ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

İsmail GÜVEN

MODELING AND COMPARISON OF CONVENTIONAL AND ACTIVE STEP VOLTAGE REGULATORS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS
ENGINEERING

ADANA-2019

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MODELING AND COMPARISON OF CONVENTIONAL AND ACTIVE STEP VOLTAGE REGULATORS

İsmail GÜVEN

MSc THESIS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of the degree of the Master of Science by the board of jury on 31/07/2019.

…………………………	………………………..	…………………….………..….
Asst. Prof. Dr. Adnan TAN SUPERVISOR	Assoc. Prof. Dr. Ahmet TEKE MEMBER	Asst. Prof. Dr. Murat Mustafa SAVRUN MEMBER

This MSc Thesis is written at the Department of Electrical and Electronics Engineering of Institute of Natural and Applied Sciences of Çukurova University.

Registration Number:

Prof. Dr. Mustafa GÖK
Director
Institute of Natural and Applied Sciences

Note: The usage of the presented specific declarations, tables, figures, and photographs either in this thesis or in any other reference without citation is subject to "The law of Arts and Intellectual Products" number of 5846 of Turkish Republic.

ABSTRACT

MSc THESIS

MODELING AND COMPARISON OF CONVENTIONAL AND ACTIVE STEP VOLTAGE REGULATORS

İsmail GÜVEN

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Supervisor : Asst. Prof. Dr. Adnan TAN
Co-Supervisor : Asst. Prof. Dr. Tahsin KÖROĞLU
Year: 2019, Pages: 140
Jury : Asst. Prof. Dr. Adnan TAN
: Assoc. Prof. Dr. Ahmet TEKE
: Asst. Prof. Dr. Murat Mustafa SAVRUN

Voltage quality has become more significant term because of more dynamic network structures and the raising sensitivity of customer equipment. Voltage quality includes an extensive scale of voltage irregularities and variations in voltage magnitude or waveform. Therefore, various voltage regulation techniques are implemented in distribution systems. Step Voltage Regulator (SVR) is one of the most effective voltage regulation devices available. SVR is a transformer based regulation device that is formed from one shunt connected winding and one series connected winding. SVRs detect voltage variation in the line and inject voltage by its series winding to regulate the voltage effectively. SVRs can be divided into two types as conventional and active SVRs according to their technology. Conventional SVRs that based on mechanical tap changers is inadequate for dynamic changes in the network due to its slow operation. Active SVRs consist of power electronics technology as electronic tap changers or matrix converters to enhance the voltage regulation capability of SVRs in terms of compensation response speed. In this thesis, conventional and active SVRs are modeled for 34,5 kV distribution system in MATLAB/Simulink simulation program. Their performances are evaluated through extensive simulation case studies for the compensation of undervoltage and overvoltage problems.

Keywords: Voltage regulation, electronic tap changer, Step Voltage Regulator, Matrix Converter

ÖZ

YÜKSEK LİSANS TEZİ

GELENEKSEL VE AKTİF ADIM VOLTAJ REGÜLATÖRLERİNİN MODELLENMESİ VE KARŞILAŞTIRILMASI

İsmail GÜVEN

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
ELEKTRİK - ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Dr. Öğr. Üyesi Adnan TAN
İkinci Danışman : Dr. Öğr. Üyesi Tahsin KÖROĞLU
Yıl: 2019, Sayfa: 140
Jüri : Dr. Öğr. Üyesi Adnan TAN
: Doç. Dr. Ahmet TEKE
: Dr. Öğr. Üyesi Murat Mustafa SAVRUN

Gerilim kalitesi, daha dinamik ağ yapıları ve müşteri ekipmanlarının artan duyarlılığı nedeniyle daha önemli bir terim haline geldi. Gerilim kalitesi, geniş bir gerilim düzensizliği ölçeğini ve gerilim büyüklüğü veya dalga formundaki değişimleri içerir. Bu nedenle dağıtım sistemlerinde çeşitli voltaj regülasyon teknikleri uygulanmaktadır. Adım Voltaj Regülatörü (SVR) mevcut en etkili voltaj regülasyon tekniklerinden biridir. SVR, bir şönt bağlı sargı ve bir seri bağlı sargıdan oluşan trafo bazlı bir regülasyon cihazıdır. SVR'ler hattaki voltaj değişimini tespit eder ve voltajı etkin bir şekilde düzenlemek için seri sargısı ile voltajı hatta enjekte eder. SVR'ler, teknolojilerine göre geleneksel ve aktif SVR'ler olarak iki türe ayrılabilir. Mekanik kademe değiştiricili geleneksel SVR'ler, yavaş çalışması nedeniyle ağdaki dinamik değişimler için yetersizdir. Aktif SVR'ler, kompanzasyon tepki hızı bakımından SVR'lerin voltaj regülasyon kapasitesini artırmak için elektronik kademe değiştiricileri veya matris dönüştürücüler gibi güç elektroniği teknolojisinden oluşur. Bu tezde, geleneksel ve aktif SVR'ler 34,5 kV dağıtım sistemi için MATLAB/Simulink simülasyon programında modellenmiştir. Performansları, düşük ve yüksek gerilim güç kalitesi problemlerinin iyileştirilmesi için yapılan kapsamlı simülasyon vaka çalışmaları ile değerlendirilmiştir.

Anahtar Kelimeler: Voltaj regülasyonu, elektronik kademe değiştirici, kademeli voltaj regülatörü, Matris Dönüştürücü

EXTENDED SUMMARY

An ideal power network must supply all loads on the line at constant voltage and without interruption. However keeping the voltage constant along the line is very difficult in practice, because transformers, cables and conductors, etc. devices which the current flows through cause the voltage to drop along the line. All electrically operated devices are designed to operate at a defined voltage range, so their performances decrease, their life is shortened, even they are damaged when working with over voltage or low voltage.

Power quality basically depends on quality of voltage. Therefore, when talking about power quality, the issue that is actually interested is often voltage. The quality of the energy is often impaired by the load. Since currents drawn by loads in a power system cannot be controlled, only the voltage can be controlled and the system power quality can be improved by increasing the voltage quality.

Mainly, four techniques are used for compensating line voltage. These include reducing the series resistance and reactance of the line, reducing the load current, improving the power factor, and regulating the voltage. When these methods are examined, the investment costs of the first two methods are high and require a long installation preparation time. The third option is achieved by installing shunt capacitors in the required areas of the line, but the improvement rate of this method is around 2-3%. This ratio is insufficient to compensate many voltage quality problems. One of the most effective methods for compensating the line voltage is to use voltage regulators in the required regions of the line to adjust the line voltage in real time and continuously.

The use of voltage regulators in power distribution systems has begun in developed countries in the 1940s. It was used especially in USA because of its huge lands. In the USA, generation point was far away from the consumption points, and these consumption points were also far from each other. The introduction of many new electronic devices which were sensitive to voltage variations had increased consumer complaints. Because of these voltage quality problems consumers began to demand better quality electricity. In order to improve power distribution systems, nearly thousands of voltage regulators were placed on various region of the country.

The step voltage regulators in distribution networks are tightly dependent on the transformers tap changers due to their capability of meeting the needs for the conventional distribution systems with being secure and operating effectively for years. However, mechanical tap changers have some limitations and significant disadvantages.

In parallel with the development of solid state power electronic components, from 1985 onwards, electronic tap changers without moving mechanical parts were developed. Advantages of transformers with electronic tap-changers compared to mechanical tap-changers are better performance, smaller size, weight and lower maintenance cost.

There is an occurrence a need for more adaptable functioning in latest distribution grids due to the active variations in generation and load. Voltage regulators operating in a conventional manner cannot cope with dynamic changes on grid. In addition, the increased use of distributed generation makes the transformer voltage regulators with tap changers inadequate for voltage regulation. The basic problem of this inadequacy is the intermittent and slow operation of the tap changers.

Matrix converter is one of the most effective devices for voltage regulators. Hence, besides voltage compensation, it also improves the power factor correction and regulation of voltage sag/swell. In addition, it is much more faster than conventional voltage regulators. Matrix converters have been widely used in low-power applications, but recent research has shown that this structure can be used in high power applications.

In this thesis study, by modeling the voltage regulators with mechanical tap changer, electronic tap changer and matrix converter, the differences between each

other is examined. The advantages of matrix converter based voltage regulators in terms of speed and continuity compared to conventional voltage regulators is examined. It is also presented by modeling that the matrix converter voltage regulators eliminate some voltage quality problems besides voltage compensation, unlike conventional voltage regulators.

GENİŞLETİLMİŞ ÖZET

İdeal bir güç şebekesi hat üzerindeki tüm yükleri kesintisiz ve sabit voltajda sağlamalıdır. Bununla birlikte, hat boyunca gerilimi sabit tutmak pratikte çok zordur. Üzerinden akım geçen trafolar, kablolar ve iletkenler gibi cihazlar voltajın hat boyunca düşmesine neden olur. Elektrikle çalışan tüm cihazlar belli bir gerilim aralığında çalışacak şekilde tasarlanmıştır.

Güç kalitesi temelde voltaj kalitesine bağlıdır. Bu nedenle, elektrik kalitesi hakkında konuşurken, aslında ilgilenen konu genellikle gerilimdir. Güç terimi voltaj ve akımın çarpımı ile orantılıdır. Güç kaynağı sistemi sadece voltaj kalitesini kontrol edebilir; belirli yüklerin çekebileceği akımları kontrol edemez. Bu nedenle, güç kalitesi alanındaki standartlar, besleme geriliminin belli sınırlar dahilinde tutulması için belirlenmiştir.

Temel olarak, voltajı düzeltmek için dört yöntem vardır: Seri direnci ve reaktansı azaltmak, yük akımını azaltmak, güç faktörünü düzeltmek, voltaj regülasyonunu kullanmak. İlk iki seçenek, yüksek kurulum maliyeti ve uzun hazırlık süresi gerektirir. Üçüncü seçenek, güç faktörünü düzeltmek için hat boyunca şönt kapasitörleri kullanmaktır, ancak gerilim iyileştirme oranı % 2-3 arasındadır, bu oran da genellikle çoğu voltaj problemini düzeltmek için yeterli değildir. Kaynak gerilimini arttırarak veya azaltarak voltajı gerçek zamanlı ve sürekli olarak ayarlamak için voltaj regülatörlerinin kurulması en uygun çözümü sağlar.

Güç dağıtım sistemlerinde voltaj regülatörlerinin uygulanması, 1940'lı yıllarda, başta ABD olmak üzere gelişmiş ülkelerde, merkezlerin üretim noktalarından uzak geniş alanlara yayılmış sistemlerde uygulanmaya başlamıştır. Bununla birlikte oluşan voltaj salınımlarına duyarlı, büyük miktarda yeni elektro-elektroniklerin kullanılması tüketicilerin şikayetlerini artırdı. Tüketiciler, kaliteli güç dağıtımını talep etmeye başladı. Bu nedenle, günümüzde güç beslemesinin

kaliteli olmasını sağlamak ve tüketim noktalarına uygun gerilim ayarlamalarının yapılması amacıyla ülkede çeşitli noktalara binlerce regülatör kurulmuştur.

Geçtiğimiz yüz yılda dağıtım hatlarında kullanılan voltaj regülatörlerinin yapısı kademe değiştiricili trafolara dayanmaktadır. Voltaj regülatörlerinin geleneksel dağıtım sistemlerinin gerekliliklerini yerine getiren etkili ve güvenilir bir teknoloji olduğu kanıtlanmıştır. Fakat, mekanik kademe değiştiricilerin belirli sınırları ve dezavantajları vardır. Bunlar; geç tepki vermeleri, uzun operasyon süreleri, bakım gereklilikleri ve belirli bir çalışma ömürlerinin olmasıdır.

Güç elektroniği elemanlarındaki gelişmelere paralel olarak 1985 yılından itibaren kademe değiştiricilerde elektronik ekipmanlarda kullanılmaya başlanmıştır. İlk zamanlarda elektronik ve mekanik parçalardan oluşan hibrid kademe değiştiricileri üretilirken daha sonra sadece elektronik malzemelerden üretilen kademe değiştiricileri voltaj regülatörlerin yapısında kullanılmaya başlanmıştır. Mekanik kademe değiştiricisindeki yavaş çalışmaya sebep olan dönen mekanik aksamın yerine tristör, IGBT vb. güç elektroniği ekipmanları kullanılarak kademe değiştirme hızı nispeten arttırılmıştır.

Bununla birlikte, modern dağıtım sistemleri, yük tarafındaki ve üretimdeki dinamik değişiklikleri dikkate alan daha esnek bir operasyon gerektirir. Geleneksel bir şekilde çalışan voltaj regülatörleri bu yeni zorluklarla başa çıkamazlar. Bunun arkasındaki başlıca sebep kademe değiştiricilerinin kesintili ve yavaş çalışmasıdır.

Doğrudan AC / AC dönüşümü bu nedenle diğer tür dönüştürücülerden daha verimli ve güvenilirdir. Bu yüzden voltaj regülatörlerinin yapısında kademe değiştirici yerine matris dönüştürücü kullanılmasına dair bazı çalışmalar yapılmıştır. Matris dönüştürücülü voltaj regülatörü, giriş güç faktörünü, çıkış voltajını ve frekansını bağımsız olarak kontrol edebilir. Matris dönüştürücüler düşük güçlü uygulamalarda yaygın olarak kullanılmaktadır, ancak son araştırmalar bu yapının yüksek güçlü uygulamalarda kullanılabileceğini göstermiştir. Son yıllarda yapılan araştırmalar ve çalışmalar matris dönüştürücülerin yüksek güçlü uygulamalarda kullanılabileceğini göstermiştir. Literatürde matris dönüştürücülü voltaj regülatörlerine dair bazı yayınlar mevcuttur.

Bu tez çalışmasında, mekanik kademe değiştiricili, elektronik kademe değiştiricili ve matris dönüştürücülü voltaj regülatörleri modellenerek birbirleri arasındaki farklar incelenmiştir. Matris dönüştürücülü voltaj regülatörlerinin, geleneksel kademeli regülatörlere göre hız ve süreklilik olarak üstünlükleri incelendi. Ayrıca matris dönüştürücülü voltaj regülatörlerinin geleneksel kademeli regülatörlerden farklı olarak gerilim kompanzasyonunun yanı sıra bazı gerilim kalitesi problemlerini de giderdiği modellenerek sunulmuştur.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Asst. Prof. Dr. Adnan TAN who made this thesis possible for his esteemed guidance, encouragement, friendship and support during my studies. He has provided invaluable technical assistance and personal advice. It has been a great honor to have Asst. Prof. Dr. Adnan TAN as a supervisor.

I would like to thank to Assoc. Prof. Dr. Ahmet TEKE and Asst. Prof. Dr. Murat Mustafa SAVRUN for accepting to be the member of examining committee for my thesis.

I would like to thank my co-supervisor Asst. Prof. Dr. Tahsin KÖROĞLU for his valuable support.

I wish to express my special thanks to Asst. Prof. Dr. Mustafa İNCİ for sharing his knowledge and experience on Matrix Converters.

Finally, I wish to express my deepest gratitude to my wife Fatma Aysu GÜVEN who has been extremely supportive of me throughout this entire process and has made countless sacrifices to help me get to this point. I would especially like to thank my family for their endless support, encouragement and patience.

CONTENTS **PAGE**

LIST OF TABLES

PAGE

LIST OF FIGURES **PAGE**

LIST OF SYMBOLS

e_r : per unit resistance drop
e_x : per unit reactance drop
ϕ : Power factor angle
P : Active Power
Q : Reactive Power
V_S : Source voltage
V_{SNev} : New source voltage
V_{max} : Maximum voltage
V_{min} : Minimum voltage
V_{GEN} : Generator voltage
Q_{line} : Line reactive power
Q_{load} : Load reactive power
Q_{shunt} : Shunt reactive power
R : Resistance
X : Reactance
H : Henry
ΔV : Voltage change
S1 : Switch 1
S2 : Switch 2
V_1 : Primer voltage of transformer
V_2 : Seconder voltage of transformer
I_1 : Primer current of transformer
I_2 : Seconder current of transformer
N_1 : Primary winding
N_2 : Secondary winding
F_c : Multiplication factor of an autotransformer

S : Apparent Power

a : Turn ratio of transformer

S : Source point of SVR

L : Load point of SVR

SL : Source - Load point of SVR

r : Raise position of reverse switch

l : Lower position of reverse switch

E_1 : Input voltage of SVR

E_2 : Output voltage of SVR

a_r : Raise regulation ratio of SVR

a_l : Lower regulation ratio of SVR

a_R : Regulation ratio of SVR

V_{SET} : Setting voltage value of LDC

R_{SET} : Set resistance value of LDC

V_{SET} : Setting resistance value of LDC

V_{RR} : Voltage regulating relay

V_0 : Output voltage of circuit

N_{CT} : Current transformer primary rating of LDC

N_{PT} : Potential transformer primary rating of LDC

$S_{\alpha\beta}$: Switching function of Matrix Converter

M_r : Modulation ratio of PWM

M_i : Modulation index of PWM

V_r : Reference signal of PWM

V_c : Triangular carrier signal of PWM

V_m : Measuring voltage for SVR

V_{ref} : Reference voltage for SVR

LIST OF ABBREVIATIONS

AC	:	Alternating Current
ANSI	:	American National Standards Institute
BDS	:	Bi-Directional Switch
CT	:	Current Transformer
DC	:	Direct Current
DG	:	Distributed Generation
D-STATCOM	:	Dynamic Static Synchronous Compensator
DVR	:	Dynamic Voltage Restorer
FACTS	:	Flexible AC Transmission System Controllers
FC-TCR	:	Fixed Capacitor Thyristor Controlled Reactor
HV	:	High Voltage
IEC	:	International Electrotechnical Commission
IEEE	:	The Institute of Electrical and Electronics Engineers
IGBT	:	Insulated Gate Bipolar Transistor
IGCT	:	Integrated Gate-Commutated Thyristors
LDC	:	Line Drop Compensation
LV	:	Low Voltage
LVR	:	Line Voltage Regulator
MC	:	Matrix Converter
MCT	:	Metal-Oxide Semiconductor-Controlled Thyristor
MOSFET	:	Metal-Oxide Semiconductor Field-Effect Transistor
MV	:	Medium Voltage
OLTC	:	On Load Tap Changer
PET	:	Power Electronic Transformer
PWM	:	Pulse Width Modulation
RMS	:	Root Mean Square

S-PWM	:	Sinusoidal Pulse Width Modulation
SPMC	:	Single Phase Matrix Converter
STATCOM	:	Static Synchronous Compensator
SVC	:	Static Var Compensator
SVR	:	Step Voltage Regulator
THD	:	Total Harmonic Distortion
USA	:	United States of America

1. INTRODUCTION

1.1. Background and Research Motivation

Power Quality is one of the most important concerns of distribution network companies and customers. Voltage control should be carried out in transmission and distribution systems in order to keep the voltage within the proper range. Power quality criteria needs an invariable voltage in spite of changings in load current. Consumers demand electricity without interruption and minimum disturbance. Suppliers have to guarantee electricity supply to meet consumers' necessities. General schematic of power transmission and distribution system is shown in Figure 1.1.

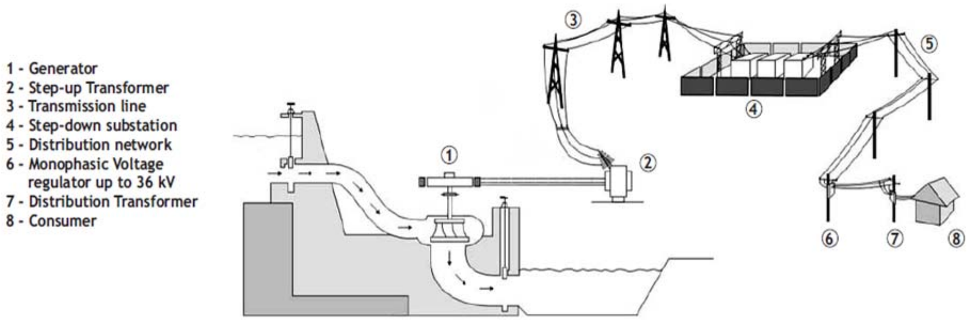


Figure 1.1. General schematic of power transmission and distribution system (Yaskawa, 2016)

Power quality includes an extensive scale of voltage irregularities and variations in voltage magnitude or waveform. Irregularities in voltage quality is caused by the operation of power grid or units connected to it. Some voltage irregularities are supply voltage variations which may occur in big load changes at the consumer side, voltage drops due to short circuits in the power network, fast voltage variations due to the variety of production.

The distribution network must provide the same electrical energy to all customers at the beginning, middle or end of the line. The voltage should be kept in the allowable range along the whole distribution line. Therefore, voltage regulation in distribution systems is an absolute necessity. Various voltage regulation methods are used to solve most voltage quality problems in the distribution grids and to provide a constant range of voltage along the line.

The conventional active voltage regulation methods used in distribution grids are as follows (Mahmud & Zahedi, 2016).

- Distribution transformer with On-Load Tap-Changers (OLTC)
- Shunt capacitors and reactors
- Series Voltage Regulators (SVRs) or Line Voltage Regulators (LVRs)

In this thesis work, SVRs are focused on particularly. SVRs are placed along the distribution line in order to maintain voltage within the desired limit. SVR is a transformer based regulation device that is formed from one shunt connected winding and one series connected winding. It detects voltage variation in the line and inject voltage by its series winding to regulate the voltage effectively. SVRs are capable of regulating the voltage in any feeder separately (Sarathy & Raghav, 2018).

SVRs can be classified basically into two types as conventional and active. Conventional SVRs are produced using a transformer with mechanical tap changing mechanism to compensate voltage. SVRs based mechanical tap changers have been used for years to maintain the voltage at the desired level in passive distribution networks. However, they have some limitations and significant disadvantages due to mechanical parts. Due to developing technologies and variable new load characteristics, distribution networks have become more dynamic and changes on the system have become to occur frequently and rapidly. Conventional SVRs based on mechanical tap changers cannot meet the need for sufficient regulation for dynamic changes in the network because of their slow operation.

Due to these limitations, mechanical tap changers are replaced with electronic tap changers in the structure of SVRs. These active SVRs with electronic tap changers perform better regulation than conventional tap changers due to their quick response to voltage changes. The power electronics elements used in the electronic tap changers are generally thyristors. Recently, IGBTs have also been used. On the other hand, electronic tap changer based SVRs are still inadequate for some power quality problems such as voltage sags/swells. Because such events happen very quickly and electronic tap changers based SVRs cannot react quickly enough to compensate for these events.

The matrix converter is a topology that improves the performance of active SVRs. Matrix converter based SVRs do not have a tap changer part. The necessary compensation voltage is injected serially through the matrix converter structure. The time delay due to the tap change operation does not occur in this type of regulator. Therefore, it is much faster than conventional regulators and electronic tap changer based SVRs. In addition, Matrix Converter based SVR provides power factor correction and compensation of voltage sag/swell. Matrix converters have been widely used in low power applications in the past, but in recent years, they have been used in high power applications.

When the literature is examined in detail, it is seen that there are many publications about conventional SVRs and electronic tap changer based SVRs. In addition, there are publications in comparison of mechanical tap changers and electronic tap changers based SVRs. However, there are a few detailed publications in which conventional SVRs are compared with Matrix Converters based SVRs in terms of their structure and performance.

1.2. Scope and Objectives of the Thesis

The work in this thesis consists of modeling and simulation of conventional and active SVRs. In the scope of this thesis, SVR is modeled with mechanical tap changer, electronic tap changer and Matrix Converter. A 34.5 kV distribution grid consists of three 40 km distribution feeders connected in parallel and provides power to an RL load of 10,5 MVA (lagging to 0.8 pf). There is a 3 Mvar capacitor bank on the load side to provide reactive power compensation. Three phase step voltage regulator is modeled with three star connected single phase 2 MVA, 19920 kV / 2988 kV transformers. The SVR is located at the 20th km of the line for each phase in order to maintain line voltage stable. SVRs are modeled with different structures as mechanic, electronic and Matrix Converter.

Simulation results of mechanical switches, electronic switches and Matrix Converters based SVRs are presented. Simulation results consist of voltage regulation performance comparison of these three types regulator topologies. The simulation results of the voltage regulation performance of conventional voltage regulators and active voltage regulators are presented with different power quality problem cases. Case studies are implemented on mechanical tap changer and thyristor tap changer based SVRs and matrix converter based SVRs individually and the results are interpreted.

1.3. Contributions of the Thesis

This thesis project provides the following original contributions to the research and application area of SVR;

- Complete simulation models are developed for the conventional and active SVRs in MATLAB/Simulink.
- A line drop control, voltage regulation control and tap changer control algorithms are developed for mechanical and thyristor controlled tap changer based SVRs.
- An advanced control algorithm, which combines the line drop control and the instantaneous line voltage magnitude detection algorithms, is proposed for the matrix converter based SVR.

- The voltage regulation performances of conventional and active SVRs are investigated with comprehensive case studies. The superior sides and the weaknesses of each type SVR are exposed in detail.

1.4. Outline of the Thesis

The content of the thesis is organized as follows:

In Chapter 2, classification, description and related standards of power quality problems, and their costs in industry are presented. Voltage compensation techniques are explained and classified.

In Chapter 3, a comprehensive literature review on SVRs is presented. SVR studies in literature are classified according to their switching based topologies.

In chapter 4, the fundamentals of SVR are presented. The mechanical and thyristor based tap changer SVRs, i.e. conventional SVRs, are explained in detail.

In Chapter 5, modeling and simulation results of conventional and Matrix Converter SVRs are presented. Single phase Matrix Converters SVRs are explained in detail. The modeling and simulation parameters are explained.

In Chapter 6, Simulation results for different case studies are given and evaluated. The simulation results are presented and discussed.

In Chapter 7, general conclusions of this thesis work are given. A summary of the obtained results in this thesis work is presented. In addition, recommendations about future works are explained.

2. POWER QUALITY AND VOLTAGE REGULATION STRATEGIES

The term power quality has been widely used in the power industry since the end of 1980s (Dugan R.C., Mcgranaghan M.F., 2003). In the early days, there were hesitations about using the term power quality, but from the second half of the 1990s onwards it became a very important concept for power distribution. There are many different opinions about the content of power quality. It is seen that the term power quality is used in different meanings in various sources. Some sources use “Quality of Power Supply” or “Voltage quality” terms, which are similar but a little different terminology (Bollen, 2001).

Power Quality can be defined as the capability of power system to transmit and distribute electricity to end users within the permitted limits. The term power quality refers to all conditions where the source voltage or load current waveform is diverged from the sinusoidal waveform for any phase. Power quality problems can be classified in two categories; voltage quality problems and current quality problems (Sannino, 2001).

Voltage quality is related to the separation of the voltage from its ideal waveform. A sine wave which has a constant frequency and magnitude refers the ideal voltage. The voltage quality term is generally used in European publications. It can also be considered as the quality of the product provided to the customers by the power supply system.

Current quality is actually a supplemental definition. It is related to the separation of the current from its ideal waveform. A sine wave which has a constant frequency and magnitude refers the ideal current. Furthermore, this sinusoidal wave must be in phase with the source voltage. Voltage and current are very relevant terms, so the separation of one of these from the ideal will make it difficult for other one to remain ideal.

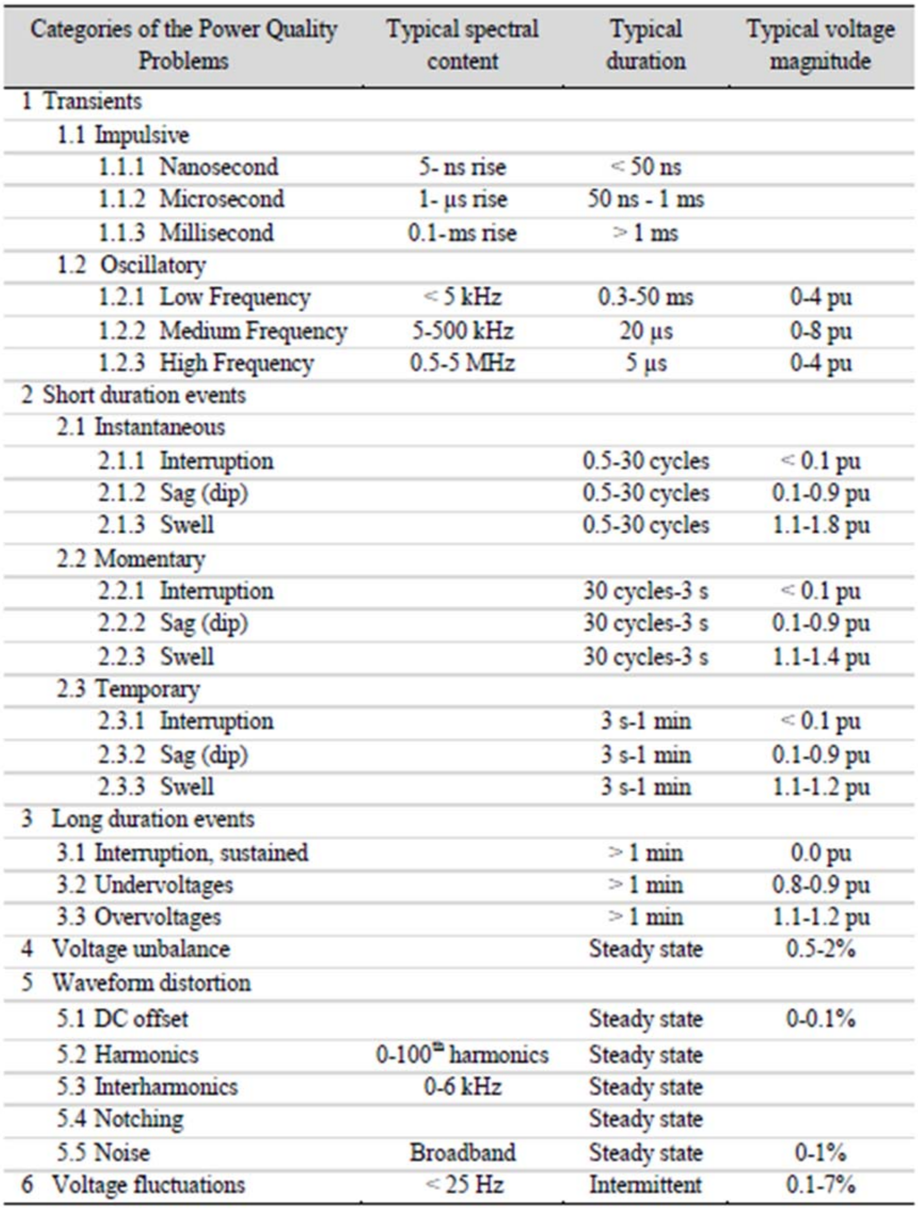
Power quality is generally referred to as a combination of voltage and current quality. The power is directly proportional to the current and voltage. When viewed from the source side only the quality of the voltage can be controlled, and the quality of the current drawn by different loads cannot be controlled. For this reason, the standards about power quality have been established to keep the supply voltage within specified ranges. (Dugan et al, 2003).

Distributed voltage's quality is affected by all users whom are connected to power grid. All voltage regulations should take account two types of cost. First type of cost related with specific consumers occurs due to equipment failures or damages. The second type is all development and improvement costs of the power grid. These costs cause raised tariffs for all users. While Interruptions influence all grid users, voltage disturbances may affect limited users.

Voltage quality has become more significant term because of the raising sensitivity of customer equipment. Likewise, raised emissions of voltage irregularities by customer appliance could be foreseen due to energy efficient equipment, which makes fast load switching. As distributed generation becomes widespread, voltage irregularities will increase.

2.1. Classification of Power Quality Problems

Power quality term is often used as voltage quality. The reason for this is that the events, which are defined as power quality problems, are disturbances that occur in the magnitude, period and waveform of the voltage signal. Many of the voltage events occur when the value of the voltage increases or decreases for a certain period of time and again returns to its normal values. Therefore, voltage events can be expressed by the duration of the event and the change in the value of the voltage. However, it is not always possible to make a single definition of voltage events. Accordingly, when the standards regarding power quality or voltage quality are examined, there are serious differences in terms and definitions used. All types power quality problems are categorized according to their duration and amplitudes in Figure 2.1.



Categories of the Power Quality Problems	Typical spectral content	Typical duration	Typical voltage magnitude
1 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5- ns rise	< 50 ns	
1.1.2 Microsecond	1- µs rise	50 ns - 1 ms	
1.1.3 Millisecond	0.1- ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low Frequency	< 5 kHz	0.3-50 ms	0-4 pu
1.2.2 Medium Frequency	5-500 kHz	20 µs	0-8 pu
1.2.3 High Frequency	0.5-5 MHz	5 µs	0-4 pu
2 Short duration events			
2.1 Instantaneous			
2.1.1 Interruption		0.5-30 cycles	< 0.1 pu
2.1.2 Sag (dip)		0.5-30 cycles	0.1-0.9 pu
2.1.3 Swell		0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles-3 s	< 0.1 pu
2.2.2 Sag (dip)		30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell		30 cycles-3 s	1.1-1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s-1 min	< 0.1 pu
2.3.2 Sag (dip)		3 s-1 min	0.1-0.9 pu
2.3.3 Swell		3 s-1 min	1.1-1.2 pu
3 Long duration events			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8-0.9 pu
3.3 Overvoltages		> 1 min	1.1-1.2 pu
4 Voltage unbalance		Steady state	0.5-2%
5 Waveform distortion			
5.1 DC offset		Steady state	0-0.1%
5.2 Harmonics	0-100th harmonics	Steady state	
5.3 Interharmonics	0-6 kHz	Steady state	
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0-1%
6 Voltage fluctuations	< 25 Hz	Intermittent	0.1-7%

Figure 2.1. Power quality problems (Electrical Power System Quality, 2012)

2.1.1. Voltage Sags (Dips)

Voltage sag is defined as the change in rms voltage value between 0.1 and 0.9 pu in the period between 0.5 cycle and 1 minute (Dugan R.C., Mcgranaghan M.F., 2003).

It is one of the most common power quality problems in distribution systems. It generally occurs during system faults, network failure and overloading. Sags are unpredictable because they are largely random events. The voltage sag is a two-dimensional distortion event. Because the level of deterioration increases depending on both the depth of the sag and the duration of the sag. These events are best explained by statistical concepts. Voltage sags may cause malfunctions of the devices according to the magnitude and duration of the voltage, and the frequency of occurrence may cause failure of these devices (Electrical Power System Quality, 2012).

"Sag" defines the short-duration voltage drop. This term is referred to as "dip" in IEC standards. The two terms can be used interchangeably.

2.1.2. Voltage Swells

Voltage swell is defined as the change in rms voltage value between 1.1 and 1.8 pu in the period between 0.5 cycle and 1 minute (Dugan R.C., Mcgranaghan M.F., 2003).

Voltage swells are not as frequent as voltage sags. The voltage swells are generally caused by system failures. They occur frequently in large production facilities. In case of phase-to-earth fault in power system, voltage swell occurs in other phases. In addition, switching of a large inductive or resistive load or switching of a group of large capacitors, switching operation in the distribution system, and various events including lightning strike events near supply networks causes swells in low voltage distribution systems and users who connected to these systems (Osman, 2013).

2.1.3. Overvoltage and Undervoltage

Overvoltage and undervoltage are long duration voltage variations refer to the change in the effective value of the voltage for more than 1 minute.

Overvoltage is defined as the increase in the effective value of the voltage between 1.1 and 1.2 pu over a period of one minute (Dugan R.C., Mcgranaghan M.F., 2003).

Overvoltages are usually caused by switching loads. The reasons of the overvoltage are; system's weakness or voltage control techniques are insufficient. switching off a large load or wrong voltage regulation operation and incorrect tap changing operation on the transformers cause overvoltages (Genç, 2015).

Undervoltage is defined as the decrease in the effective value of the voltage between 0.8 and 0.9 pu over a period of one minute (Dugan R.C., Mcgranaghan M.F., 2003).

The reason of undervoltage is the opposite of the events that caused overvoltage. De-energizing of capacitors or switching on large loads is the cause of undervoltage. Overloaded systems can also cause an undervoltage (Genç, 2015).

2.1.4. Voltage Unbalance (Imbalance)

A three-phase power system is called symmetrical or balanced if the current and voltages of all three phases have the same magnitude and a 120-degree difference between the phase angles. If no one of these conditions is present, the system is characterized as an unstable or non-symmetrical system. Voltage imbalance is expressed as a percentage (Genç, 2015).

The most important reason for the voltage imbalance in electrical power systems is that single-phase loads cannot be distributed equally in a 3-phase system. Single-phase loads produce negative symmetrical components in other phases they are not connected to, resulting in voltage imbalance. Large voltage imbalances cause overheating of the devices (OSMAN, 2013).

2.1.5. Voltage Fluctuations (Flickers)

Voltage fluctuation is the random or systematic variation of the effective value of the voltage between 0.9 and 1.1 pu. Two types of voltage fluctuations are defined in IEC 6100-2-1. These are voltage fluctuations from the distribution network and voltage fluctuations from user loads. Voltage fluctuations due to consumer loads are called flickers (Dugan R.C., Mcgranaghan M.F., 2003).

Flicker events happen as a result of a rapid decrease or increase in voltage. These sudden decreases and increases are caused by disturbances that occur during the generation, transmission and distribution of electrical energy. The most important reason for these sudden increases and decreases is that very sudden changing loads connected to the network. Arc furnaces are the most common reason of flickers (Genç, 2015).

2.1.6. Interruption

Interruptions are divided into two categories according to their duration; short-duration and sustained interruptions. Short-duration interruption is the case that the source voltage or load current decrease below 0.1 pu for less than one minute. Sustained interruptions is the decrease in the effective value of the voltage below than 0.1 pu over a period of one minute (Chattopadhyay, Mitra, & Sengupta, 2011)

There are many reasons for interruptions in electricity distribution system as malfunctions in hardware in the distribution system, faults in control systems, opening of breakers and fuses. Sustained interruptions are usually caused by errors that cause permanent damage to the system (Osman, 2013).

2.1.7. Transients

The term transient events is used for events that are unwanted but short-time. It expresses the undesired and inherent situations (Bollen, 2001). Transients are sudden changes in current and voltage in the power system. Transient events are distortions in the voltage range of several milliseconds. However, although their duration of action is short, their effects are very high and the rate of increase is very fast. Therefore, it is one of the major problems of voltage quality that needs to be taken into consideration.

Transients occur instantaneously, hence it is difficult to detect them. They last less than 1 ms and can only be recorded with recorders. They cause system crashes, loss of data, and unexpected failure of motor speed controllers. They can permanently damage the devices. There are many different causes of transients, such as lightning strikes, switching operations in power system like tap changing on transformers or capacitor bank switching, consumers' devices and etc.

Transients characteristics are mainly dependent on the resistance, inductance and capacitance values of the power grid. Peak value, rise time, drop time and oscillation frequency information are necessary for defining a transient. Transient events can be divided into two categories considering their duration of impact; impulsive and oscillatory.

2.1.8. Harmonics

Harmonics are sinusoidal voltages and currents with frequencies at the multiple of the fundamental operating frequency in the network. It is a kind of voltage waveform distortion. Harmonics are one of the most important factors causing energy quality (Dugan R.C., Mcgranaghan M.F., 2003).

Harmonic distortions can be indicated by the amplitude and angles of the harmonics at each frequency. Harmonic distortion can also be expressed as total harmonic distortion (THD) as a single magnitude. THD value is obtained by measuring the effective value of the harmonic distortion.

Harmonic distortion may occur because of non-linear equipments and loads such as thyristor, IGBT, MOSFET switching devices at high frequencies, arc furnaces, welding machines, frequency changers, rectifiers, induction heating (Genç, 2015).

2.2. Power Quality Standards

Power quality standards have been defined by various institutions. The power quality standards defined for the various problems proposed by IEEE, IEC and ANSI are shown in Table 2.1.

Table 2.1. Some power quality standards of IEEE and IEC

Phenomena	**Standards**
Classification of Power Quality	IEC 61000-4-30-2008, IEEE 1159-2009 IEC 61000-4-4-2012, IEEE 1409-2012
Voltage Sag/Swell and Interruptions	IEC 61009-1-2012, IEEE 1159-2009 IEC 61000-4-7-2002
Transients	IEC C6241-1991, IEEE 1159-2009
Harmonics	IEC 61000-3-14-2011, IEEE 519-1992
Voltage Flicker	IEC 61000-3-3-2008

2.3. Cost of Power Quality Problems

The common usage of non-linear loads and various failures in power systems have led to a significant deterioration of power quality. Besides, massive use of control and electronic devices requires a much higher level of power quality. Minor or short-term changes in power quality result in significant financial losses on these devices which are very sensitive to these changes (Zhao, Zhao, & Jia, 2004).

It is well known by the users of the distribution system as well as the power distribution system operating companies that there is a cost to provide power quality. However, in case of distortion of power quality, the cost should be well studied. Figure 2.2 shows the share of power quality problems in the United States. According to the chart, almost half of the occurring PQ problems are sags and swells (Targosz & Manson, 2007).

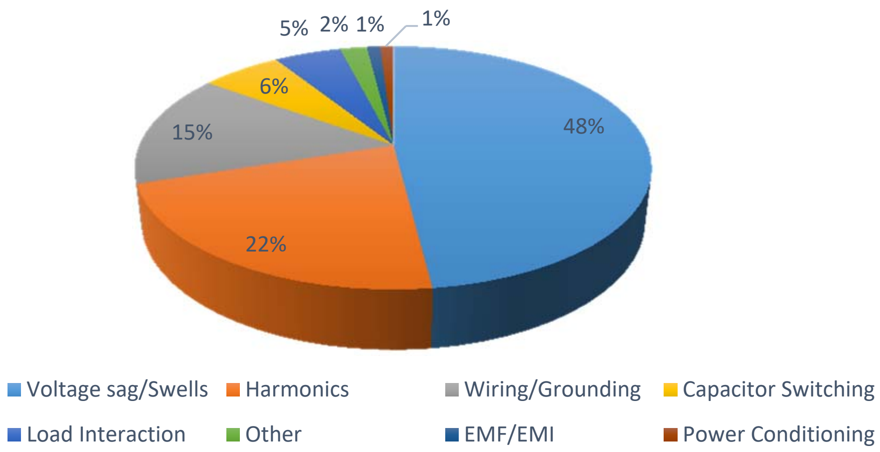


Figure 2.2. PQ problems occurred at customers side in America (Bhattacharyya, Myrzik, & Kling, 2007)

Voltage sags lead to serious losses in the industry. However, the amount of the financial losses also varies due to the load characteristic. Figure 2.3 shows the financial losses in different sectors as a result of voltage sags. As seen in the graph, the size of the cost caused by voltage sags, which constitute a significant part of power quality problems, differs considerably according to the industrial sectors. The resulting cost of the textile industry shows that the level of immunity against the voltage drops of the equipment and machinery used is sufficient. Hence, not to take precautions against power quality problems or to take very limited or low cost measures may be enough for this sector (Bhattacharyya et al., 2007).

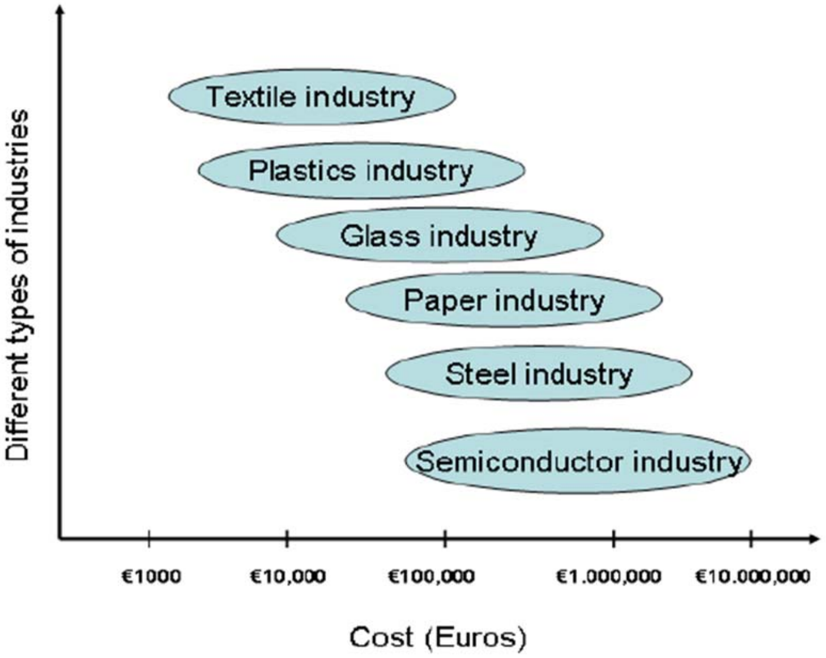


Figure 2.3 Economical losses in various sectors because of voltage sags (Bhattacharyya et al., 2007)

On the other hand, the cost of the semiconductor industry, where nanotechnology is used extensively, is very serious, and it is essential to take necessary measures to ensure that the devices and equipment used in this direction are not affected by the voltage variations in the distribution network.

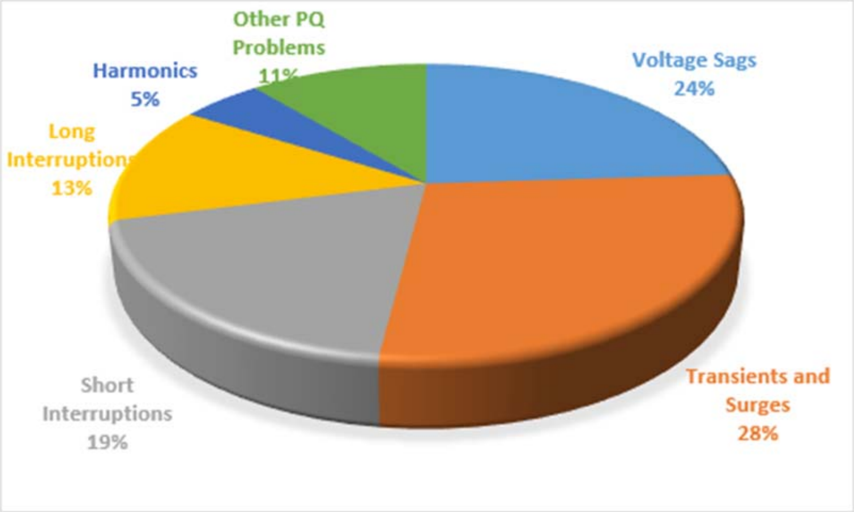


Figure 2.4. Percentage of PQ costs in EU-25 countries

According to the European Union PQ report, the cost of PQ problems in the countries of the European Union is € 150 billion per year. This cost reflects the size of the cost caused by all PQ problems. Figure 2.4 shows the percentage distribution of the cost of € 150 billion. Accordingly, the shortest-term changes in the voltage change cause the most loss in terms of cost. (Andersson & Nilsson, 2002).

2.4. Voltage Regulation Strategies

Voltage regulation is not much needed in urban areas because of short distribution lines. On the other hand, distribution and transmission lines are much longer in rural areas. Voltage drop and other voltage quality problems are likely to occur in these long lines. Therefore, voltage regulation methods must be applied to these lines in order to keep voltage within allowable range. Voltage regulation methods can be mainly classified in two groups; series and shunt (Sarathy & Raghav, 2018).

2.4.1. Series Voltage Regulation

Series regulation contains all types of compensation devices connected in series. This regulation method injects a voltage into the existing network voltage or uses a reactive element to change the line impedance. It operates as a controllable voltage source.

In order to make serial voltage regulation, one of the following three basic methods should be applied;

- Changing the voltage set point of the line
- Inserting a voltage to the line at an optimal place
- Changing the impedance of the line by adding a passive element in series

The last method is not much preferred because it is difficult to control. The use of the first two methods is more common in series voltage regulation. In the first method, OLTCs are used for changing voltage set points. OLTC is in built of the HV/ MV transformer, and according to load conditions set point is changed manually or automatically. This regulation operation is often done by voltage regulators placed at the most ideal points of the line and grid voltage is varied according to line conditions (Sarathy & Raghav, 2018).

2.4.1.1. OLTC in HV/MV Substation

OLTC is the most frequent series voltage regulation method that used in distribution networks. The function of OLTCs is to control the HV / MV voltage. OLTCs will cause a voltage drop due to transformer losses and power factor of the system (Paper & Tobias, n.d.). Calculation of the voltage drop in the transformer system is done as follows (Sarathy & Raghav, 2018);

$$\Delta V_{\mathrm{transformer}} = e_r \cos(\phi) \pm e_x \sin(\phi) \tag{2.1}$$

e_r represents per unit resistance, e_x represents per unit reactance drop, and ϕ is the power factor angle. The minimum impedance of the transformer is 12.5% for 63 - 100 MVA transformers according to the IEC 60076-5 (Sarathy & Raghav, 2018). This impedance value will cause a voltage drop loaded cases. Here, OLTCs are located inside the HV / MV transformer in order to keep the voltage constant by compensating this voltage drop. Since the MV / LV transformers do not use OLTC, they use off-load tap changers, the voltage on the MV side must be kept constant. If Line Drop Compensation (LDC) is active, the voltage set point of the line will change and a voltage level will be maintained in which the loads connected to the distribution line can operate continuously and properly. The OLTC changes the voltage set point according to the current load condition to keep the voltage of the line within the desired range. This can be seen Figure 2.5.

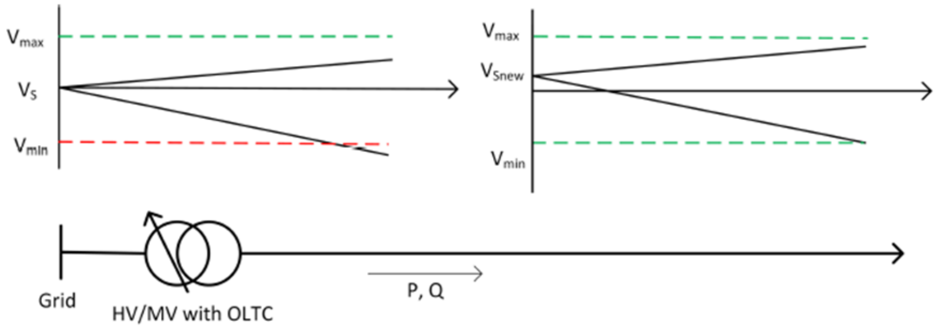


Figure 2.5. Voltage regulation with OLTC by adjusting set point
(Sarathy & Raghav, 2018)

When there are multiple feeder connection on the same line, this practice may be inadequate. Since most feeders do not have the same load and production characteristics, keeping the voltage within the desired ranges becomes very complex in transformer stations using a single OLTC (Carlen et al., 2015). To avoid exceeding the desired voltage limits, a new control algorithm is studied in (Conti & Greco, 2007). In this method, the most suitable voltage set point is obtained by using the information from the feeders and loads and the transformer values. The presence of the communication system is very necessary for these algorithms (Sarathy & Raghav, 2018).

2.4.1.2. Step (Line) Voltage Regulators

SVRs are widely used to provide particular control over the feeder in the distribution grid (Conti & Greco, 2007). Since feeders are controlled individually, other feeders are not affected unnecessarily. Unlike OLTCs, SVRs can be placed at several points where they are needed for voltage compensation. The SVR can change the voltage set point to maintain the voltage constant at the HV / MV busbar. A basic schematic of the SVR is shown in Figure 2.6. SVRs are described in chapter 4 in detail.

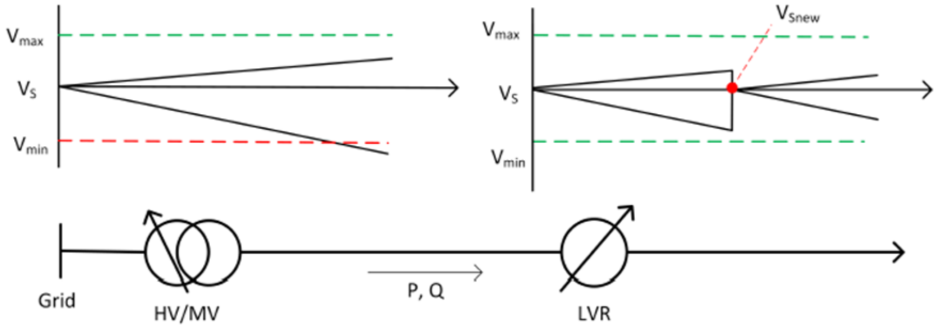


Figure 2.6. Voltage Regulation after SVR (Sarathy & Raghav, 2018)

2.4.1.3. Dynamic Voltage Regulators

The DVR is equipped with power electronics components and it converts AC-DC to DC- AC. A basic schematic of the DVR is shown in Figure 2.7.

Since power electronic equipment is used in the structure of DVRs, their controls are more effective and response times are very fast (Taher, Fard, & Kashani, 2018). DVRs are actually used to protect critical loads against all kinds of voltage disturbances in distribution networks, rather than preventing complete power outages. DVRs are also used to eliminate power quality problems. Since these converters consist of power electronic equipment, the investment costs are a little high (Sarathy & Raghav, 2018).

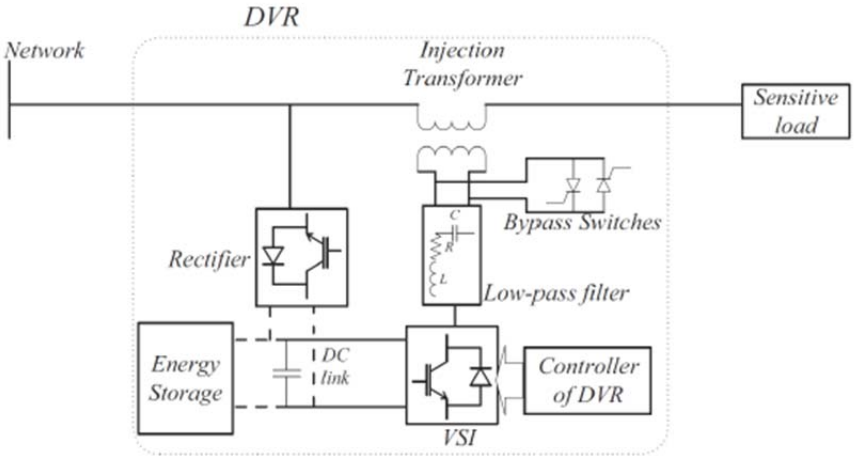


Figure 2.7. Structure of DVR (Taher et al., 2018)

2.4.2. Shunt Voltage Regulation

Shunt regulation contains all types of compensation devices connected in shunt. This regulation method injects a lagging or leading current into the network to control the voltage. It operates as a controllable current source.

In this method, a reactive element is connected to the network in parallel to provide voltage regulation. This element exports or imports reactive power from grid. The voltage increase due to a generator and the reactive power variable required to regulate it are presented in the following equation.

$$\mathrm{V_{GEN}} - \mathrm{V_S} \approx \mathrm{RP} + \mathrm{XQ} \tag{2.2}$$

where Q represents all reactive power consumed by the system components. The effective equation expressed by considering these components is below:

$$Q = Q_{line} + Q_{load} \pm Q_{shunt} \tag{2.3}$$

The reactive power consumed by the line and the load is expressed as Ql_{ine} and Q_{load}, respectively. The Shunt regulating element Q_{shunt} can both generate and consume reactive power. Therefore, it is expressed both negative and positive in the equation (Sarathy & Raghav, 2018).

2.4.2.1. Conventional Shunt Compensation Techniques

Mechanically switched shunt capacitors and inductors are some of the oldest and currently used traditional shunt elements. The shunt capacitor is used to increase the voltage and the shunt reactor is used to lower the voltage at the connection point (Stetz et al., 2014). However, these compensators are not able to perform a proper regulation when there are non-stable characteristics loads and generations in the network (Dixon, Moran, Rodriguez, & Domke, 2005).

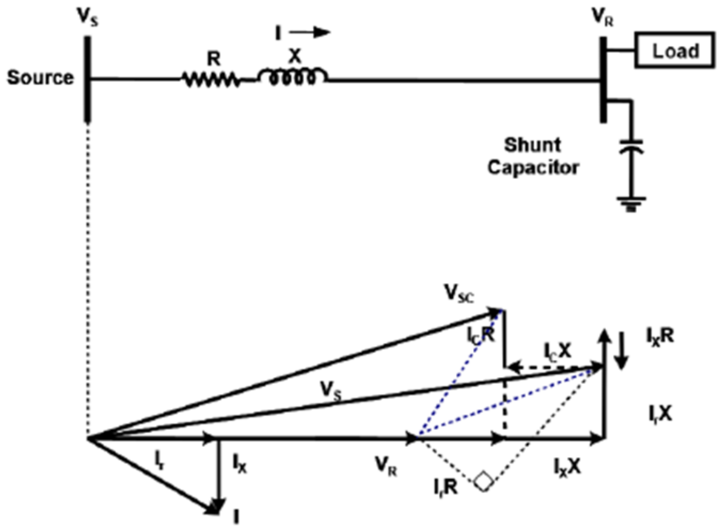


Figure 2.8. Phasor diagram of voltage after shunt regulation Compensation (Davis, Broadwater, & Hambrick, 2007)

Synchronous capacitors are synchronous machines that make reactive power injection into the network. Thus, they supply the voltage required by the network and raise the short circuit capacity (Yang Liu, Yang, Zhang, & Peng, 2014). The drawbacks of synchronous capacitors are the maintenance costs and space requirements as they consist of mechanical parts (Sarathy & Raghav, 2018).

2.4.2.2. FACTS Based Shunt Compensation Technologies

Flexible AC Transmission system (FACTS) devices are power electronics based application, thus they are faster than traditional mechanical compensators (shunt capacitor, serial capacitor, phase shift, etc.). These devices increase the stable operating limits of the electrical systems when properly adjusted. The purpose of usage these devices in distribution networks is generally to eliminate voltage fluctuations (Kojima, Isotani, & Yamada, 2017). Commonly used FACTS devices for shunt compensation in distribution networks are Static VAr Compensators (SVCs) and Synchronous Static Compensators (STATCOMs).

The main task of the SVC is to inject capacitive or inductive current depending on the control data to the busbar to which it is connected (Bauer & De Haan, 1998). The static VAr compensator allows the control of the consumed reactive power from the system and control the system voltage within the allowable limit. The most well-known forms are FC-TCR and TSC-TCR (Padiyar, 2007).

SVCs use static switch and do not have a rotating mechanic in their structure, hence they are very fast in response (within 2-3 cycles) to voltage changes. This fast response time makes the system more stable.

Simply the STATCOM consists of a connection transformer, converter and a DC capacitor. STATCOM is also called a voltage-based converter (VSC). In order to regulate the busbar voltage, it consumes or injects reactive from or to grid which it is connected (Ertay & Aydoğmuş, 2012).

STATCOMs need self-commutated switches to achieve its duty. STATCOMs have a faster response time to disturbances than SVCs and also has a more compact structure (Padiyar, 2007).

3. LITERATURE REVIEW ON SVRs

In the literature review section, especially studies published in the last few years and related works published in the wider time interval have been reviewed.

Step voltage regulator was invented and patented in USA in 1942 (John, 1944). This prototype was further developed and became its present form in 1950 (Lennox, 1954). Its main task is to regulate the voltage in the network in order to improve the voltage quality.

Conventional voltage regulators are based on transformers with tap changers. Tap changers have been in use since 1890 in order to regulate the voltage in distribution grids (Short, 2018). Tap changers are located in the structure of the power transformers and used for changing the transformer output voltage. The purpose of changing the output voltage of the transformer is to solve the voltage drop problem in the long distance electrical networks.

Tap changers can be classified in three categories (Bayliss & Hardy, 1999), according to their operation types.

- Off-circuit tap changers: They can work only if the transformer is de-energized. Therefore, they do not require much maintenance. The tap changing is carried out manually by means of manpower via a lever or wheel.
- Off-load tap changer: They can work only if there is no load current. During the tap changing operation, the transformer is energized but it must be disconnected from the main supply. Tap changing operation is generally performed manually.
- On-load tap changers: They can work during the load current is flowing through transformer. OLTCs are explained in detail in chapter 4. In this thesis, tap changer expression corresponds to on load tap changer (Fourie, 2010).

Classification of tap changers used in power transformers is shown in Figure 3.1.

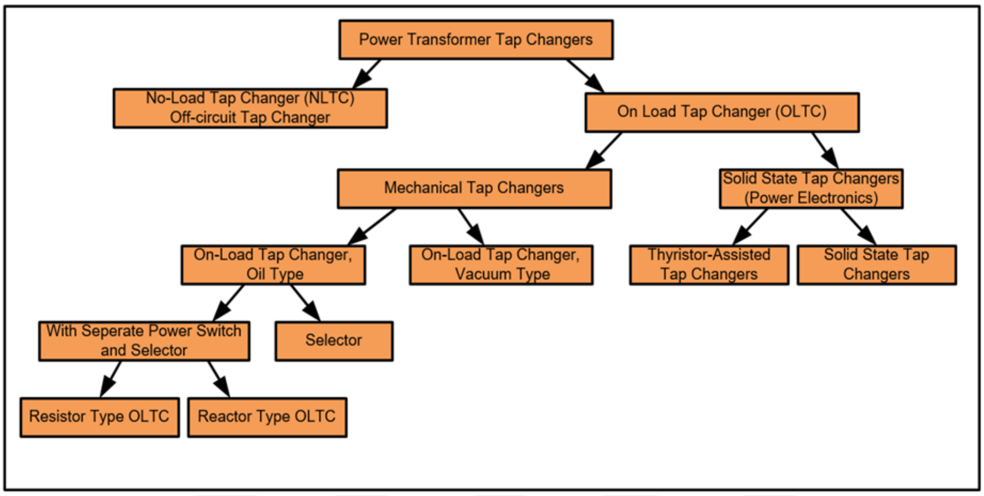


Figure 3.1. Classification of tap changers (Korpikiewicz & Mysiak, 2017)

3.1. Mechanical Tap Changers

In conventional voltage regulators, mechanical switches have been used to carry out step changes (Jawad Faiz & Siahkolah, 2011; J. W. Liu, Choi, & Chen, 2003). The benefits of using mechanical tap changer is that it has high overload rating and small on state resistance, hence low steady state losses (Chandra Mouli, 2013).

On the other hand, mechanical tap changers have some limitations and significant disadvantages. The main source of the faults that encountered in transformers are tap changers' failures (Kang & Birtwhistle, 2001). Disadvantages and limits of mechanical tap changers are summarized below (Gao, Lu, & Luo, 2002):

- The arc in switches' contacts while tap-changing operation: This arc that occurs during tapping causes spreading of the oil around the contacts and hence the contacts wear out.
- High maintenance and service cost: Maintenance of mechanical tap changers have to be carried out periodically because of the arc event and the abrasion of the moving mechanical components.
- Low tap-changing speed: The first reason of this slow speed is tap-change process is done mechanically, and the second reason is the time required to store the energy that needs to tap changing operation. It takes about 100 seconds for a mechanical tap changer to reach stage 19 from stage 1 (Jiang, Shuttleworth, Al Zahawi, Tian, & Power, 2001).
- High losses: Using of resistances in tap changers causes high losses during tap changing operation.

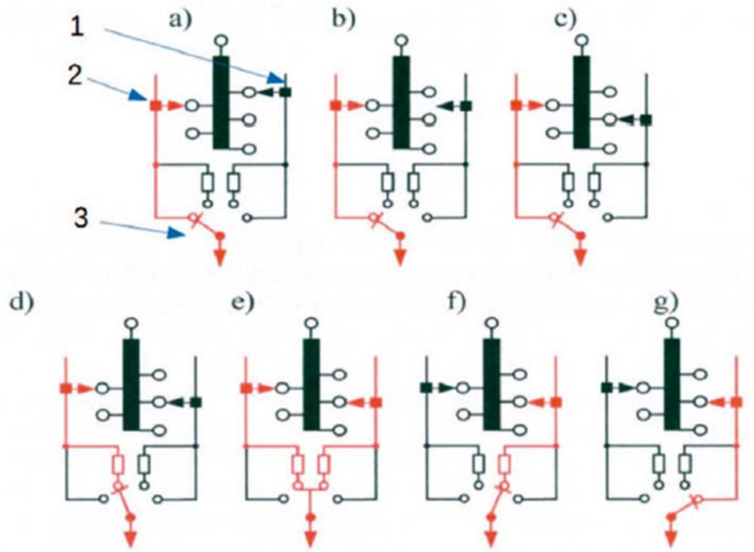


Figure 3.2. Mechanical tap changer operation with selector and power switch (Korpikiewicz & Mysiak, 2017)

Figure 3.2 shows the simple tap structure of a mechanical tap changer with selector and power switch, and sequence of tap change operations. 1 and 2 represents selector switches, 3 represents power switch and active current path for each step is specified as red. In lower power transformer applications, the tap changer consisting of only selector switches and absence of power switch is used. It has simpler structure.

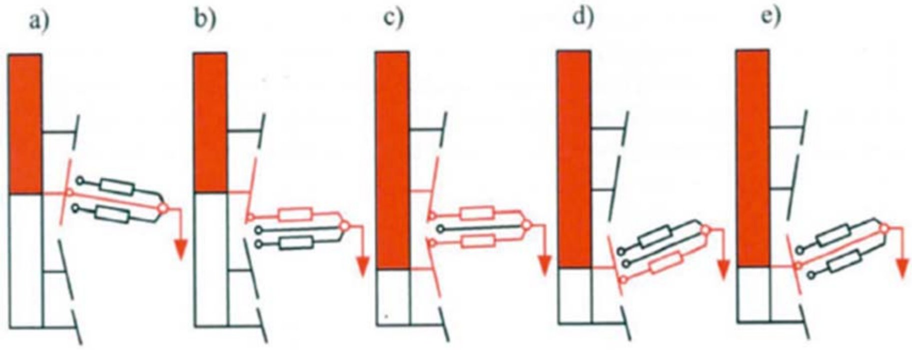


Figure 3.3. Mechanical tap changer operation with only selector switch (Korpikiewicz & Mysiak, 2017)

In parallel with the development of solid state power electronic components, from 1985 onwards, electronic tap changers without moving mechanical parts were developed. Advantages of transformers with electronic tap changers compared to mechanical tap changers are higher performance, lower volume, weight and maintenance cost (J Faiz & Siahkolah, 2008).

Solid state tap changers have very high toleration to surges occurring in the network. A suitable protection circuit needed to be designed in order to use this wide tolerance feature (Bauer & De Haan, 1997). The use of a solid-state tap changer for the first time was in 1986 in Norway (Tommy Larsson, Innanen, & Norstrom, 1997), then this version was developed in 10 years. The purpose of this device was to compensate the voltage level in power system against the voltage drops. A report for solid state tap changers (Wood, Bapat, & Putkovich, 1988) has been presented in many articles in the following years (Degeneff, 1997; Demirci, Torrey, Degeneff, Schaeffer, & Frazer, 1998; Hietpas & Naden, 2000; Jang & Choe, 1998; Meyer & Van Coller, 1999; Villegas et al., 1998, 1998; Yousef-Zai & O'kelly, 1996).

The main purpose of the first solid-state tap changer models was replacing mechanical switches with electronic switches directly (Yousef-Zai & O'kelly, 1996). However, these designs were very costly because they required usage of large number of electronic switches.

A different design was presented in (Demirci et al., 1998) that decreases the number of taps and electronic switches, and also increase the number of steps. With this design, a model which can be used in both serial and parallel connections for a wide voltage and power range has been created (J Faiz & Siahkolah, 2008).

Despite the improvements in the structure of the mechanical tap changers, there are significant limitations and disadvantages. As mentioned before, the main source of the faults that encountered in transformers are mechanical tap changers' failures (05, 1983; Bengtsson, 1996; Gao et al., 2002; Jiang et al., 2001). New designs for tap changers have been proposed to overcome these limitations and drawbacks. These can be categorized in two groups as electronically assisted (or hybrid) and fully electronic (or solid-state) tap changers (Harlow, 2001; Shuttleworth, Tian, Fan, & Power, 1996).

3.2. Electronically Assisted (Hybrid) OL Tap Changers

The purpose of this type of tap changers is to place semiconductor power switches to the side of the mechanical switches and to reduce the arc event during the tap change as much as possible. In these tap changers, the selector system and the diverter switches are still mechanical parts.

The first hybrid tap changer model was proposed in (Robert & Ashman, 1969). This circuit significantly reduces the arc event. However, the biggest drawback of this design is that the two thyristors are permanently connected to the circuit of the diverter switches, although they are open for short periods during the tap change operation, and possibly burned. This is a problem for reliability. An alternative configuration is presented in (Cooke & Williams, 1990) to eliminate this disadvantage. The purpose of this circuit is that two thyristors are connected only while the tap change operation. This design increased reliability of the configuration. A modified diverter configuration was presented in (Cooke & Williams, 1992) that uses only one resistor pass.

The purpose of the configurations viewed so far was to reduce the arc event. However, the tap-change operation was still very slow because of using conventional switch structure. In order to enhance power quality by using tap changer in (J Faiz & Siahkolah, 2004, 2005), tap changing operation needed to be fast. In this case, an electronic tap changer ensures proper operation while a conventional tap changer cannot respond well (Jawad Faiz & Siahkolah, 2006a).

In order to work the tap changer faster, a different configuration has been proposed in (Shuttleworth, Power, Tian, Jiang, & Al Zahaei, 1997), that using dual state electromechanical actuated vacuum switches. While three steps in resistive OL tap changers last approximately 15 s, this operation last 0,5 s in this structure. Changing the vacuum switches increases the mechanical reliability of the configuration. On the other hand, electrical reliability of this structure is low because of the permanent connection of solid state switches and using of high-cost vacuum switches. A different hybrid tap changer configuration has been presented in (Gao et al., 2002), that selector and diverter switches are combined. Hybrid tap changers using solid-state power switches considerably reduce the arc event (J Faiz & Javidnia, 2000), but they have drawbacks as they have still moving mechanical parts in their structure (Jawad Faiz & Siahkolah, 2006a).

3.3. Fully Electronic (Solid-state or Static) OL Tap Changers

Fully electronic tap changer idea was firstly proposed in 1973 (J Faiz & Javidnia, 2000; O’kelly & Musgrave, 1973) for only special applications. A detailed and extensive study was implemented using conventional techniques to limit current circulation between taps in the electronic tap changer in the 1990s (Yousef-Zai & O'kelly, 1996).

There is not moving mechanical parts in these tap changers and they use semiconductor power switches. This proposed topology is a simple structure arranged with solid state power switches. That is, the number of voltage steps and semiconductor power switches is the same as the number of taps of the transformer. Therefore, the number of thyristors and voltage ratings are high in this structure when a large number of steps are required, and this results a high cost. In order to reduce the cost, two different structures are presented in (Yousef-Zai & O'kelly, 1996) by developing the switches arrangement. An electronic tap changer was presented in (T Larsson, Innanen, & Norstrom, 1997) as a rapid regulating structure to protect critical loads against voltage variations. Here, a different approaches about placing of electronic tap changers were proposed. In order to reduce costs again, a new topology was presented in (Degeneff, 1997). In this study, the switches arrangement was changed again and a new modulation technique, discrete-cycle modulation (DCM), was used for improving the control method. Higher voltage steps and a decreasing the maximum current of the thyristors are the good aspects of this topology. Another study using the DCM technique and its good and bad aspects was presented in (Demirci et al., 1998).

Switching of tap changers is generally done with four different techniques. These are; with no modulation, phase modulation, discrete cycle modulation and pulse width modulation. In order to control voltage certainly, a modulation technique was proposed in (Ram, Prasanth, Bauer, & Barthlein, 2014).

The superior aspects of fully electronic OLTCs compared to other tap changers are listed below,

- Very low maintenance cost: Since the moving mechanical parts are not used in the tap changing operation, the arc event is eliminated. Hence, maintenance costs for arc damage are significantly reduced, and mostly even maintenance is not needed (J Faiz & Siahkolah, 2008).

- Quick operation: Each tap change can performed in half a cycle because of using very high speed solid state power switches.
- Capability of tap jumping: Since there is no need for transition resistance in this structure, the circulating current between taps is virtually equal to zero. Therefore tap jumping is possible without problem.
- Improvement of performance: As the solid state power switches are fast and have controllability, and also lack of mechanical moving parts in the structure increases the performance and ability of tap changer. Because the disadvantages of moving mechanical parts will be eliminated. One of the most important ability of these structures is opportunity of achieving more steps with less taps. The reason of this is the semiconductor power switches can be configured as a fast static regulator with unlimited number of configurations. Due to this feature, they can be used as custom power devices which can compensate the PQ problems (Harlow, 2001).
- Limitless tap-changing operation: Since only semiconductor switches are used in the structure, no wear occurs on the switches if correct switching is performed.

Despite all the advantages described so far, the costs of fully electronic tap changers are higher than other structures. This higher cost is one of the most important obstacle to the common usage of this structure (J Faiz & Siahkolah, 2002). The main variables affecting the cost of the electronic tap changer are as follows.

- Number of semiconductor power switches and their voltage and current limits.
- Number of transformer taps, because each tap requires insulating equipment and besides its own specific insulators.

In order to create a more cost-effective structure, the number of equipment above must be reduced. For this purpose, the systematic arrangements of the tap windings and switches designs have been presented in (J Faiz & Siahkolah, 2002; Jawad Faiz & Siahkolah, 2006c, 2006d).

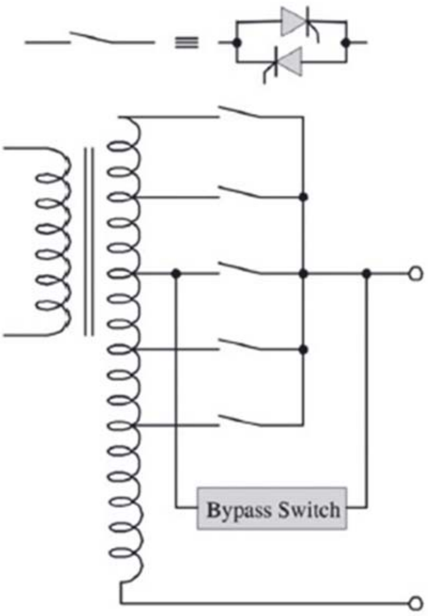


Figure 3.4. Electronic tap changer based thyristor (Korpikiewicz & Mysiak, 2017)

Electronic tap changers designed to improve voltage quality are presented in (Bauer & De Haan, 1997, 1998, 1999; Bauer, de Haan, & Paap, 1996; Bauer, De Haan, & Paap, 1997; Bauer & Schoevaars, 2003; Bucknall & Ciaramella, 2009; Cárdenas, Pena, Clare, & Wheeler, 2010; Chang, Albuyeh, Gilles, Marks, & Kato, 1990; Garcés & Molinas, 2011, 2010; Grainger, Stevenson, & Stevenson, 2003;

Guo, Hill, & Wang, 2001; Lee, Wheeler, & Klumpner, 2010; Milosevic & Begovic, 2004; Monteiro, Silva, Pinto, & Palma, 2010; Tamai, Abe, Odaka, Sato, & Sakuma, 2009; Vu, Pruvot, Launay, & Harmand, 1996). The structures of these configurations look like a high-frequency ac / ac converters. The idea of high-frequency soft switching has been proposed in (Taha, 2016; Villegas et al., 1998) to decrease the pressure on the electronic tap changers. Proposed topologies make the system more dynamic.

3.4. Drawbacks of Conventional Voltage Regulators

The most common solutions among voltage regulators are electromagnetic devices based on a conventional transformer with a tap changer (Choi & Kim, 2001). They are the easiest devices of regulating voltage profile. VRs can change the phase angle of the line voltages. However, they could not compensate power factor directly. In order to correct power factor, there is a need of using another devices such as capacitor banks or harmonic filters. Other solutions proposed for this purpose are power electronic devices such as Voltage source converter operated as STATCOM, D-STATCOM and SVC. Hence, it shows that two different devices have to be needed for performing voltage regulation and power factor correction (Garces & Trejos, 2011a).

On the other hand, conventional voltage regulators may be insufficient in some cases in distributed generation applications. They could even lead to a voltage drop. The VR is not capable of generating reactive power. Hence, when the voltage drops due to the increase in the reactive power demand at the line voltage, the VR changes the tap to increase the voltage. In these topologies, regulating voltage is more important than correcting the power factor. Increased demand for reactive power weakens the stability of the system (Garces & Trejos, 2011a).

In addition, conventional tap changers have a limited time response. Tap change speeds may remain slow for some future distribution system applications.

Matrix converters can perform the tasks mentioned above alone. They regulate voltage and also correct the some power quality problems.

3.5. Literature Review on Matrix Converter Based SVRs

Matrix converter topology was first proposed by Gyugyi and Pelly in 1976 (Bhavsar & Chandwani, 2013). In this study, Gyugyi presented a three-phase matrix converter topology that can achieve direct AA-AA frequency transformation. The basis of this matrix converter is based on the frequency converter principle. The main disadvantage of this proposed first matrix converter was the presence of some harmonics that could not be successfully eliminated by the filter at the input current and output voltage. This problem was solved by Venturini and Alessina in the early 1980s (Alesina & Venturini, 1989). In the following periods, matrix converter control algorithms based on more robust mathematical calculations have been developed. Matrix transformer studies, which began in 1976 by Gyugyi and continued with Venturini in 1980, focused on a three-phase matrix converter.

In the last two decades, the researches for matrix converters have explained their application potential, but due to their complex structure, many application studies have not been conducted. With improved technology, the ease of signal processing has reduced the control complexity of matrix converters, and improvements in semiconductor structures have increased the applicability of matrix converters. Matrix converter switch is shown in Figure 3.5.

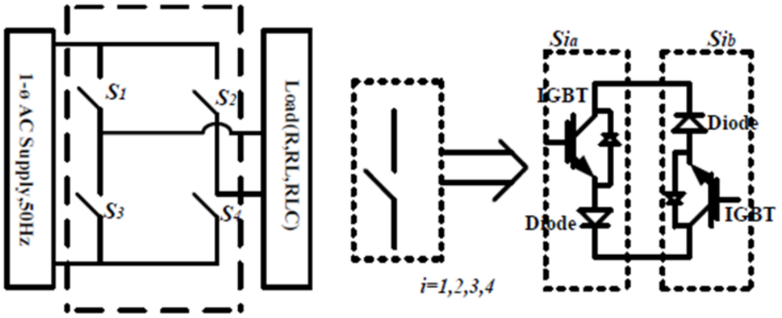


Figure 3.5. Matrix Converter switch configuration

There are not many studies in the literature about matrix converter based voltage regulators in their topologies.

A voltage regulator based on a three phase matrix converter is presented in (Garces & Trejos, 2011b). This study demonstrates the potential strengths and weaknesses of the matrix converter based voltage regulator for distribution networks. It has been shown that conventional voltage regulators are insufficient to regulate in rapidly changing network events, hence voltage regulators based on matrix converters are a suitable solution. AC voltage regulators with high frequency transformer based Matrix converter is presented in (Udovichenko, 2016). Matrix converter is modeled with a series injected transformer in order to compensate the feeder voltage of MV network In (Ali & Wolfs, 2014). 3ϕ-1ϕ (Yushan Liu et al., 2016), 3ϕ-3ϕ (Kunov, 2014) and 1ϕ-1ϕ (Zainuddin, Baharom, Yassin, & Muhammad, 2018) matrix converter based transformers are proposed in order to perform voltage regulation.

Three-phase hybrid transformer with a matrix converter for mitigation of source voltage sag and swell is proposed in (Szczesniak, 2019; Szcześniak & Kaniewski, 2015). In addition, matrix converter based active voltage regulator model for LV distribution networks is presented in (Alcaria, Pinto, & Silva, 2013; Pinto, Alcaria, Monteiro, & Silva, 2016). This model performs successfully to compensate sags and swells up to 20% and also accomplish the power factor correction in MV network.

4. FUNDAMENTALS OF STEP VOLTAGE REGULATOR

The use of step voltage regulators in power distribution systems has begun in developed countries in the 1940s. It was used especially in USA because of its huge lands. In the USA, generation point was far away from the consumption points, and these consumption points were also far from each other. The introduction of many new electronic devices which were sensitive to voltage variations had increased consumer complaints. Because of these voltage quality problems consumers began to demand better quality electricity. In order to improve power distribution systems, nearly thousands of voltage regulators were placed on various region of the country. These installed voltage regulators have reduced consumer complaints, reduced losses in the distribution system, increased the profitability of power distribution companies and contributed to supply better quality power by distributing regulated voltage to the consumer (Yaskawa, 2016).

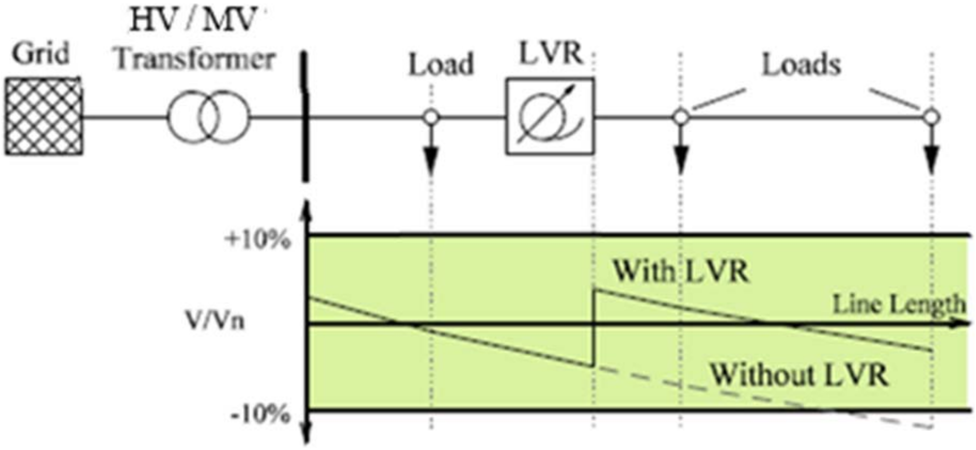


Figure 4.1. Operation principle of SVR (Holt, Maasmann, & Rehtanz, 2017)

Generally, the final voltage regulation equipment in the distribution networks is the distribution (HV / MV) transformer. This equipment cannot achieve maintain the line and load voltages in the desired voltage band. In order to extend this regulation band, an additional equipment is required, which improves the voltage quality. One of the devices used for this purpose is the Step Voltage Regulator (SVR). It can be named as Line Voltage Regulator (LVR). SVR can be mounted at any desired point in the line.

The optimal location of SVR depends on the distribution grid specifications, the loads connected to it and the connection points of the distributed generators to the network. Figure 4.2. shows an example of power system diagram.

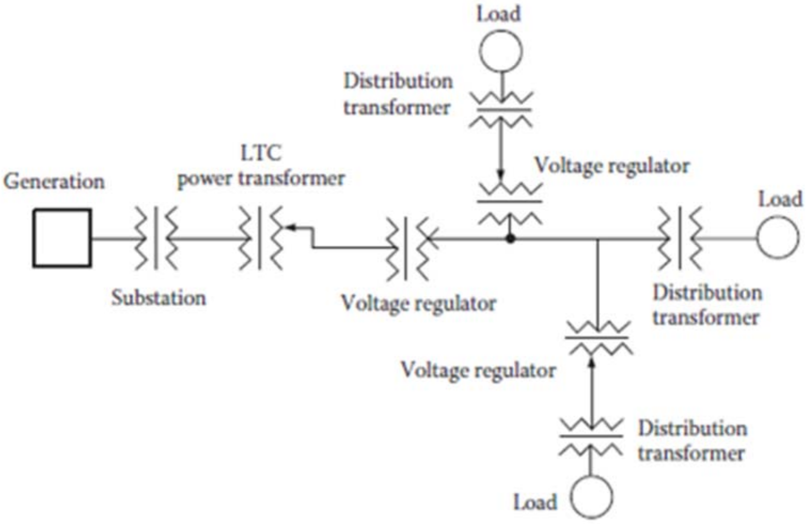


Figure 4.2. Power System (Colopy, 2012)

An autotransformer and a tap changing mechanism forms the structure of a SVR. In order to change a voltage, taps on the series winding of an autotransformer need to be changed. In order to understand the voltage regulator theory, the concept of tap changing regulator and autotransformer must be known.

4.1. Tap Changing Transformer

Tap changing transformer is an effective method to mitigate the voltage variation problem. Tap changers can be divided into two classes (Jawad Faiz & Siahkolah, 2006b). These are “Off-circuit or no-load tap changers” and ‘On-load or underload tap changers (OLTC)’.

In order to make a tap changing operation with No-load tap changer, it has to be disconnected from the load. Hence, no current flows over the taps while tap changing operation. Vice versa, OLTC can change its tap position even if it is connected to the load. Hence, the power is supplied without interruption during tap changing operation. Because of this feature, tap changers are more useful in distribution systems, but their structures are more complex and costs are higher.

OLTC’s working principle is illustrated in Fig 4.3. If switch S1 closes, the voltage on load is equal to Tap1 voltage. If a tap changing operation is needed from S1 to S2, it needs to be done is the simultaneous opening of S1 and closing of S2. If this ideal operation is done successfully, short circuit will be prevented, and current will flow on circuit without interruption. In fact, it is almost impossible to perform the tap change operation, which meets the above requirements (Chandra Mouli, 2013).

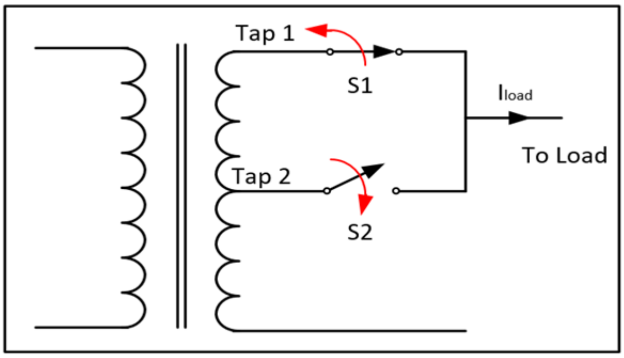


Figure 4.3. Tap changing on On Load Tap Changer

The application in practice is as follows:

- **Break and Make:** Firstly S1 is opened and then S2 is closed. A short interruption on the load will be happened, this is an undesirable situation as seen in the Figure 4.4. This result is very similar to circuit breaker operation. Arcing occurs after interrupting the current and observing huge overvoltage on its contacts because of the load's and line's inductivity. Therefore, every tap must be produced in a manner similar to the features of a circuit breaker for blocking high currents on high voltages, which is not efficient and cheap. Hence, this operation is not a practical.

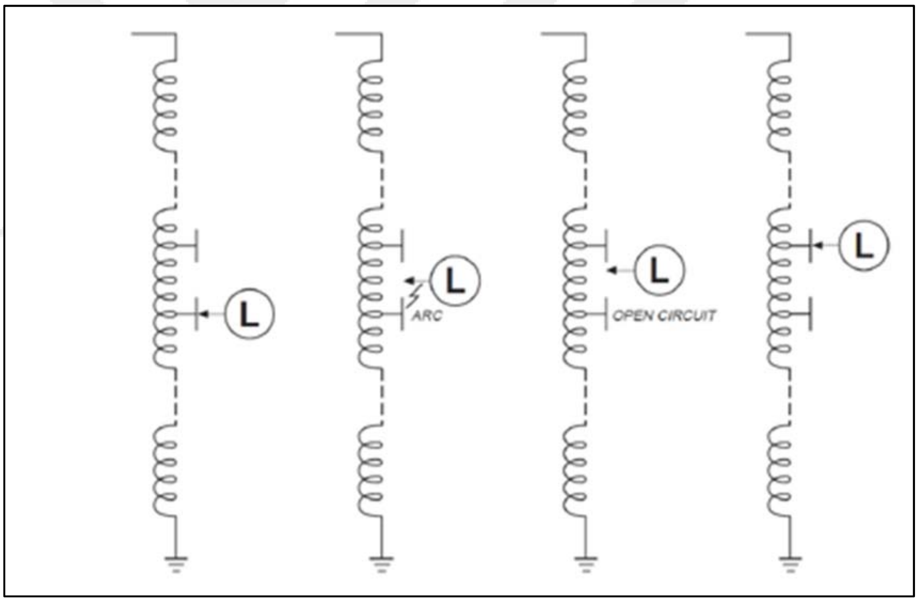


Figure 4.4. Tap changes in case absence of bridging contact (Sarathy & Raghav, 2018)

- **Make and Break:** Firstly S2 is closed and then S1 opens. This will cause an instant short circuit between the taps. In order to prevent this short circuit, a mechanism should be implemented. One of the effective way of this mechanism is placed an impedance component between two adjacent taps which is called bridging contact. This impedance reduces currents caused by short circuit. Commonly used elements in this mechanism are inductor or resistor as seen in Figure 4.5. By using this way, there will not be open circuit, thereby, load interruption. Therefore, this way is the effective method for tap changing operation (Chandra Mouli, 2013).

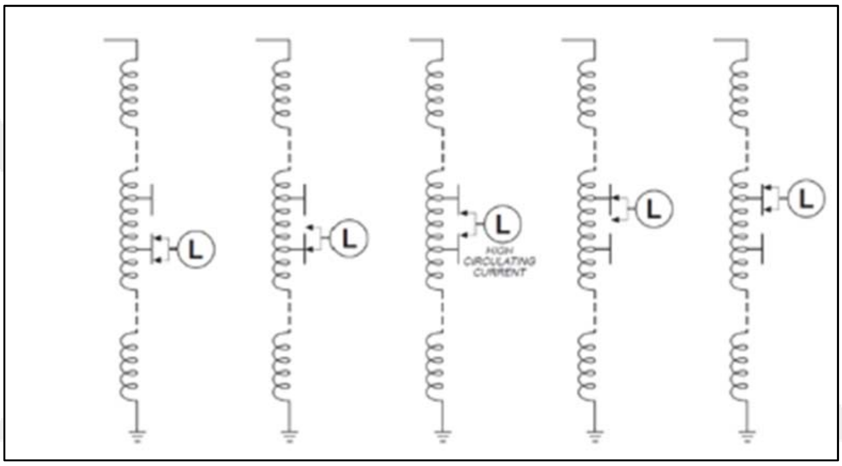


Figure 4.5. Tap changes with a bridging contact (Sarathy & Raghav, 2018)

Types of impedance forming bridging contact are shown in Figure 4.9. Both types limited circulating current during tap changing. Resistor type bridging contact is shown in Figure 4.6 (a), which needs an extra path in order to avoid any loss after tap changing. Reactor type bridging contact is shown in Figure 4.6 (b). This structure has not necessity of extra path, hence there will be no loss (Sarathy & Raghav, 2018).

Figure 4.6. (a) Bridging contact with reactor (b)Bridging contact with resistor (Sarathy & Raghav, 2018)

Conventional OLTC systems were performed in voltage regulators and on transformers. They implement tap changing operation with mechanical switches which are operated with help of a motor. It was assumed that the flow of power would be unidirectional when these tap changers were designed. After implementing distributed generation in our systems, bidirectional flow of power and power fluctuations in distribution grid has started to show up. Hence, conventional mechanical tap changers' performance has been inadequate and also their life-time has reduced because of frequent tap changings (Sarathy & Raghav, 2018).

4.2. Conventional Two Winding Transformer

A transformer is an electrical machine that transfers the voltage from one electrical circuit to another with the principles of electromagnetic induction by keeping the frequency of electrical energy constant. It converts the electrical energy of a circuit into another energy, at a very high efficiency, with a change in voltage and current magnitude. This electrical transfer accomplishes with the help of two coils.

The AC voltage applied to the primary of the transformer generates a magnetic field around the primary winding. The direction and magnitude of this magnetic field varies depending on the direction and magnitude of the AC voltage in the primary. The resulting magnetic field causes a voltage to be induced on the output coil (secondary).

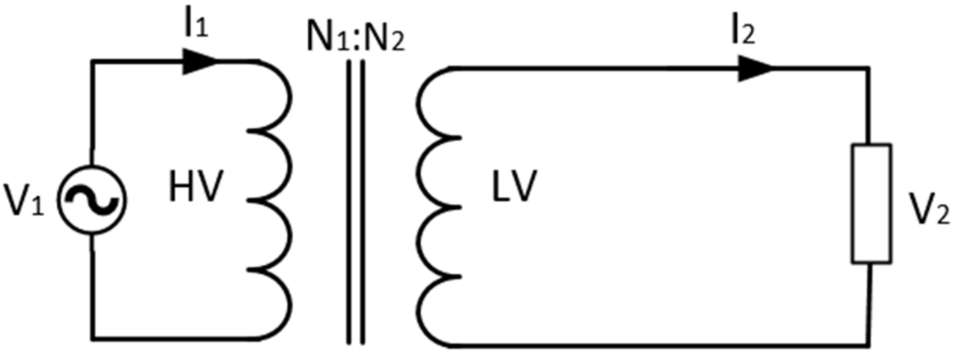


Figure 4.7. Ideal two winding transformer with turn ratio a= N_1/N_2

An ideal conventional two winding transformer is shown in Figure 4.7. HV winding represents the primary high voltage and LV winding represents the secondary low voltage. There are magnetic coupling between these windings through the iron core. The ratio of the windings to each other a=N_1/N_2 defines the turn ratio of the transformer. V_1, V_2, I_1 and I_2 represent voltages and currents of primary and secondary. For an ideal transformer without leakage impedance, following equations can be obtained:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} \tag{4.1}$$

Let tap position is expressed by x. If taps are placed on the secondary side, x can be used instead of N_2. By using Eq 4.1, following equation Eq 4.2. can be obtained:

$$V_2 = \left(\frac{V_1}{N_1}\right) x \qquad I_1 = \left(\frac{I_2}{N_1}\right) x \tag{4.2}$$

Therefore, by changing the tap position, secondary side voltage varies while the voltage at primary side is constant (Chandra Mouli, 2013).

4.3. Autotransformer

In a conventional transformer, primary and secondary windings are connected magnetically but there is electrically insulation between each other. In autotransformer, there is magnetically connection between windings as well as electrically. However, there is a single continuous winding which is mutual to both primary and secondary in autotransformer.

An autotransformer is a compact and cost-efficent device in order to provide variable secondary voltage. Two operation modes are shown in Figure 4.8, the left one is boost (step up) mode and the right one is buck (step down) mode. In autotransformer there is a series connection between HV and LV windings. HV winding is regarded as the primary or shunt winding. LV winding is regarded as the secondary or series winding. If connection of the source and the load is changed, buck and boost mode operation can be achieved (Chandra Mouli, 2013).

As previously mentioned, there is a connection electrically between series and shunt windings. Hence, most of the power is directly transferred in autotransformer. Thus, the transformed power through the windings magnetically is a lot smaller than the power on the terminals. In order to describe the ratio between these two power, the capacity multiplication factor (F_C) term is used. This term defines the rate of transferred power from the terminals to the power which is transformed over the windings. The equations related to the Fc is following:

$$F_C = \frac{S\ (\text{Through put})}{S\ (\text{Transformed})} \qquad (4.3)$$

For boost mode multiplication factor is calculated from Eq. 4.4,

$$F_C = \frac{r}{r-1} \tag{4.4}$$

For boost mode multiplication factor is calculated from Eq. 4.5,

$$F_C = \frac{r}{1-r} \tag{4.5}$$

For Buck and Boost mode r is calculated from Eq. 4.6,

$$r = \frac{V_2}{V_1} \tag{4.6}$$

For example; if HV side is rated to 1 pu, the LV side is rated to 0.1 pu voltage and also the load rated current is 1 pu. In this situation, Fc will be 10. Thus, it can be easily say that if an ordinary transformer works as an autotransformer, ten times much higher power could be transferred (Chandra Mouli, 2013).

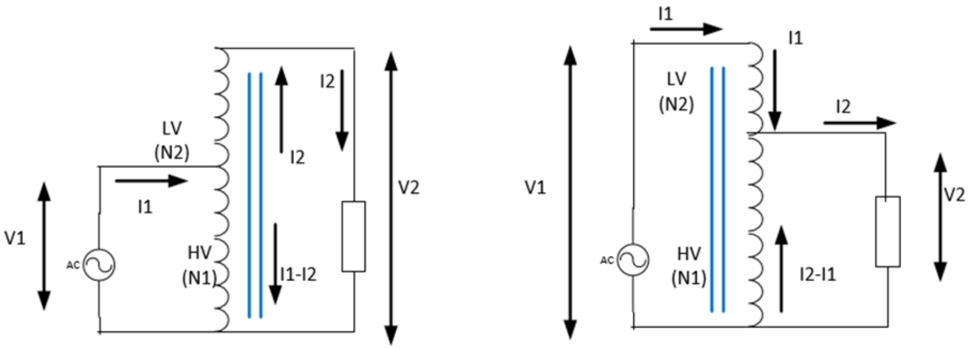


Figure 4.8. Autotransformer operation left is boost, right is buck

4.4. Function Principle of SVR

The main purpose of step voltage regulator (SVR) is to maintain load voltage constant within the desired range without creating much phase angle shift. Step voltage regulator is a type of custom power device that has no energy storage ability. Voltage regulation process is needed an external power supply system (J. W. Liu et al., 2003). SVR controls the line voltage in order to restore the received system voltage within acceptable limits.

An SVR comprises of an autotransformer and a tap changing mechanism. The series winding is tapped, and the tap changing mechanism has a reverse switch which is used for determining the polarity of the tapped voltage. A SVR restores output voltage by adding or subtracting the tapped series winding to/from shunt winding according to reverse switch polarity. Thus the voltage at the source side is increased (boost operation) or decreased (buck operation). The tap position is determined by a compensator circuit (Davis et al., 2007).

The voltage regulator is actually a transformer. As with conventional transformer operation, the alternating voltage applied to the primary side will cause a voltage induction on the secondary side, whose magnitude will be determined according to the turn ratio. In cases where the transformer is used as a regulator, the coil on the primary side is called an exciting or shunt winding, and the coil on the secondary side is called regulating or series winding (Davis et al., 2007).

In general, the SVR is an autotransformer. There is an electrical coupling between windings as well as magnetic coupling. As previously mentioned, the electrical connection type between the windings determines the operation mode of the autotransformer; step-up (boost) or a step-down (buck).

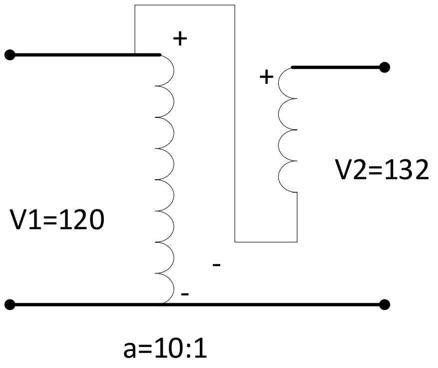


Figure 4.9. Step up transformer

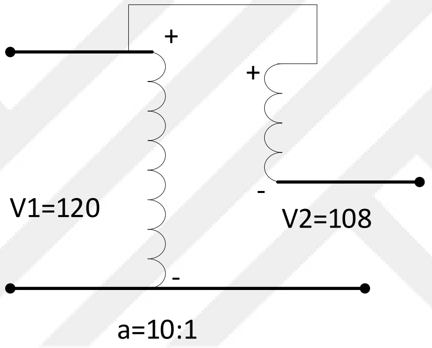


Figure 4.10. Step down transformer

In Figure 4.9., there is a step up transformer. Turn ratio of this transformer is referred as ‘a’.

$$a = \frac{N_1}{N_2} \tag{4.7}$$

If a=10 and the primary voltage is 60 V, then 6 V will be transformed on the series winding. After adding this voltage to the primary voltage, 66 V induces on the secondary side.

In Figure 4.10, there is a step down transformer. In this type of transformer, the series' winding polarity is reversed, vice versa regulating winding voltage 6 V is subtracted from 60 V, and the 54 V reads on the secondary side.

In order to make slight changes in the output voltage, the series winding can be divided into 8 equal parts as seen in figure 4.12. Each part is named as a tap.

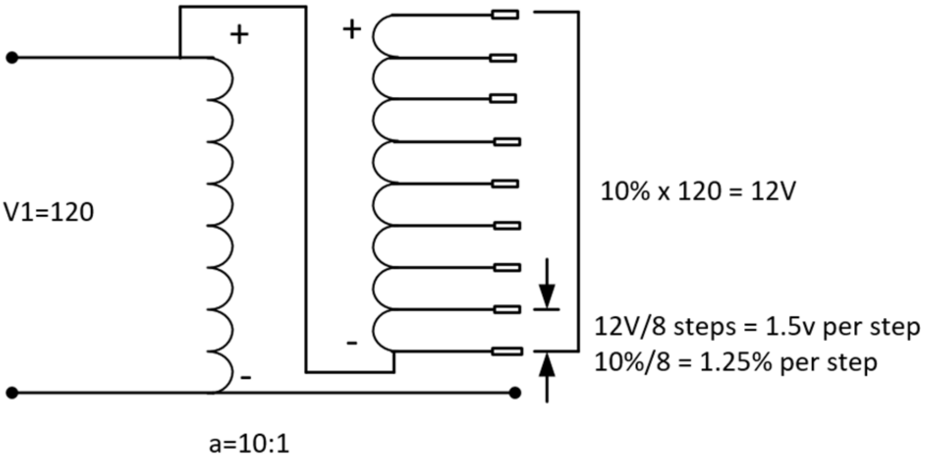


Figure 4.11. SVR with tap changer

The output voltage is 60 V when the stage is in neutral position (N). The 6 volts on the series winding are divided into 8 taps, each corresponding to 0.75 V or 1.25% changes in voltage. As mentioned before bridging reactor is added to circuit for preventing open circuit situation while tap change operation. This structure can be seen in Figure 11. Both fingers are on N tap “0”, if the primary voltage is 60 V, the output will be 60 V. When the tap change operation starts, moving fingers move to Tap 1 by applying make and break rule. As soon as the upper and bottom fingers pass completely the adjacent tap, tap change operation will be completed. This tap changing continues until the required tap number is reached to achieve the target voltage value. In mechanical tap changers, the taps increase or decrease in sequence. It is not possible to skip to the adjacent tap.

In order to achieve changing polarity of series winding, reverse switch is added to the circuit as shown in Figure 4.12. Series and shunt windings are connected to each other with reverse switch (Davis et al., 2007).

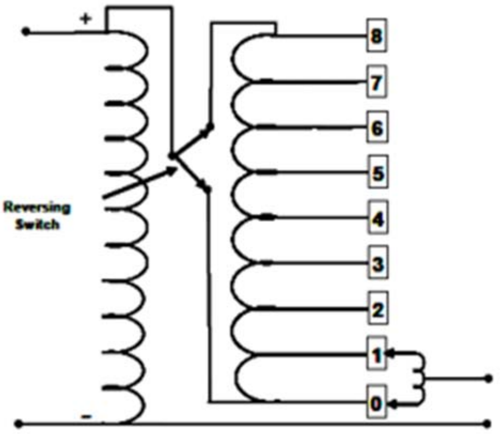


Figure 4.12. SVR with reversing switch (Davis et al., 2007)

4.5. Types of SVR

A standard SVR is generally designed to change voltage in the +/-10% range. This operation is achieved usually in 32 steps, 16 steps up and 16 steps down. Thus, this corresponds to a 0,625% voltage change per step. There are two connection types for voltage regulators; Type A and Type B which are defined by ANSI/IEEE C57.15-1986 standard. In Figure 4.13 and 4.14 Type A and Type B regulator can be seen (Kersting, 2009).

This classification is made according to the place where the series winding is placed. Series windings are placed on the load side in Type A, and on the source side in Type B. They are also named as “straight” for type A and “inverted” for type B (Kojovic, 2006).

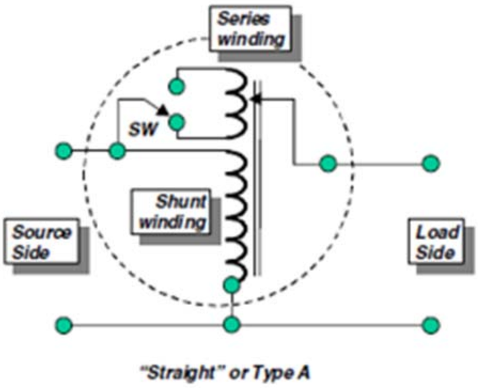


Figure 4.13. Type A Step Voltage Regulator (Kojovic, 2006)

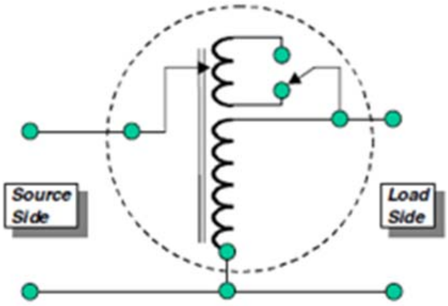


Figure 4.14. Type B Step Voltage Regulator (Kojovic, 2006)

4.6. Single Phase Step Voltage Regulator

The series winding is connected to the load side (L) in Type A SVR configuration as shown in Figure 4.15. The reverse switch is in the raise (r) status, the series winding current I_2 is upward direction and shunt winding current I_1 is downward direction. The excitation current changes because of connecting to the source (S). If the reverse switch is changed to lower status (l), unlike the first case, I_2 will be down and I_1 will be upward direction (Davis et al., 2007).

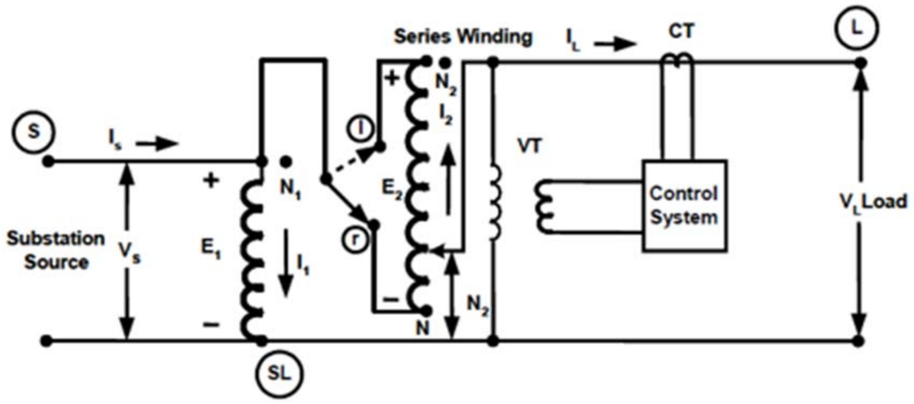


Figure 4.15. Type A Step Voltage Regulator (Davis et al., 2007)

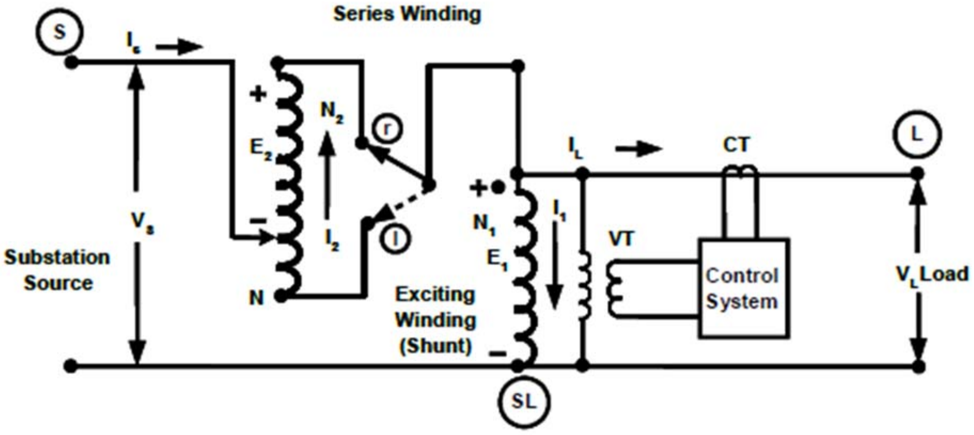


Figure 4.16. Type B Step Voltage Regulator (Davis et al., 2007)

The most widespread SVR type is single phase Type B step voltage regulator. The series winding is connected to the source in this configuration. The type B SVR is shown in Figure 4.16, which the reverse switch is in the raise status (r).

In this configuration, the shunt winding current does not change because of connecting to the load side.

The equations about source voltages/currents and output voltages/currents for Type B regulator in the raise and lower positions are as following;

$$\mathrm{N_1I_1 = N_2I_2} \tag{4.8}$$

$$\mathrm{\frac{E_1}{N_1} = \frac{E_2}{N_2}} \tag{4.9}$$

$$\mathrm{E_1 = V_L} \tag{4.10}$$

$$\mathrm{I_S = I_2} \tag{4.11}$$

From Equation (4.9) and (4.10),

$$\mathrm{E_2 = \frac{N_2}{N_1}\,E_1 = \frac{N_2}{N_1}\,V_L} \tag{4.12}$$

From Equation (4.8) and (4.11),

$$\mathrm{I_1 = \frac{N_2}{N_1}\,I_2 = \frac{N_2}{N_1}\,I_S} \tag{4.13}$$

Raise Position Equations

$$\mathrm{I_L = I_S - I_1} \tag{4.14}$$

$$\mathrm{V_S = E_1 - E_2} \tag{4.15}$$

From Equation (4.10), (4.15) and (4.12),

$$V_S = E_1 - E_2 = E_1 - \left(\frac{N_2}{N_1} E_1\right) = V_L - \frac{N_2}{N_1} V_L \tag{4.16}$$

$$V_S = \left(1 - \frac{N_2}{N_1}\right) V_L \tag{4.17}$$

From Equation (4.13), (4.14)

$$I_L = I_S - I_1 = I_S - \left(\frac{N_2}{N_1} I_S\right) \tag{4.18}$$

$$I_L = \left(1 - \frac{N_2}{N_1}\right) I_S \tag{4.19}$$

Raise direction turns ratio can be defined as,

$$a_r = \left(1 - \frac{N_2}{N_1}\right) \tag{4.20}$$

And substituting into Equation (4.17) and (4.19),

$$V_S = a_r V_L \tag{4.21}$$

$$I_L = a_r I_S \tag{4.22}$$

Lower Position Equations

$$I_L = I_S + I_1 \tag{4.23}$$

$$V_S = E_1 + E_2 \tag{4.24}$$

$$V_S = E_1 + E_2 = E_1 + \left(\frac{N_2}{N_1} E_1\right) = V_L + \left(\frac{N_2}{N_1} V_L\right) \tag{4.25}$$

$$V_S = \left(1 + \frac{N_2}{N_1}\right) V_L \tag{4.26}$$

From Equation (4.13) and (4.23)

$$I_L = I_S + I_1 = I_S + \left(\frac{N_2}{N_1} I_S\right) \tag{4.27}$$

$$I_L = \left(1 + \frac{N_2}{N_1}\right) I_S \tag{4.28}$$

Lower direction turns ratio can be defined as,

$$a_l = \left(1 + \frac{N_2}{N_1}\right) \tag{4.29}$$

And substituting into Equation (4.26) and (4.28)

$$V_S = a_l V_L \tag{4.30}$$

$$I_L = a_l I_S \tag{4.31}$$

It is evident that the only difference in the voltage and current equations for both positions of the reverse switch, r and l, is the sign of N_2 / N_1 ratio. It is negative for raise status and it is positive for lower status. It is no need to know the turn ratio between series and shunt windings, because each tap stands for a voltage

change of 0.625% or 0.00625 per unit. Hence, the effective voltage regulator ratios, a_r and a_l could be formulized as following (Davis et al., 2007);
For Type B regulator,

$$\mathrm{a_r}\,,\ \mathrm{a_l} = 1 -,+(0.00625 * \text{tap position}) \tag{4.32}$$

For the Type A regulator,

$$\mathrm{a_r}\,,\ \mathrm{a_l} = 1+,-\,(0.00625 * \text{tap position}) \tag{4.33}$$

According to the type of regulators, the equations between the source voltages/currents and output voltages/currents whether in step up or step down is generalized in Table 1 (González-Morán, Arboleya, Mojumdar, & Mohamed, 2018).

$$\mathrm{V_S} = \mathrm{a}_R V_L \tag{4.34}$$

where a_R represents regulation ratio for both raise and lower cases and it can be defined as,

$$\mathrm{a_R} = 1 \pm \frac{\text{Total \% Range}}{\text{\# of Steps}} \tag{4.35}$$

Table 4.1. General equations for single phase SVRs

Type	**Voltage Eq.**	**Current Eq.**	**a_R for Raise**	**a_R for Lower**
A	$\mathbf{V_S = \frac{1}{a_R}\, V_L}$	$\mathbf{I_S = a_R\, I_L}$	$\mathbf{a_R = 1 + \frac{N_2}{N_1}}$	$\mathbf{a_R = 1 - \frac{N_2}{N_1}}$
B	$\mathbf{V_S = \mathit{a_R} V_L}$	$\mathbf{I_S = \frac{1}{\mathit{a_R}}\, I_L}$	$\mathbf{a_R = 1 - \frac{N_2}{N_1}}$	$\mathbf{a_R = 1 + \frac{N_2}{N_1}}$

4.7. Three Phase Step Voltage Regulator

For all type of the connections, the general three-phase model is shown in Figure 4.17.

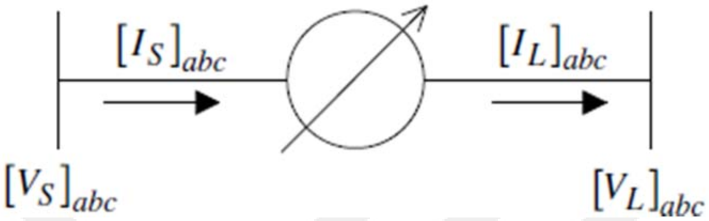


Figure 4.17. Three phase regulator model (Kersting, 2009)

$$[V_S]_{abc} = \text{a}\,[V_L]_{abc} \tag{4.36}$$

$$[I_S]_{abc} = \text{d}\,[I_L]_{abc} \tag{4.37}$$

If 3 single-phase voltage regulators in the above figure are connected in wye, the voltages will be line-to-neutral voltages. If connection type changes to delta, the voltages will indicate line-to-line voltage. On the other hand, currents are the line currents by phase in all connection types (Kersting, 2009).

Voltage and current equations for wye grounded connected three voltage regulators are;

$$\begin{bmatrix} V_{AG} \\ V_{BG} \\ V_{CG} \end{bmatrix} = \begin{bmatrix} a_{R_a} & 0 & 0 \\ 0 & a_{R_b} & 0 \\ 0 & 0 & a_{R_c} \end{bmatrix} . \begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} \tag{4.38}$$

$$[V_{LG}]_{ABC} = [a]\,[V_{LG}]_{abc} \tag{4.39}$$

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} \frac{1}{a_{R_a}} & 0 & 0 \\ 0 & \frac{1}{a_{R_b}} & 0 \\ 0 & 0 & \frac{1}{a_{R_c}} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4.40}$$

$$[I_{ABC}] = [d]\,[I_{abc}] \tag{4.41}$$

In the above equations, upper cases represents source side, and lower cases represents load side voltages and currents. The above equations are prepared assuming that the tap settings of each regulator may be different from each other.

4.8. Connection Types of Three Phase Voltage Regulators

Single-phase SVRs can be used in network with the following configurations;

- A single-phase regulator
- One phase of a three-phase wye or delta circuit
- A three-phase, three-wire wye or delta circuit with two regulators (open delta)
- A three-phase, four-wire, multi-grounded wye circuit with three regulators
- A three-phase, three-wire wye or delta circuit with three regulators (closed delta)

4.8.1. Connection of a Regulator to Single Phase Circuit

Figure 4.18 shows the model of a single-phase voltage regulator, which used for maintaining line voltage. In this circuit, "S" stands for source, "L" stands for load, "SL" stands for neutral according to ANSI standards.

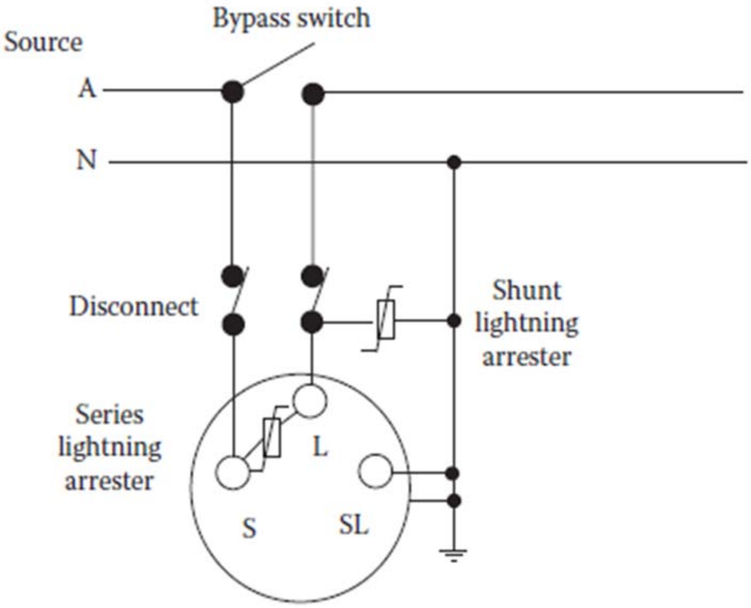


Figure 4.18. SVR connection in a single phase circuit (Colopy, 2012)

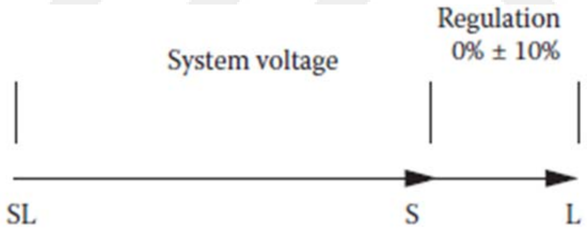


Figure 4.19. Phasor diagram of a SVR for single phase circuit regulation

The regulator to be produced must be able to withstand fault currents and surge voltages due to consecutive switching and lightning.

4.8.2. Connection of a Regulator to Each Phase in Wye Circuit

Regulators connected in wye operate independently in each phase. Voltage regulation between each phase and neutral is done by only the regulator connected to that phase. The phase angles between the voltages and currents do not change. In this type of connection, the loads in each phase do not need to be balanced. The current caused by unbalanced loads will flow through the neutral line. The wye connected regulator circuit and phasor diagrams are shown in Figure 4.20 and 4.21 (Colopy, 2012).

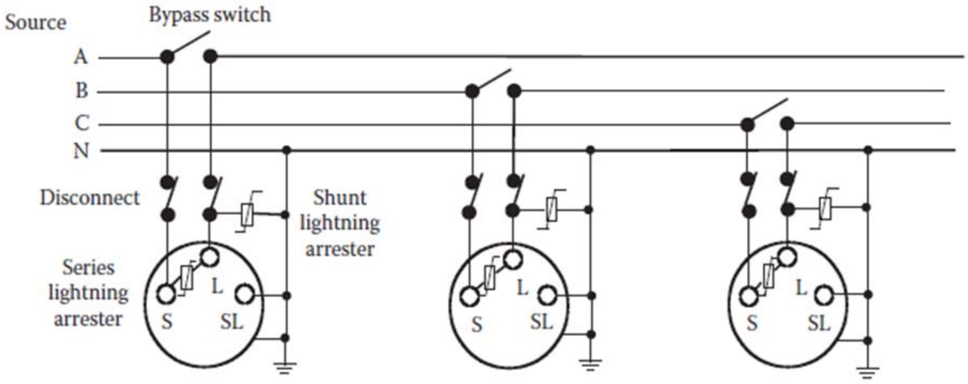


Figure 4.20. Connection of three SVRs for a three-phase, four-wire, multigrounded wye circuit regulation (Colopy, 2012)

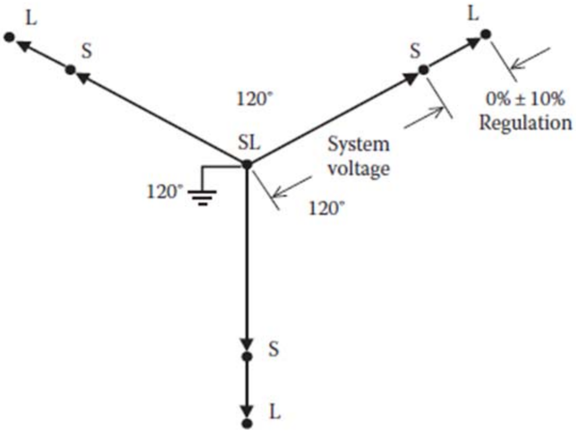


Figure 4.21. Phasor diagram of three SVRs for a three-phase, four wire, multigrounded wye circuit regulation

In three-wire wye regulator connection, the neutral point can slip, which can cause absence of stable reference point of the regulator. As a result, the regulator may not work properly due to the overstressed insulation. Hence, if the stabilization of the neutral is not achieved, it is wrong to connect three regulators in ungrounded wye configuration on a three-phase, three-wire type.

4.8.3. Connection of a Two Regulator in Wye or Delta Circuit

There are interrelation between regulators in open/closed delta connection configurations. Thus, regulation in one phase causes a voltage change in other phases.

As shown in Figure 4.22, two single-phase regulators are used in the open delta configuration. Each regulator independently regulates the voltage in the phase to which it is connected. The third phase, to which the regulator is not connected, is regulated as the average of the regulation rate in the other two phases. For example; if two phases are regulated ±10% by regulators, the third phase will also be regulated ±10% as shown in Figure 4.23 (Colopy, 2012).

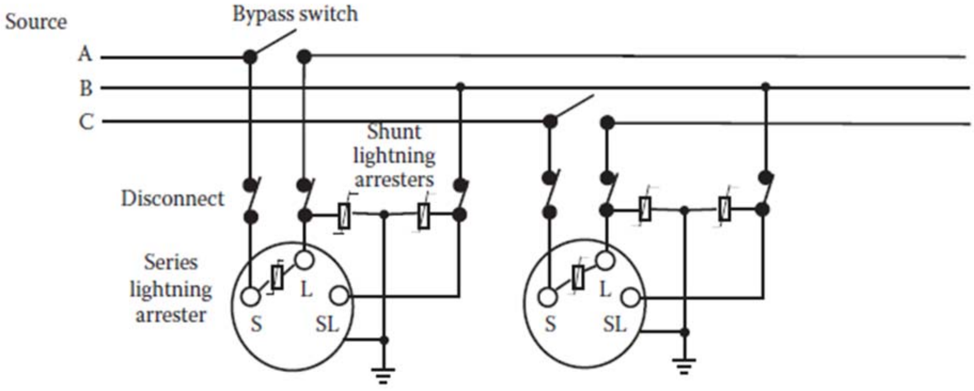


Figure 4.22. Connection of two SVRs for a three-phase, three-wire wye or delta circuit regulation (Colopy, 2012)

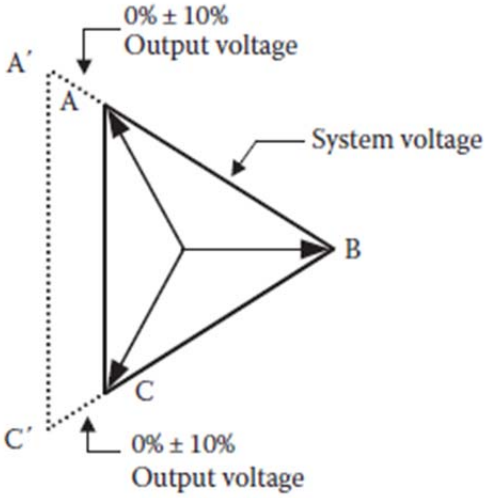


Figure 4.23. Phasor diagram of two SVRs for a three-phase circuit regulation

4.8.4. Connection of a Regulator to Each Phase in Delta Circuit

As shown in Figure 4.24, three single-phase regulators are used in the closed delta configuration. The regulation amount of each phase varies with the regulation amount of each regulator. With the closed delta arrangement, 50% more regulation can be achieved than the open delta arrangement. A 10% voltage regulation in the phase obtained by the regulator operation provides a 5% voltage regulation in the next phase. When three regulators work to provide maximum regulation, these interactions increase the amount of regulation to ± 15% as shown in Figure 4.25 (Colopy, 2012).

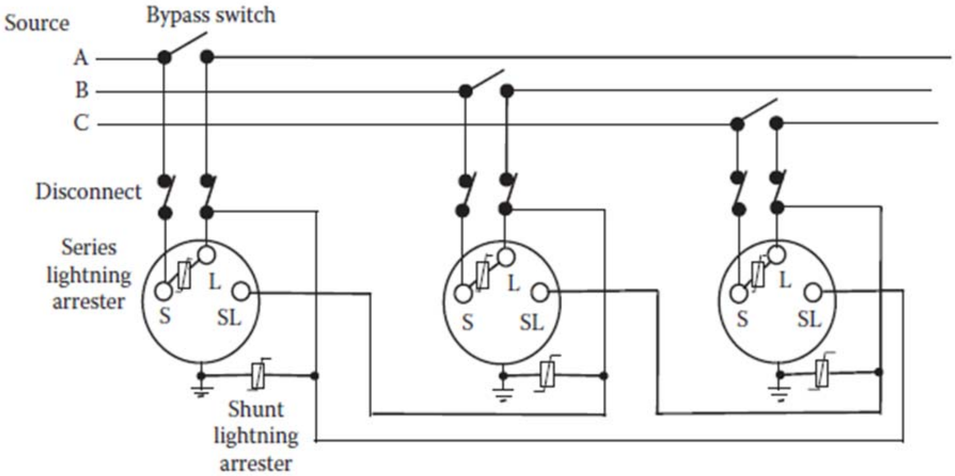


Figure 4.24. Connection of three SVRs in a three-phase, three-wire delta circuit (Colopy, 2012)

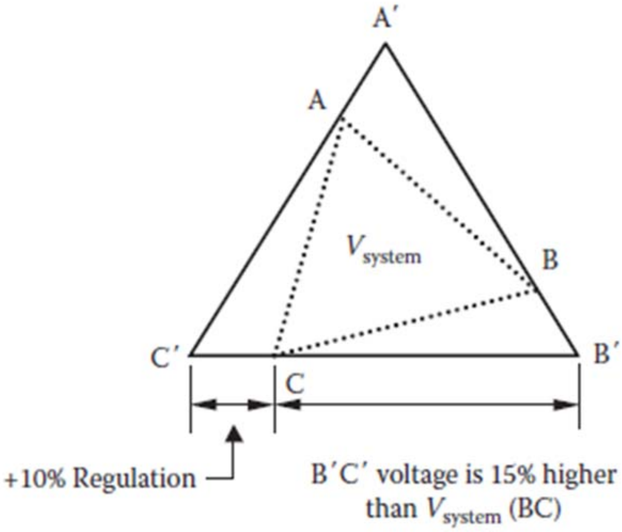


Figure 4.25. Phasor diagram of closed-delta-connected SVRs

When any regulator works, voltage value of other two regulators will be affected. Hence, there is a necessity to make extra tap changes in order to maintain the voltage balance. On the other hand, in delta connections (open or closed), a 30 ° phase shift occurs between the voltage and current of the regulator. These causes arcs on the tap changer's contacts and consequently reduction in their life (Colopy, 2012).

4.9. KVA Ratings

In order to select the most suitable voltage regulator for a system, the kVA rating of the regulator have to be calculated correctly. To find the KVA rating value, it is necessary to have the following listed data;

- Connection type (wye or delta) of regulator to the system
- Which type regulator is going to be used (single or three phase)
- Line or feeder kVA rating or load current
- Needful voltage regulation magnitude

According to above information, the kVA rating of the regulator can be calculated by the Equation (4.42).

$$\text{Rated kVA} = \text{Rated Load Current (A) x Regulation Range (kV)} \qquad (4.42)$$

To explain this equation with an example; suppose there is a voltage regulator with a regulation range of 10%, to be connected to a single-phase 4,800 V line-to-ground circuit and rated load current is 250 A. The rated kVA of this regulator is;

$$\text{Rated kVA} = 250\text{ A} \times (0.10 \times 4{,}800\text{ kV}) = 120\text{ kVA}$$

In case that the load rated current value is unknown and the rated kVA value is known, the current can be determined Equation (4.43) and (4.44) according to type of circuit is single or three phase. For single phase, Equation (4.43) can be used.

$$\text{Rated Current} = \frac{\text{Rated kVA}}{\text{Rated kV (line} - \text{ground)}} \qquad (4.43)$$

For three phase, Equation 4.43 can be used.

$$\text{Rated Current} = \frac{\text{Rated kVA}}{\sqrt{3}\ \text{x Rated kV (line} - \text{line)}} \qquad (4.44$$

Rated voltages and currents according to various voltage values and connection types are listed in Table A.1 in Appendix A according to IEEE Std C57.15-2009-IEEE (IEC 60076-21) and NBR 11809/1992 standards. This table is created by accepting ±10% voltage regulation range (Colopy, 2012).

4.10. Step Voltage Regulator Control System

Voltage regulator uses Line Drop Compensation method for maintaining load voltage at desired level. LDC is used for compensating voltage drop on the line. During this operation, there is no need any communication connection. LDC calculates line voltage drop between transformer and load by using the current and voltage of transformer secondary side. Basic Operation of LDC is shown in Figure 4.26.

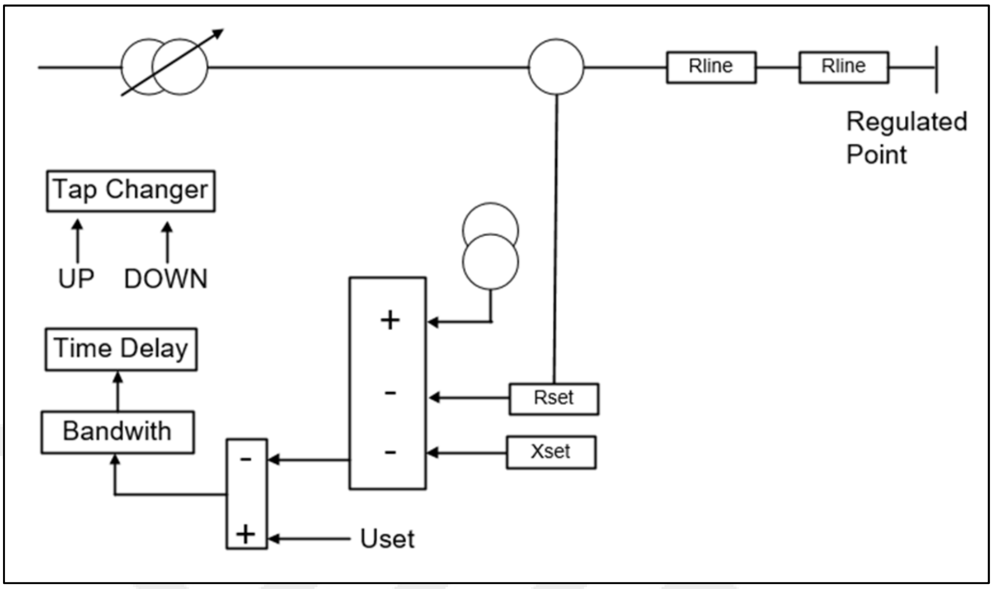


Figure 4.26. Basic operation of LDC

There are four setting parameters for controlling voltage by LDC method with SVR.

- Voltage set point: The intended voltage value to be kept at the output
- Bandwidth: the permissible voltage range to be regulated.
- Time Delay: the time allowed for the tap change to start, if the measured output voltage is out of the specified range.
- Line Drop Compensator settings

4.10.1. Voltage Set Point

V_{SET} is the setting value of the desired load voltage which is needed to be observed at load side. The parameters that determine the set voltage are the regulator rating value and the feeder voltage. It is on a 120 V base. This set point voltage can be find with following equation;

$$\mathrm{V} = \frac{\text{Distribution Transformer Ratio}}{\text{Regulator VT Ratio}} \text{ x } 120 \tag{4.45}$$

If the distribution transformers’ ratio is 7800/120, thus a ratio will be 65:1. If the regulator VT ratio is 60:1, the set point voltage will be obtained by equation-(4.44);

$$\mathrm{V} = \frac{65}{60} \text{ x } 120 = 130$$

4.10.2. Time Delay

The time that the controller waits from the moment when the line voltage exceeds the limit values until the start of the tap change operation is called time delay and is expressed in seconds. Some of the voltage problems occur momentarily and then disappear. There is no need to change the tap in these short-term temporary voltage events. By setting a time delay, for example 20 s, the regulator is prevented from reacting unnecessarily to these transient events, thereby enabling tap change only during long-term voltage variations. Applications to date show that this time delay should be at least 15 seconds. This minimum time is determined to cover the time such as starting the motor, faults, etc.

Another purpose of using the time delay is to control effectively more than one voltage regulators connected in series on the same network. Generally, in a distribution system, regulator mountings are made at certain intervals starting from the substation in order to compensate the voltage on the feeder. In addition, line regulators can be mounted out on the main line for regulating significant loads. The voltage regulator on the substation should first interfere in the voltage variations in the feeder. The line regulator should deal with the regulation in its region while the line regulator should adjust as required for its particular region. To do this, the time delay of the voltage regulator on the substation side should be lower than the line regulator. It will then react earlier and regulate the voltage within its limits. If this regulator achieves to bring the line voltage within the desired range, there is no need operation of other regulators. Thus, this coordination results efficient operation. It is recommended that there should be at least 15 seconds between operations of the two regulators. An example of setting the time delays in a distribution system with multiple regulators is given in Figure 4.28 (Colopy, 2012).

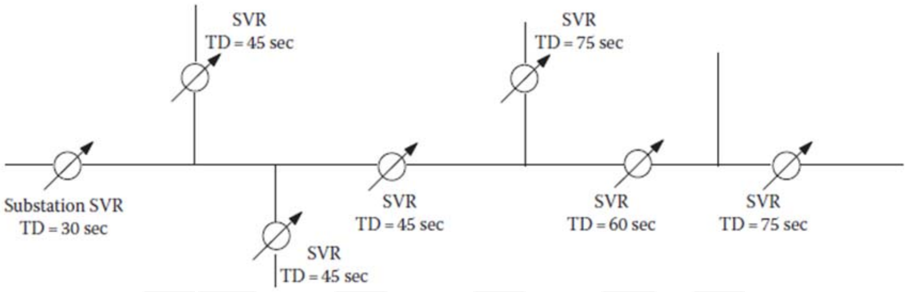


Figure 4.27. Cascading single phase voltage regulators (Colopy, 2012)

4.10.3. Deadband

LDC adjusts the load voltage VL to VSET by changing the tap position of the VR considering the deadband in distribution lines. Deadband is the allowable range of the voltage control relay and it is commonly chosen between %1 and %3 of the base voltage. The taps can only be changed when the relay voltage is not within the bandwidth. For example, if the set point voltage is 230 V and the deadband is 4 V, tap will not change between 228 and 232 V.

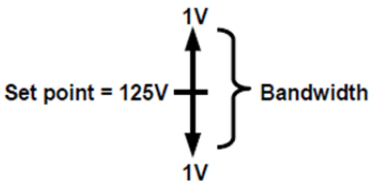


Figure 4.28. Bandwith of SVR

In order to maintain V_L at desired value, voltage regulator alters the tap position in case of two different scenarios; the subtraction of V_S and V_D is higher than the sum of V_{SET} and deadband, or lower than the subtraction of V_S and deadband as shown below (Kersting, 2009),

$$V_S - V_D > V_{SET} + \text{Deadband} \tag{4.46}$$

or

$$V_S - V_D < V_{SET} - \text{Deadband} \tag{4.47}$$

4.10.4. Line Drop Compensator Settings

Line Drop Compensator is used for adjusting the voltage regulator taps in order to maintain the line voltage at the desired level. A simple circuit model of a compensator can be seen in Figure 4.30 (Romero, 2010).

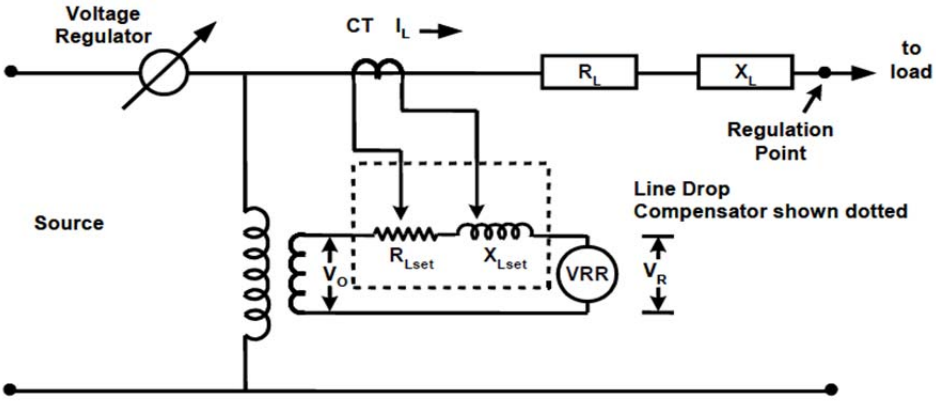


Figure 4.29. Line Drop Compensator Settings (Davis et al., 2007)

The voltage regulation relay (VRR) is used to turn back the regulator to a set voltage value after a voltage variation. A low voltage is read on the VRR relatively to the load current and power factor. When the VRR is set correctly, the regulator output voltage and the set point will be the same, in case of no load current. The main basis of LDC can be shown in Figure 4.30. Load voltage (V_L or

V_R) is not equal to bus voltage (V_0) from the VT. The reason of this difference is voltage drop on the line. The voltage drop (V_D) is the vectorial sum of the voltage phasors I_R and I_X (Davis et al., 2007).

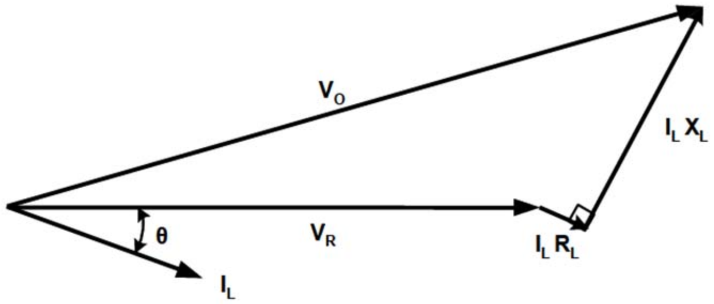


Figure 4.30. Phasor Diagram for LDC

$$V_L = V_S - V_D \approx V_S - I_L Z_{SET} = V_S - I_L(R_{SET} + JX_{SET}) \tag{4.48}$$

$$V_L = V_0 - V_D \approx V_0 - I_L Z_{SET} = V_0 - I_L(R_{SET} + JX_{SET}) \tag{4.49}$$

where V_L and V_S are actual load and transformer secondary side voltages, I_L is the line current, R_{SET} and X_{SET} are compensator's R and X settings. V_D is the voltage drop in the network. θ is the power factor angle of the load current from the CT. By using above equation, the regulation point voltage (V_R) or the voltage across the VRR is obtained (Kersting, 2009).

R_{SET} and X_{SET} setting values are input in units of volts and they can be determined by using following formulas;

$$R_{SET} = \frac{N_{CT}}{N_{PT}} R \tag{4.50}$$

$$X_{SET} = \frac{N_{CT}}{N_{PT}} X \tag{4.51}$$

Where R is the line resistance (ohms), x is the line reactance (ohms), NCT is the current transformer primary rating and NPT is the potential transformer ratio. When choosing CTP, it should be ensured that it must be equal or bigger than the minimum nominal line current value.

5. MODELING OF CONVENTIONAL AND ACTIVE SVRS

This chapter will focus on the design and simulation of conventional and active Step Voltage Regulators. Conventional SVRs are examined as mechanical tap changers. Active SVRs are examined as electronic tap changers and Matrix Converters in this thesis study. For all three SVR models, the common simple model system shown in Figure 5.1 is designed.

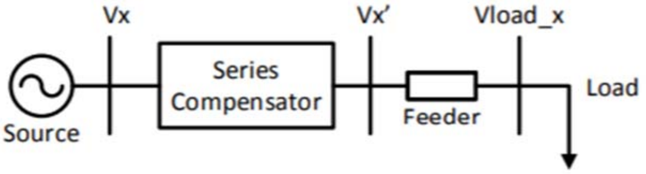


Figure 5.1. Simple SVR model

The phase voltage Vx' after series compensation is as follows:

$$\overline{V_x'} = \overline{V_x} + \overline{\Delta V_x}$$

Denklemi buraya yazın.

Simulations are performed in MATLAB/Simulink to observe performance of the design models. The simulation models consist of an AC source, distribution line, SVR and a load. Different simulation models are designed for conventional and active SVRs.

5.1. Modeling and Simulation Design of Mechanical Tap Changer Based SVR

In this section, mechanical tap changer based SVR is modeled on a single-phase distribution line as shown in Figure 5.2.

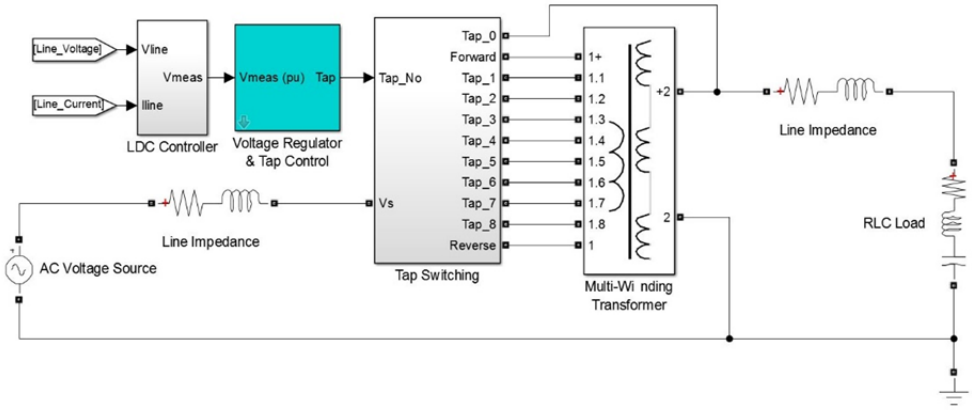


Figure 5.2. Single phase conventional SVR model

The structure of the conventional SVR model consists of four basic parts as shown in Figure 5.2. These are LDC Control unit, tap control unit, switches for realizing tap changing operation and a transformer which output varies according to number of steps.

5.1.1. LDC Control Unit

LDC unit calculates the voltage decrease or increase along the line and sends this measurement information to the voltage regulator. The block diagram of its operation is explained in detail in chapter 4. The simulation model is shown in Figure 5.3.

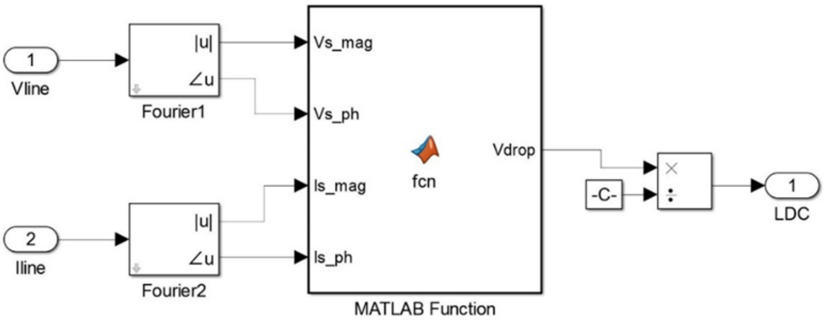


Figure 5.3. Modeling of LDC unit

In order to obtain voltage decrease or increase, the LDC function is written. This LDC function needs a line voltage and current value. The incoming line voltage and current information is separated into phasors and magnitudes by Fourier analysis. In addition, the line impedance value and the rms value of the nominal line voltage has to be entered in the code. The LDC function uses this information to calculate the voltage increase or decrease along the line. This calculation is done according to following function code. In the code Vload_nomrms represent the reference voltage (V_{ref}). The difference between V_{ref} and the calculated load voltage is determine the voltage variation in the line.

```
function Vdrop  = fcn(Vs_mag, Vs_ph, Is_mag, Is_ph)
%#codegen
Rline = 20*0.196;
Xline = 2*pi*50*20*1.44e-3;
Zline = Rline + i*Xline;
Vs = (Vs_mag/sqrt(2))*cosd(Vs_ph) + i*(Vs_mag/sqrt(2))*sind(Vs_ph);
Is = (Is_mag/sqrt(2))*cosd(Is_ph) + i*(Is_mag/sqrt(2))*sind(Is_ph);
Vload_calcrms = abs(Vs - (Is*Zline));
Vload_nomrms = 34500/sqrt(3);
Vdrop =  Vload_nomrms - Vload_calcrms;
```

5.1.2. Voltage Regulator and Tap Changer Control Unit

In order to control tap changing operation according to receive voltage difference value from LDC Unit, the simulation model shown in Figure 5.4 is used. This block is used in “Three-Phase On-Line Tap Changing Regulating Transformer” model which is available in Matlab Simulink SimPowerSystems library. This block models of a voltage regulator that controlling tap positions of a regulating transformer.

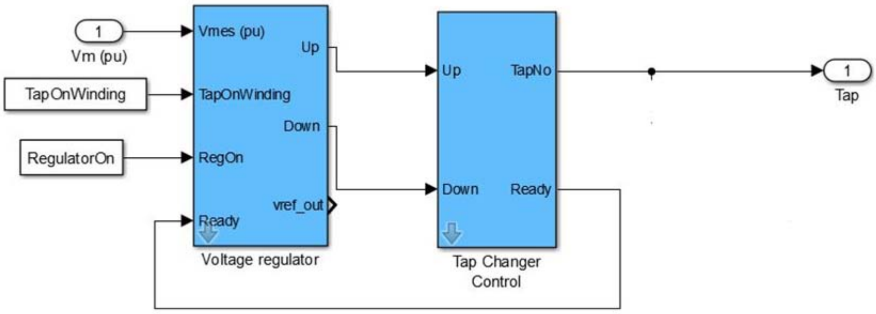


Figure 5.4. Modeling of tap changer control unit

There are some required parameter values must be entered before starting the voltage regulator. These parameters are shown in Figure 5.5.

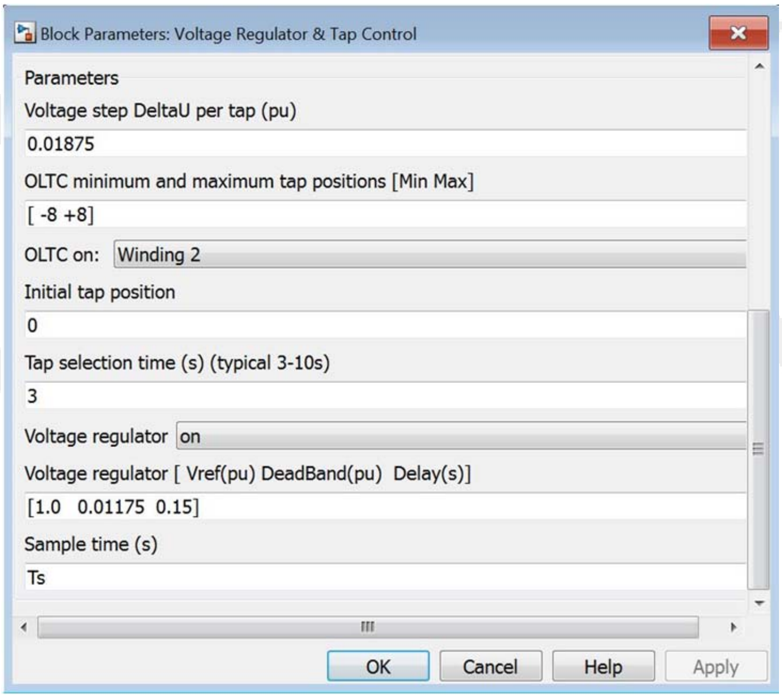
The ‘Voltage Step DeltaU per tap (pu)’ parameter defines that each step change corresponds how many volts in pu. This value is determined by using the voltage compensation range of regulator and ‘OLTC minimum and maximum tap positions’ which is another required parameters. If the regulation range of the regulator is ±15% and the minimum and maximum tap position is -8 and +8, the ΔU will be;

$$\text{Max. Regulation Range} = \Delta\text{U} * \text{ Max Tap Position}$$

$$\Delta\text{U} = \frac{0.15}{8} = 0{,}01875$$

‘Initial tap position’ must be defined before starting. ‘0’ is the neutral position of the regulator. 'Tap selection time' parameter specifies the time to change tap by one position. Typical 3-10 seconds selection time obtained with mechanical tap changers.

The voltage regulator is in service if 'Voltage regulator' parameter = 'on'. The target voltage value must be entered as the reference voltage ‘V_{ref}’ in pu. Deadband and time delay are another required parameters.



Block Parameters: Voltage Regulator & Tap Control

Parameters

Voltage step DeltaU per tap (pu): 0.01875

OLTC minimum and maximum tap positions [Min Max]: [-8 +8]

OLTC on: Winding 2

Initial tap position: 0

Tap selection time (s) (typical 3-10s): 3

Voltage regulator: on

Voltage regulator [Vref(pu) DeadBand(pu) Delay(s)]: [1.0 0.01175 0.15]

Sample time (s): Ts

Figure 5.5. Matlab block parameters of SVR

The voltage regulator selects the appropriate tap position in order to maintain signal applied at the ‘V_{meas}’ input at the specified reference value (V_{ref}) within the specified deadband. The voltage regulator asks for a tap change if;

Abs(V_{LDC}) > Deadband/2 during a time t > Delay

According to result of above condition, regulator determines the tap operation direction, up or down. The flowchart of this block function is shown in Figure 5.6.

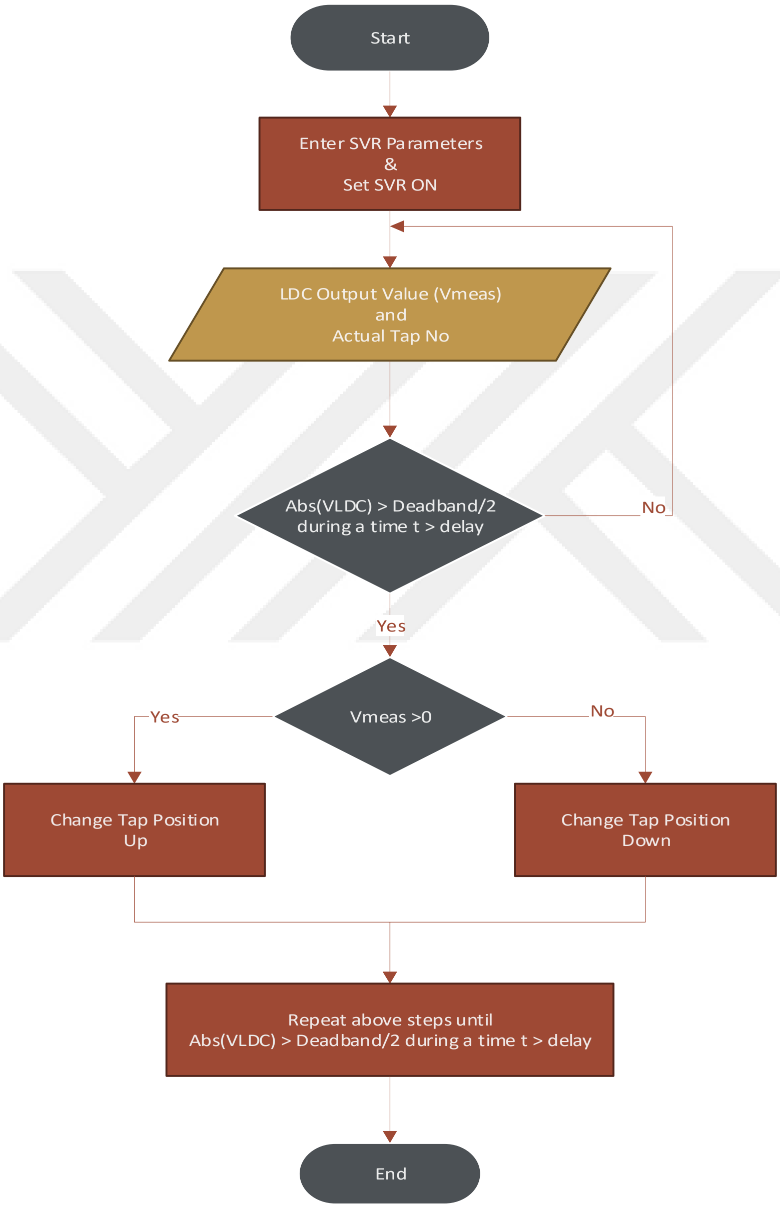


Figure 5.6. The flowchart of SVR operation

The simulation parameters of voltage regulator that used in this thesis work are as follows;

Table 5.1. Voltage Regulator setting parameters for mechanical tap changer SVR

Voltage Regulator Settings	
Regulation Range	15%
Voltage Step DeltaU per Tap (pu)	0,01875
Minimum and Maximum Tap Positions	Min -8 , Max +8
Inital Tap Position	0
Vref (pu)	1
Tap Selection Time (s)	3
DeadBand (pu)	0,02
Delay (s)	0,15

5.1.3. Transformer and Tap Switches Modeling

As explained detailed in Chapter 4, there are two types of SVR; Type-A and Type-B. The SVR model used in this thesis is constructed by using two winding transformer as shown in Figure 5.7. Type-B SVR, which has a wider application area, is used in the designed models. In this type of SVR series winding is placed on the source side. When modeling the transformer, the series winding is divided into equal taps and these taps are designed to change the turn ratio of the transformer according to the selected tap value received from the SVR control unit.

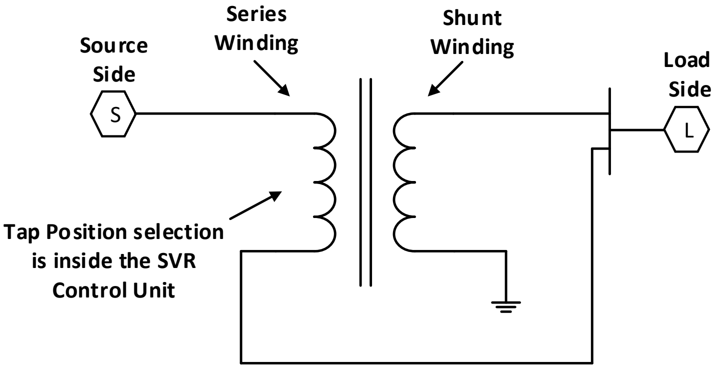


Figure 5.7. Type-B SVR model

A single phase multi-winding transformer is used for each phase in the simulation model as shown in figure 5.8. The three transformers are connected in grounded wye.

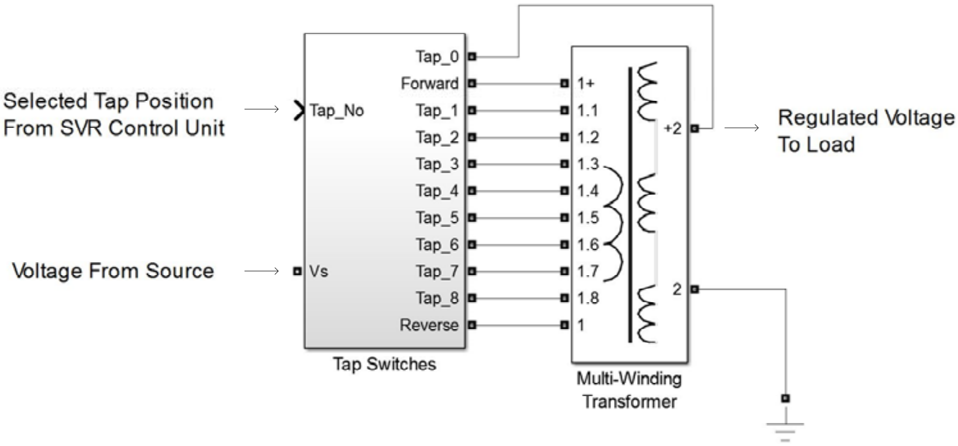
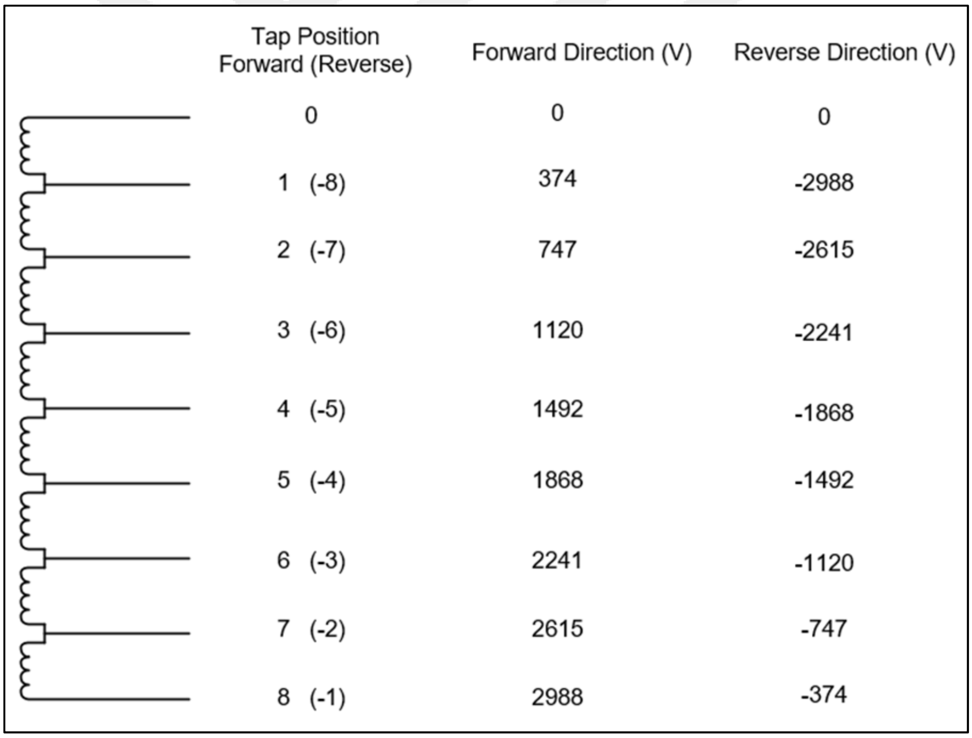


Figure 5.8. Matlab model of transformer and tap switches block

In each transformer, series winding is divided into 8 equal parts. In order to obtain ±15% voltage regulation in this designed system, the voltage value corresponding to each tap is shown in Figure 5.9 according to selection switch position. This figure shows the amount of voltage that SVR injects to the system for each step. In the network design, the source voltage value is determined as

34500 $V_{L\text{-}L}$. This value corresponds to 19920 $V_{L\text{-}N}$. As mentioned above, the series winding is divided into 8 equal parts and voltage compensation can be done in reverse direction with reverse switch, hence there are a total of 17 tap positions (16 tap position plus neutral ‘0’). SVR injects a voltage of 19920 V x 2% = 2988 V during a voltage regulation of + 15%. There are 8 tap positions in positive direction. Therefore, each step corresponds to 2988/8 = 374 V. Likewise, for a voltage regulation of -15%, the line must be injected with -2988 V and each tap change corresponds to -374 V. Each tap implements a voltage regulation of ±0.01875 pu. Thus, a total of 17 tap positions, including tap 0, allow a voltage variation from 0.85 pu to 1.15 pu by steps of 0.01875 pu.



Tap Position Forward (Reverse)	Forward Direction (V)	Reverse Direction (V)
0	0	0
1 (-8)	374	-2988
2 (-7)	747	-2615
3 (-6)	1120	-2241
4 (-5)	1492	-1868
5 (-4)	1868	-1492
6 (-3)	2241	-1120
7 (-2)	2615	-747
8 (-1)	2988	-374

Figure 5.9. Transformer tap voltages

The simulation parameters of transformers that used in this thesis work are as follows;

Table 5.2. Transformer Setting Parameters

Multi-Winding Transformer Parameters	
Nominal Power	2 MVA
Primary Phase to Phase Voltage	1992 V (rms)
Secondary Phase to Phase Voltage	19920 V (rms)
Turns Ratio	10
Base Operation Frequency	50 Hz
Primary Winding Resistance	10 mΩ
Secondary Winding Resistance	1 Ω
Primary Winding Inductance	0,126 mH
Secondary Winding Inductance	1,26 mH
Connection	50
Magnetization Resistance	90 Ω
Magnetization Reactance	0,31 H
Number of Taps (equally spaced)	8

In the simulation model, mechanical switch is modeled as shown in Figure 5.10 for each tap. The operation time of this mechanical switch is defined in the parameter setting of the voltage regulator. A reactor is used for limiting circulating current during tap changing operation as explained in Chapter 4. The reactor used in the simulation model consists of a resistor and an inductor. The parameter values of this resistor and inductor are 50 mΩ and 10μH.

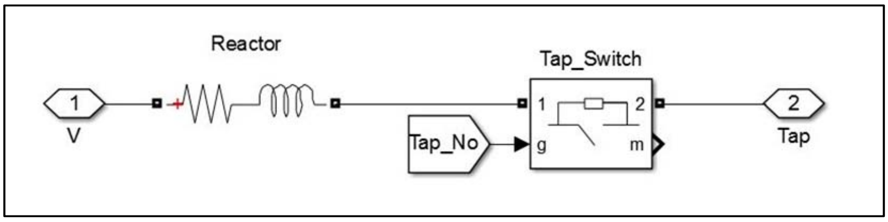


Figure 5.10. Mechanical tap switch simulation model

All tap switches are placed in the 'Tap switches' block that is shown in Figure 5.8. According to the received tap change command from the SVR control unit, related switches turn on. The important point here is that the taps increase or decrease in sequence in mechanical tap changers based SVRs. It is not possible to skip to the adjacent tap. Therefore, only one switch can be turned on at a time. Considering that each step change (approx. 3-10 s), this constraint makes the time required for the regulation too long.

5.2. Modeling and Simulation Design of Electronic Tap Changer Based SVR

In this section, electronic tap changer based SVR is modeled on a single-phase distribution line. The same model is used with mechanical tap changer as shown in Figure 5.2.

LDC Unit, Voltage Regulator and Tap Changer Control Unit of electronic tap changer based SVR are same with the mechanical tap changer based SVR. The only difference in this units tap selection time of regulator. While the tap selection time is 3 s in mechanical tap changer based SVR, this time is 0.02 s in electronic tap changer based SVR. All other parameter settings are same in two models for above units.

Table 5.3. Voltage Regulator setting parameters for electronic tap changer SVR

Voltage Regulator Settings	
Regulation Range	15%
Voltage Step DeltaU per Tap (pu)	0,01875
Minimum and Maximum Tap Positions	Min -8 , Max +8
Inital Tap Position	0
Vref (pu)	1
Tap Selection Time (s)	0.02
DeadBand (pu)	0,02
Delay (s)	0,15

The main difference between these two models is the switch type used in the ‘Tap switches’ block. In this model, the mechanical switch is replaced with the power electronics switch. Thyristor is used as the power electronics switch. An electronic tap switch based thyristor simulation model is designed as shown in Figure 5.11.

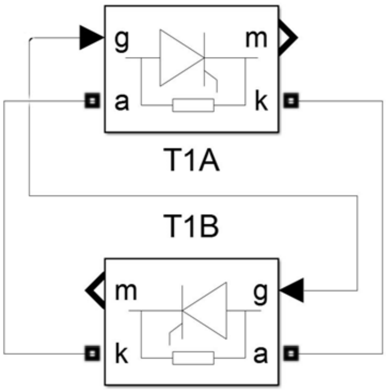


Figure 5.11. Thyristor tap switch Matlab model

5.3. Modeling and Simulation Design of Matrix Converter Based SVR

MC is a direct AC to AC power converter device, which is used semiconductor switches without necessity of any dc link or power storage component. The MCs have more advantages than conventional AC/AC converters, which have rectifier stage. MC perform conversion with sinusoidal input and output waveforms. It limits higher order harmonics. Power flow in MC is bi-directional, because of this controlling of input power factor is easier. Absence of limited energy storing capacitors provides MCs to use minimal energy storage equipment. On the other hand, there are some disadvantages of MC. Its input/output voltage transfer ratio is limited max. to 87 %. (Ronald, Sheela, & Mary, 2013)

MCs can be classified in two types based on a number of phases; three phase MC and Single phase MC. In this thesis, single phase MC is used in simulation models.

In this section, MC based SVR is modeled on a single-phase distribution line as shown in Figure 5.12.

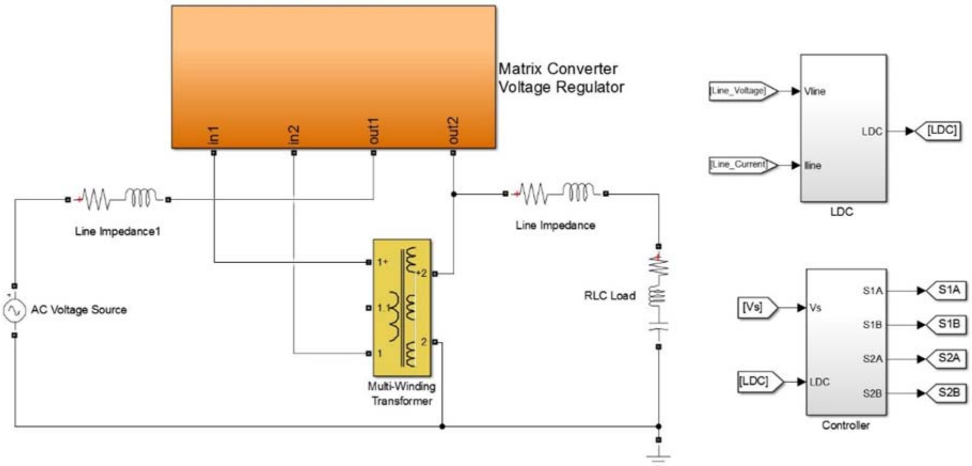


Figure 5.12. Single phase Matrix Converter based SVR Matlab model

5.3.1. Single Phase Matrix Converter

One of the main concerns of electrical engineering is controlling and converting of electrical energy. Nowadays, these requirements have become more complex due to the increase in consumer needs about power quality and load diversity. In order to control and transform AC power, a new type of converter called Matrix converter was developed which has a very simple and compact structure (Sreenivasulu, Kumar, & Vyjayanthi, 2016).

Single-phase matrix converter is a direct AC-AC conversion device that fed from a single-phase constant voltage and frequency AC supply and provide a single-phase output waveform at the desired magnitude and frequency at the output. It is a forced commutated converter. The single-phase matrix converter topology is shown in Figure 5.13.

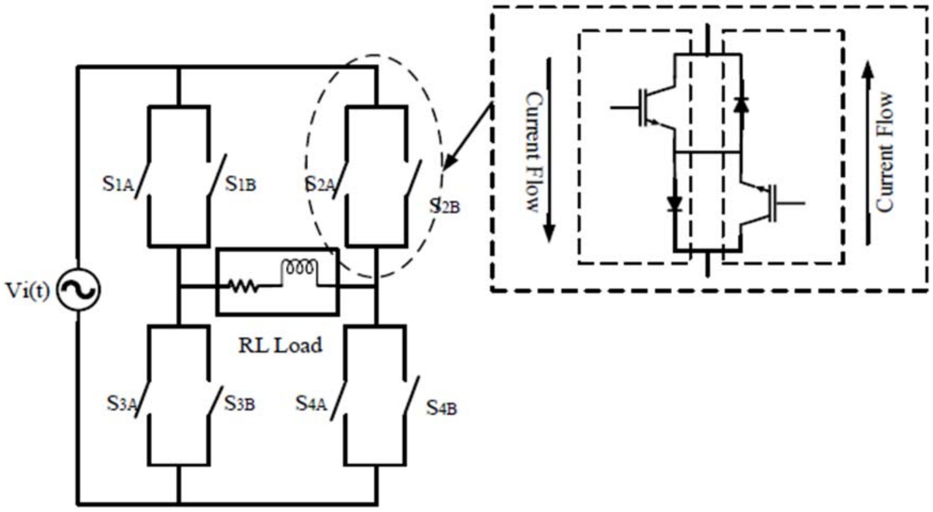


Figure 5.13. Single phase matrix converter circuit (Sidharth, Sonar, & Bhullar, 2017)

The structure of the SPMC composes of four bidirectional switches. These controlled switches create a 2x2 array. The probable switch states of the single-phase matrix converter can be represented in the form of a matrix, as in the case of three-phase matrix converters, thus it is called matrix converter.

The input and output voltage equations of the SPMC (Zuckerberger, Weinstock, & Alexandrovitz, 1997) are given by following equations considering the load.

$$v_i(t) = \sqrt{2}\, V_i \sin w_i t \tag{5.6}$$

$$v_0(t) = \sqrt{2}\, V_0 \sin w_0 t \tag{5.7}$$

$$v_0(t) = R\, i_0(t) + L\, \left(\frac{i_0(t)}{dt}\right) \tag{5.8}$$

where ‘i’ represents input and ‘o’ represents output (Hanafi, Idris, Hamzah, & Saparon, 2006).

Common emitter bidirectional switch is one of the most preferred and practical switch configuration for Matrix Converters. This type bidirectional switch composes of 2 diodes and 2 IGBT switches connected in anti-parallel arrangement. The reason of using IGBT and diode is IGBT’s fast switching feature, and diode’s reverse blocking feature.

Every bidirectional switch could block voltage and conduct current in forward and reverse direction. During forward direction, S1a is switched ON and current flows through on it. During reverse direction, S1b is switched ON and current flows through on it. In each direction, respective diode is forward biased.

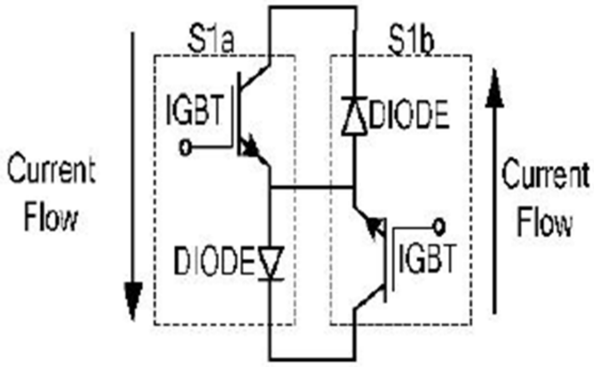


Figure 5.14. Bidirectional Switch (Hanafi et al., 2006)

As previously described, in order to achieve power conversion, there are several power converters like voltage regulators, cycloconverters, choppers, rectifiers and inverters. All this converters have different circuit configurations. Single phase Matrix Converter is a power converter that achieve all these power conversions with a single circuit. Thus, it provides an advantage in terms of weight, size and cost reduction (Hanafi et al., 2006).

5.3.2. SPMC as an AC Voltage Regulator

Fixed AC voltage can be converted to variable AC voltage without changing frequency by AC voltage regulator. Output voltage can be controlled by changing modulation index value. During positive half cycle, switches S1a and S4a switched ON to obtain positive output voltage. During negative half cycle, switches S1b and S4b switched ON to obtain negative output voltage. The circulations of current for this operation are shown in Figures 5.16 and 5.17.

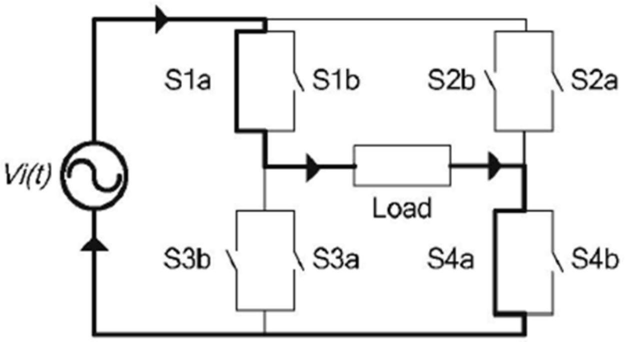


Figure 5.15. SMPC as AC voltage regulator, positive half cycle (Hanafi et al., 2006)

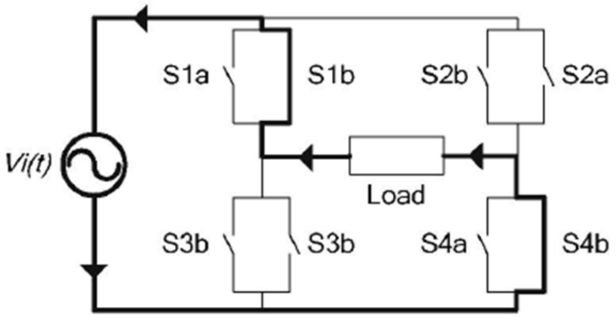


Figure 5.16. SMPC as AC voltage regulator, negative half cycle (Hanafi et al., 2006)

5.3.3. The bidirectional switch realization

Matrix converters needs to use bi-directional switches that conduct current in both directions and have the ability to block reverse voltages. Nowadays, bidirectional switches can not be still produced as a single semiconductor switch element. The bidirectional switch structure is realized with combinations of conventional one-directional semiconductor switches (Li, 1998; Xu, Plikat, Constapel, Korec, & Silber, 1997). In general, bidirectional switches are classified in three groups:

- Diode Bridge Bidirectional Switch
- Bidirectional Switches With Parallel Arrangement
- Bidirectional Switches With Series Arrangement (Common Emitter and Common Collector)

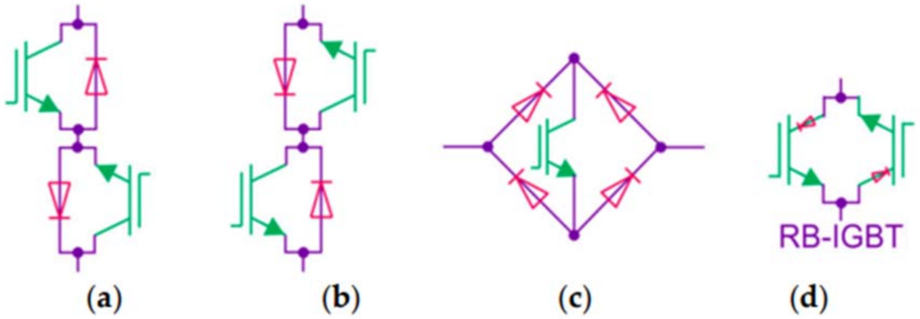


Figure 5.17. (a) common emitter, (b) common emitter, (c) diode bridge, (d) reverse block-IGBT (Szczesniak, 2019)

Controlled semiconductor switches such as IGBT, MOSFET, MCT and IGCT can be used to create these structures. IGBT is most preferred semiconductor switch in all bidirectional switch configurations, because it has high switching abilities and it is able to carry high current through on it (Hanafi et al., 2006). In this thesis, IGBTs and diodes are used in common emitter bidirectional switches with series arrangement, as shown in Figure 5.18 (c), for modeling of Matrix Converters. This arrangement provides independent control of current direction.

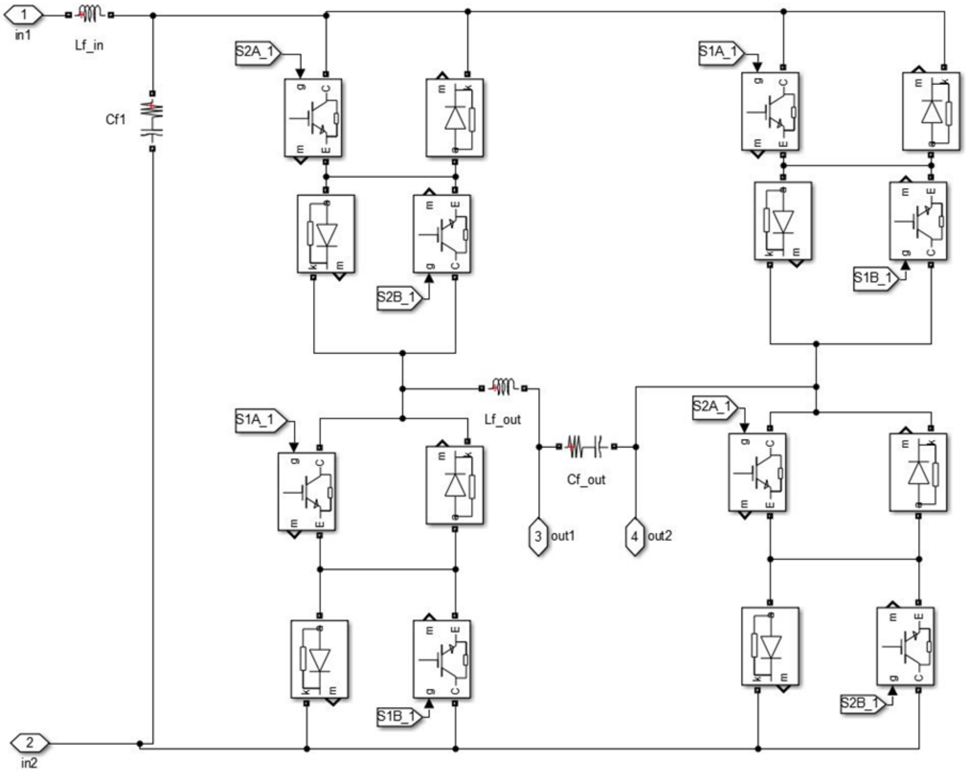


Figure 5.18. Simulation model of MC bidirectional switch arrangement

5.3.4. Input / Output Filters

The input and output filters act as interfaces between the AC network and the matrix converter as shown in Figure 5.20. The filters are used for smoothing the input current and fulfilling the necessities of Electro Magnetic Interference (EMI).

The main feature of the input filter is to prevent significant variations in the input voltage of the MC while each modulation signal and to prevent undesired harmonic currents flowing towards the AC network (Alesina & Venturini, 1989). In addition, the input voltage and current will not be affected by a rapid change in noise in the output switch by using the input filter. This filtering accomplished by adding a small LC filter between the MC and the network as shown in Figure 5.20.

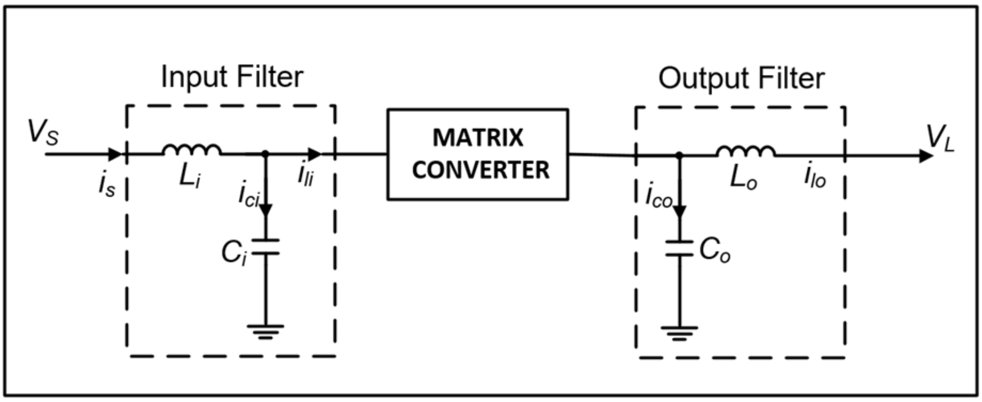


Figure 5.19. Input and Output Filter of Single Phase Matrix Converter

5.3.1. Controller of Matrix Converter Based Voltage Regulator

In this section, the controller of the Matrix Converter based voltage regulator will be modeled. Sinusoidal pulse width modulation (SPWM) is used to obtain the gate signals applied to the switches. Clarke-park transformations and PLL technique are used to generate the reference signal used in SPWM.

5.3.1.1. Sinusoidal Pulse Width Modulation

Pulse width modulation (PWM) is a commonly used method to control the output of AC-AC converters. PWM has low sensitivity to noise and voltage changes. PWM technique helps to reduce harmonics in output voltage. The aim of this technique is to compare the reference wave with the triangular carrier wave to obtain desired output voltage. When the reference voltage waveform is greater or smaller than the carrier waveform, a positive or negative DC voltage is generated. This obtained output DC voltage is equal to the rms value of the AC waveform, thus PWM operation does not cause harmonic deterioration. Square wave PWM and Sinusoidal PWM (SPWM) are two of the most applied PWM techniques in

AC-AC power converter applications (Ahirrao, Gaware, Kakade, Kharade, & Chawda, 2014). In this thesis, SPWM is used to obtain gating pulses applied to bidirectional switches.

SPWM is based on a comparison of high frequency triangular carrier wave and low frequency reference sine wave. The number of pulses produced per each cycle is determined by modulation ratio (M_r). M_r is obtained by the following formula,

$$\mathrm{M_r} = \frac{\text{Frequency of carrier waveform}}{\text{Frequency of modulating waveform}} \tag{5.9}$$

Figure 5.22 shows how SPWM is obtained; Figure 3.3 shows SPWM-a and SPWM-b output waveforms and determination switching moments.

The intersection points of these two waves determine the switching moments. The carrier waveform determines the number of pulses to be generated during each half period. Switching frequency of the system is equal to carrier wave frequency. The ratio of the amplitude of the reference signal (Vr) to the amplitude of the carrier signal (V_c) gives the modulation index (M_i) as given in Equation 5.10. The output voltage amplitude is proportional to Mi. Thus, the output voltage amplitude can be controlled by changing the M_i (Zahirrudin Idris, Hamzah, & Hamzah, 2005; Zahiruddin Idris, Hamzah, & Omar, 2005).

$$\mathrm{M_i} = \frac{\mathrm{V_r}}{\mathrm{V_t}} \tag{5.10}$$

The increase in the modulation index as described above increases the amplitude of the output voltage. However, the inductive elements in the AC grid or the load prevent the high-frequency components with high carrier from spreading significantly. Hence, the increase in carrier frequency results in increasing the number of switching in each cycle. In parallel, the loss of power also increases. In general, the switching frequencies between 2-15 kHz are sufficient for most applications.

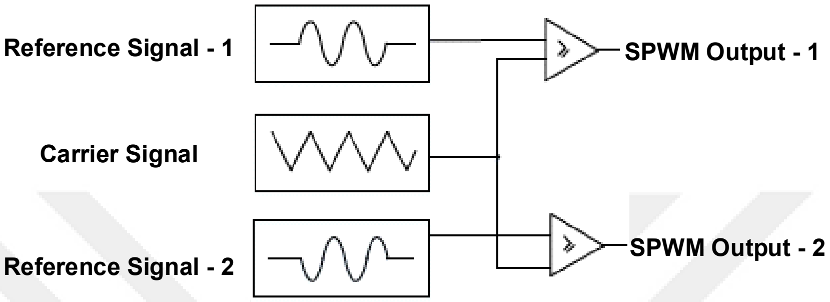


Figure 5.20. Connection diagram of obtaining SPWM

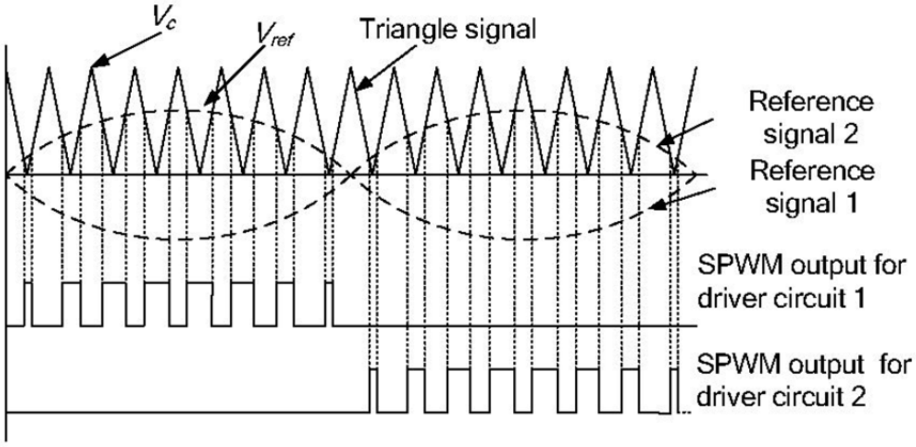


Figure 5.21. Waveform of SPWM operation (Hanafi et al., 2006)

The PWM technique performs its function well as long as m≤1. If m> 1, there will be periods that there is not intersection point of the carrier waveform and reference signal as shown in Figure 5.22. This is called over-modulation. This is sometimes allowed to obtain higher AC output voltage, although the voltage's spectral content is slightly weakened (Ahirrao et al., 2014).

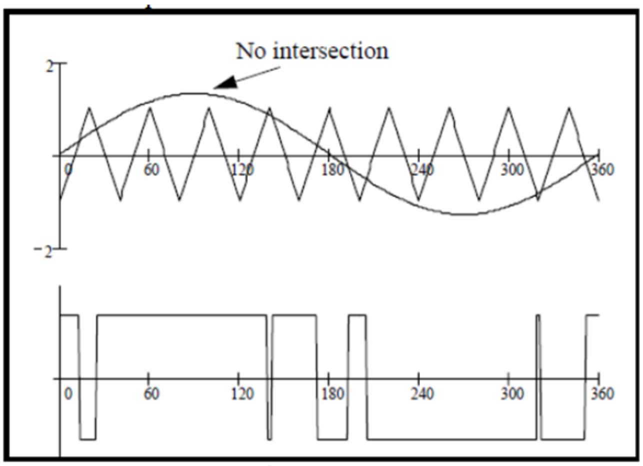


Fig.7 SPWM

Figure 5.22. Over- modulation of SPWM (Ahirrao et al., 2014)

5.3.1.2. Generating Gate Signals

Proper generation of gate signals has a major impact on the performance of the matrix converter. Hence, the reference signal must be generated correctly. In this thesis work, the method shown in Figure 5.28 is used to generate a reference signal.

Clarke and park transformations are used for representing three phase ac signals transformed into two dc quantities in order to reduce complexity of the system with dc values instead of ac values. Clarke transformation is performed first. As a result of the Clark transformation, the three phase balanced AC signal component is transferred to the complex plane and its projections on α (real) and β (imaginary) axes are obtained. Since single phase SVR structures are used in this thesis, a virtual β is created with Clarke transform to simulate three phases.

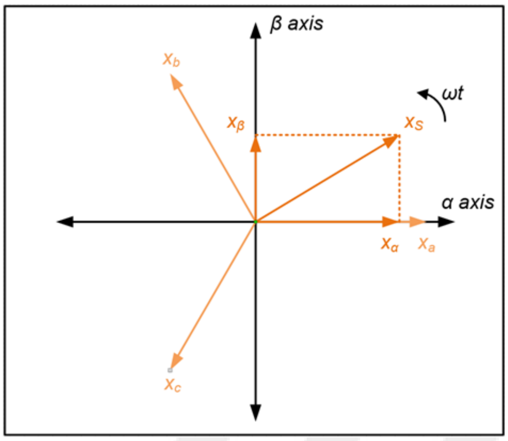


Figure 5.23. Geometrical representation of Clarke transformation (Tan, 2015)

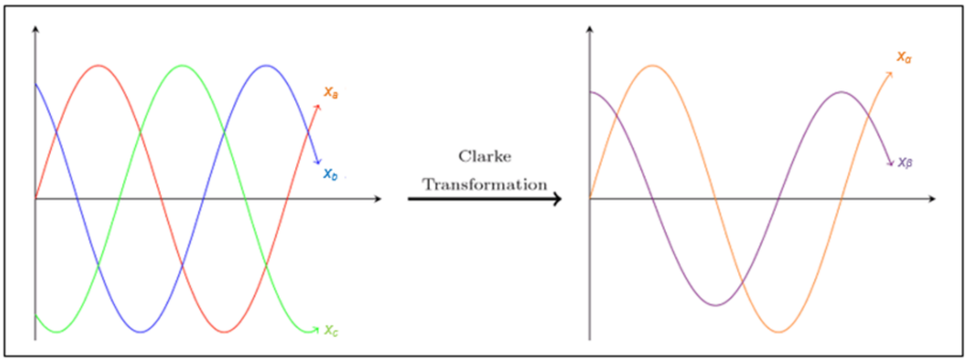


Figure 5.24. Clarke Transformation

PLL block is used for obtaining angular velocity of ac signals. Park transformation is the process of obtaining the dq rotating frame by rotating the αβ stationary frame by the angular velocity of the ac signals. Thus, ac signals transformed into two dc quantities (Tan, 2015). This process is shown in Figure 5.28.

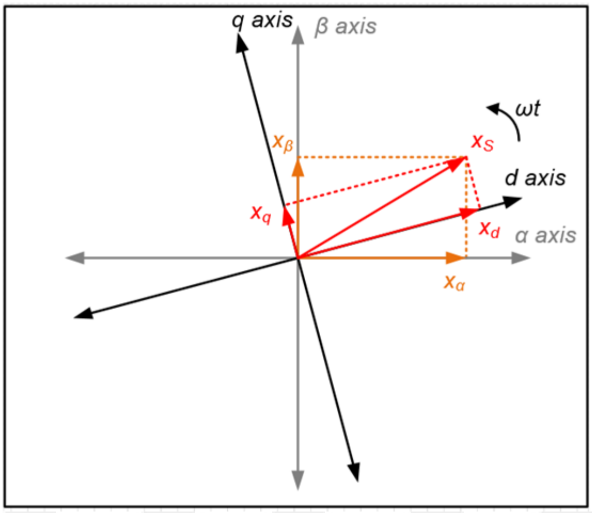


Figure 5.25. Geometrical representaion of Park transformation (Tan, 2015)

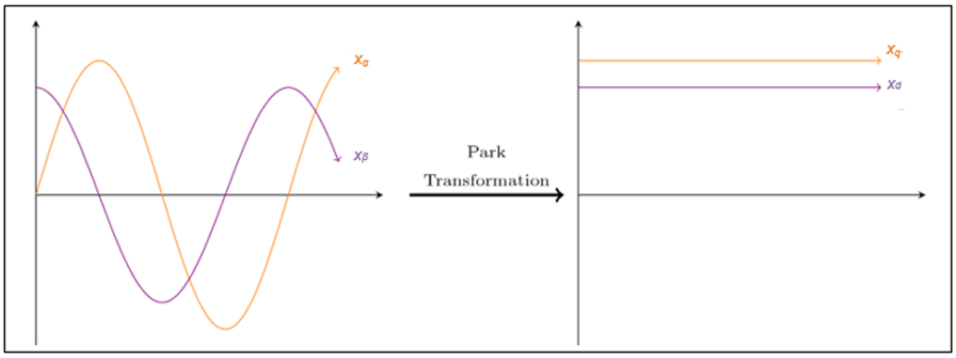


Figure 5.26. Park Transformation

Magnitude of reference voltage is obtained by some mathematical calculations as illustrated in Figure 5.28 with using the output of this transformations. Low pass filter is used to prevent harmonics in the network from affecting the reference signal.

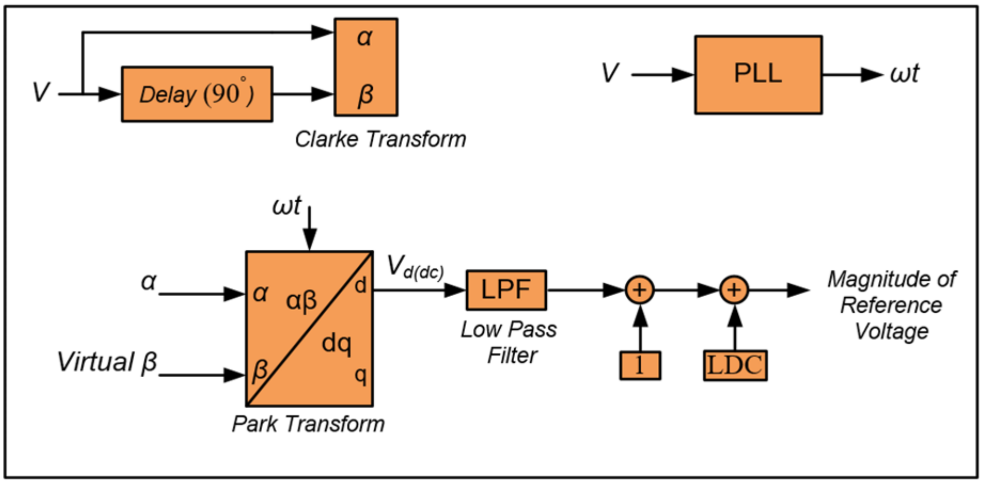


Figure 5.27. Generating Reference Signals

In order to generate gate signals for Matrix Converter switches, SPWM method is used as shown in figure 5.29. The generating reference voltage is compared with triangular carrier wave for obtaining gate signals.

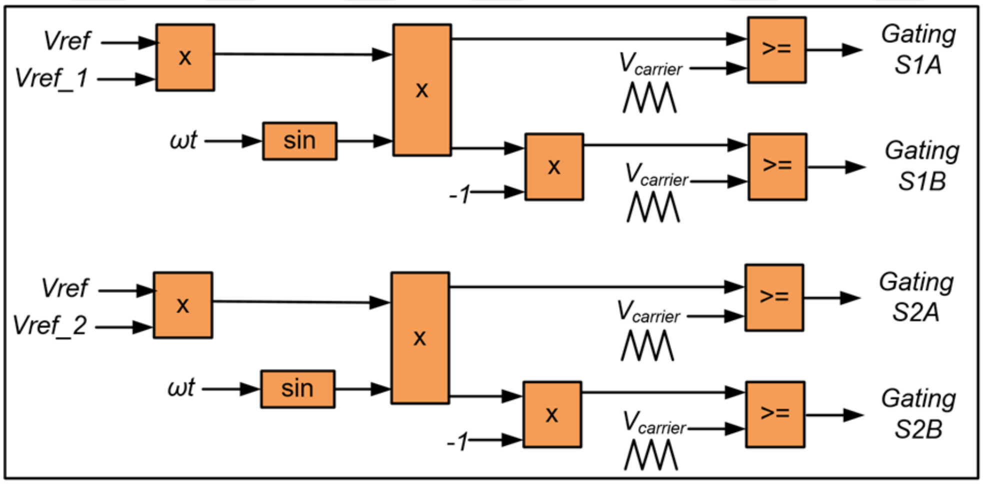


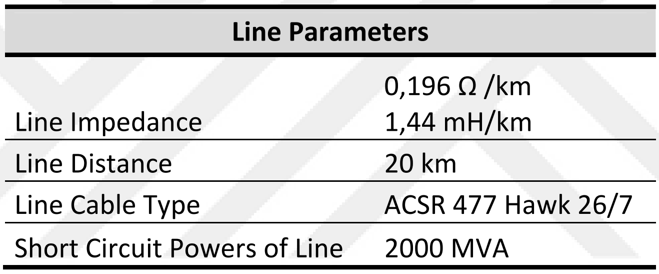
Figure 5.28. Generating Gate Signals with SPWM

5.4. Source, Line and Load Modeling

A three-phase voltage source in series with RL branch is used for modeling. The source parameters are shown in Table 5.4.

The MV line can be modeled as a series impedance with resistance and inductance. Line length is determined as 40 km and the SVR is placed at 20 km. The parameters of the line are listed in Table 5.4. If the network voltage is smaller than 69 kV and the length of the line is not greater than 80 km, the capacitance effect can be neglected (Sarathy & Raghav, 2018). The MV distribution network model is used in the design.

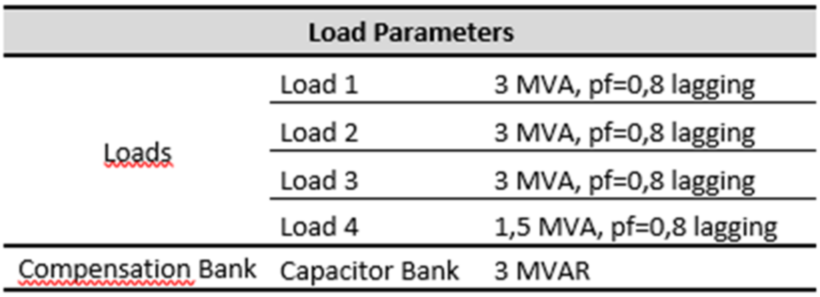
Table 5.4. Line Parameters



Line Parameters	
Line Impedance	0,196 Ω /km 1,44 mH/km
Line Distance	20 km
Line Cable Type	ACSR 477 Hawk 26/7
Short Circuit Powers of Line	2000 MVA

The loads are modeled by using a series RL load and capacitor. There are four RL loads and two capacitor banks for each phase in this study. These loads are connected in grounded wye. The load parameters are listed in Table 5.5.

Table 5.5. Load parameters



Load Parameters		
Loads	Load 1	3 MVA, pf=0,8 lagging
	Load 2	3 MVA, pf=0,8 lagging
	Load 3	3 MVA, pf=0,8 lagging
	Load 4	1,5 MVA, pf=0,8 lagging
Compensation Bank	Capacitor Bank	3 MVAR

6. SIMULATION RESULTS

6.1. Overview of Simulation Studies

In this section, simulation results of mechanical switch, electronic switch and Matrix Converter based voltage regulators are presented. Simulation results consist of voltage regulation performance comparison of these three types regulator topologies. Different power quality case studies are examined and the results are interpreted. MATLAB R2016a / Simulink software tool is used for simulations.

A 34.5 kV distribution grid consists of three 40 km distribution feeders connected in parallel and provides power to an RL load of 10,5 MVA (leading to 0.8 pf). There is a 3 Mvar capacitor bank on the load side to provide reactive power compensation. Three phase step voltage regulator is modeled with three star connected single phase 2 MVA, 19920 kV / 2988 kV transformers. The SVR is located at the 20th km of the line for each phase in order to maintain line voltage stable.

Conventional and active SVR models are designed as a single-phase in Chapter 5. In this section that SVR models are connected in three-phase. A three-phase simulation model shown in Figure 6.1 is commonly used for SVRs based mechanical and electronic tap changer. In Figure 6.2, the SVR based Matrix Converter simulation circuit is shown.

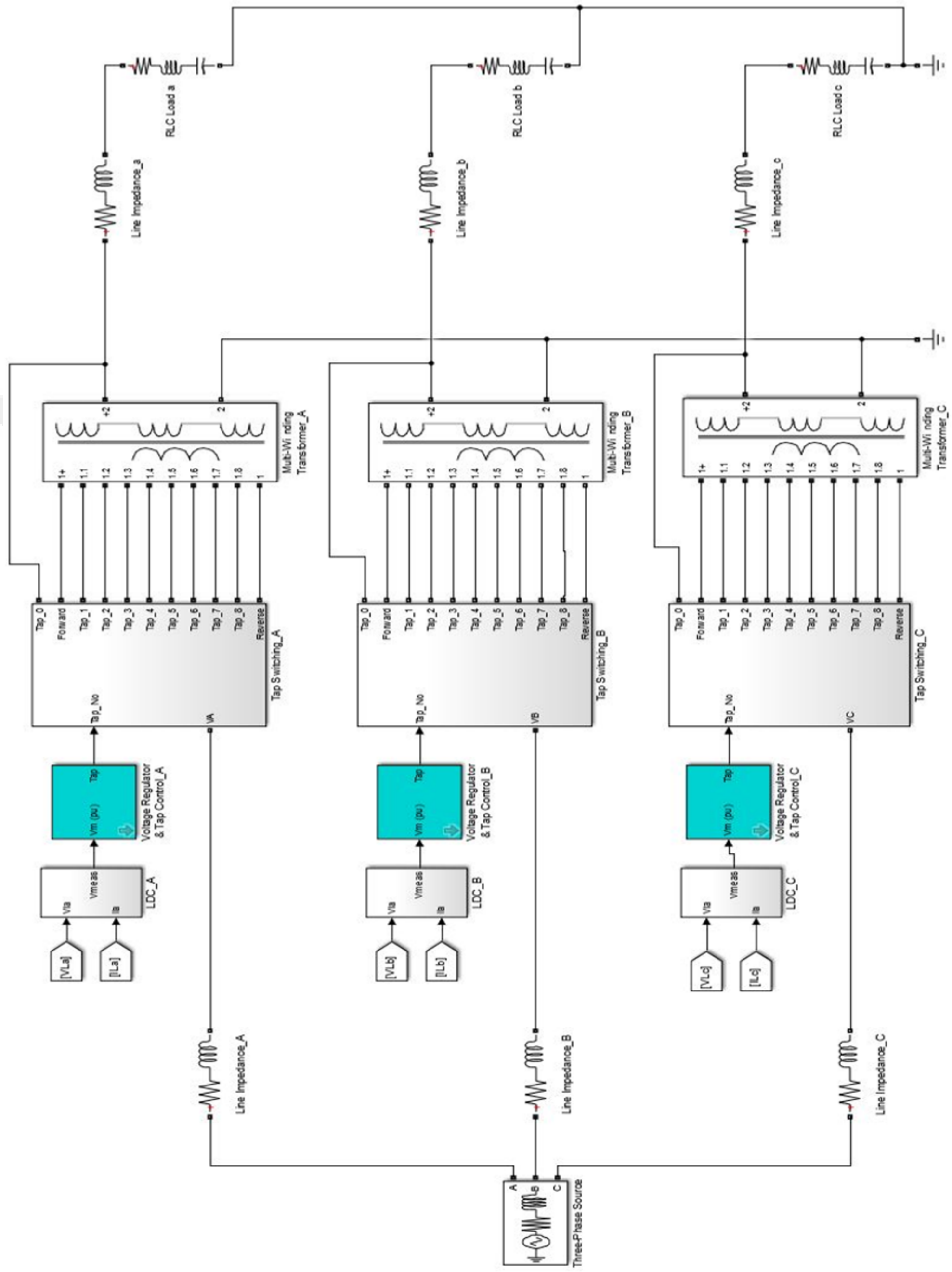


Figure 6.1. Three phase SVR model based mechanic and thyristor tap changers

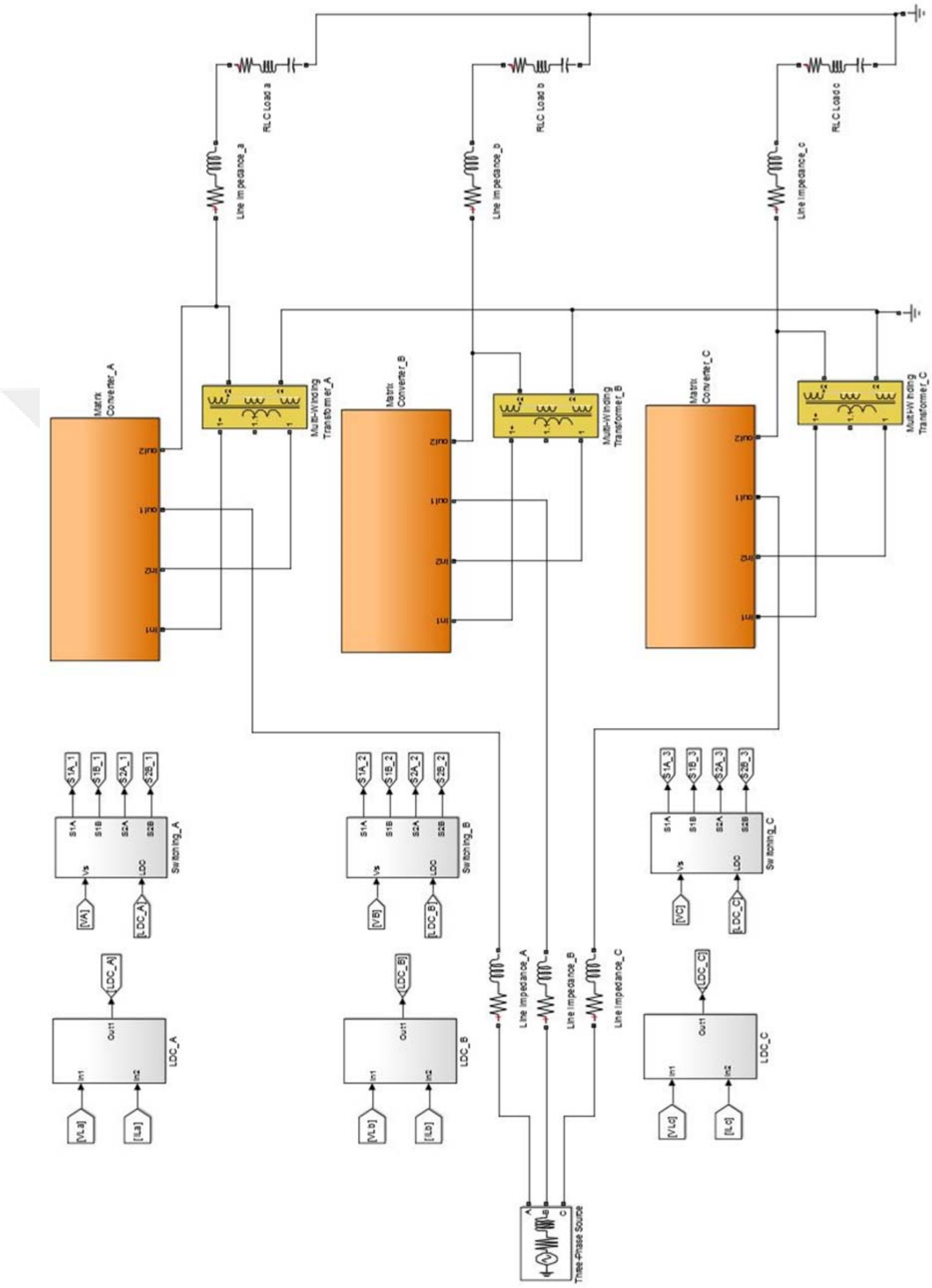


Figure 6.2. Three phase SVR model based Matrix Converter

6.2. Simulation Results for the Fundamental Operation of SVRs

In this part of simulation results, positive and negative voltage regulation is observed. Voltage can be compensated by SVR positively or negatively according to system voltage stability. Both regulations is simulated separately with using single phase SVR model in Figure 6.1. In order to simulate both regulation types, load parameters is configured as in table 6.5.

Table 6.1. Load conditions for positive and negative regulations

Load No	Positive Regulation	Negative Regulation
Load 1	ON	OFF
Load 2	ON	OFF
Load 3	ON	OFF
Load 4	ON	OFF
Capacitor Bank	OFF	ON

Positive voltage regulation is shown in Figure 6.6. This figure shows the SVR input voltage (blue), output voltage (red), and the regulation voltage (green) supplied by the SVR for 15% positive regulation. It is shown that the regulation voltage is in-phase with the input voltage in order to achieve 15% rise in output voltage. The SVR is located at the 20th km of the line. Hence, a voltage drop occurs between source and regulator because of the line impedance. It can be observed that output voltage is 19,85 kV (rms) when the input voltage is 17,25 kV (rms). The regulation is 2596 V (rms), which is equal to the 15% of the regulator input voltage (=17,25 kV x 15%)

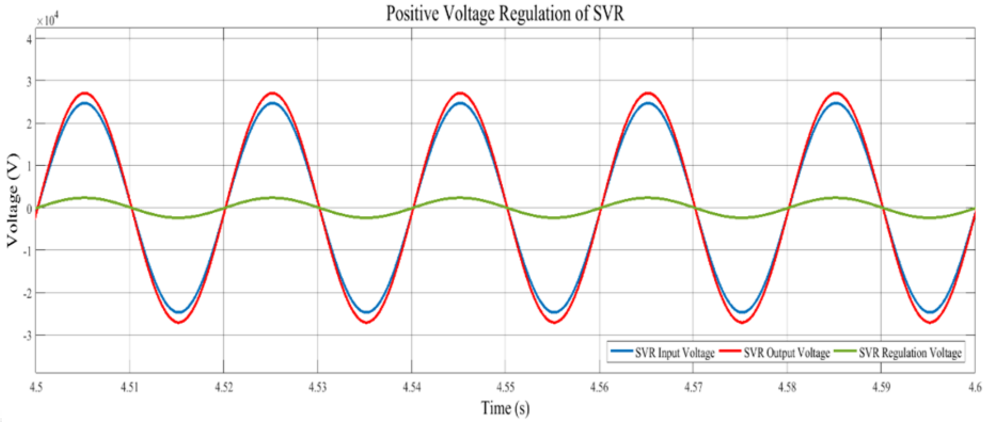


Figure 6.3. Positive regulation of SVR

Figure 6.7. shows 15% negative voltage regulation. The regulation voltage is out of phase with the input voltage in order to achieve 15% decrease in output voltage. The results shows that output voltage is 18,05 kV (rms) when the input voltage is 21,24 kV (rms). The regulation is 3186 V (rms), which is equal to the 15% of the regulator input voltage (=21,24 kV x 15%)

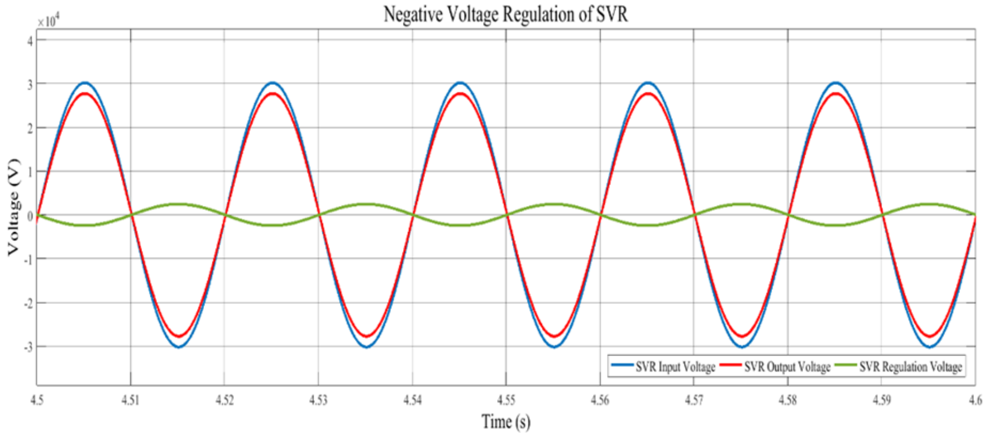


Figure 6.4. Negative regulation of SVR

6.3. No SVR vs With SVR

In this section, the function of SVR is investigated on regulating line and load voltage. In order to investigate the role of SVR in the system, the Figure 5.2 model is simulated individually with and without SVR and the results were compared. For the sake of clarity, SVR is located next to the source. Thus, the source voltage for this model will remain constant throughout the simulation period. The function of SVRs has been examined for both positive and negative regulation capabilities described in chapter 4.

In the simulation results in Figure 6.5 and 6.6, it can be seen how SVR compensates line and load voltages. Total RL loads are active in the system. When these loads are active, voltage drop occurs on the line due to line impedance and loads. SVR increases line and load voltages 15% by eight tap changing proses.

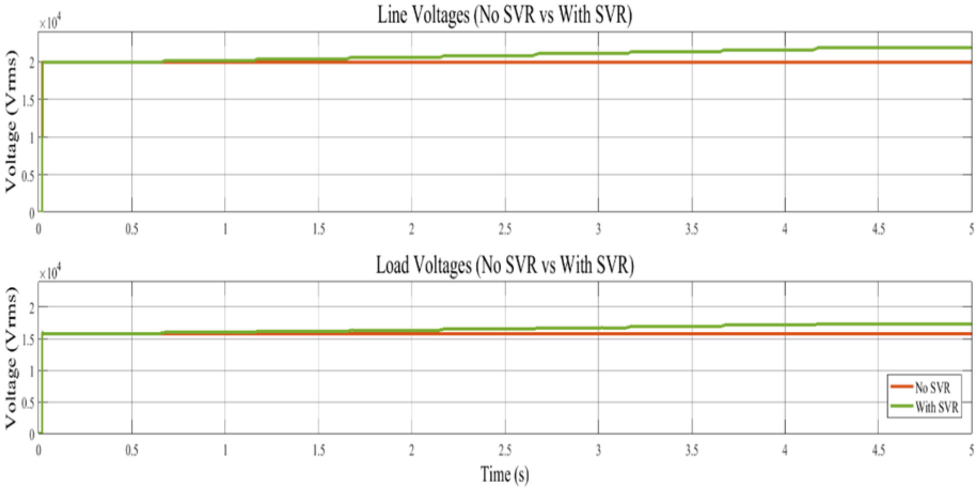


Figure 6.5. Simulation results for No SVR vs with SVR for positive regulation rms

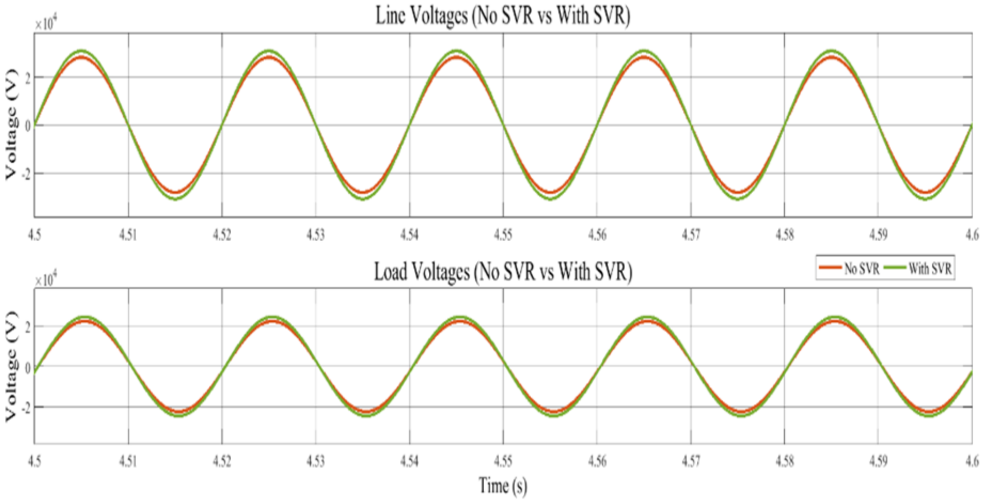


Figure 6.6. Simulation results for No SVR vs with SVR for positive regulation

When the RL loads in the system are deactivated and the compensation banks are activated. It is observed that the voltage on the line increases. To compensate for this voltage increase, negative voltage regulation is required. SVR reduces the number of taps and reduces line and load voltages by 15%.

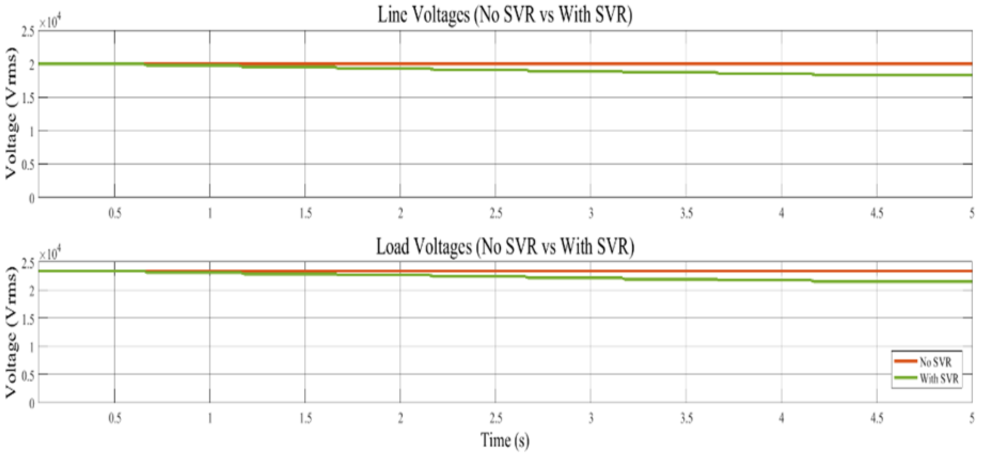


Figure 6.7. Simulation results for No SVR vs with SVR for negative regulation rms

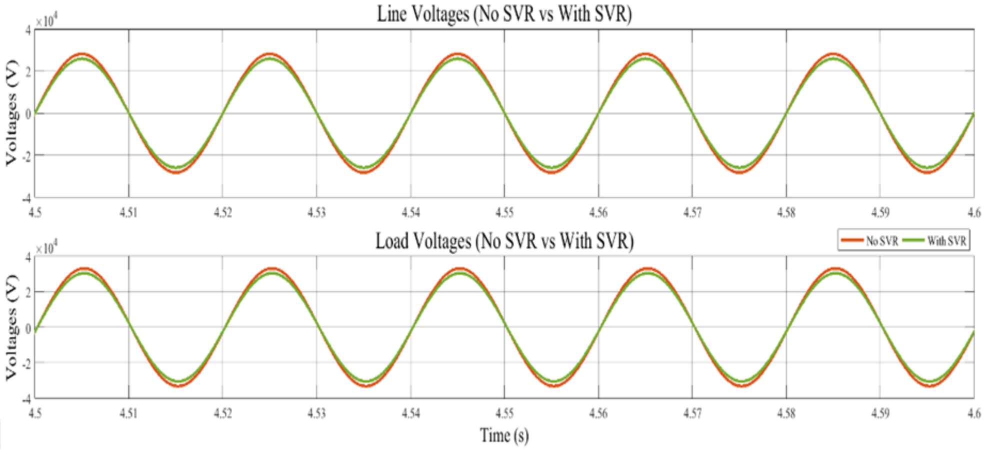


Figure 6.8. Simulation results for No SVR vs with SVR for negative regulation

In both cases indicates that the line voltage regulation is performed effectively with SVR.

6.4. Case Studies and Simulation Results

In this section, the simulation results of the voltage regulation performance of conventional voltage regulators and active voltage regulators are presented with the following cases. As mentioned in the previous chapters, there can be some unstable situations on distribution and transmission networks. For instance, overvoltage, undervoltage, unbalance.

Overvoltage and undervoltage cases are examined and the results are interpreted in this section. Case studies are implemented on mechanical tap changer and thyristor tap changer based SVRs and matrix converter based SVRs individually.

Since the tap change operation in the conventional voltage regulator is a slow mechanical process ('Tap selection time' is defined as 3 seconds in the parameter settings window), the simulation time is set to 115 seconds to compare the performance of each of the three models for the specified cases. The system parameters are described in modeling and overview of simulation sections. Details of case cases to be simulated are shown in Table 6.2.

Table 6.2. Case studies

<table>
<tr><th>Case No</th><th>Case Name</th><th>Duration</th><th colspan="3">Case Description</th></tr>
<tr><td>0</td><td>Start-Up</td><td>0s - 5s</td><td colspan="3">All Loads OFF
Compensation OFF</td></tr>
<tr><td>I</td><td>Undervoltage</td><td>5s – 45s</td><td colspan="3">All Loads ON @5s
Compensation ON @5s</td></tr>
<tr><td>II</td><td>Overvoltage</td><td>45s – 75s</td><td colspan="3">Load 1 OFF @45s
Load 2 OFF @45s
Load 3 OFF @45s
Load 4 ON
Capacitor Bank ON</td></tr>
<tr><td rowspan="2">III</td><td rowspan="2">Unbalance</td><td rowspan="2">75s – 115s</td><td>Phase A</td><td>Phase B</td><td>Phase C</td></tr>
<tr><td>Load 1 ON @75s
Load 2 ON @75s
Load 3 ON @75s
Load 4 ON
Capacitor Bank OFF @ 75s</td><td>Load 1 ON @75s
Load 2 ON @75s
Load 3 ON @75s
Load 4 ON
Capacitor Bank ON</td><td>Load 1 ON @75s
Load 2 ON @75s
Load 3 ON @75s
Load 4 OFF @75s
Capacitor Bank ON</td></tr>
</table>

6.4.1. Results of Cases Implementation on Conventional and Active SVRs

In this part of the simulation results, the performances of conventional and active SVRs are investigated for all four cases explained in Table 6.2. Figure 6.1 is used for mechanical and thyristor tap changers based SVR and Figure 6.2 is used for Matrix Converter based SVR.

The presentation of the simulation results is designed as comparing four different parameters for each SVR type. These parameters are the line voltages to be regulated by the SVR, load voltages, tap changes and active/reactive powers for each phases. In addition, the status of these parameters in the absence of SVR on the line are also investigated.

In case 0, the normal operation of the circuit is analyzed. Initially, all loads and compensation units are deactivated and the simulation is started at no load situation. There is not any unstable situation on distribution grid within this period. This start-up operation lasts 5 seconds. In this case, controller of the SVR not detects any voltage variation, because there is no line current in this case. Thus, SVR does not operate within this period. All line and load voltages magnitudes are 1 pu in this case.

In case I, all loads and compensation capacitor bank are get involved to the line at 5th seconds. The load parameters is given in Table 5.5 in detail. Hence, 10.5 MW RL loads and 3 Mvar reactive loads are active in the system in this case. This decreases the line voltage to 0.95 pu as shown in Figure 6.9. Undervoltage status is occurred in the system as a result of this case. Since all loads are activated at the same time, instantaneous distortions occur in line voltage at start moment of this case.

In case II, overvoltage case is investigated. In 45th second, Loads 1, Loads 2 and Loads 3 are separated from the line as defined in the Table 6.2. Hence 9 MW RL loads is removed from the system. This operation results increases in the line voltage, since the capacitor bank is still connected to the line.

In case III, an unbalanced situation is designed on the distribution line. As can be seen in table 6.2, the three RL loads, which has been deactivated in case II, are activated in 75th seconds. On the other hand, only the Load 1 in phase C, and the Capacitor Bank in phase A is deactivated. Thus, imbalances between phases occur. This case leads to voltage decreases in the line voltages at different magnitude in each phase as shown in Figure 6.9.

Figure 6.9 shows line voltages variations for each phase when SVR is not used in the system. As can be seen, the power quality problems experienced on the line in all three cases continue throughout the duration of the problem. Because there are not any devices on the line to regulate the voltage or any voltage compensation technique is applied. The load voltages are affected in the same way as the line voltages in case of no regulation techniques in the system as shown in Figure 6.10.

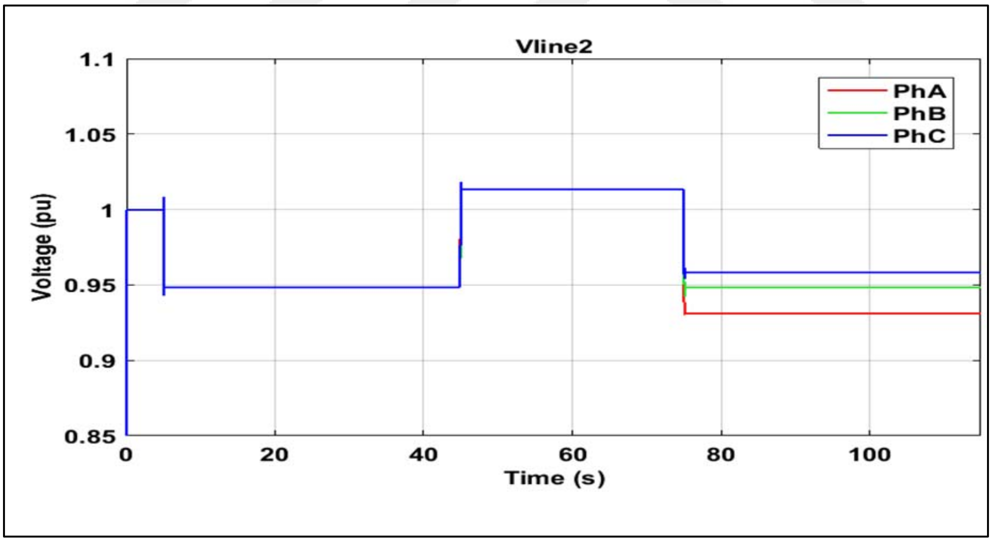


Figure 6.9. Line Voltages in the absence of SVR on the line

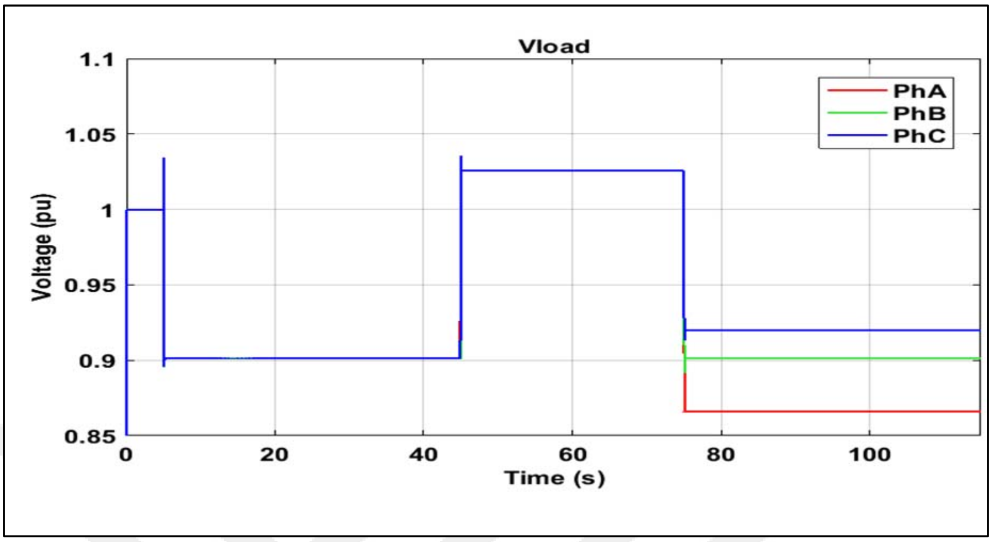


Figure 6.10. Load Voltages in the absence of SVR on the line

Figures 6.11, 6.12 and 6.13 illustrate how each type of SVR regulates the line voltages of the system individually. Vline2 refers to the voltage of the line between the voltage regulator and the loads. The SVR regulates the voltage of this line so that the voltage on the load side remains stable.

The operations of the SVRs for each case can be summarized as follows.

In case I, for mechanical and thyristor tap changer based SVRs, LDC Controller of the SVR detects the voltage decreasing and starts the tap changing operation. Initial tap position is set to ‘0’ for start-up case. Firstly, it determines the required tap number to regulate the line voltage according to defined reference voltage value which is set to 1 pu as can be seen in the regulator setting parameters in Table 5.1 and 5.3. The compensation process can be seen obviously in Figure 6.11 and 6.12. SVRs compensate the line voltage positively. The Matrix Converter based SVR adjusts the output voltage according to the magnitude of the incoming voltage drop information in the LDC and injects positive voltage in series to the line as shown in Figure 6.13.

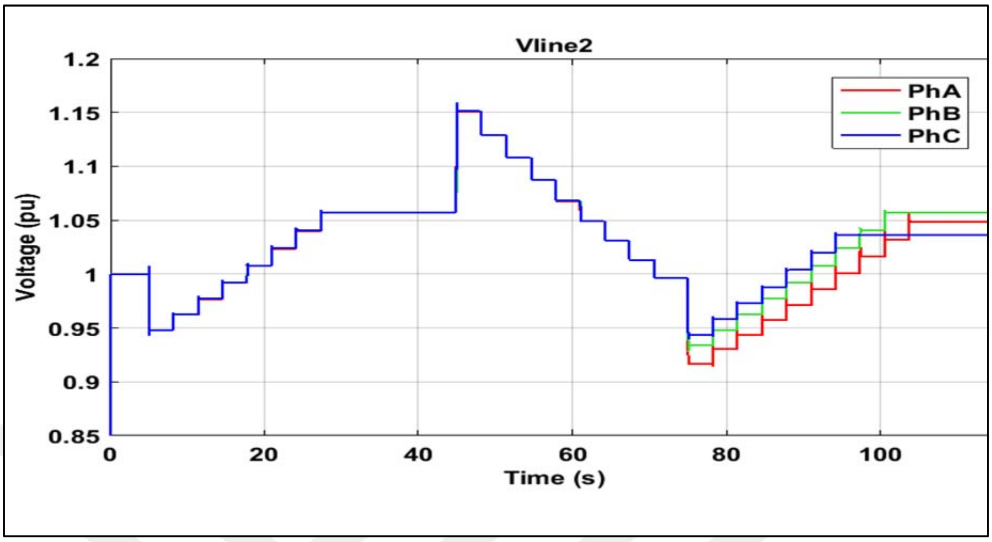


Figure 6.11. Line voltages in case of mechanical tap changer based SVRs

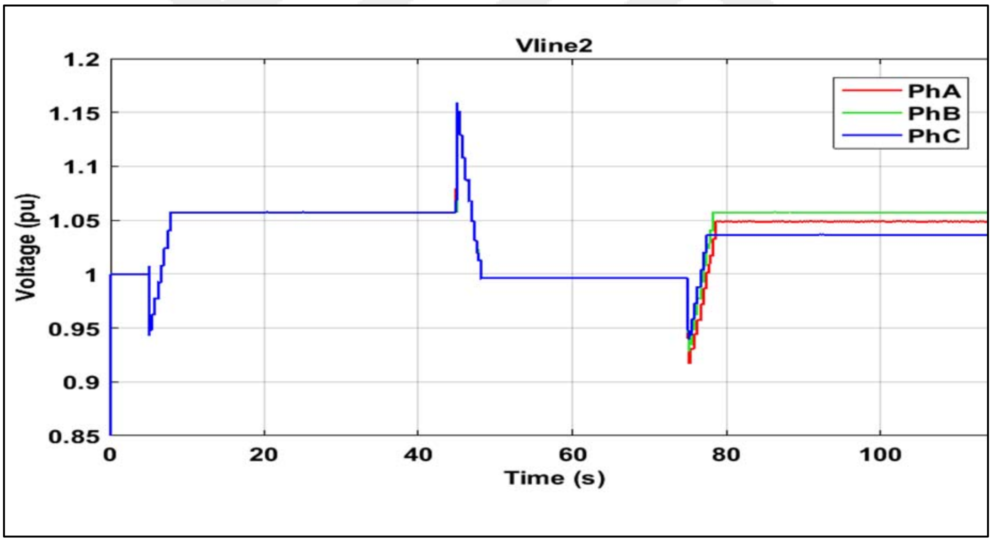


Figure 6.12. Line voltages in case of thyristor tap changer based SVRs

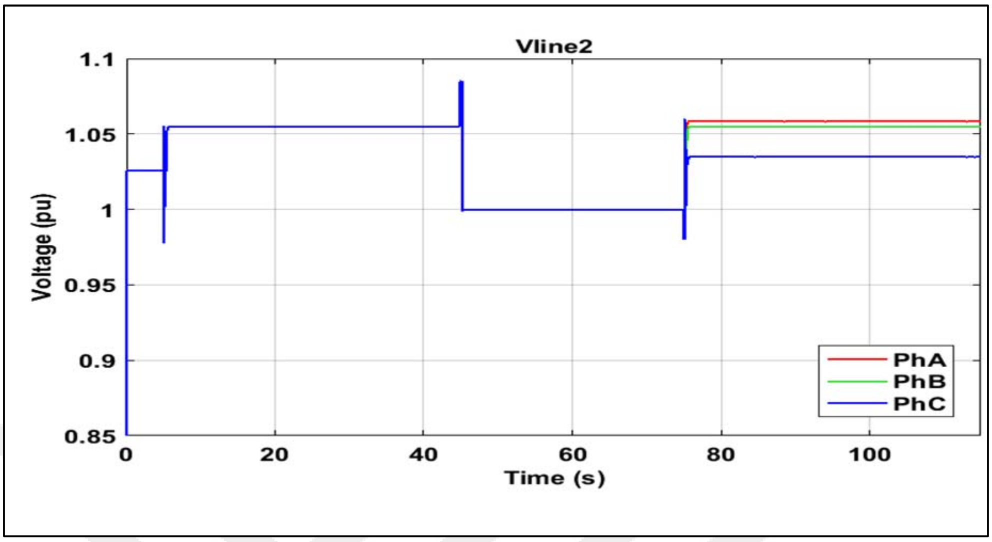


Figure 6.13. Line voltages in case of Matrix Converter based SVRs

In case II, LDC Controller of the SVR detects the voltage increases and starts the tap changing operation again for mechanical and thyristor tap changer based SVRs. The tap position is remained at '+7' from case I. In the face of increases in line voltage, the controller decides to terminate positive compensation and starts to negative compensation. Hence, the SVR supplies a negative voltage to the line in order to compensate this voltage increase. The Matrix Converter based SVR adjusts the output voltage according to the magnitude of the incoming voltage drop information in the LDC and this time injects negative voltage in series to the line as shown in Figure 6.13.

The regulation of the line voltage acts directly on the load side as shown in figures 6.14, 6.15 and 6.16.

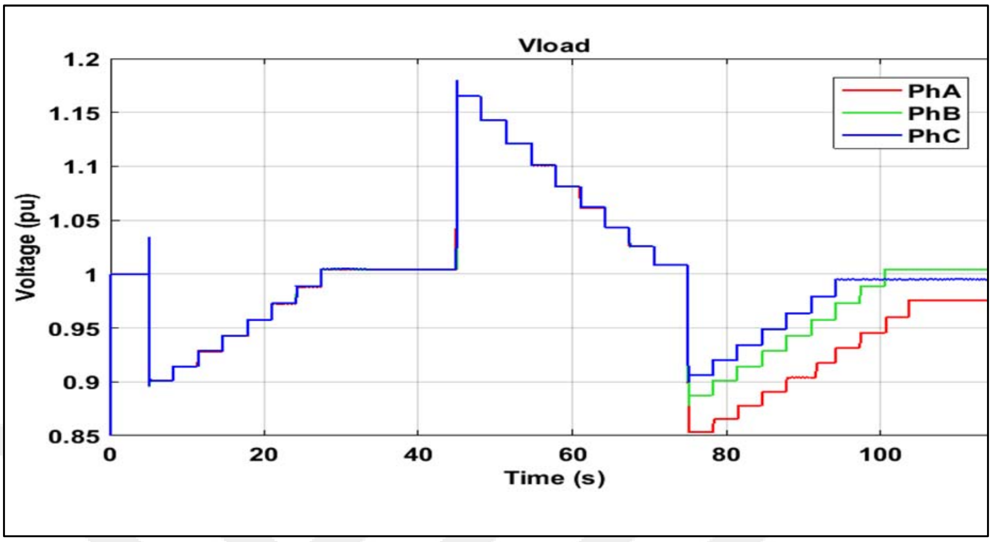


Figure 6.14. Load voltages in case of mechanical tap changer based SVRs

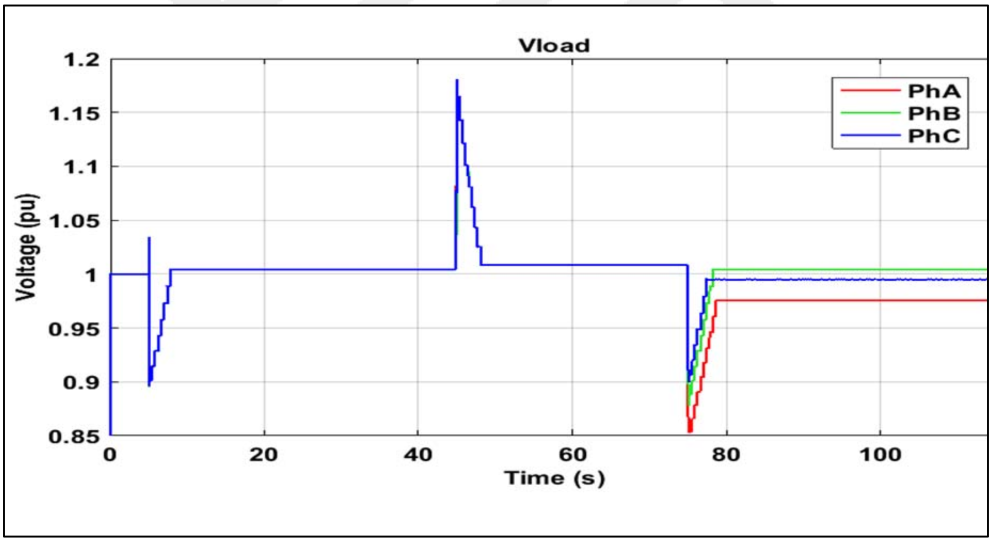


Figure 6.15. Load voltages in case of thyristor tap changer based SVRs

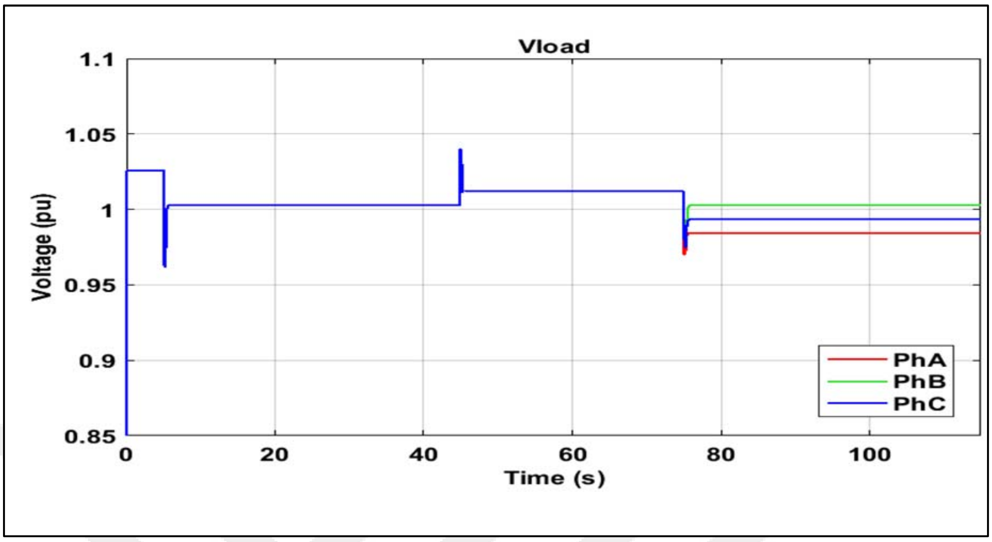


Figure 6.16. Load voltages in case of Matrix Converter based SVRs

Case III, an unbalanced situation case, leads to voltage decreases in the line voltages at different magnitude in each phase as shown in Figures 6.11, 12 and 13. LDC controllers in each phase detects individually this voltage variation in negative direction. Each LDC redefines the required tap position after making calculations in order to achieve proper regulation for mechanical and thyristor based tap changers. It is shown that, at the end of Case II, all tap positions are remained at '-1' for all phases. As a result of unbalanced changes in phases, the new target tap numbers is determined '+8' for phase A, '+7' for phase B, and '+5' for phase C.

Matrix converter based SVRs are injected as positive voltage for each phase according to LDC signal as shown in Figure 6.16.

It is observed that line voltages are increased for all phases in different values after SVR operations.

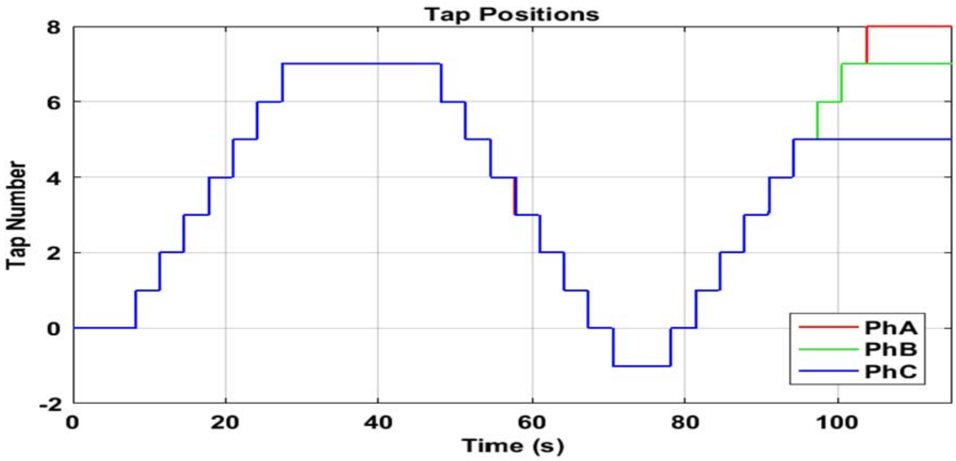


Figure 6.17. Tap positions for mechanical tap changer based SVRs

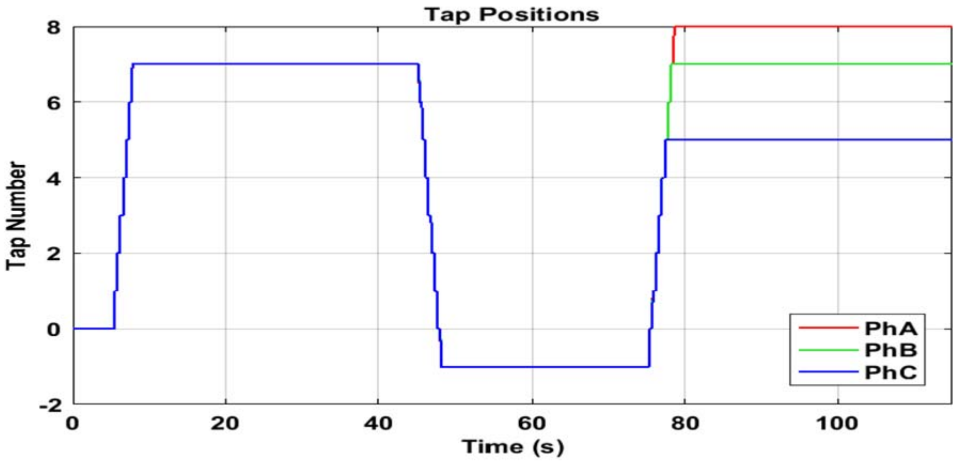
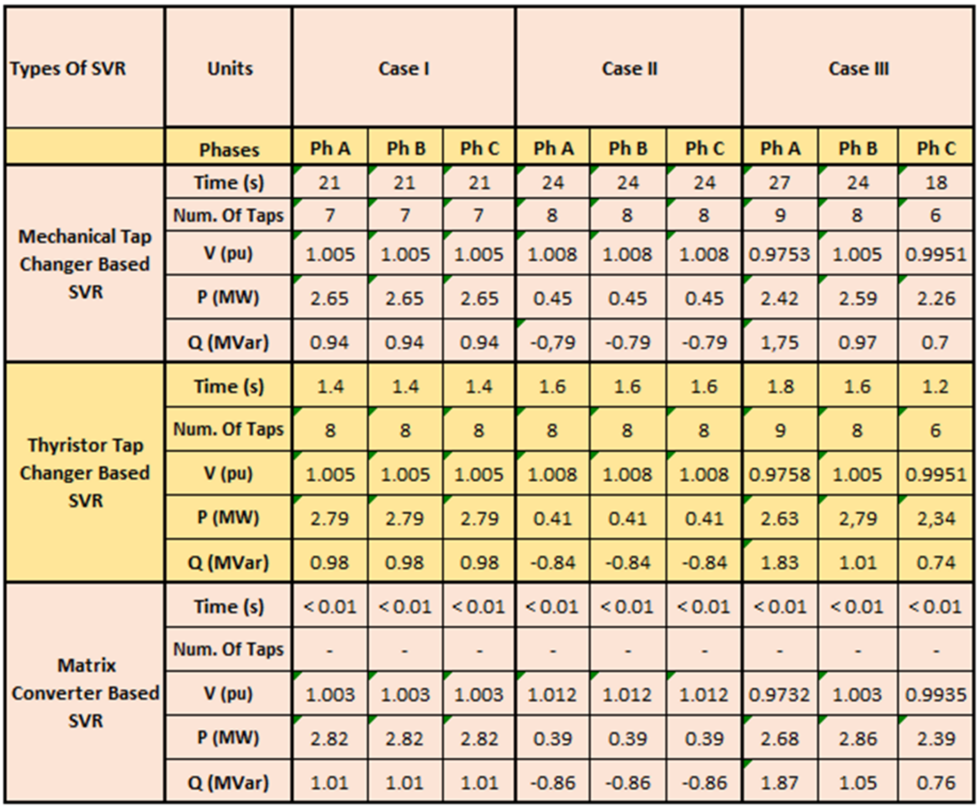


Figure 6.18. Tap positions for thyristor tap changer based SVRs

As described in the section 4, changeovers between taps have to be done sequentially in the conventional tap changers. It is not possible to switch to another level by bypassing the adjacent tap. While the SVR is performing tap reduction in case II, it starts to increase tap positions in the new state. It continues to change the tap from level ‘-1’ to target tap positions. This corresponds to nine tap change operations (≈27 s) for A phase, eight tap change operations (≈24 s) for B phase, and six tap change operations (≈18 s) for C phase in case III.

The regulation times, number of tap operations, load voltages and active/reactive load powers for each SVR during all case study period are given in Table 6.3

Table 6.3. Results of case studies



Types Of SVR	Units	Case I			Case II			Case III		
	Phases	Ph A	Ph B	Ph C	Ph A	Ph B	Ph C	Ph A	Ph B	Ph C
Mechanical Tap Changer Based SVR	Time (s)	21	21	21	24	24	24	27	24	18
	Num. Of Taps	7	7	7	8	8	8	9	8	6
	V (pu)	1.005	1.005	1.005	1.008	1.008	1.008	0.9753	1.005	0.9951
	P (MW)	2.65	2.65	2.65	0.45	0.45	0.45	2.42	2.59	2.26
	Q (MVar)	0.94	0.94	0.94	-0,79	-0.79	-0.79	1,75	0.97	0.7
Thyristor Tap Changer Based SVR	Time (s)	1.4	1.4	1.4	1.6	1.6	1.6	1.8	1.6	1.2
	Num. Of Taps	8	8	8	8	8	8	9	8	6
	V (pu)	1.005	1.005	1.005	1.008	1.008	1.008	0.9758	1.005	0.9951
	P (MW)	2.79	2.79	2.79	0.41	0.41	0.41	2.63	2,79	2,34
	Q (MVar)	0.98	0.98	0.98	-0.84	-0.84	-0.84	1.83	1.01	0.74
Matrix Converter Based SVR	Time (s)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Num. Of Taps	-	-	-	-	-	-	-	-	-
	V (pu)	1.003	1.003	1.003	1.012	1.012	1.012	0.9732	1.003	0.9935
	P (MW)	2.82	2.82	2.82	0.39	0.39	0.39	2.68	2.86	2.39
	Q (MVar)	1.01	1.01	1.01	-0.86	-0.86	-0.86	1.87	1.05	0.76

The active and reactive line power after operations of three type SVRs are presented in Figure 6.19, 6.20 and 6.21.

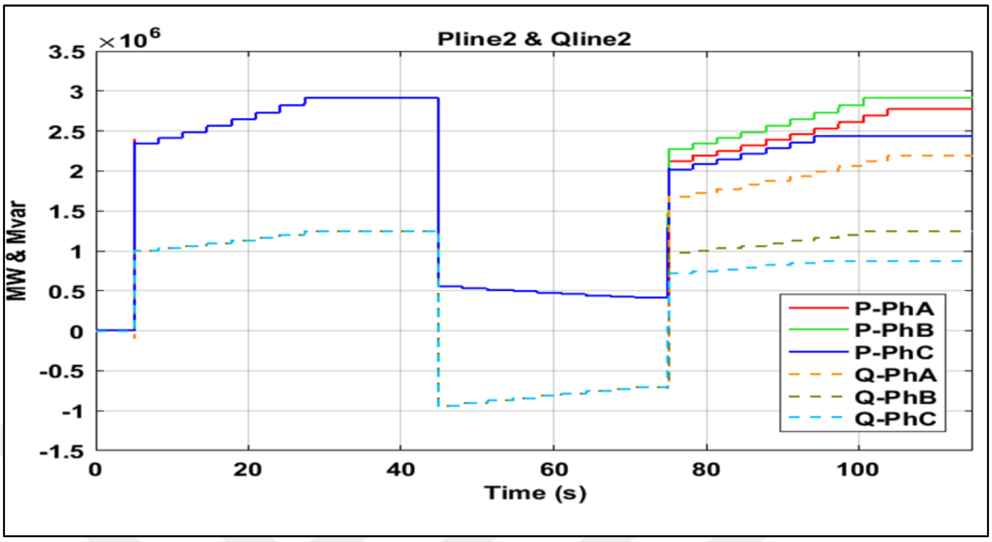


Figure 6.19. Line Powers in case of mechanical tap changer based SVR

As can be seen from the results, power loss is high in conventional tap changer SVRs, while this loss is low in active SVRs.

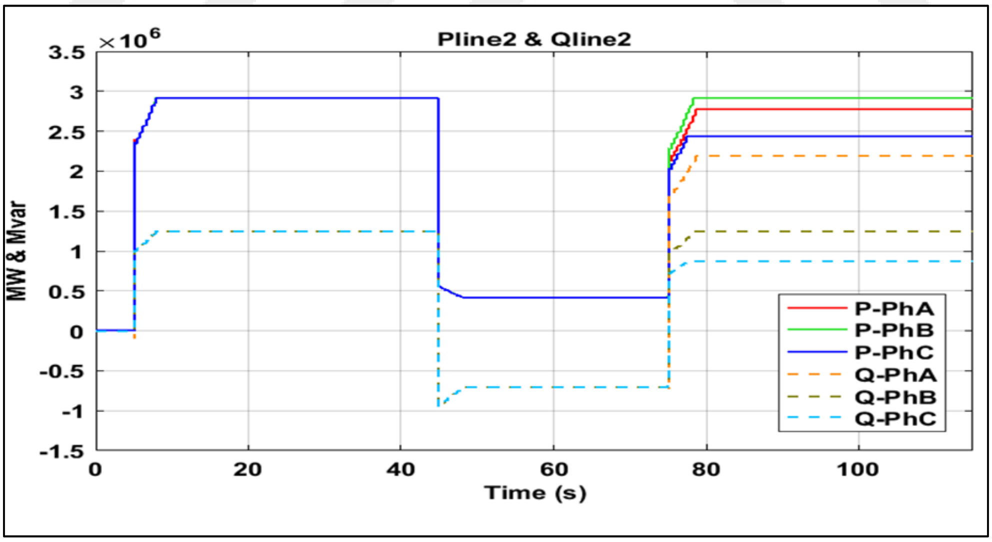


Figure 6.20. Line Powers in case of thyristor tap changer based SVR

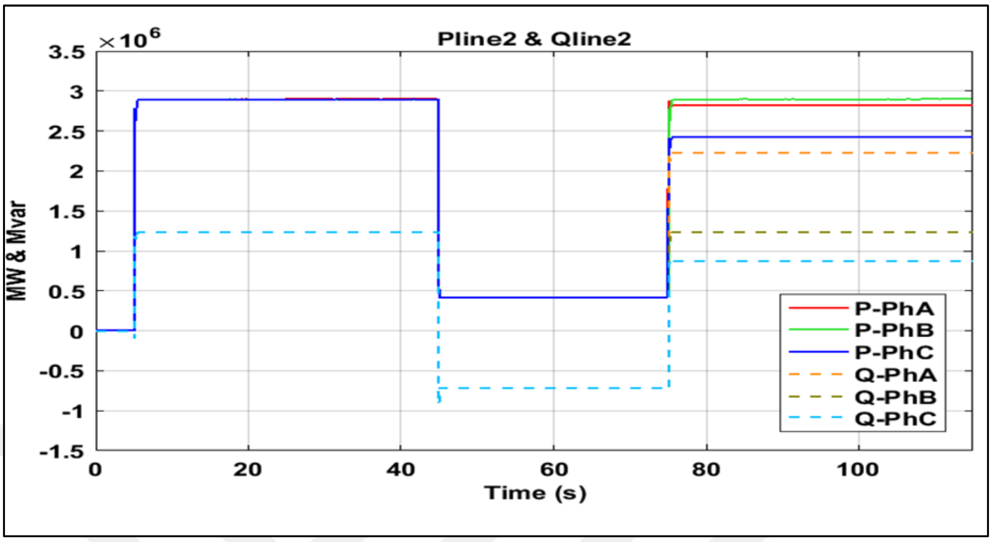


Figure 6.21. Line Powers in case of Matrix Converter based SVR

The active and reactive values of the line and load voltages for each phase during the entire case period are given in Table 6.4 and Table 6.5.

As can be seen from the simulation results, in cases where the system voltage drops, the line and load power decreases as the regulation time increases. Therefore, active SVRs have a higher power value than conventional SVRs.

The active and reactive load powers after operations of three type SVRs are presented in Figures 6.22, 6.23 and 6.24.

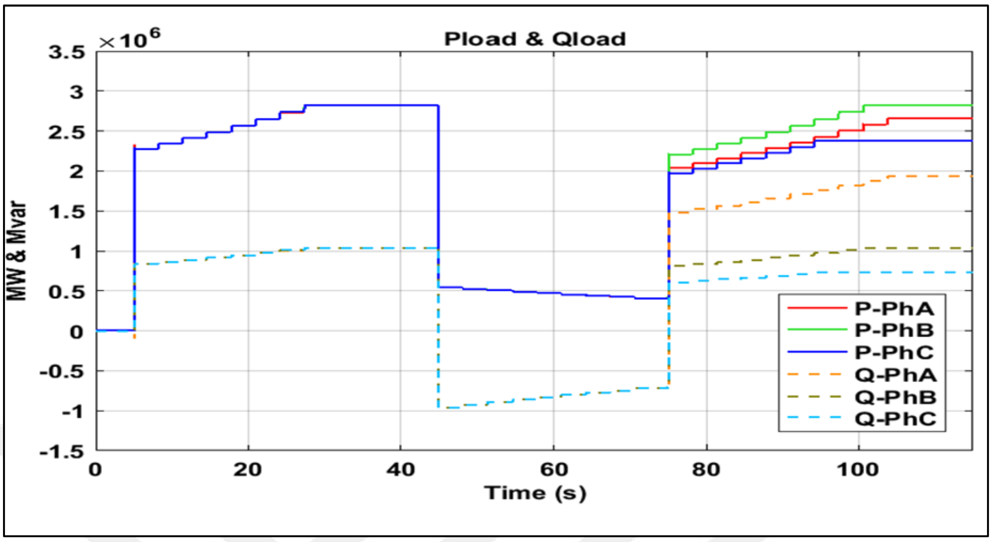


Figure 6.22. Load Powers in case of mechanical tap changer based SVR

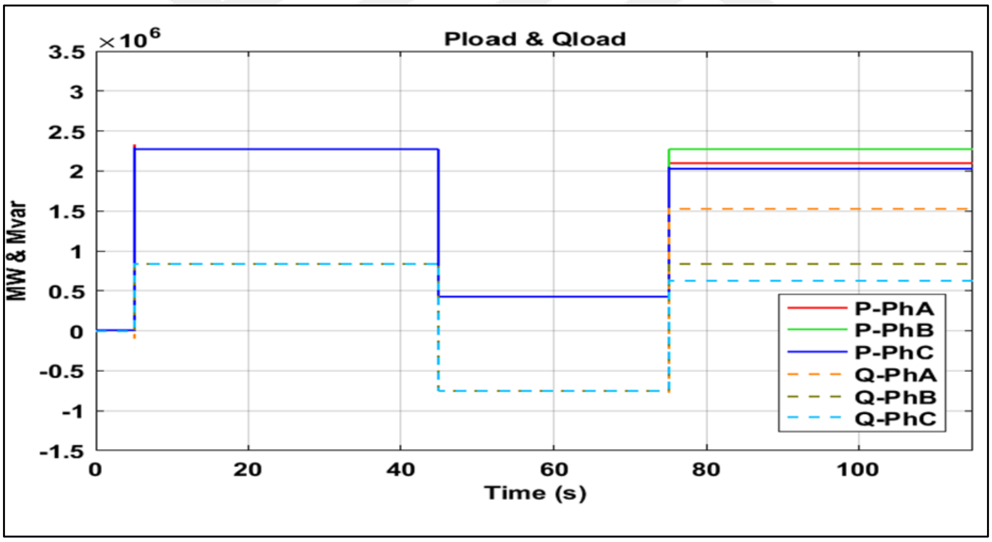
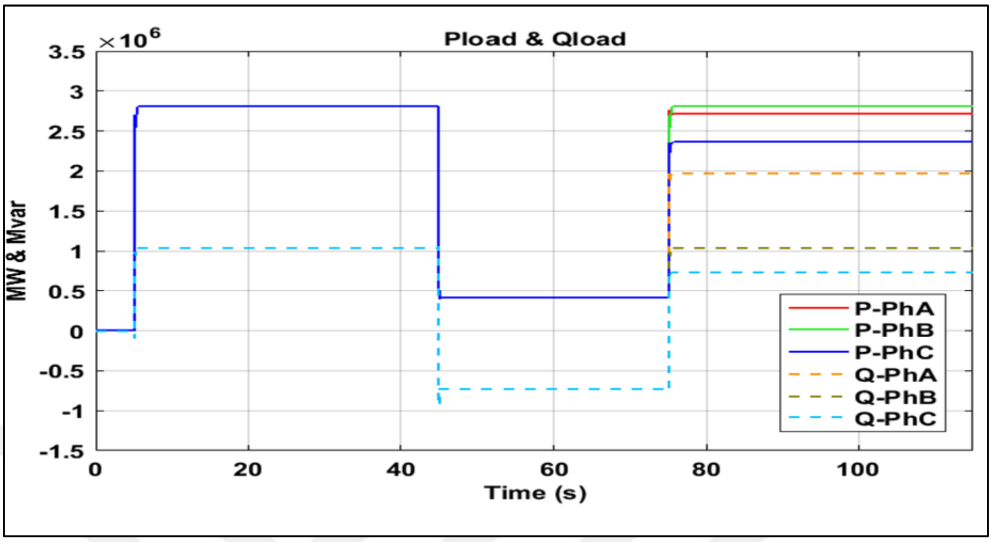


Figure 6.23. Load Powers in case of thyristor tap changer based SVR



Total harmonic distortions of matrix converter based SVRs are shown in Figures 6.25, 6.26 and 6.27.

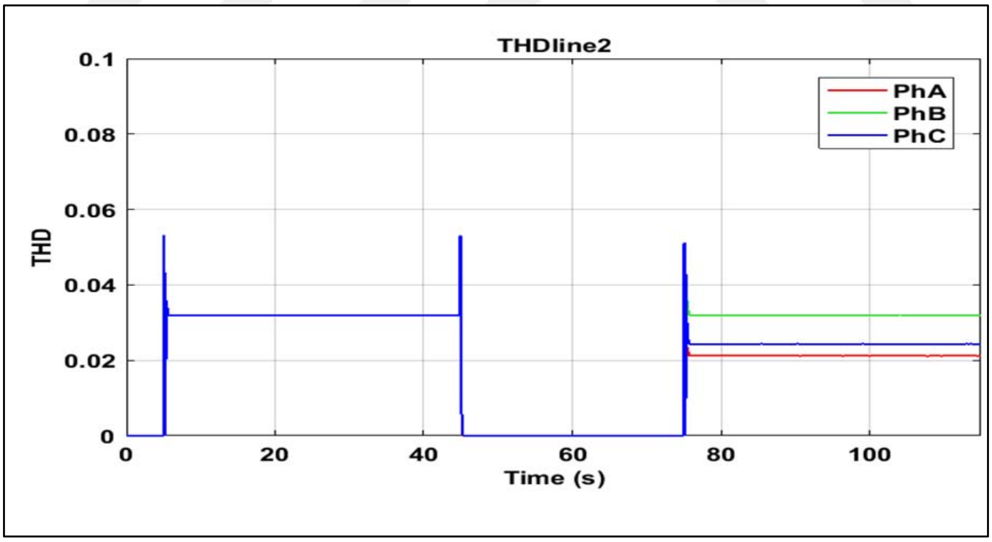


Figure 6.24. THD of line voltages in case of Matrix Converter based SVR

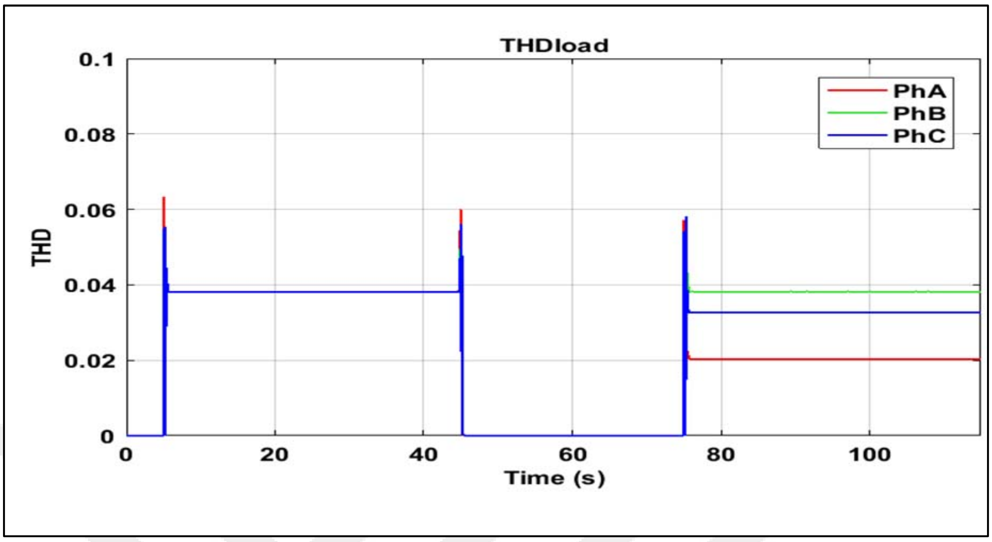


Figure 6.25. THD of load voltages in case of Matrix Converter based SVR

It is shown that the THDs are nearly between 5-6% for all three cases in load and line voltages.

7. CONCLUSION AND FUTURE WORKS

The main purpose of the distribution systems is to provide sufficient and good quality voltage to the customers. In order to achieve this phenomena, a well designed regulation system should be available to maintain the line voltage constant against various problems in distribution system. There are generally two types of regulation techniques, series and shunt. One of the most effective series regulation techniques is using SVR.

Although the mechanical tap changers used in the structures of conventional voltage regulators are robust and able to operate at high powers, they have a slow response, long operation times, maintenance requirements and a limited operating life. In order to overcome these limitations and disadvantages, power electronic elements can be used in the structures of tap changers instead of mechanical moving parts. Firstly, hybrid tap changers consisting of electronic and mechanical components are produced and then only tap changers made of electronic materials are used in the structure of tap changers. The switching speed is relatively increased by using power electronic equipment such as thyristor, IGBT etc. instead of the rotating mechanical component which causes slow operation and other limitations in the mechanical tap changer. However, modern distribution systems require a more flexible operation that takes into account dynamic changes in the load side and production. Voltage regulators operating in a conventional manner cannot cope with these new challenges. In this thesis, in order to improve the performance of voltage regulators in the face of dynamic changes in the network, the use of Matrix Converters instead of tap changer in the structure of voltage regulators is examined.

The main aim of this thesis is to investigate conventional and active Step Voltage Regulators performances according to various criteria. Conventional SVRs are modeled with mechanical tap changers. Active SVRs are modeled in two different topologies; with thyristor tap changers and Matrix Converter.

The results are observed by simulating these three different topologies separately in a simulation circuit with the same distribution network parameters in MATLAB/Simulink. A 20 MVA MV network is designed for simulation. A voltage regulator of 2 MVA is used for all three topologies. In order to explain the importance of the voltage regulator in the distribution system, the simulation circuit is simulated with/without SVR and it is seen that the voltage regulator effectively regulates the system voltage. In order to compare the performance of the three topologies modeled in various aspects, four different cases are defined. The responses and performances of the three topologies of SVR are observed for each case.

A line drop control, voltage regulation control and tap changer control algorithms are developed for mechanical and thyristor controlled tap changer based SVRs. An advanced control algorithm, which combines the line drop control and the instantaneous line voltage magnitude detection algorithms, is proposed for the matrix converter based SVR.

When the results are examined in detail, it is observed that the response time of the mechanical tap changers based SVR is very long against dynamic voltage changes and it is not possible to eliminate the voltage variation within the limits of the short events. When the results of the thyristor tap changer based SVR model are examined for the same cases, it is observed that the response times are faster than the mechanical tap changer based voltage regulators, but the duration is not sufficiently short for dynamic changes in the line yet. It has also been observed that these two step voltage regulator models are inadequate in regulating sag and swell voltage problems.

Matrix Converter based SVR performance is the best among the three regulators due to its rapid response to line voltage variations. As can be seen from the cases, mechanical tap changers based SVRs needs 30 s for line regulation, while Matrix converter based SVRs regulate the line voltage around 20 ms.

7.1. Future Works

The studies accomplished in thesis work can be furthered in various aspects in the future. In this section, some recommendations for future work are presented.

- The comparisons of conventional and Matrix Converter SVRs are simulated in the absence of distributed sources. The performance and comparison of SVRs in distribution grids with distributed generation could be examined.
- The radial network is used in simulation models for distribution grid. All cases could be implemented in mesh network.
- Case analyzes can be performed to investigate comprehensive sag swell compensation performances of active SVRs.
- A more effective controller can be used to generate the reference signal for the Matrix Converter.

REFERENCES

05, C. W. G. (1983). An international survey on failures in large power transformers in service. *Electra*, *88*.

Ahirrao, D., Gaware, B., Kakade, P., Kharade, P., & Chawda, S. (2014). Analysis of single phase matrix converter. *International Journal of Engineering Research and Applications*, *4*(3), 856–861.

Alcaria, P., Pinto, S. F., & Silva, J. F. (2013). Active voltage regulators for low voltage distribution grids: The matrix converter solution. *4th International Conference on Power Engineering, Energy and Electrical Drives*, 989–994. IEEE.

Alesina, A., & Venturini, M. G. B. (1989). Analysis and design of optimum-amplitude nine-switch direct AC-AC converters. *IEEE Transactions on Power Electronics*, *4*(1), 101–112.

Ali, S., & Wolfs, P. (2014). A matrix converter based voltage regulator for MV rural feeders. *2014 IEEE PES General Meeting| Conference & Exposition*, 1–5. IEEE.

Andersson, T., & Nilsson, D. (2002). *Test and evaluation of voltage dip immunity*.

Bauer, P., & De Haan, S. W. H. (1997). Protective device for electronic tap changer for distribution transformers. *EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS*, *4*, 4–282. PROCEEDINGS PUBLISHED BY VARIOUS PUBLISHERS.

Bauer, P., & De Haan, S. W. H. (1998). Electronic tap changer for 500 kVA/10 kV distribution transformers: design, experimental results and impact in distribution networks. *Conference Record of 1998 IEEE Industry Applications Conference. Thirty-Third IAS Annual Meeting (Cat. No. 98CH36242)*, *2*, 1530–1537. IEEE.

Bauer, P., & De Haan, S. W. H. (1999). Solid state tap changers for utility transformers. *1999 IEEE Africon. 5th Africon Conference in Africa (Cat. No. 99CH36342)*, *2*, 897–902. IEEE.

Bauer, P., de Haan, S. W. H., & Paap, G. C. (1996). Solid-state control for transformer tap changing. *Proc. PEMC*, 39–44.

Bauer, P., De Haan, S. W. H., & Paap, G. C. (1997). Electronic tap changer for 10 kV distribution transformer. *EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS*, *3*, 3–1010. PROCEEDINGS PUBLISHED BY VARIOUS PUBLISHERS.

Bauer, P., & Schoevaars, R. (2003). Bidirectional switch for a solid state tap changer. *IEEE 34th Annual Conference on Power Electronics Specialist, 2003. PESC'03.*, *1*, 466–471. IEEE.

Bayliss, C. R., & Hardy, B. J. (1999). Transmission and Distribution. *Electrical Engineering, 2nd Ed. Newnes*.

Bengtsson, C. (1996). Status and trends in transformer monitoring. *IEEE Transactions on Power Delivery*, *11*(3), 1379–1384.

Bhattacharyya, S., Myrzik, J. M. A., & Kling, W. L. (2007). Consequences of poor power quality-an overview. *2007 42nd International Universities Power Engineering Conference*, 651–656. IEEE.

Bhavsar, S., & Chandwani, H. (2013). *Topological Advancements in Matrix Converter Technology : A Review Paper*. 6044–6054.

Bollen, M. H. J. (2001). *Understanding Power Quality Problems (Voltage Sags And Interruptions)*. Retrieved from https://books.google.com.tr/books?id=xElMPgAACAAJ

Bucknall, R. W. G., & Ciaramella, K. M. (2009). On the conceptual design and performance of a matrix converter for marine electric propulsion. *IEEE Transactions on Power Electronics*, *25*(6), 1497–1508.

Cárdenas, R., Pena, R., Clare, J., & Wheeler, P. (2010). Analytical and experimental evaluation of a WECS based on a cage induction generator fed by a matrix converter. *IEEE Transactions on Energy Conversion*, *26*(1), 204–215.

Carlen, M., Cornelius, F., Tepper, J., Jakobs, R., Schneider, M., Wiesler, H., … Buschmann, I. (2015). Line Voltage Regulator for voltage adjustment in MV-grids. *23rd International Conference and Exhibition on Electricity Distribution (CIRED)*.

Chandra Mouli, G. R. (2013). *Design of a power electronic assisted series compensator for grid voltage regulation*.

Chang, S.-K., Albuyeh, F., Gilles, M. L., Marks, G. E., & Kato, K. (1990). Optimal real-time voltage control. *IEEE Transactions on Power Systems*, *5*(3), 750–758.

Chattopadhyay, S., Mitra, M., & Sengupta, S. (2011). Electric power quality. In *Electric Power Quality* (pp. 5–12). Springer.

Choi, J.-H., & Kim, J.-C. (2001). Advanced voltage regulation method of power distribution systems interconnected with dispersed storage and generation systems. *IEEE Transactions on Power Delivery*, *16*(2), 329–334.

Colopy, C. (2012). *Step-Voltage Regulators*. 1–26. https://doi.org/10.1201/b12110-9

Conti, S., & Greco, A. M. (2007). Innovative voltage regulation method for distribution networks with distributed generation. *19th International Conference on Electricity Distribution*.

Cooke, G. H., & Williams, K. T. (1990). Thyristor assisted on-load tap changers for transformers. *1990 Fourth International Conference on Power Electronics and Variable-Speed Drives (Conf. Publ. No. 324)*, 127–131. IET.

Cooke, G. H., & Williams, K. T. (1992). New thyristor assisted diverter switch for on load transformer tap changers. *IEE Proceedings B (Electric Power Applications)*, *139*(6), 507–511. IET.

Davis, M. W., Broadwater, R., & Hambrick, J. (2007). *Modeling and testing of unbalanced loading and voltage regulation*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Degeneff, R. C. (1997). *A new concept for a solid-state on-load tap changers*.

Demirci, O., Torrey, D. A., Degeneff, R. C., Schaeffer, F. K., & Frazer, R. H. (1998). A new approach to solid-state on load tap changing transformers. *IEEE Transactions on Power Delivery*, *13*(3), 952–961.

Dixon, J., Moran, L., Rodriguez, J., & Domke, R. (2005). Reactive power compensation technologies: State-of-the-art review. *Proceedings of the IEEE*, *93*(12), 2144–2164.

DUGAN R.C., MCGRANAGHAN M.F., B. H. W. (2003). *Electrical Power Systems Quality*. New York: McGraw-Hill.

Electrical Power System Quality. (2012). Retrieved from https://books.google.com.tr/books?id=DuUt4QFvByIC

ERTAY, M. M., & AYDOĞMUŞ, Z. (2012). GÜÇ SİSTEMLERİNDE FACTS UYGULAMALARI. *Uluslararası Teknolojik Bilimler Dergisi*, *4*(2), 40–58.

Faiz, J., & Javidnia, H. (2000). *Fast response solid-state on load transformers tap-changer*.

Faiz, J., & Siahkolah, B. (2002). Optimal configurations for taps of windings and power electronic switches in electronic tap-changers. *IEE Proceedings-Generation, Transmission and Distribution*, *149*(5), 517–524.

Faiz, J., & Siahkolah, B. (2004). Effect of solid-state on-load distribution tap-changer on power quality enhancement. *Int. J. Eng., IR Iran*, *17*, 143–156.

Faiz, J., & Siahkolah, B. (2005). Sag mitigation by an electronic tapchanger: specifications and comparisons with other custom power tools. *IEE Proceedings-Generation, Transmission and Distribution*, *152*(5), 697–704.

Faiz, J., & Siahkolah, B. (2006a). Differences between conventional and electronic tap-changers and modifications of controller. *IEEE Transactions on Power Delivery*, *21*(3), 1342–1349.

Faiz, J., & Siahkolah, B. (2006b). Differences between conventional and electronic tap-changers and modifications of controller. *IEEE Transactions on Power Delivery*, *21*(3), 1342–1349. https://doi.org/10.1109/TPWRD.2005.861323

Faiz, J., & Siahkolah, B. (2006c). New controller for an electronic tap changer—Part I: Design procedure and simulation results. *IEEE Transactions on Power Delivery*, *22*(1), 223–229.

Faiz, J., & Siahkolah, B. (2006d). New controller for an electronic tap changer—Part II: Measurement algorithm and test results. *IEEE Transactions on Power Delivery*, *22*(1), 230–237.

Faiz, J., & Siahkolah, B. (2008). Implementation of a low-power electronic tap-changer in transformers. *IET Electric Power Applications*, *2*(6), 362–373.

Faiz, J., & Siahkolah, B. (2011). *Electronic tap-changer for distribution transformers* (Vol. 2). Springer Science & Business Media.

Fourie, R. (2010). *The development of a igbt-based tap changer*. Stellenbosch: University of Stellenbosch.

Gao, D., Lu, Q., & Luo, J. (2002). A new scheme for on-load tap-changer of transformers. *Proceedings. International Conference on Power System Technology*, *2*, 1016–1020. IEEE.

Garcés, A., & Molinas, M. (2010). High frequency wind energy conversion from the ocean. *The 2010 International Power Electronics Conference-ECCE ASIA-*, 2056–2061. IEEE.

Garcés, A., & Molinas, M. (2011). A study of efficiency in a reduced matrix converter for offshore wind farms. *IEEE Transactions on Industrial Electronics*, *59*(1), 184–193.

Garces, A., & Trejos, A. (2011a). A voltage regulator based on matrix converter for smart grid applications. *2011 Ieee Pes Conference on Innovative Smart Grid Technologies Latin America (Isgt La)*, 1–6. https://doi.org/10.1109/ISGT-LA.2011.6083186

Garces, A., & Trejos, A. (2011b). A voltage regulator based on matrix converter for smart grid applications. *2011 IEEE PES CONFERENCE ON INNOVATIVE SMART GRID TECHNOLOGIES LATIN AMERICA (ISGT LA)*, 1–6. IEEE.

Genç, Y. (2015). *Güç kalitesi problemlerinde geleneksel kontrol teorisi ve bulanik mantik kontrol teorisinin karşilaştirilmasi*.

González-Morán, C., Arboleya, P., Mojumdar, R. R., & Mohamed, B. (2018). 4-Node Test Feeder with Step Voltage Regulators. *International Journal of Electrical Power & Energy Systems*, *94*, 245–255.

Grainger, J. J., Stevenson, W. D., & Stevenson, W. D. (2003). *Power system analysis*.

Guo, Y., Hill, D. J., & Wang, Y. (2001). Global transient stability and voltage regulation for power systems. *IEEE Transactions on Power Systems*, *16*(4), 678–688.

Hanafi, H. M., Idris, Z., Hamzah, M. K., & Saparon, A. (2006). Modelling & simulation of single-phase matrix converter as a frequency changer with sinusoidal pulse width modulation using MATLAB/simulink. *2006 IEEE International Power and Energy Conference*, 482–487. IEEE.

Harlow, J. H. (2001). Discussion of" Fast response GTO assisted novel tap changer. *IEEE Transactions on Power Delivery*, *16*(4), 826–827.

Hietpas, S. M., & Naden, M. (2000). Automatic voltage regulator using an AC voltage-voltage converter. *IEEE Transactions on Industry Applications*, *36*(1), 33–38.

Holt, M., Maasmann, J., & Rehtanz, C. (2017). Line voltage regulator based on magnetic-controlled inductors for low-voltage grids. *CIRED-Open Access Proceedings Journal*, *2017*(1), 278–281.

Idris, Z., Hamzah, M. K., & Hamzah, N. R. (2005). Modelling & Simulation of a new Single-phase to Single-phase Cycloconverter based on Single-phase Matrix Converter Topology with Sinusoidal Pulse Width Modulation Using MATLAB/Simulink. *2005 International Conference on Power Electronics and Drives Systems*, *2*, 1557–1562. IEEE.

Idris, Z., Hamzah, M. K., & Omar, A. M. (2005). Implementation of single-phase matrix converter as a direct ac-ac converter synthesized using sinusoidal pulse width modulation with passive load condition. *2005 International Conference on Power Electronics and Drives Systems*, *2*, 1536–1541. IEEE.

Jang, D.-H., & Choe, G.-H. (1998). Step-up/down ac voltage regulator using transformer with tap changer and PWM ac chopper. *IEEE Transactions on Industrial Electronics*, *45*(6), 905–911.

Jiang, H., Shuttleworth, R., Al Zahawi, B. A. T., Tian, X., & Power, A. (2001). Fast response GTO assisted novel tap changer. *IEEE Transactions on Power Delivery*, *16*(1), 111–115.

John, K. (1944, January 4). *Step-voltage regulator*. Google Patents.

Kang, P., & Birtwhistle, D. (2001). Condition assessment of power transformer on-load tap-changers using wavelet analysis. *IEEE Transactions on Power Delivery*, *16*(3), 394–400.

Kersting, W. H. (2009). The modeling and application of step voltage regulators. *2009 IEEE/PES Power Systems Conference and Exposition*, 1–8. IEEE.

Kojima, T., Isotani, H., & Yamada, M. (2017). Distribution Static Var Compensators and Static Synchronous Compensators for Suppressing Voltage Fluctuation. *FUJI ELECTRIC REVIEW*, *63*(1), 36–40.

Kojovic, L. A. (2006). Coordination of distributed generation and step voltage regulator operations for improved distribution system voltage regulation. *2006 IEEE Power Engineering Society General Meeting*, 6–pp. IEEE.

Korpikiewicz, J. G., & Mysiak, P. (2017). Classical and solid-state tap-changers of HV/MV regulating transformers and their regulators. *Acta Energetica*.

Kunov, G. (2014). Matlab-Simulink model of solid-state transformer realized with matrix converters. *2014 18th International Symposium on Electrical Apparatus and Technologies (SIELA)*, 1–4. IEEE.

Larsson, T., Innanen, R., & Norstrom, G. (1997). Static electronic tap-changer for fast phase voltage control. *1997 IEEE International Electric Machines and Drives Conference Record*, TC3-4. IEEE.

Larsson, T., Innanen, R., & Norstrom, G. (1997). Static Electronic Tap-Changer for fast phase voltage control. *Electric Machines and Drives Conference Record, 1997. IEEE International*, TC3/4.1-TC3/4.3. https://doi.org/10.1109/IEMDC.1997.604265

Lee, M. Y., Wheeler, P., & Klumpner, C. (2010). Space-vector modulated multilevel matrix converter. *IEEE Transactions on Industrial Electronics*, *57*(10), 3385–3394.

Lennox, T. C. (1954, May 4). *Step voltage regulator*. Google Patents.

Li, H. (1998, August 11). *Bidirectional lateral insulated gate bipolar transistor*. Google Patents.

Liu, J. W., Choi, S. S., & Chen, S. (2003). Design of step dynamic voltage regulator for power quality enhancement. *IEEE Transactions on Power Delivery*, *18*(4), 1403–1409.

Liu, Y., Liu, Y., Abu-Rub, H., Ge, B., Balog, R. S., & Xue, Y. (2016). Model predictive control of a matrix-converter based solid state transformer for utility grid interaction. *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 1–6. IEEE.

Liu, Y., Yang, S., Zhang, S., & Peng, F. Z. (2014). Comparison of synchronous condenser and STATCOM for inertial response support. *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2684–2690. IEEE.

Mahmud, N., & Zahedi, A. (2016). Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. *Renewable and Sustainable Energy Reviews*, *64*, 582–595.

Meyer, A. S., & Van Coller, J. (1999). Electronic tap changers for use with ultra-light rural distribution lines. *1999 IEEE Africon. 5th Africon Conference in Africa (Cat. No. 99CH36342)*, *2*, 909–912. IEEE.

Milosevic, B., & Begovic, M. (2004). Capacitor placement for conservative voltage reduction on distribution feeders. *IEEE Transactions on Power Delivery*, *19*(3), 1360–1367.

Monteiro, J., Silva, J. F., Pinto, S. F., & Palma, J. (2010). Matrix converter-based unified power-flow controllers: Advanced direct power control method. *IEEE Transactions on Power Delivery*, *26*(1), 420–430.

O'kelly, D., & Musgrave, G. (1973). Improvement of power-system transient stability by phase-shift insertion. *Proceedings of the Institution of Electrical Engineers*, *120*(2), 247–252. IET.

OSMAN, U. (2013). *AlçaGerilim DağitiSistemlerinde GüKalitesi*.

Padiyar, K. R. (2007). *FACTS controllers in power transmission and distribution*. New Age International.

Paper, W., & Tobias, J. (n.d.). *Specifying HV / MV Transformers at Large Sites for an Optimized MV Electrical Network*.

Pinto, S. F., Alcaria, P., Monteiro, J., & Silva, J. F. (2016). Matrix converter-based active distribution transformer. *IEEE Transactions on Power Delivery*, *31*(4), 1493–1501.

Ram, G., Prasanth, V., Bauer, P., & Barthlein, E. M. (2014). Comparative analysis of on-load tap changing (OLTC) transformer topologies. *16th International Power Electronics and Motion Control Conference and Exposition, PEMC 2014*, 918–923. https://doi.org/10.1109/EPEPEMC.2014.6980624

Robert, M. E., & Ashman, W. G. (1969). A thyristor assisted mechanical on-load tap-changer. *Proc. Inst. Elect. Eng., Power Thyristors and Their Applications*, 185–192.

Romero, D. S. (2010). Voltage regulation in distribution systems-Tap changer and Wind Power. *Lund: Faculty of Engineering, Lund University*.

Ronald, S. D., Sheela, A., & Mary, S. J. (2013). Three phase to three phase direct matrix converter using SPWM technique. *International Journal of Soft Computing and Engineering*, *3*(2), 2231–2307.

Sannino, A. (2001). Power quality improvement in an industrial plant with motor load by installing a static transfer switch. *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No. 01CH37248)*, *2*, 782–788. IEEE.

Sarathy, P., & Raghav, P. (2018). *Analysis and Optimization of Medium Voltage Line Voltage Regulators*. NTNU.

Short, T. A. (2018). *Electric power distribution handbook*. CRC press.

Shuttleworth, R., Power, A. J., Tian, X., Jiang, H., & Al Zahaei, B. A. T. (1997). *A novel thyristor-assisted tap changer scheme*.

Shuttleworth, R., Tian, X., Fan, C., & Power, A. (1996). New tap changing scheme. *IEE Proceedings-Electric Power Applications*, *143*(1), 108–112.

Sidharth, P., Sonar, S. G., & Bhullar, S. G. (2017). *Analysis and Modelling of Matrix Converter as a Frequency Changer*.

Sreenivasulu, A., Kumar, A. N., & Vyjayanthi, D. A. (2016). Modeling and simulation of matrix converter using pi and fuzzy logic controller. *International Journal Of Engineering Sciences & Research Technology (IJESRT)*.

Stetz, T., Kraiczy, M., Diwold, K., Braun, M., Bletterie, B., Mayr, C., … MacGill, I. (2014). High Penetration PV in Local Distribution Grids-Outcomes of the IEA PVPS Task 14 Subtask 2. *29th European Photovoltaic Solar Energy Conference and Exhibition*, *15*(1), 3994–3999.

Szczesniak, P. (2019). Challenges and Design Requirements for Industrial Applications of AC/AC Power Converters without DC-Link. *Energies*, *12*(8), 1581.

Szcześniak, P., & Kaniewski, J. (2015). Hybrid transformer with matrix converter. *IEEE Transactions on Power Delivery*, *31*(3), 1388–1396.

Taha, M. H. (2016). *On Load Single Phase Solid State Tap Changer*.

Taher, S. A., Fard, H. T., & Kashani, E. B. (2018). New switching approach for DVR using one cycle control method. *Ain Shams Engineering Journal*, *9*(4), 2227–2254.

Tamai, Y., Abe, Y., Odaka, A., Sato, I., & Sakuma, A. (2009). A high performance 1 mva matrix converter suitable for wind power systems. *Proc of. China Wind Power Conference. Beijing*.

Tan, A. (2015). *Design and implementation of Shunt Hybrid Active Power Filter*. Çukurova.

Targosz, R., & Manson, J. (2007). Pan-European power quality survey. *2007 9th International Conference on Electrical Power Quality and Utilisation*, 1–6. IEEE.

Udovichenko, A. V. (2016). AC voltage regulators with high frequency transformer review. *2016 17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)*, 583–588. IEEE.

Villegas, G., Vaquero, J., Echavarría, R., Horta, S., Perez, M. A., & Martinez, S. (1998). Quasi-resonant fast on-load two tap changing stabilizer: towards the AC soft switching. *6th IEEE Power Electronics Congress. Technical Proceedings. CIEP 98 (Cat. No. 98TH8375)*, 177–183. IEEE.

Vu, H., Pruvot, P., Launay, C., & Harmand, Y. (1996). An improved voltage control on large-scale power system. *IEEE Transactions on Power Systems*, *11*(3), 1295–1303.

Wood, P., Bapat, V., & Putkovich, R. P. (1988). *Study of improved load-tap-changing for transformers and phase-angle regulators*. Electric Power Research Inst., Palo Alto, CA (USA); Westinghouse Electric ….

Xu, S., Plikat, R., Constapel, R., Korec, J., & Silber, D. (1997). Bidirectional LIGBT on SOI substrate with high frequency and high temperature capability. *Proceedings of 9th International Symposium on Power Semiconductor Devices and IC's*, 37–40. IEEE.

Yaskawa. (2016). Instructions Manual for HP20D/HP20F. *Motoman Robotics*, *6*, 1–81.

Yousef-Zai, F. Q., & O'kelly, D. (1996). Solid-state on-load transformer tap changer. *IEE Proceedings-Electric Power Applications*, *143*(6), 481–491.

Zainuddin, Z., Baharom, R., Yassin, I. M., & Muhammad, K. S. (2018). Solid-State Transformer (S2T) of Single Phase Matrix Converter. *International Journal of Power Electronics and Drive Systems*, *9*(3), 997.

Zhao, C., Zhao, X., & Jia, X. (2004). System innovation for solving power quality problems based on environmental economic. *IEEE PES Power Systems Conference and Exposition, 2004.*, 41–45. IEEE.

Zuckerberger, A., Weinstock, D., & Alexandrovitz, A. (1997). Single-phase matrix converter. *IEE Proceedings-Electric Power Applications*, *144*(4), 235–240.

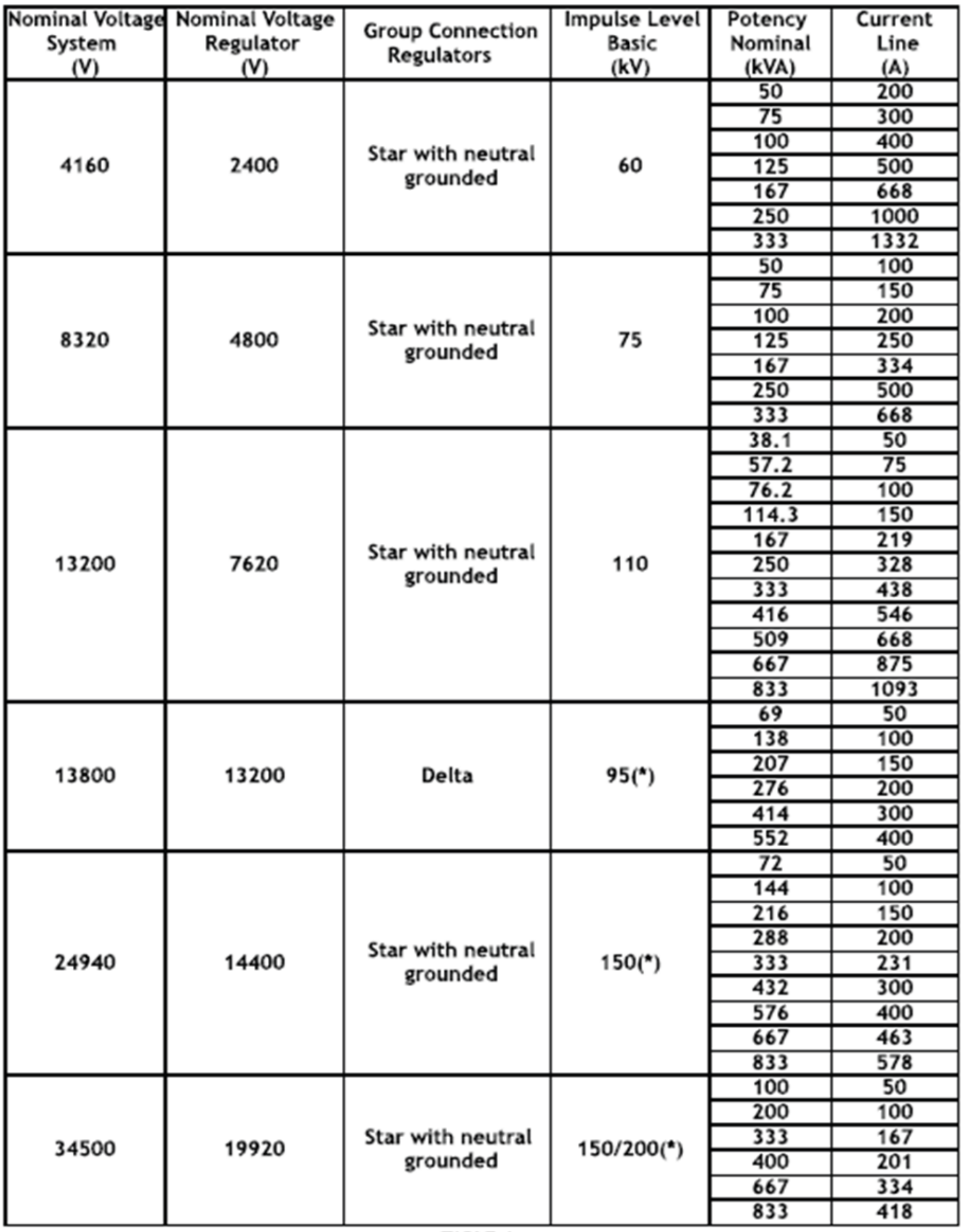
CURRICULUM VITAE

İsmail GÜVEN was born in Mersin, Turkey in 1984. He received his B.Sc. degree in Electrical and Electronics Engineering Department from Çukurova University. After completion his B.S. education, he worked as an Electrical and Electronics Engineer in IMTECH Infra Data Turkey, and TEMSA automotive factory until 2010. He has been working as an Electrical and Automation Maintenance Engineer in İsdemir since 2010. His research areas are automation systems, electric machinery, water plants.

APPENDIX

APPENDIX A: KVA Rating of Regulators

Table A.0.1. Regulator standardized by NBR 11809/1992



Nominal Voltage System (V)	Nominal Voltage Regulator (V)	Group Connection Regulators	Impulse Level Basic (kV)	Potency Nominal (kVA)	Current Line (A)
4160	2400	Star with neutral grounded	60	50	200
				75	300
				100	400
				125	500
				167	668
				250	1000
				333	1332
8320	4800	Star with neutral grounded	75	50	100
				75	150
				100	200
				125	250
				167	334
				250	500
				333	668
13200	7620	Star with neutral grounded	110	38.1	50
				57.2	75
				76.2	100
				114.3	150
				167	219
				250	328
				333	438
				416	546
				509	668
				667	875
				833	1093
13800	13200	Delta	95(*)	69	50
				138	100
				207	150
				276	200
				414	300
				552	400
24940	14400	Star with neutral grounded	150(*)	72	50
				144	100
				216	150
				288	200
				333	231
				432	300
				576	400
				667	463
				833	578
34500	19920	Star with neutral grounded	150/200(*)	100	50
				200	100
				333	167
				400	201
				667	334
				833	418