Finding the new tap position
S=sign(N);
if S<0
    for i=12:p
        k=i-11;
        if k==No
            y(11)=0;
            y(i)=1;
        end
    end
end
```

```
if S>0
    for i=1:10
        if i==No
            y(11)=0;
            y(11-i)=1;
        end
    end
end
if No==0
    y(11)=1;
end
end
```

Appendix B – Load Schedule

The load schedule of each terminal of the residential compound is modelled based on the below information.

Location and number			LTG	Small power socket	W/H	W/M	Cooker Unit	A/C	LTG	Small power socket	W/H	W/M	Cooker Unit	A/C	Total Load (W)
			Quantity						100	200	2000	2000	4000	1000	
Villa	Salon	1	10	6				1	1000	1200	0	0	0	1000	3200
	Dining Room	1	4	2				1	400	400	0	0	0	1000	1800
	Corridor	2	4	2					800	800	0	0	0	0	1600
	Bedroom	3	3	3				1	900	1800	0	0	0	3000	5700
	Toilet	5	2		1				1000	0	10000	0	0	0	11000
	Maid Room	1	2	2				1	200	400	0	0	0	1000	1600
	Maid Toilet	1	1						100	0	0	0	0	0	100
	Kitchen	1	4	5		1	1		400	1000	0	2000	4000	0	7400
	Balcony	3	2	1					600	600	0	0	0	0	1200
	Backyard	1	2						200	0	0	0	0	0	200
	Load (W)								5600	6200	10000	2000	4000	6000	33800
	Total Load (kW)								33.8						
Amenity Area	Restaurant	1	10	6	1	1	2	2	1000	1200	2000	2000	8000	2000	16200
	Gym	1	6	10				2	600	2000	0	0	0	2000	4600
	Swimming Pool	1	6						600	0	0	0	0	0	600
	Toilet	4	2		2				800	0	16000	0	0	0	16800
	Jacoozi	2	1		1				200	0	4000	0	0	0	4200
	Sauna	2	1		1				200	0	4000	0	0	0	4200
	Load (W)								3400	3200	26000	2000	8000	4000	46600
	Total Load (kW)								46.6						
Miscalleneous	Play Ground # 1	1	10						1000						1000
	Play Ground # 2	1	10						1000						1000
	Play Ground # 3	1	10						1000						1000
	Mosque	1	10	5				2	1000	1000	0	0	0	2000	4000
	Street Lighting	1	30						3000						3000
	Guard Room	1	2	2				1	200	400	0	0	0	1000	1600
Pumps	Irrigation Pump Room	1		20000											20000
	Drianage Pump Room	1		20000											20000
	Sewage Pump Room	1		50000											50000
Total Area Load (kW)															*858*

Appendix C – Cable Data

The data of the cable for each plot in the residential compound model is given in the below tables

Tree Network

Feeder #	*Lengths*			*Cable*				
	EX 1	EX 2	Length (m)	Size	R(Ohm/km)	L (H/Km)	R (Ohm)	L (Ohm)
1	SS	Villa # 15	72	4Cx300	0.0801	2.26E-04	0.00577	1.63E-05
	Villa # 15	Villa # 14	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	Villa # 14	Villa # 13	8	4Cx300	0.0801	2.26E-04	0.00064	1.81E-06
	Villa # 13	Villa # 12	17	4Cx300	0.0801	2.26E-04	0.00136	3.84E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06
2	SS	Villa # 20	65	4Cx300	0.0801	2.26E-04	0.00521	1.47E-05
	Villa # 20	Villa # 21	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	Villa # 21	Villa # 1	9	4Cx300	0.0801	2.26E-04	0.00072	2.03E-06
	Villa # 1	Villa # 2	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06
3	SS	Villa # 16	78	4Cx300	0.0801	2.26E-04	0.00625	1.76E-05
	Villa # 16	Villa # 17	17	4Cx300	0.0801	2.26E-04	0.00136	3.84E-06
	Villa # 17	Villa # 10	17	4Cx300	0.0801	2.26E-04	0.00136	3.84E-06
	Villa # 10	Villa # 11	17	4Cx300	0.0801	2.26E-04	0.00136	3.84E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06
4	SS	IRR Pump	32	4Cx25	0.9270	2.61E-04	0.02966	8.35E-06
5	SS	Pump	45	4Cx70	0.3420	2.39E-04	0.01539	1.07E-05
6	SS	DR Pump	50	4Cx25	0.9270	2.61E-04	0.04635	1.31E-05
7	Amenity	OD. LTG	10	4Cx300	0.0801	2.26E-04	0.00080	2.26E-06
	OD. LTG	Mosque	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06
8	Villa # 19	Villa # 18	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	Villa # 18	Villa # 4	16	4Cx300	0.0801	2.26E-04	0.00128	3.62E-06
	Villa # 4	Villa # 3	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06
9	SS	Villa # 7	80	4Cx300	0.0801	2.26E-04	0.00641	1.81E-05
	Villa # 7	Villa # 6	5	4Cx300	0.0801	2.26E-04	0.00040	1.13E-06
	Villa # 6	Villa # 5	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	Villa # 7	Villa # 8	16	4Cx300	0.0801	2.26E-04	0.00128	3.62E-06
	Villa # 8	Villa # 9	18	4Cx300	0.0801	2.26E-04	0.00144	4.07E-06
	T-joint	KWH	10	4Cx70	0.3420	2.39E-04	0.00342	2.39E-06

Radial Network

Transformer to SS edge (m)	*Distance from SS to each kWH Plot (m)*	*Cable Size*	*CCC (A)*	*VD% TX to KWH*	*Z (Ohm/km)*		*Z (Ohm)*	
					R	*L*	*R*	*L*
Villa # 1	125	4C70	123	0.95	0.3420	2.39E-04	0.0428	2.984E-05
Villa # 2	110	4C70	123	0.84	0.3420	2.39E-04	0.0376	2.626E-05
Villa # 3	116	4C70	123	0.88	0.3420	2.39E-04	0.0397	2.769E-05
Villa # 4	131	4C70	123	1.00	0.3420	2.39E-04	0.0448	3.127E-05
Villa # 5	131	4C70	123	1.00	0.3420	2.39E-04	0.0448	3.127E-05
Villa # 6	116	4C70	123	0.88	0.3420	2.39E-04	0.0397	2.769E-05
Villa # 7	101	4C70	123	0.77	0.3420	2.39E-04	0.0345	2.411E-05
Villa # 8	116	4C70	123	0.88	0.3420	2.39E-04	0.0397	2.769E-05
Villa # 9	131	4C70	123	1.00	0.3420	2.39E-04	0.0448	3.127E-05
Villa # 10	132	4C70	123	1.00	0.3420	2.39E-04	0.0451	3.151E-05
Villa # 11	122	4C70	123	0.93	0.3420	2.39E-04	0.0417	2.912E-05
Villa # 12	116	4C70	123	0.88	0.3420	2.39E-04	0.0397	2.769E-05
Villa # 13	131	4C70	123	1.00	0.3420	2.39E-04	0.0448	3.127E-05
Villa # 14	126	4C70	123	0.96	0.3420	2.39E-04	0.0431	3.008E-05
Villa # 15	111	4C70	123	0.84	0.3420	2.39E-04	0.0380	2.650E-05
Villa # 16	117	4C70	123	0.89	0.3420	2.39E-04	0.0400	2.793E-05
Villa # 17	132	4C70	123	1.00	0.3420	2.39E-04	0.0451	3.151E-05
Villa # 18	126	4C70	123	0.96	0.3420	2.39E-04	0.0431	3.008E-05
Villa # 19	111	4C70	123	0.84	0.3420	2.39E-04	0.0380	2.650E-05
Villa # 20	105	4C70	123	0.80	0.3420	2.39E-04	0.0359	2.506E-05
Villa # 21	120	4C70	123	0.91	0.3420	2.39E-04	0.0410	2.864E-05
Dr. Pump	50	4C25	73	0.59	0.9270	2.61E-04	0.0464	1.305E-05
Irr. Pump	32	4C25	73	0.38	0.9270	2.61E-04	0.0297	8.352E-06
Sew Pump	45	4C70	123	0.51	0.3420	2.39E-04	0.0154	1.074E-05
Amenity	60	4C70	123	0.63	0.3420	2.39E-04	0.0205	1.432E-05
DB (Mosque + Guard Room)	30	4C16	65	0.15	1.4660	2.55E-04	0.0440	7.638E-06
DB (Lighting)	70	4C16	65	0.36	1.4660	2.55E-04	0.1026	1.782E-05

Appendix D – Residential Compound Load Model

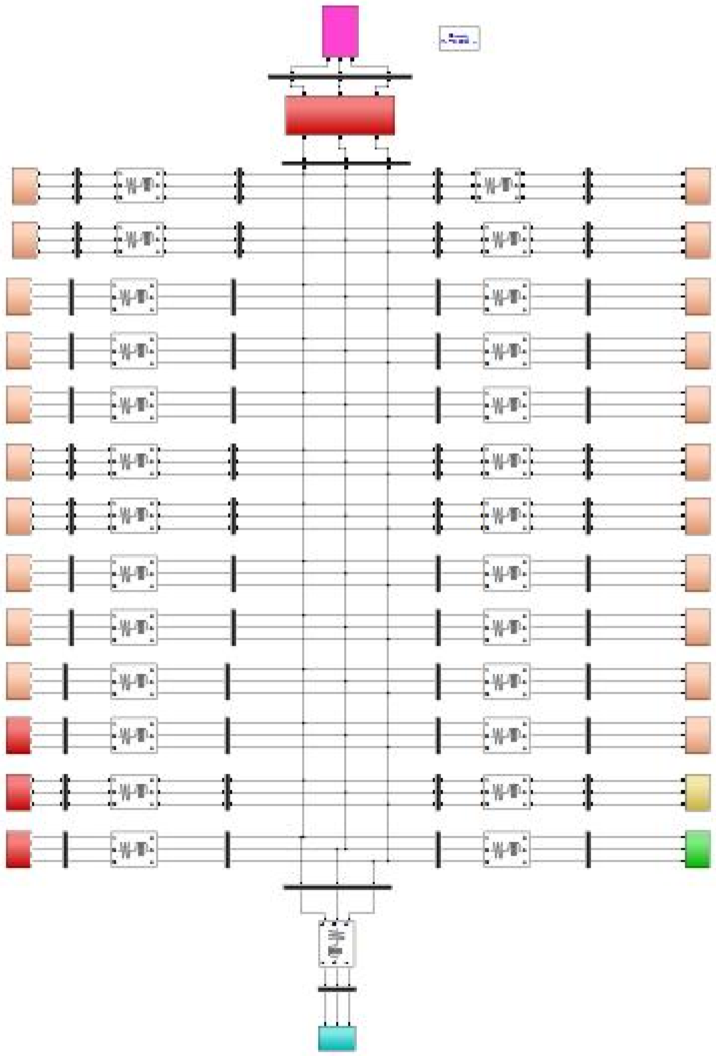
The load model of each plot is given in the below table along with the total load of the residential compound

Plot / Node	Time (hr)																							
	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Villa # 1	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.25	0.50
Villa # 3	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.25	0.25	0.25	0.25	0.25	1.00	1.00	1.00	0.50	0.50	0.25	0.25	0.50	0.50
Villa # 4	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.75	0.75	0.25	0.50	0.50
Villa # 5	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50
Villa # 6	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Villa # 7	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.25	0.25	0.25
Villa # 8	0.50	0.50	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 9	0.50	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 10	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.25	0.25
Villa # 11	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 12	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.25	0.50
Villa # 13	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.25	0.25	0.25	0.25	0.25	1.00	1.00	1.00	0.50	0.50	0.25	0.25	0.50	0.50
Villa # 14	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.75	0.75	0.25	0.50	0.50
Villa # 15	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50
Villa # 16	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Villa # 17	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.25	0.25	0.25
Villa # 18	0.50	0.50	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 19	0.50	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Villa # 20	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.75	0.50	0.50	0.50	0.50	0.25	0.25
Villa # 21	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.75	0.75	0.75	0.25	0.25	0.25	0.75	0.75	0.25
IRR Pump	0.10	0.10	0.10	0.10	0.10	0.75	0.75	0.75	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
SEW Pump	1.00	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DRA Pump	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Mos + GR	0.25	0.25	0.25	0.25	0.25	0.75	0.25	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50
Amenity	0.50	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00
O. Lighting	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Load (%)	38.2	29.2	27.2	27.2	25.2	27.1	32.6	39.8	47.3	49.3	47.3	49.6	41.8	39.8	54.6	69.3	69.4	65.5	53.0	55.0	51.1	47.1	47.0	47.0

Appendix E – SIMULINK Models

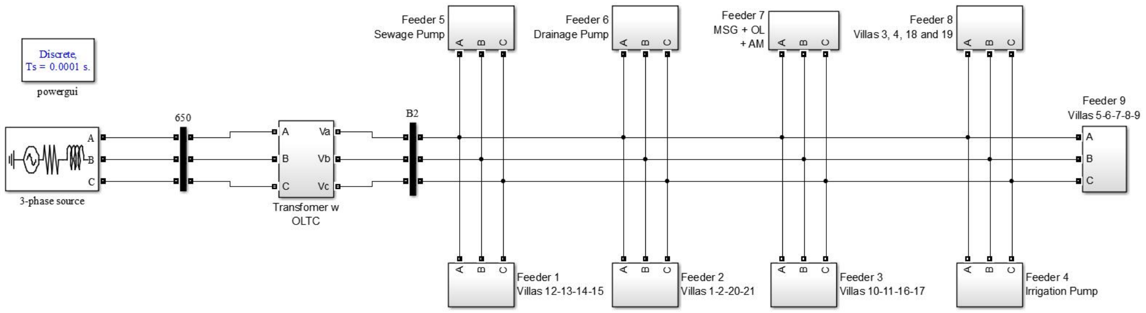
The below figures present the SIMULINK models for both radial and tree network

Radial Network

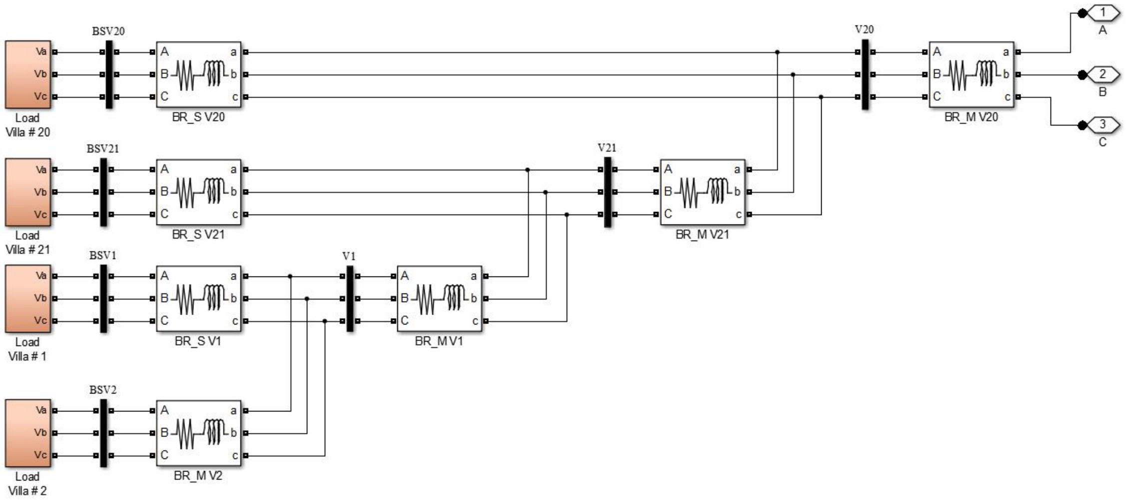


Each color represents the same plot as that shown in chapter # 4.

Tree Model



Each one the feeders (subsystems) is branched as follows:



Each sub-system of the load is modelled as shown the example of villa # 21 below:

Villa 21 Load Model