ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Meral AY

PSCAD MODELING OF TRANSMISSION LINES IN İSTANBUL DISTRICT, PROBLEMS AND IMPROVEMENT OF THE SYSTEM USING STATCOM

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on …/…/2015.

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ABSTRACT

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PSCAD MODELING OF TRANSMISSION LINES IN İSTANBUL DISTRICT, PROBLEMS AND IMPROVEMENT OF THE SYSTEM USING STATCOM

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An electric power system can be controled completely and flexibly if reactive power compensation is fulfilled through power electronic based devices. In recent years, rapid development of power electronics devices is provided to develop a number of control devices under the term Flexible Alternating Current Transmission Systems (FACTS) that can be used both to increase transmission capacity and to enhance transient stability of power system.

In this study, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line which is operated by Turkish Electricity Transmission Incorporated Company (TEİAŞ) 1. Transmission Installation and Operation Group Management in İstanbul district is modeled by using conductor constants subroutine of Power System Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) with operator data. Also, three phase 6-pulse Static Synchronous Compensator (STATCOM) which is a FACTS device and located under PSCAD/EMTDC like a disposed module is used for compensation purposes.

The performances of obtained conductor model and prototype STATCOM are observed by using graphically interface of PSCAD/EMTDC. The computer simulation results show that STATCOM substantially has a place in regulating voltage and compensating loads and increasing the transmitted active power amount.

Key Words: FACTS, Transmission Lines, Compensation, VSC, STATCOM

ÖZ

YÜKSEK LİSANS TEZİ

İSTANBUL BÖLGESİNDEKİ İLETİM HATTININ PSCAD' TE MODELLENMESİ, PROBLEMLER VE STATCOM KULLANILARAK MEVCUT DURUMUN İYİLEŞTİRİLMESİ

Meral AY

ÇUKUROVA ÜNİVERSİTESİ
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Güç sistemlerinin kompanzasyonunun güç elektroniği tabanlı aygıtlar ile yapılması halinde güç sistemi tam ve esnek bir şekilde kontrol edilebilir. Son yıllarda gelişen güç elektroniği sayesinde ortaya çıkan Esnek Alternatif Akım İletim Sistemi (FACTS) denetleyicileri ile hem güç taşıma kapasitesinin arttırılabileceği hem de kararlılığın daha kolay sağlanabileceği ortaya çıkmıştır.

Bu tez çalışmasında, İstanbul bölgesindeki Türkiye Elektrik İletim Anonim Şirketi (TEİAŞ) 1. İletim Tesis ve İşletme Grup Müdürlüğü tarafından işletilen 154 kV İkitelli-Yenibosna 1-2 çift devre havai iletim hattı, işletmeci verileri ile PSCAD/EMTDC içerisinde yer alan hat sabitleri alt programı kullanılarak modellenmiştir. Ayrıca, PSCAD/EMTDC' de hazır modül olarak yer alan ve FACTS aygıtı olan, üç fazlı 6-darbeli Statik Senkron Kompanzatör (STATCOM) kompanzasyon amacıyla uygulanmıştır.

PSCAD/EMTDC programının grafiksel ara yüzü kullanılarak elde edilen iletken modeli ve STATCOM prototipinin performansı gözlemlenmiştir. Bilgisayar benzetim programının sonuçları, STATCOM' un gerilim regülasyonu ve yüklerin kompanzasyonunda çok büyük önem taşımakta olduğunu ve iletilebilir aktif güç miktarını arttırdığını göstermektedir.

Anahtar Kelimeler: FACTS, İletim Hatları, Kompanzasyon, GBD, STATCOM

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LIST OF SYMBOLS

α	: Phase Angle of the Inverter Voltage
B	: Transmission Line Capacitive Susceptance
f	: Transmission Line Frequncy
f_l	: Frequncy of the Sine Wave
f_S	: Frequncy of the Carrier Wave
G	: Transmission Line Conductance
δ	: Relative Angle Between the STATCOM and AC Bus
I	: Transmission Line Current
I_d	: Inverter Direct Component Current
I_f	: Timed Fault Logic Current
I_q	: Inverter Quadrature Component Current
I_{qref}	: Inverter Reference Quadrate Component Value
m_a	: Amplitute Modulation Ratio
m_f	: Frekans Modulation Ratio
P_{load}	: Load Active Power
P_m	: PCC Active Power
Q_{load}	: Load Reactive Power
Q_m	: PCC Reactive Power
R	: Transmission Line Resistance
r'	: Transmission Line pu Resistance
S_B	: Transmission Line Appearent Power Base Value
θ	: Reference Angle Value
U_B	: Transmission Line Voltage Base Value
V_C	: Converter Output Voltage
$V_{control}$	: Peak Amplitude of the Sine Wave
V_d	:Voltage Direct Component

V_{dc} : Converter DC Voltage

V_{load} : Load AC Voltage

V_{n} : PCC AC Voltage

V_{nS} : STATCOM AC Voltage

V_{pu} : PCC pu Voltage

V_{pu_load} : Load pu Voltage

V_{q} : Voltage Quadrature Component

V_{qref} : Voltage Reference Value

V_{S} : Source AC Voltage

$V_{triangle}$: Peak Amplitude of the Carrier Wave

X : Tie Transformer Leakage Reactance

X_{L} : Transmission Line Inductive Reactance

x' : Transmission Line pu Inductive Reactance

Y : Transmission Line Admittance

y' : Transmission Line pu Admittance

Z : Transmission Line Impedance

LIST OF ABBREVATIONS

AC	: Alternative Current
CMC	: Cascade Multilevel Converter
CSC	: Current Source Converter
DC	: Direct Current
EMTDC	: Electromagnetic Transients Including DC
ENTSO-E	: Europen Network of Transmission System Operators of Electricity
EPRI	: Electric Power Research Instute
FACTS	: Flexible Alternating Current Transmission Systems
GTO	: Gate Turn Off
IEEE	: Institute of Electrical and Electronics Engineers
IGBT	: Insulated Gate Bipolar Transistor
IGCT	: Integrated Gate Commutated Thyristor
MCM	: Mega Circular Mile
OPGW	: Optical Ground Wire
PCC	: Point of Common Coupling
PI	: Proportional Integral
PID	: Proportional Integral Derivative
PLL	: Phase Lock Loop
PU	: Per Unit
PSCAD	: Power System Computer Aided Design
PWM	: Pulse Width Modulation
SPWM	: Sinusoidal Pulse Width Modulation
STATCOM	: Static Synchronous Compensator
SVG	: Statitic VAR Generator
SVC	: Static VAR Compensator
TCPS	: Thyristor Controlled Phase Shifter
TCR	: Thyristor Controlled Reactor
TCSC	: Thyristor Controlled Series Capacitor
TEİAŞ	: Turkish Electricity Transmission Incorparated Company
TEİAŞ	: Türkiye Elektrik İletim Ananonim Şirketi
TSC	: Thyristor Switched Capacitor

T-STATCOM	: Transmission Static Synchronous Compensator
TVA	: Tenessee Valley Authority
VAR	: Volt Amper Reactive
VSC	: Voltage Source Converter

1. INTRODUCTION

Electric utilities of today are facing more problems with trying to provide economical electric power to their customers and trying to allow an increase in the amount of power that is transferred between interconnected utilities and independent power producers. This increase in power flow leads to transmission networks becoming heavily loaded, causing the thermal capacity of the line to reach their limits. In the event of a contingency in the system, the lines are required to carry an even larger load. With the increased power flow due to heavy loading, the system reactive power loses increase dramatically; this loss of reactive power may eventually lead to voltage instability (Reason, 1989). Voltage stability is one of the most important problems faced in power system operation and control. Recently a lot of attention has been paid to the subject of dynamic voltage stability. It is well known that the major components of the power system affecting the dynamic voltage stability are constant power loads and transmission lines (Overby and Dobson, 1994).

The rapid development of power systems generated by increased demand for electric energy initially in industrialized countries and subsequently in emerging countries led to different technical problems in the systems, e.g., stability limitations and voltage problems (Hideaki, 1999). Due to many reasons such as, an increasing demand for energy, the constraints in the building of new transmission lines and the disadvantages of the conventional compensation devices, it has been necessary to maximize the efficiency of existing energy transmission systems. The analysis of the choices available for maximizing the existing energy transmission systems, solution has seen as the power electronics with high level of trust ability and stability. The rapid development of the power electronics technology makes it possible the development of a new technology for the control of the power systems, called “Flexible Alternating Current Transmission Systems (FACTS)” (Ertay and Aydoğmuş, 2012).

The Electric Power Research Institute (EPRI) has initiated the development of Flexible AC Transmission Systems (FACTS) in which power flow is dynamically controlled by various power electronic devices. The two main objectives of FACTS

are to increase the transmission capacity of lines and control power flow over designated transmission routes (Gyugyi, 1994).

With the development in economy and fast advancing technology, the usage of electrical energy increases every year. The upward trend of electrical energy consumption from power networks increases the demand of reactive energy because the production, transmission and distribution of electrical energy are all realized in AC (Karaduman, 2012). Long distance ac power transmission requires reactive power compensation.

Reactive power compensation is an important issue in the control of electric power system. Reactive power from the source increases the transmission losses and reduces the power transmission capability of the transmission lines. Moreover, reactive power should not be transmitted through the transmission line to a longer distance (Xavier et al., 2013).

Various solutions have been used to deal with the problem of voltage. One of the most common, and perhaps the cheapest, is the shunt capacitor (Azares, 2013). Shunt capacitors were first employed for power factor correction in the year 1914 (Frank and Ivner, 1981). Shunt capacitors are available in two types: fixed and switched (Grebe, 1996). The selection of shunt capacitors depends on many factors, the most important of which is the amount of lagging reactive power taken by the load. In the case of widely fluctuating loads, the reactive power also varies over a wide range. Thus, a fixed capacitor bank may often lead to either over-compensation or under-compensation. Variable VAR compensation is achieved using switched capacitors (Frank and Landstrom, 1971). Depending on the total VAR requirement, capacitor banks are switched into or switched out of the system. The smoothness of control is solely dependent on the number of capacitors switching units used. The switching is usually accomplished using relays and circuit breakers. However, these methods based on mechanical switches and relays have the disadvantage of being sluggish and unreliable. Also they generate high inrush currents, and require frequent maintenance (Frank and Ivner, 1981).

Synchronous condensers have played a major role in voltage and reactive power control for more than 60 years. Functionally, a synchronous condenser is

simply a synchronous machine connected to the power system. After the unit is synchronized, the field current is adjusted to either generate or absorb reactive power as required by the ac system. The machine can provide continuous reactive power control when used with the proper automatic exciter circuit. Synchronous condensers have been used at both distribution and transmission voltage levels to improve stability and to maintain voltages within desired limits under varying load conditions and contingency situations. However, synchronous condensers are rarely used today because they require substantial foundations and a significant amount of starting and protective equipment. They also contribute to the short circuit current and they cannot be controlled fast enough to compensate for rapid load changes. Moreover, their losses are much higher than those associated with static compensators, and the cost is much higher compared with static compensators. Their advantage lies in their high temporary overload capability (Miller, 1982).

Static VAR compensators were first developed in the late 1960s for the compensation of large fluctuating loads such as electric arc furnaces (Schauder, 1995). Over the last twenty years, a large number of different static VAR generators, using power electronic technologies have been proposed and developed (Dixon et al. 2005). A SVC consists of capacitor or reactor banks with at least one being switched by thyristors. Typically they are thyristor controlled reactor (TCR) based. To achieve continuous leading or lagging reactive power regulation, they are used in conjunction with fixed capacitors or thyristor-switched capacitors (TSC). The phase angle is modulated for the thyristors to provide smoother control and flexibility of the switching devices. Due to the chopped reactive load of using thyristors, this creates harmonics in the system, which requires filters, adding to the reactive power themselves since they are capacitive. In addition, the response time is limited by the inherent time delay in thyristor gating control (Jin et al, 1994). TCR and TSC can reduce the response time but their reactive power output is dependent on the ac system voltage (Lee et al, 2003). SVC systems cause harmonic current problems while they solve reactive power problems. This requires constant shunt filters or special transformer connections for these systems (Çetin, 2007).

The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors by various switching power converters was disclosed by Gyugi in 1976 (Hingorani and Gyugyi, 1999). With the advanced developments in power semiconductor technology, a new type of compensator has been presented. This compensator is the static synchronous compensator (STATCOM) based on force commutated power semiconductors (Schauder et al., 1995; Karaduman, 2012).

Static Synchronous Compensation (STATCOM) is a Flexible AC Transmission System (FACTS) device, which is connected as a shunt to the network, for generating or absorbing reactive power. By controlling the reactive power in the transmission line, voltage regulation and maximum active power flow can be achieved. In addition, STATCOM can also increase power system stability by damping power oscillations. STATCOM functions as a synchronous voltage source. It can provide reactive power compensation without the dependence on the ac system voltage (Lee et al, 2003).

The STATCOM converters used in transmission system applications should control a few tens or hundreds of MVArs, operate at medium voltage levels and are connected to EHV (Extra High Voltage) or HV (High Voltage) transmission system buses via specially designed coupling transformers. These are called Transmission STATCOMs (T-STATCOM) in the literature (Gültekin et al., 2012)

The major attributes of STATCOM are quick response time, less space requirement, optimum voltage platform, higher operational flexibility and excellent dynamic characteristics under various operating conditions. These controllers are also known as STATic COMpensator (STATCOM), advanced static VAR compensator (ASVC), advanced static VAR generator (ASVG), STATic CONdenser (STATCON), static var generator (SVG), synchronous solid-state VAR compensator (SSVC), VSC-based SVC or self-commutated SVC or static synchronous compensator (SSC or S^2C) (Singh et al., 2009).

The advantages of STATCOM over other compensators have been expressed:

- Size, weight and cost reduction,
- Precise and fast reactive power control with fast response,

- Possible harmonic filtering capability (Schauder et al., 1995; Karaduman, 2012).

STATCOM is the static equivalent of conventional rotary reactive power compensation system which is an idle synchronous motor known as Synchronous Condenser, designed with the use of power semiconductors. STATCOM can generate reactive power both in inductive and capacitive regions, and also it has the ability of responding quickly to the Reactive Power changes in electricity system or loads.

Main functions of STATCOM systems can be summarized in that way:

- Controlling the reactive power flow,
- Regulating the voltage on the point it is connected to,
- Increasing transient and dynamic stability limits in the Electricity System (TUBITAK, 2006).

The thesis is organized as follows:

Chapter 2 gives place to literature review of the FACTS modeling studies.

In Chapter 3, the Flexible AC Transmission System (FACTS) is described. Thyristored and self-commutated compensators are compared. FACTS technology implementation is summarized.

In Chapter 4, the STATCOM device is described. Multi-Pulse Voltage Source Converter and Multi-Level Voltage Source Converter are given. STATCOM's operating principle and control strategy are explained.

Chapter 5 informs about Turkish electricity transmission system. First, the simulation model is introduced. Secondly, PSCAD/EMTDC modeling of 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line is presented.

In Chapter 6, the simulation results are given. Designed basic line models, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line model and STATCOM prototype is presented with obtained from simulated results of PSCAD/EMTDC. The system voltage, load voltage, system active power, load active

power, system reactive power and load reactive power waveforms are given for each case.

In Chapter 7, first, the important conclusions of the study are given. Secondly, suggestions are presented.

2. LITERATURE REVIEW

Mori et al. (1993) described the technical problems and their solutions in the development of the large capacity SVG. In addition, the system configuration of the 80 MVA SVG, its technical features and test results were explained. A static var generator (SVG) which was installed at the Inuyama switching station of the Kansai Electric Power Co., using self-commutated inverters of 80 MVA capacity was developed and successfully applied to an actual 154 kV power system to stabilize the power system. The SVG consisted of 48-pulse multiple inverters whereby GTO thyristors were applied and the controller adopts direct digital control (DDC), which used 16-bit microprocessors. After installing it at a power system site, a field teat was conducted to confirm the system stabilizing effect. The test results displayed the expected performance, and the SVG was proved to be an effective power system stabilizer.

Gyugyi (1994) described a novel approach in which solid-state synchronous voltage sources were employed for the dynamic compensation and real time control of power flow in transmission systems. The synchronous voltage source was implemented by a multi-pulse inverter using gate turn-off (GTO) thyristors. It was capable of generating internally the reactive power necessary for network compensation, and was also able to interface with an appropriate energy storage device to negotiate real power exchange with the ac system. The study developed a comprehensive treatment of power flow control using solid-state synchronous voltage sources for shunt compensation, series compensation, and phase angle control. It also described the unique unified power flow controller that was able to control concurrently or selectively all three network parameters (voltage, impedance, transmission angle) determining power transmission. Comparison of the synchronous voltage source approach with the more conventional compensation method of employing thyristor-switched capacitors and reactors showed its superior performance (including the unmatched capability of using both reactive and real power compensation to counteract dynamic disturbances), uniform applicability, smaller physical size, and potentially lower overall cost.

Schauder et al. (1995) described the fundamental operating principles, functional characteristics, and basic control approach of the STATCOM, with particular reference to a ±100 MVAR prototype planned to be installed at the Tennessee Valley Authority (TVA) Sullivan Substation. That installation has been the first demonstration of a STATCOM under the EPRI Flexible AC Transmission Systems (FACTS) program, and has been the largest installation of its type in the world. EPRI and the Tennessee Valley Authority (TVA) were being teamed with the Westinghouse Science and Technology Center (WSTC) to develop and install the first domestic STATCOM for electric power transmission applications. That development program was part of EPRI's overall FACTS initiative. The prototype STATCOM was rated for ±100 MVAR and was been installed at the Sullivan substation of the TVA power system, near Johnson City, Tennessee.

Sen (1998) described the STATCOM, a solid-state voltage source inverter coupled with a transformer, was tied to a transmission line. A STATCOM injects an almost sinusoidal current, of variable magnitude, at the point of connection. This injected current was almost in quadrature with the line voltage, thereby emulating an inductive or a capacitive reactance at the point of connection with the transmission line. The functionality of the STATCOM model was verified by regulating the reactive current flow through it. That was useful for regulating the line voltage. In that study a STATCOM was modeled using an EMTP simulation package. The STATCOM which was a voltage source inverter injects an almost sinusoidal current to the transmission line at the point of connection. This injected current was almost in quadrature with the line voltage, thereby emulating an inductive reactance or a capacitive reactance at the point of connection.

Lee et al. (2003) performed a circuit-level evaluation of four modern STATCOM systems, namely True-48-Pulse and Quasi-48-Pulse STATCOMs, Cascade 7-Level and Binary 7-Level Inverters. The comparison was based on a number of factors including circuit topology, harmonic distortion, system losses, GTO quantities, their specific applications and other considerations. The theoretical results were verified by simulation with the use of MATLAB-Simulink Power System Blockset. It was shown that the Quasi-48-Pulse STATCOM retained most of

the True-48-Pulse STATCOM features while its design was simpler and costs less. Both designs were suitable for reactive power compensation at transmission level. The Cascade 7-Level Inverter was more flexible and has a wider range of applications. Binary 7-Level Inverter gived a low cost design to achieve similar performance of Cascade 7-Level Inverter. The above information provided a basic guideline for engineer to design their system according to different specifications.

Dirik and Özdemir (2008) developed, firstly, a new model of STATCOM which is a structure of flexible a.c. transmission systems for carrying out computer simulations. Then, performances of two different controllers were investigated by using this model in a sample power system. These controllers were conventional PI controller and fuzzy logic controllers. The STATCOM model was based on input-output active power balance of 48-pulse converter. The Simulation studies were carried out on MATLAB/Simulink environment. The simulation results showed that PI controller structure has enough performance to control STATCOM. Also, although fuzzy logic controller used in simulation has only one input and three rules, it successfully performs control actions. It was established that performance of this controller can be further improved by increasing the number of input variables and rules.

Goel et al. (2010) used Static Synchronous Compensator (STATCOM) for voltage stability and the compensation of reactive power. The STATCOM contained an Insulated Gate Bipolar Transistor (IGBT) based voltage source converter for voltage control and reactive power compensation. The STATCOM was used to control the reactive power with the voltage source converter in combination with a DC voltage source. The values of the DC link capacitor and battery source were optimized using the Genetic Algorithm technique and the simulations results for the same were observed under the inductive as well as capacitive load conditions. The comparison of voltage compensation for various conditions showed that the performance of STATCOM tuned with GA was the best and closest to the nominal value of voltage. The simulation was done in MATLAB for STATCOM and Voltage Source Converter (VSC).

Li and Song (2011) established the south China electric field and simulation of STATCOM model, configuration in wind farms was at fault, whether the compensation device for STATCOM the system simulation proved STATCOM in improving the wind farms transient stability, inhibit the voltage drop wind farms has better performance. STATCOM control system included two PI controller, each PI controller coefficient and the needed to install proportion integral coefficients, the choice of parameters directly affected the performance of the control system and the influence of the operation characteristic STATCOM. Wind power systems discussed in the basic working principle and STATCOM control strategy and establish the relevant model, and the simulation of the actual system. The simulation results showed that STATCOM to maintaining the system, improve the wind power system voltage stability has a good result.

Gültekin et al. (2012) in their research work, design and implementation of a 154 kV, ± 50 MVAr Transmission STATCOM (T-STATCOM) was carried out primarily for the purposes of reactive power compensation and terminal voltage regulation, and secondarily for power system stability. The implemented T-STATCOM consisted of five 10.5 kV, ±12 MVAr Cascaded Multilevel Converter (CMC) modules operating in parallel. The power stage of each CMC was composed of five series connected H-Bridges (HB) in each phase, thus resulting in 21-level line-to-line voltages. Due to modularity and flexibility of implemented HBs, a CMC module power density of 250 kVAr/m³ was reached, thus making the mobility of the system implementable. DC link capacitor voltages of HBs were perfectly balanced by means of the Modified Selective Swapping Algorithm proposed. The field tests carried out at full load in the 154 kV transformer substations where T-STATCOM was installed and put into service have shown that the steady-state and transient responses of the system were quite satisfactory.

Sarıbulut (2012) described the control algorithms of conventional methods such as Fourier Transform, Wavelet Transform, Reference-Frame Transformation Methods, Fuzzy Logic and Artificial Neural Networks were examined for the disturbances detection and compensation and illustrated graphically. The advantages and disadvantages of these methods were also analyzed and given in details. In

additions, new methods for the harmonic currents extraction, voltage sag detection and compensation for the negative effects of these disturbances were proposed. The performance comparisons of the conventional and proposed methods were realized by using the power quality mitigation devices such as Active Power Filter (APF) and Dynamic Voltage Restorer (DVR) in PSCAD simulation program.

Xavier et al. (2013) made an attempt to obtain the real time performance of STATCOM using both PI and ANN (Artificial Neural Network) controller in dSPACE environment. The performance of STATCOM was analyzed by giving load disturbance. It was observed that the STATCOM under ANN controller had less peak overshoot and steady state error. It also had faster response than PI controller. Hence ANN controller performed better than PI controller. Also it was found that using dSPACE, experimental verification of real time control system can be easily achieved.

3. FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)

Flexible AC Transmission Systems (FACTS) devices have been used in power systems since the 1970s for the improvement of its dynamic performance.

Voltage stability is one of the biggest problems in power systems. The series and shunt compensation are able to increase the maximum transfer capabilities of power network. Concerning to voltage stability, such compensation has the purpose of injecting reactive power to maintain the voltage magnitude in the nodes close to the nominal values, besides, to reduce line currents and therefore the total system losses. Instability in power system could be relieved or at least minimized with the help of most recent developed devices called Flexible AC Transmission System (FACTS) controllers.

- Principal Causes of Voltage Stability Problems

  Some of the main causes for occurrence of voltage instability are:

  - Due to unsuitable locations of FACTS controllers,
  - High Reactive Power Consumption at Heavy Loads,
  - Occurrence of Contingencies,
  - Reverse Operation of ON Load Tap-Changer (OLTC),
  - Voltage sources are too far from load centers,
  - Poor coordination between multiple FACTS controllers,
  - Presence of Constant Power Loads,
  - Difference in Transmission of Reactive Power under Heavy Loads.

- Prevention of Voltage Instability

  Some of the prevention of voltage instability by following:

  - Placement of Series and Shunt Capacitors,
  - Generation Rescheduling,
  - Placement of FACTS Controllers,
  - Under-Voltage Load Shedding,

- Blocking of Tap-Changer under Reverse Operation,
- Coordination of Multiple FACTS Controllers,
- Installation of Synchronous Condensers.

The use of Flexible AC Transmission System (FACTS) controllers in power transmission system have led to many applications of these controllers not only to improve the stability of the existing power network resources but also provide operating flexibility to the power system. In addition, with relatively low investment compared to new transmission or generation facilities, these FACTS technology allows the industries to better utilize the existing transmission and generation reserves, while enhancing the power system performance. They clearly enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources (Gupta et al., 2010).

Flexible AC Transmission Systems (FACTS) are being increasingly used in power systems, to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC system interconnections (Gültekin et al., 2012).

FACTS devices are a family of high-speed electronic devices, which can significantly increase the power system performance by delivering or absorbing real and/or reactive power. There are two generations for realization of power electronics-based FACTS controllers: the first generation employs conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second generation employs gate turn off (GTO) thyristor-switched converters as voltage source converters (VSCs). The first generation has resulted in the Static Var Compensator (SVC), the Thyristor-Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS) (Hingorani and Gyugyi, 2000). The second generation which is Self-Commutaded Compensator has produced the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC) (Song and Johns, 1999.) The two groups of FACTS controllers have distinctly different operating and performance characteristics. They

can be connected to power system at any appropriate location, in series, in shunt or in a combination of series and shunt. The SVC and STATCOM are connected in shunt, whereas TCSC and SSSC are connected in series. UPFC is connected in a combination of both shunt and series (Gupta et al., 2010).

Over the years Static Var Compensators of many different designs have been built. Nevertheless, the majority of them have similar controllable elements. The most common ones are:

- Thyristor-Controlled Reactor (TCR)
- Thyristor-Switched Capacitor (TSC)
- Thyristor-Switched Reactor (TSR)
- Mechanically Switched Capacitor (MSC) (ABB review, 2003)

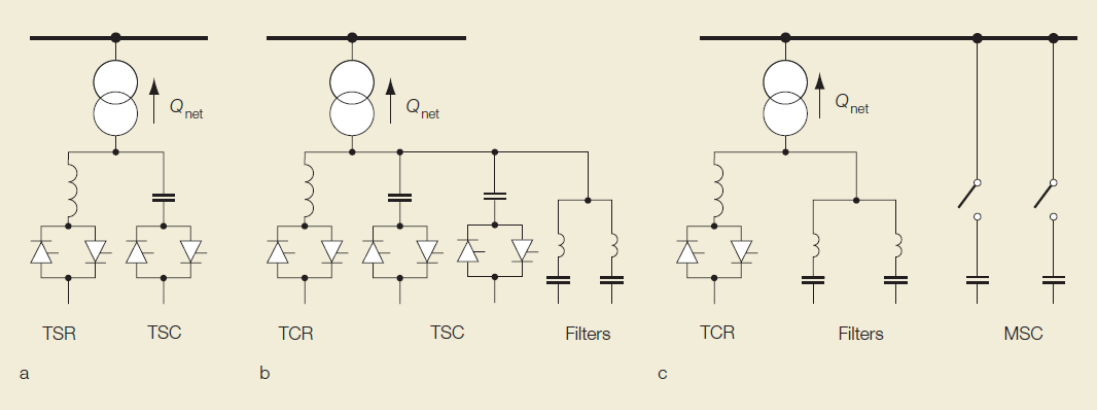


Figure 3.1. SVC configurations used to reactive power compensation in electric power systems a) TSR-TSC configuration, b) TCR-TSC configuration, c) TCR-MSC configuration *Qnet: Net reactive power to network (ABB review, 2003)

3.1. Comparison between Thyristorized and Self-Commutated Compensators

As compared with thyristor-controlled capacitor and reactor banks, self-commutated VAR compensators have the following advantages:

- They can provide both leading and lagging reactive power, thus enabling a considerable saving in capacitors and reactors. This in turn reduces the possibility of resonances at some critical operating conditions.
- Since the time response of self-commutated converter can be faster than the fundamental power network cycle, reactive power can be controlled continuously and precisely.
- High frequency modulation of self-commutated converter results in a low harmonic content of the supply current, thus reducing the size of filter components.
- They don't generate inrush current.
- The dynamic performance under voltage variations and transients is improved.
- Self-commutated VAR compensators are capable of generating 1 p.u. reactive current even when the line voltages are very low. This ability to support the power system is better than that obtained with thyristor controlled VAR compensators because the current in shunt capacitors and reactors is proportional to the voltage.
- Self-commutated compensators with appropriate control can also act as active line harmonic filters, dynamic voltage restorers, or unified power flow controllers (Dixon et al, 2005).

3.2. FACTS Technology Implementation

In the emerging deregulated power systems, FACTS controllers will provide several benefits at existing or enhanced levels of reliability such as balancing the power flow in parallel networks over a wide range of operating conditions, alleviating unwanted loop flow, mitigating inter area power oscillations, and enhancing the power-transfer capacity of existing transmission corridors (Povh, 1998; Gupta et al., 2010).

In addition to the several successful installations of the first generation, the second generation of FACTS controllers which uses GTO-based VSC configurations

is expected to evolve into another mature family of FACTS controllers as several power utilities worldwide have started installing such controllers (Gupta et al., 2010):

In 1991, a ±80 MVAR STATCOM developed by Kansai Electric Power Co. (KEPCO) and Mitsubishi Motors was installed at Inuyama Switching Station to improve the stability of a 154 kV system (Matsuno et al., 2002).

A Static Var Compensator (SVC) supplied by ABB Power Systems has been operating since 1993 in BC Hydro's power transmission network at Dunsmuir 500/230/132 kV substation on Vancouver Island in western Canada (ABB, 2011).

The design and type testing aspects of thyristor valves of Thyristor Controlled Series Capacitor (TCSC) scheme for Kanpur-Ballabhgarh 400kV line are discussed by (Lal et al., 2008).

In 1995, a ±100 MVAR STATCOM was commissioned for the Tennessee Valley Authority (TVA) (Schauder et al., 1997). The TVA STATCOM is the first of its kind, using GTO thyristor valves, to be commissioned in United States.

In 1997, American Electric Power (AEP) has selected its Inez substation in eastern Kentucky for the location of the world's first UPFC installation (Schauder et al., 1998). The UPFC is comprised of two ±160 MVA GTO thyristor-based inverters, this installation is the highest power GTO based FACTS device ever installed.

EPRI and Siemens also developed a ±200 MVAR convertible static compensator (CSC), which was installed at Marcy 345 kV substation in 2001 to provide strong dynamic voltage support and to control the power flow. Depending on the transmission control need, the installed CSC can provide four control modes where it can be controlled to operate as STATCOM, SSSC, UPFC, and IPFC (Fardanesh et al., 2002).

A ±75 MVAR STATCOM developed by ALSTOM, the first cascade multilevel-inverter based STATCOM in the world, entered commercial service at National Grid Company (NGC) East Claydon, England in 2001 (Hanson et al., 2002).

A +133/-41 MVAR STATCOM system has been installed at the Vermont Electric Power Company's Essex 115 kV substation since May 2001, to compensate for heavy increases in summertime electric usage (Reed et al., 2001).

A three-level ±100 MVAR STATCOM is installed by San Diego Gas & Electric (SDG&E) at Talega substation, California in October 2002, and is to be extended to a Back-To-Back system (Reed et al., 2002).

ABB has installed six STATCOM systems (also named SVC Light) since 1997; two installations in USA and one installation in Sweden, Germany, Finland, and France (Yu et al., 2004).

A ±250 KVAR prototype D-STATCOM was designed and installed for the first time (Bina et al., 2005). The Bharat Heavy Electric Limited (BHEL), India was successful in developing distribution scale STATCOM also known as D-STATCOM which has successfully been installed in industry (Siemens, 2014).

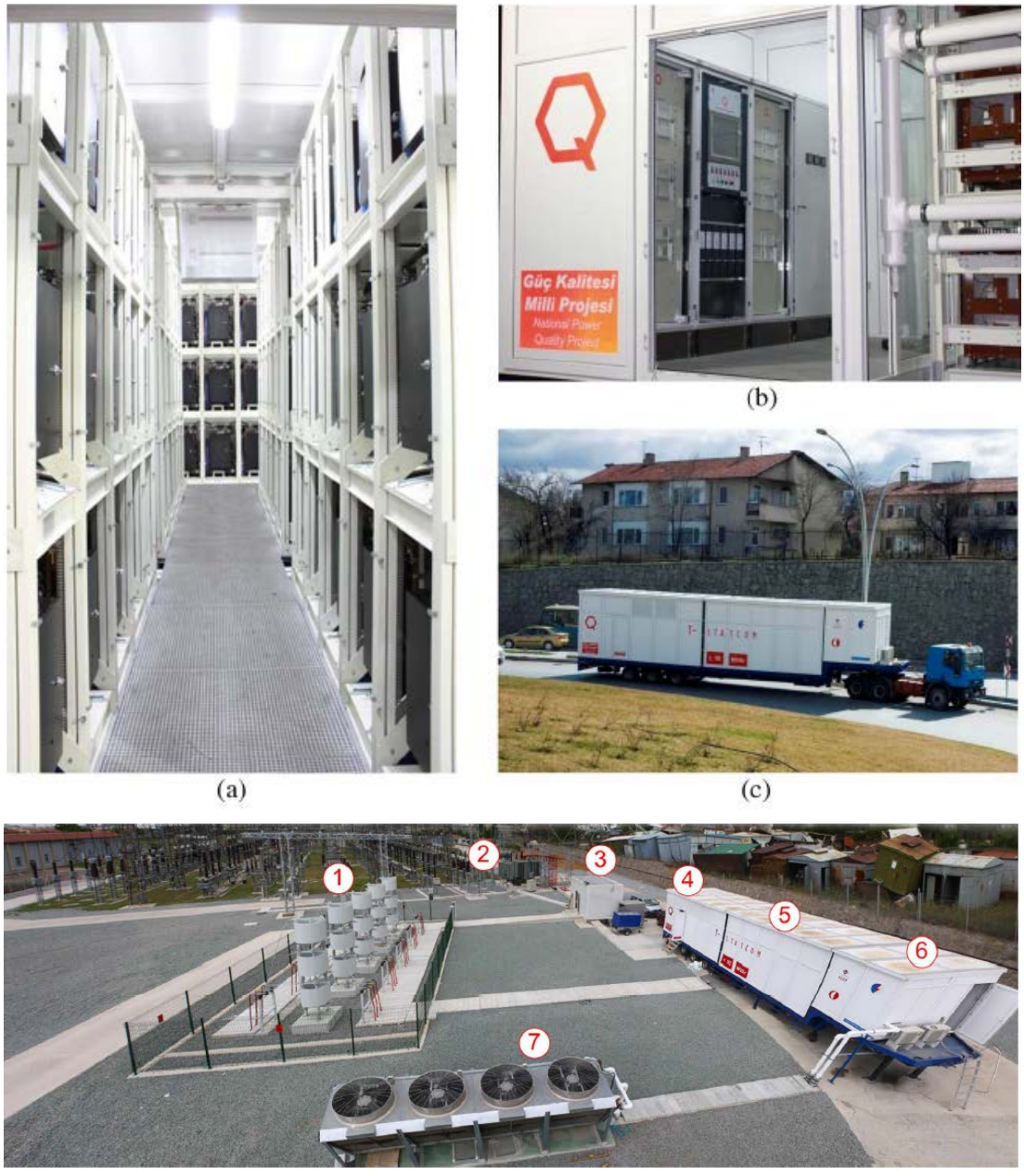
TUBITAK-UZAY developed the first Current Source Converter (CSC) based STATCOM for Turkey Coal Enterprises in 2004 (Bilgin et al., 2007). CSC STATCOM is used to solve the reactive power compensation problem of coal mining excavators (Çetin, 2007).

TUBITAK-UZAY developed the first 154-kV ±50-Mvar T-STATCOM based on 21-level CMCs for TEİAŞ Sincan Substation at Ankara in 2010 TURKEY. It is composed of five 10.5-kV, ±12-MVAr Cascaded Multilevel Converter (CMC) modules which are connected in parallel via air-core reactors. The combination of five STATCOM modules is then connected to 154kV bus via a 154/10.5kV, 50/62.5MVA, YNyn connected coupling transformer. It is a 21-level CMC based T-STATCOM and has been designed and implemented primarily for the purposes of reactive power compensation and terminal voltage regulation, and secondarily for power system stability (Gültekin et al., 2012).

Figure 3.2.d shows the typical layout of a STATCOM substation used for voltage compensation of a transmission lines. The numbered boxes in the figure are identified below:

1. Air-core series filter reactor banks,
2. 154/10.5-kV coupling transformer and its HV switchgear equipment,
3. MV switchgear,
4. Control room,

5. Power stage,
6. De-ionized water cooling pump station,
7. Water-to-air heat exchanger.



(a) (b) (c) (d)

Figure 3.2.Sincan Substation 154-kV ±50-MVAR T-STATCOM based on 21-level CMCs a) Interior view of trailer with power stages, b) Control cabinets, c) Trailer for ±50-MVAR T-STATCOM on road (W × L × H: 3700 mm × 16 800 mm × 4300 mm), d) General view of T-STATCOM (Gültekin et al., 2012)

4. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

4.1. STATCOM's Structure

The static synchronous compensator is based on a solid-state voltage source, implemented with an inverter and connected in parallel to the power system through a coupling reactor, in analogy with a synchronous machine, generating balanced set of three sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase-shift angle. This equipment, however, has no inertia and no overload capability (Dixon et al., 2005).

The STATCOM has been defined as per CIGRE/IEEE with following three operating structural components. First component is **Static:** based on solid state switching devices with no rotating components; second component is **Synchronous:** analogous to an ideal synchronous machine with 3 sinusoidal phase voltages at fundamental frequency**;** third component is **Compensator:** provided with reactive compensation (Masood et al., 2010).

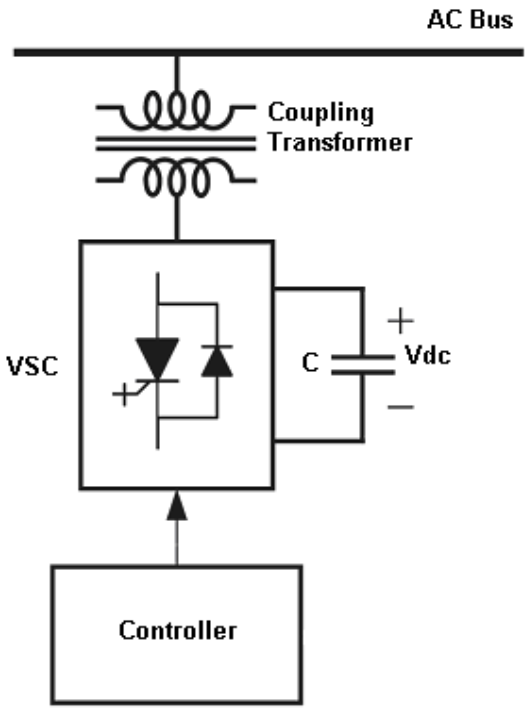
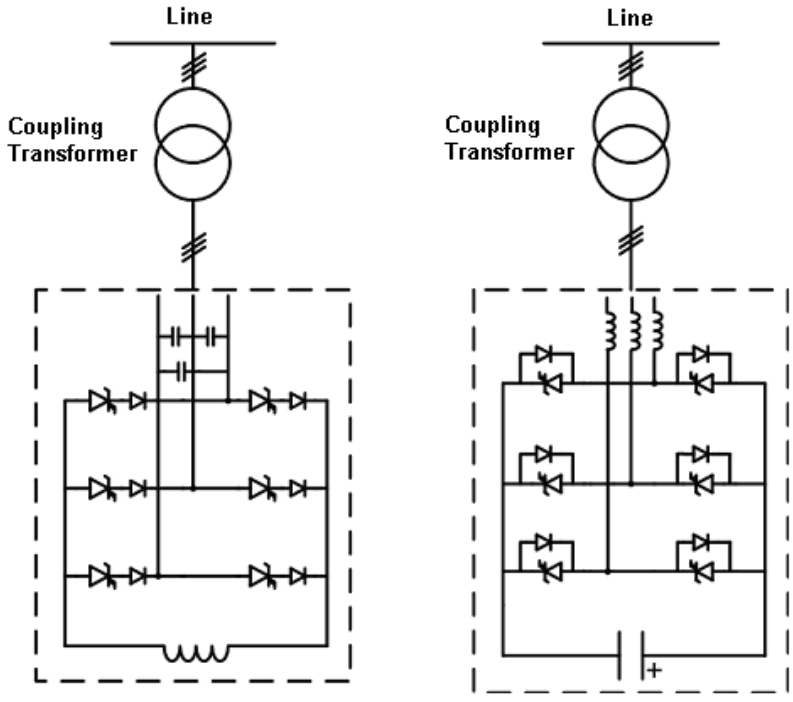


Figure 4.1. Single line circuit diagram of the STATCOM (Anadol, 2012)

It is shown in Figure 4.1, the STATCOM is consisting of VSC (Voltage Source Converter) units, DC side of which is connected to a DC capacitor to be used as an energy storage device, interfacing magnetics (main coupling transformer and/or inter-mediate/inter-phase transformers) that form the electrical coupling between converter AC output voltage (V_C) and system voltage (V_S) and a controller. VSC is the backbone of STATCOM and it is a combination of self-commutating solid-state turn-off devices (viz. GTO, IGBT, IGCT and so on) with a reverse diode connected in parallel to them (Singh et al., 2009).

STATCOM is based on power electronic converter which has an energy storage component on the DC link side. Depending on the type of storage element, either a voltage source converter (VSC) or a current source converter (CSC).



(a) (b)

Figure 4.2. STATCOM based on a) Current Source Converter (CSC) and b) Voltage Source Converter (VSC) (Bilgin, 2007)

Typical circuit diagrams for CSC and VSC are given in Figure 4.2.a. and Figure 4.2.b, respectively. In CSC configuration, the output is three phase controllable currents. In VSC configuration, the output of the converter is the three

phase controllable voltages. As shown in Figure 4.2.a, the capacitors must be placed between the CSC and AC grid in CSC based STATCOM. The VSC based STATCOM is connected to the AC grid via an inductance (also named as reactor) as shown in Figure 4.2.b (Karaduman, 2012).

However, more than 10 years ago, the focus of all the published work on STATCOM has been on using VSC topology. The reasons behind the choice of VSC over CSC are as follows:

- A CSC is more complex than a VSC in both power and control circuits. Filter capacitors are used at the ac terminals of a CSC to improve the quality of the output ac current waveforms. This adds to the overall cost of the converter. Furthermore, filter capacitors resonate with the ac-side inductances. As a result, some of the harmonic components present in the output current might be amplified, causing high harmonic distortion in the ac-side current. Besides, conventional bi-level switching scheme cannot be used in CSC.
- Unless a switch of sufficient reverse voltage with standing capability such as Gate-Turn-Off Thyristor (GTO) is used, a diode has to be placed in series with each of the switches in CSC. This almost doubles the conduction losses compared with the case of VSC.
- The dc-side energy-storage element in CSC topology is an inductor, whereas that in VSC topology is a capacitor. The power loss of an inductor is expected to be larger than that of a capacitor. Thus, the efficiency of a CSC is expected to be lower than that of a VSC (Mittal et al., 2012).

Many VSC-based topologies and configurations are adopted in the state-of-the-art STATCOM controllers and significantly, multi-pulse and multi-level topologies are widely accepted in the design of compensators (Singh et al., 2009).

4.1.1. Multi-Pulse Voltage Source Converter

An elementary six-pulse VSC which consists of three legs (phases) with two valves per leg and an electrostatic capacitor on the DC bus is illustrated in Figure 4.3. Each valve consists of a self-commutating switch with a reverse diode connected in parallel (Singh et al., 2009).

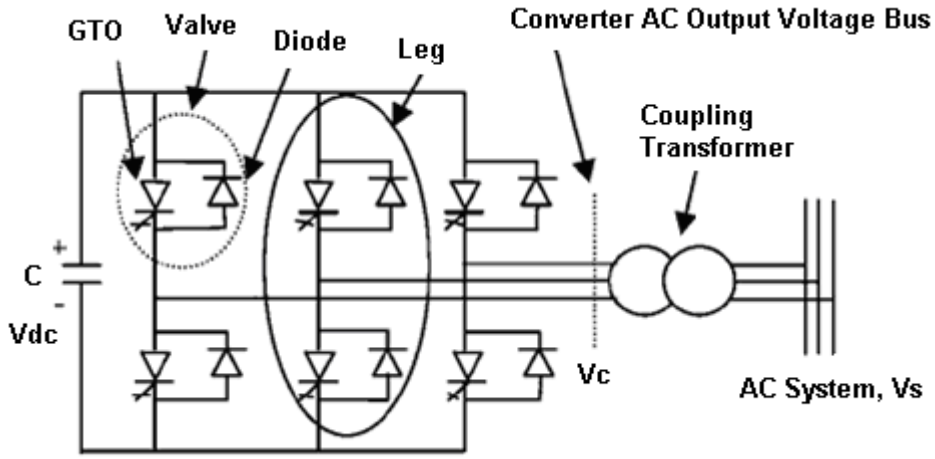


Figure 4.3. Basic two-level six-pulse VSC bridge (Singh et al., 2009)

The waveforms of the voltage-sourced converter output voltage and current are far from sinusoidal. The output voltage waveform of the six-pulse converter contains harmonics of frequencies of (6k ± l)f, and its current is composed of frequencies of 6k.f , where f is fundamental frequency and k = 1,2,3,….Passive filters can filter some of the harmonics but this method is considered to be expensive, particularly at low frequencies, where L and C passive filter components have large values and sizes.

One way of reducing the level of harmonics present in the converter output waveforms is to increase the number of converters. This method involves multiconnected, out-of-phase six-pulse converters connected to a power system through an appropriate configuration of transformers. A 6n-pulse converter can be obtained through series connection of n six-pulse converters operated from a common dc source with a successive $2\pi/6n$ phase displacement. The six-pulse converter output voltage wavefoms are shifted by transfomers with appropriate

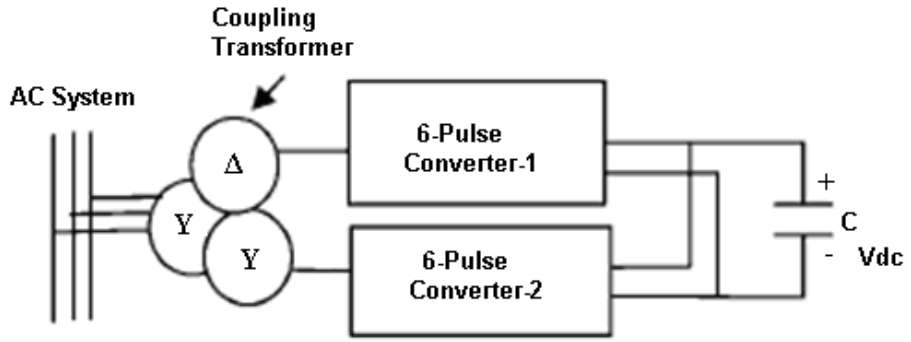
secondary winding configurations to cancel the phase displacement of the converter. The transformed outputs of all converters are in phase with each other and are summed by the series connection of all corresponding primary windings. It is necessary to have separate transfomers for each converter; otherwise phase shifts in the non-charactenstic harmonics, i.e. 6n-order harmonics, will result in a large circulating current due to a common core flux. Transformer primary side windings should not be connected parallel to the same three-phase ac buses for the same reason. Therefore, the harmonics present in the waveform of a general P-pulse converter are (P±1).f in the output voltage and P.f in the output current where P=6n and n = 1, 2, 3.... Since the order of the lowest harmonic present in the output current is the same as the pulse number and the order of the lowest harmonic contained in the output voltage is the pulse number minus one the harmonic spectrum improves rapidly by increasing the number of converters and consequently by increasing the pulse number (Uzunovic, 2001).

With the increase in pulse number, lower-order harmonics are neutralised and a very close to sinusoidal AC output voltage waveform can be realised. Compared with basic six-pulse converter, the multi-pulse configuration of STATCOM increases the achievable VAR rating, improves the harmonic performance, decreases the DC side current harmonics and reduces significantly the overall filter requirements. It is noted that increase in pulse order increases the number of electronics devices, magnetics and associated components and thus added to the cost. However, the high pulse-order STATCOM enables to improve harmonics and operational performances (Singh et al., 2009).

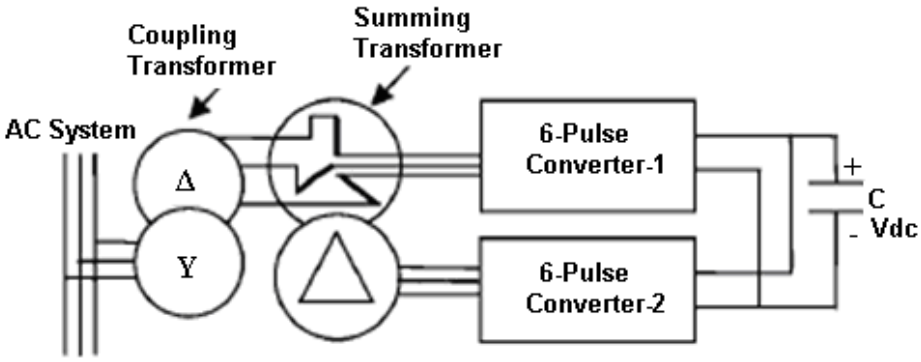
Basic two-level 12-pulse (2x6-pulse), 24-pulse (4x6-pulse) and 6N-pulse (Nx6-pulse) converter configurations are produced, two six-pulse converters, four six-pulse converters and N six-pulse converters, respectively.

Out of the few multi-pulse topologies, 12-pulse, 24-pulse and 48-pulse configurations are very common. For example typically, 12-pulse two-level converter configurations consisting of two elementary six-pulse bridges, DC side of each is connected in parallel and its AC side is either connected in series or in parallel are shown in Figure 4.4.a and Figure 4.4.b. Magnetics in a 12-pulse two-

level STATCOM is configured such that, one bridge is fed to Y–Y transformer and the other bridge to a Δ–Y transformer maintaining thereby a phase shift of 30° between two sets of fundamental AC output voltage waveform. The converter side Δ -winding has √3 times the turns as the converter side Y-winding to keep the same volts per turn in both the windings. The AC mains side windings (Y) are connected in series and can have any turn ratios to increase or decrease the output voltages. The combined output phase voltage leads to multi-stepped voltage waveform and has 12-pulse waveform with harmonics of the order of (12k ±1) that is, 11th, 13th, 23rd… and with amplitudes of 1/11th, 1/13th, 1/23rd… of fundamental amplitude, respectively (Singh et al., 2009). 12-pulse two level converter's single line diagram is shown in Figure 4.5.



(a)



(b)

Figure 4.4. Multi-pulse parallel and series converter configurations a) 12-pulse parallel converter configuration b) 12-pulse series converter configuration (Singh et al., 2009)

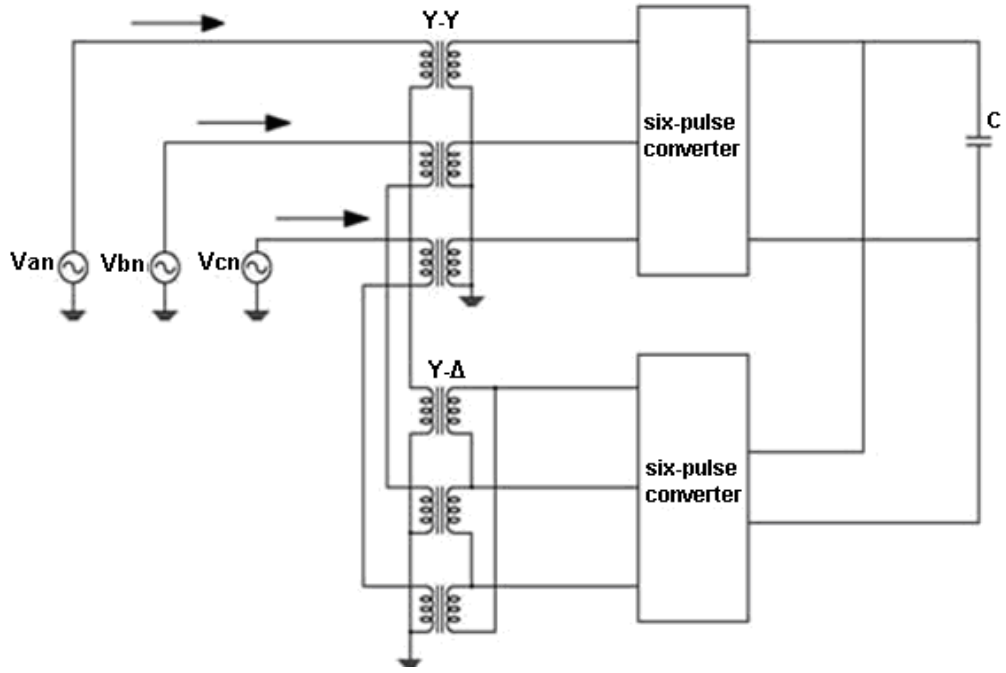


Figure 4.5.12-pulse converter single line diagram (Gültekin)

4.1.2. Multi-Level Voltage Source Converter

Another variant of topology is a multi-level VSC structure to generate multi-stepped voltage waveform close to sinusoidal nature. Owing to the complex series-parallel connection of transformers windings/circuits in multi-pulse converters, multi-level configurations have been receiving increasing attention for high voltage and high power rating applications. In multi-level topology, a synthesised staircase voltage waveform is derived from several levels of DC voltage sources obtained normally by using capacitor voltage sources, and in this category, three-level converter topologies with square-wave mode of operation is most common. An N-level topology is achieved by splitting of DC capacitors into (N-1) sections produces N-level output phase voltage and a (2N-1) level output line voltage waveform. When number of levels is high enough, harmonic content in AC output voltage is reduced to low enough to avoid the need of filters. The main features of multi-level converter are the low harmonic content of the output voltage compared with a square-wave pulse converter, decreased device voltage stress (a fraction of the total DC bus voltage) and potentially higher converter voltage and thus power rating. The multi-

level topology employing capacitor voltage synthesis technique is to be preferred to the multipulse topology employing magnetic coupling technique. Three basic types of multi-level VSCs are reported.

First type multi-point clamped converter or diyode-clamped converter in which three-level neutral point clamped (NPC) converter topology is a matured technology and on this concept many STATCOM controllers have been commercially developed. Five-level multipoint-clamped converter is shown in Figure 4.6.

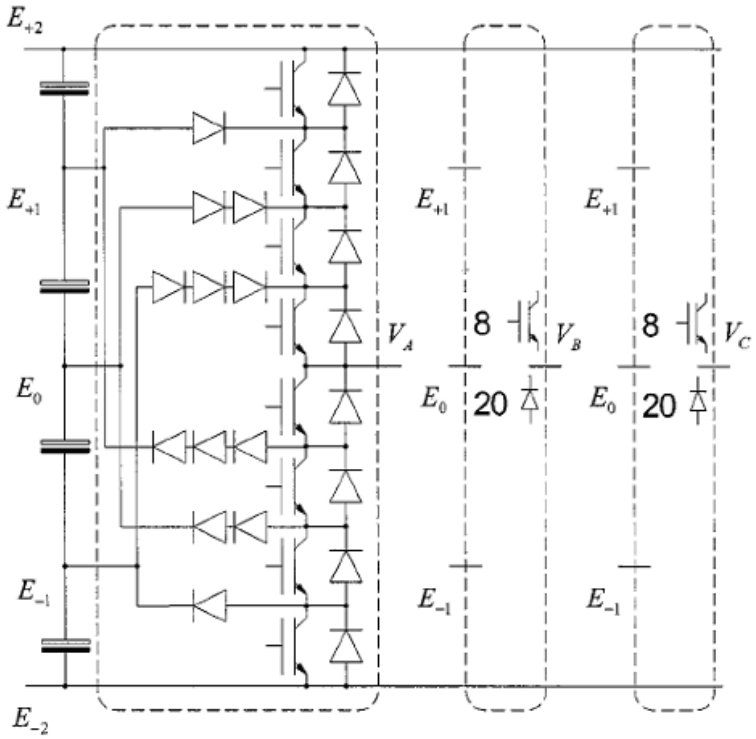


Figure 4.6. Five-level multipoint-clamped converter (Soto and Green, 2002)

The second type is chain converters based on standard H-bridge arrangements as shown in Figure 4.7 and the third is nested-cell converter or flying capacitor multi-level converter as shown in Figure 4.8. Implementations of these converters require the same number of switches for the same number of levels, but there is a wide variation in terms of passive component requirements and operational and control strategies. Such topologies are complex and therefore applications of these converters are limited. For relatively slow switching devices like GTO, application

of three-level converter topology with fundamental frequency switching has got wide acceptability in designing STATCOM for high power rating applications (Singh et al., 2009).

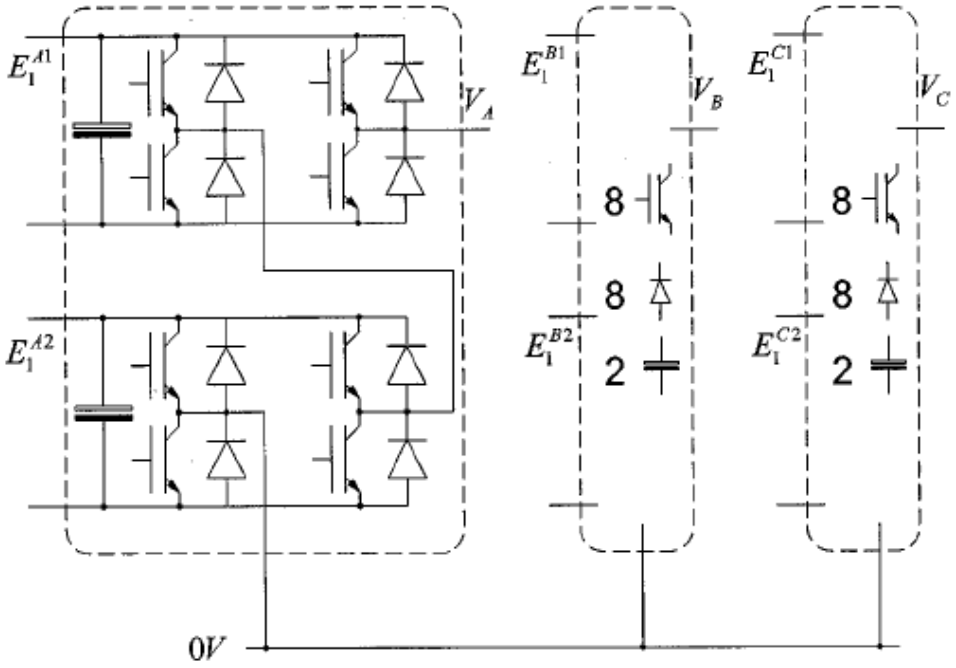


Figure 4.7. Five-level two-cell chain converter (Soto and Green, 2002)

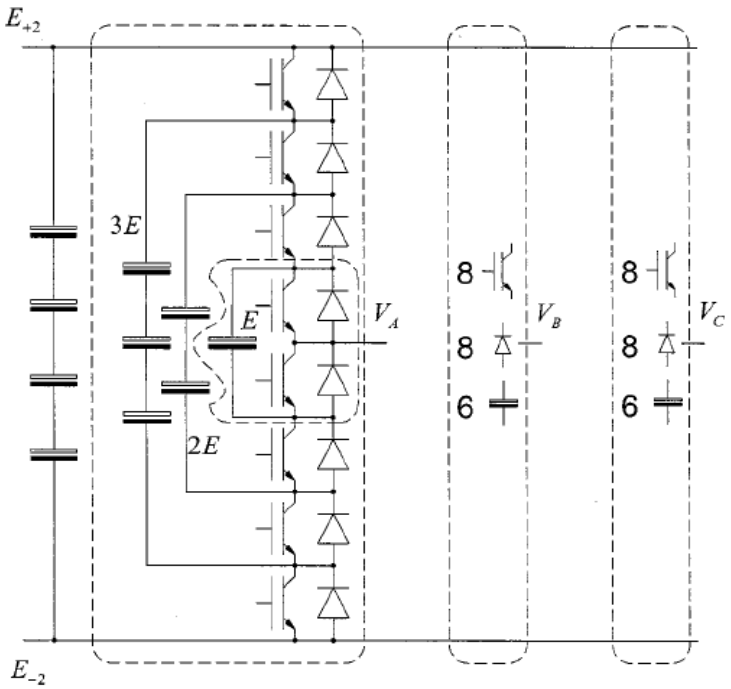


Figure 4.8. Five-level nested-cell converter (Soto and Green, 2002)

4.2. Operating Principle of the STATCOM

4.2.1. Reactive and Active Operating Principle of the STATCOM

Figure 4.9 shows the schematic representation of the STATCOM. The active power flow is controlled by the angle between the ac system and VSC voltages and the reactive power flow is controlled by the difference between the magnitudes of these voltages (Sahoo and Thyagarajan, 2009).

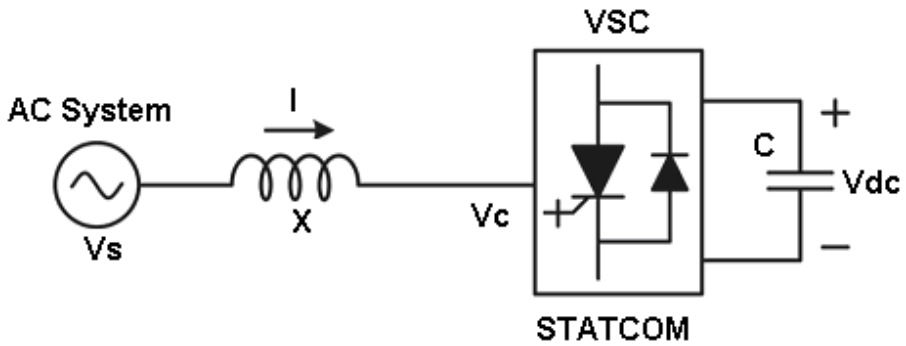


Figure 4.9. STATCOM basic schema (Anadol, 2012)

The three phase output voltage is generated by a voltage sourced dc to ac converter operated from an energy storage capacitor. By varying the amplitude of the output voltages produced, the reactive power change between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. That is, if the amplitude of the output voltage (V_C) is increased above that of the ac system voltage (V_S), then the current flows through the tie reactance (jX) from the converter to the ac system and the converter generates reactive (capacitive) power for the ac system (Figure 4.10.a). If the amplitude of the output voltage (V_C) is decreased below that of the ac system (V_S), then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power (Figure 4.10.b). If the amplitude of the output voltage (V_C) is equal to that of the ac system voltage (V_S), the reactive power exchange is zero (Figure 4.10.c) (Halvorson et al., 2010).

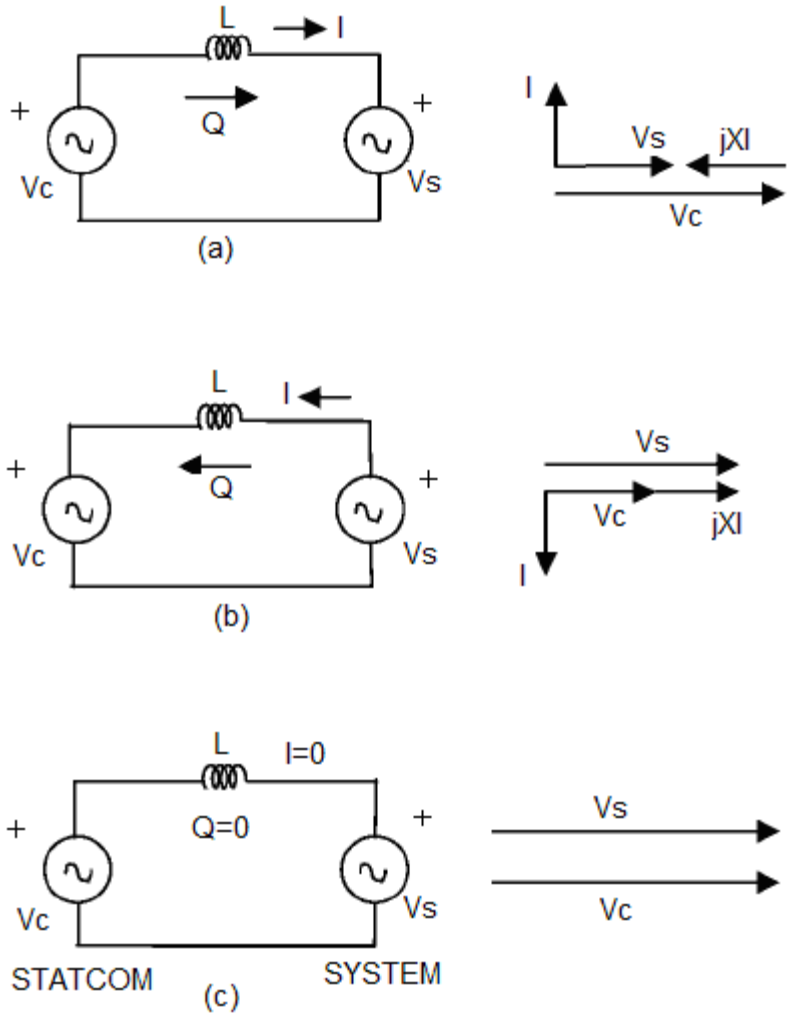
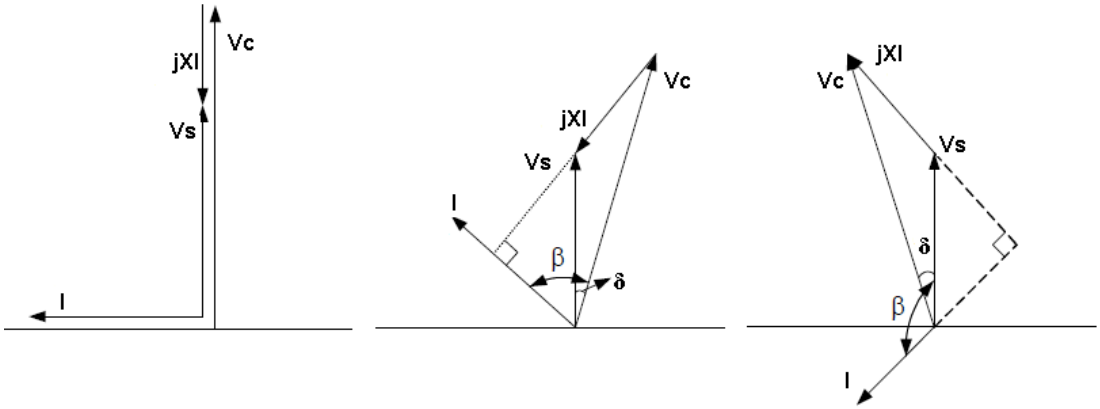


Figure 4.10. STATCOM reactive power operating principle: a) Capacitive mode, b) Inductive mode, c) Floating mode (Singh et al., 2009)

Figure 4.11.a shows the case when the angle (δ) is equal to zero and there is no real power transfer between the converter and ac system. Thus, the real power exchange between the converter and the ac system can be controlled by phase shifting the converter output voltage V_C with respect to the ac system bus voltage V_S. The converter absorbs real power from the ac system if the converter output voltage is made to lag the ac system voltage, as is shown in Figure 4.11.b, whereas the converter supplies real power from its dc capacitor to the ac system if the converter output voltage leads the corresponding ac system voltage, as is shown in Figure 4.11.c (Uzunovic, 2001). In steady-state, the output voltage of the inverter slightly lags the ac system voltage, so that the inverter absorbs a small amount of real

power from the ac system to replenish its internal losses and, thus, keep the capacitor voltage constant (Uzunovic et al., 1997).



(a) (b) (c)

Figure 4.11. STATCOM active power operating principle: a) steady-state operation, b) capacitor charging mode, c) capacitor discharcing mode (Çöteli, 2006)

If the STATCOM has no power loss and operates to supply only reactive power, then no active power exchanges between the STATCOM and the ac system. Therefore, the inverter output voltage is controlled to be exactly in phase with the system voltage. The reactive power exchange between the STATCOM and the AC system can be controlled by varying the amplitude of the inverter output voltage. The switches of the inverter and passive components are not ideal and hence the dissipative power losses exist. The energy stored in the capacitor is eventually used to compensate internal losses of the converter. Hence the voltage across the capacitor cannot sustain and will eventually collapse. Therefore, a small amount of active power is required to compensate the dissipative power loss so that the dc capacitor voltage can be maintained constant. This small amount of active power can be provided by the power system in such a way that there is a slight phase difference (δ) between the system voltage and the STATCOM output voltage (Xavier et al, 2013).

4.2.2. V-I Characteristic of the STATCOM

The STATCOM V-I characteristic is shown in Figure 4.12. This characteristic shows the STATCOM ability to support a very low system voltage; down to about 0.15 per unit, which is the value associated with the coupling transfomer reactance. A STATCOM can support system voltage at extremely low voltage conditions as long as the dc capacitor can retain enough energy to supply losses. The STATCOM also has increased transient ratings in both capacitive and inductive regions. The overload capability is about 20 % for several cycles in both regions (Uzunovic, 2001).

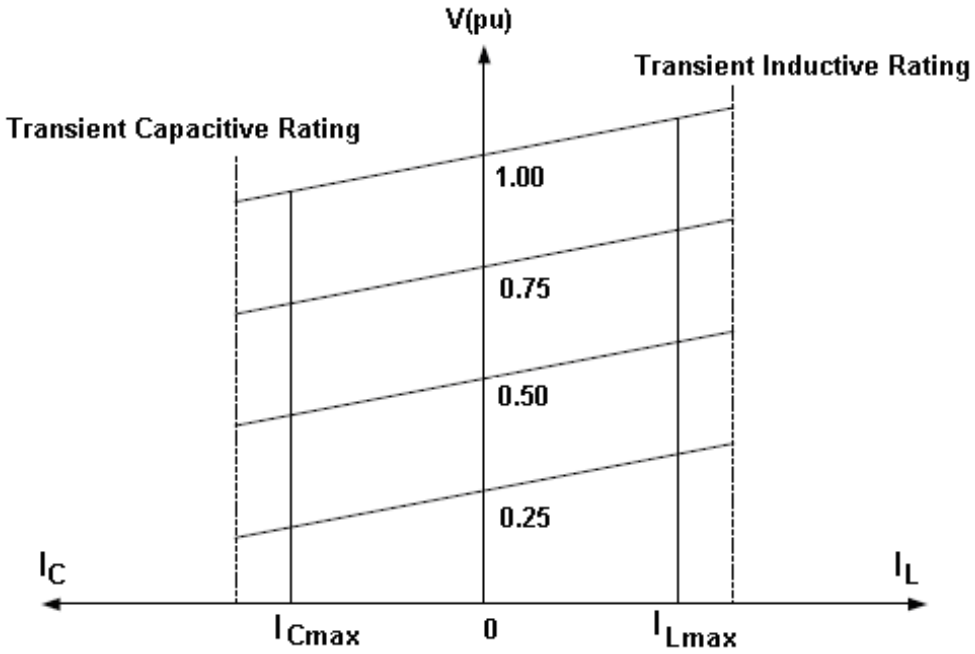


Figure 4.12. STATCOM V-I characteristic (Çöteli, 2006)

4.3. Control Strategy of the STATCOM

The basic control architecture is shown in Figure 4.13. In the process of designing and implementation of control system, acquisition of many signals is involved. Initially, the essential AC and DC voltages and current signals (instantaneous values/vectors) are sensed using sensors. In the next step, these

signals are synthesised by referans production techniques (such as d–q synchronous rotating axis transformation, alpha–beta stationery reference frame of transformation and so on). Third step involves generation of compensating command signals based on kinds of PI or PID control techniques. Fourth step is to generate required gating signals for the solid-state devices. Phase locked loop circuit (Phase Lock Loop - PLL), is normally employed to calculate phase and frequency information of the fundamental positive sequence component of system voltage which synchronises AC converter output voltage.

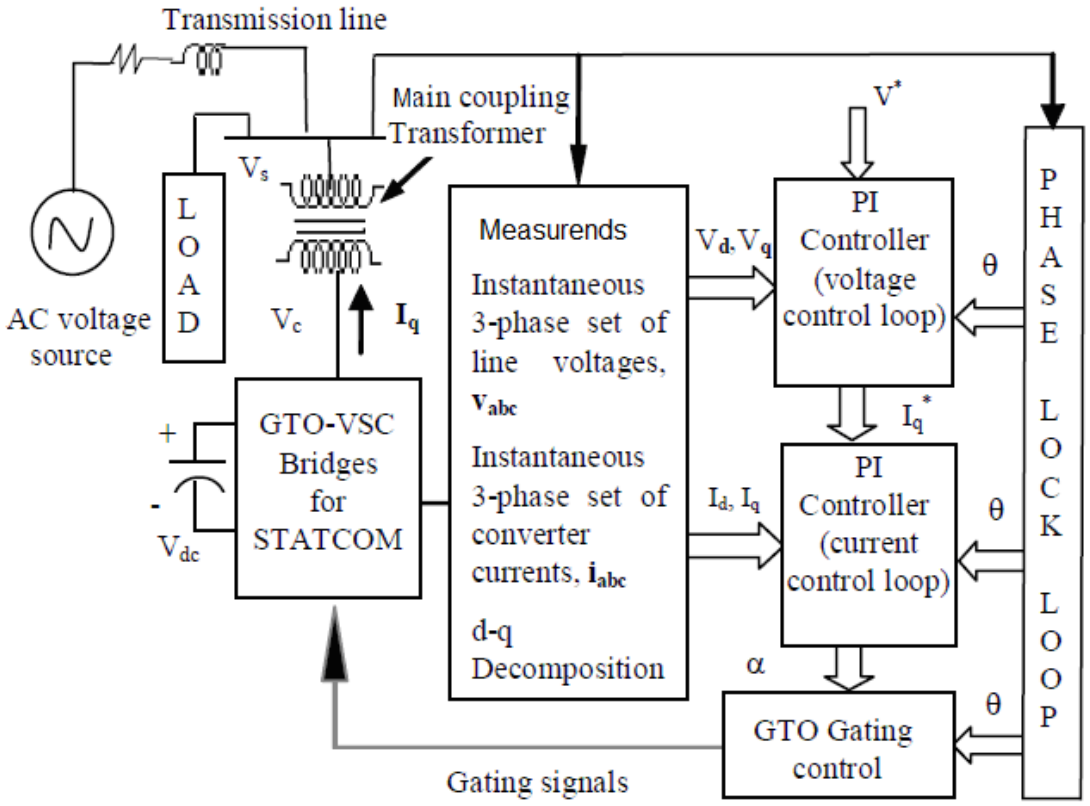


Figure 4.13. GTO-VSC based STATCOM architecture and working principle (Singh and Saha, 2007)

For STATCOM's control, two control-loop circuits namely inner current control loop and external/outer voltage control loop are employed in STATCOM power circuit. The current control loop produces the desired phase angle difference of the converter voltage relative to the system voltage and in turn, generates the gating pulses, whereas the voltage control loop generates the reference reactive

current for the current controller of the inner control loop. This control philosophy is implemented with proportional and integral control (PI control) algorithm or with a combination of proportional (P), integral (I) and derivative (D) control algorithm in d–q synchronous rotating frame (Singh et al., 2009; Anadol, 2012).

Converting the primary control is the setting of flowing through STATCOM reactive current flow. Figure 4.14 shows the reactive current control block diagram of the STATCOM. An instantaneous 3-phase set of line voltages is used to calculate the reference angle (θ), which is phaselocked to the phase A of the line voltage, (VA). An instantaneous 3- phase set of measured inverter currents, is decomposed into its real or direct component, (I_d), and reactive or quadrature component, (I_q), respectively. The quadrature component is compared with the desired reference value, (I_{qref}), and the error is passed through an error amplifier which produces a relative angle, (δ), of the inverter voltage with respect to the line voltage. The phase angle, (α), of the inverter voltage is calculated by adding the relative angle, (δ), of the inverter voltage and the phase-lock-loop angle, (θ). The reference quadrature component, (I_{qref}), of the inverter current is defined to be either positive if the STATCOM is emulating an inductive reactance or negative if it is emulating a capacitive reactance.

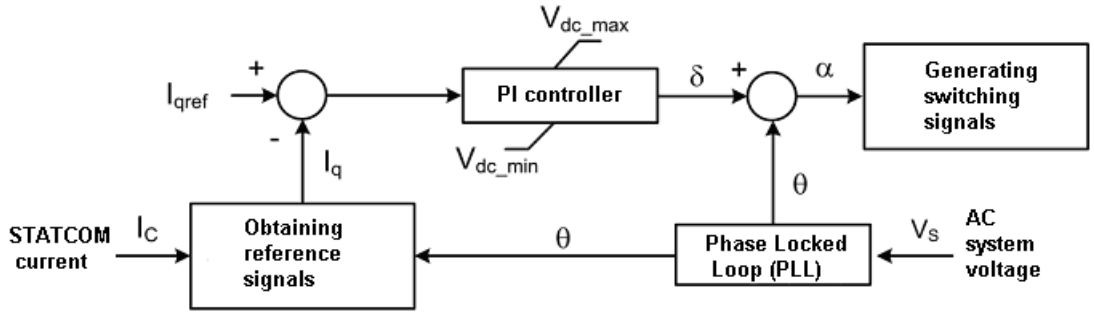


Figure 4.14. STATCOM inner current control loop (Anadol, 2012)

If one is interested in regulating the line voltage, an outer voltage control loop will automatically determine the reference reactive current, (I_{qref}), for the inner current control loop which, in turn, will regulate the line voltage. Figure 4.15 shows the voltage control block diagram of the STATCOM. An instantaneous 3-phase set

of measured line voltages is decomposed into its real or direct component, (V_d), and reactive or quadrature component, (V_q), respectively. The direct component, (V_d), is compared with the desired reference value, (Vref*), (adjusted by the droop factor, Kdroop) and the error is passed through an error amplifier which produces the reference current, (I_{qref}), for the inner current control loop. The droop factor, (Kdroop), is defined as the allowable voltage error at the rated reactive current flow through the STATCOM (Sen, 1998; Anadol, 2012).

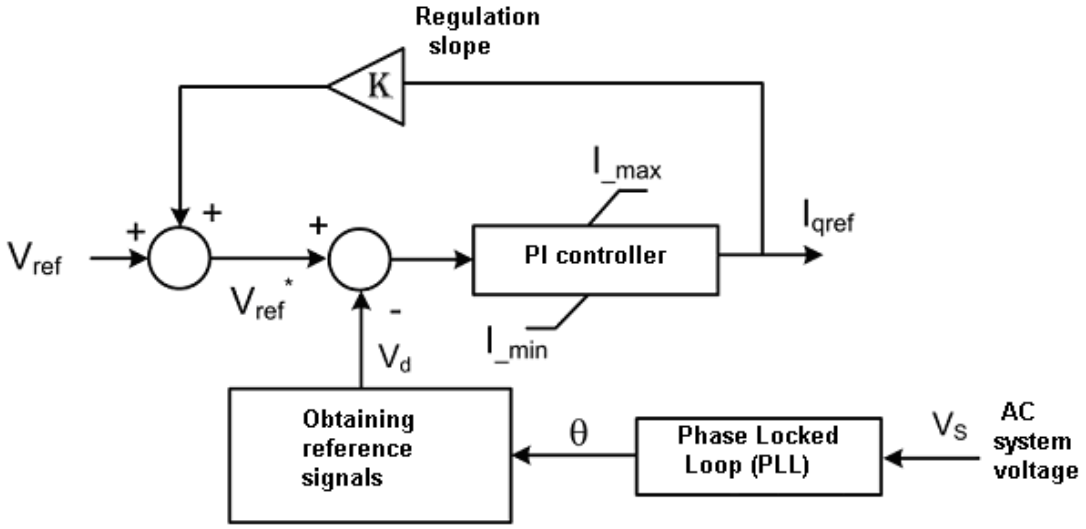


Figure 4.15. STATCOM outer voltage control loop (Anadol, 2012)

4.3.1. Pulse Width Modulation (PWM) Technical

The main advantage of PWM converters is the possibility of controlling the converter gain and consequently the converter output voltage. There are numerous PWM techniques used with different converter configurations. In the most popular PWM method is Sinusoidal PWM (SPWM) method (Uzunovic, 2001).

The conventional control method for VSCs is known as Sinusoidal Pulse Width Modulation (SPWM). SPWM is used since it produces harmonics at much frequency than the fundamental frequency, making it easier to filter. SPWM uses a reference sine wave with the desired frequency and compares it to a carrier triangle wave. When the triangle wave is greater than the sine wave, the switch is turned off.

When the sine wave is greater than the triangle wave, the switch is turned on. The control method can be used for bipolar switching or unipolar switching, with the former shown below in Figure 4.16.

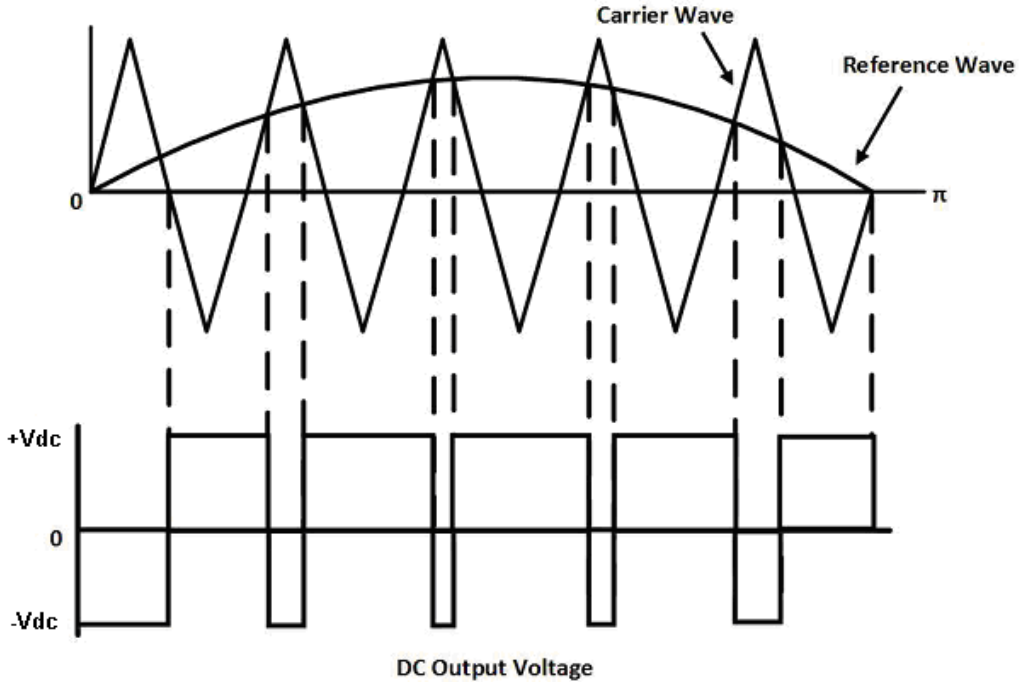


Figure 4.16. Sinusoidal Pulse Width Modulation with bipolar switching (Azares, 2013)

In this case, the sine wave controls the duty ratio of the upper switch in a branch of a VSC, which has a complementary duty ratio to the bottom switch. Thus, when the upper switch is off, the bottom switch is on, as seen in Figure 4.16.

$$m_f = \frac{f_s}{f_l} \tag{4.1}$$

$$m_a = \frac{V_{control}}{V_{triangle}} \tag{4.2}$$

Two modulation variables are used to control the output voltage. The first is the frequency modulation ratio m_f in Eq. (4.1), where f_s is the frequency of the

carrier wave and f_l is the frequency of the sine wave and also the fundamental frequency of the desired output voltage. This ratio determines the harmonic spectrum for a certain degree of control and for a given modulation pattern. The other modulation variable is m_a in Eq. (4.2), where $V_{control}$ is the peak amplitude of the sine wave and $V_{triangle}$ is the peak amplitude of the carrier wave. Depending on the value of m_a, will determine what region the inverter is operating in. For $0 \leq m_a \leq 1$, linear modulation occurs which is desired, since the output voltage varies linearly with m_a and the DC voltage (Azares, 2013).

The most important feature of PWM (Pulse Width Modulation) control method provides the DC voltage to stay constant, however in this study case the varying DC voltage method has been used. By this method, the controlling of supplied or attracted reactive power (Q) to the bus, that is given by STATCOM is possible by changing the amplitude of the V_C output voltage of the convertor. By that for the linear the DC voltage of the convertor at the input and the AC voltage of the convertor at the output are proportional, controlling reactive power can be done by changing DC voltage of capacitor. In order to do this, reactive power control can be made by charging or discharging the capacitor. The applications that carry out by this method is called “indirect control”. If the angle of δ is kept high enough to attract the active power that over all the total power loss, then the capacitors will charge and the output voltage of convertor V_C will increase. This will cause to increase of the reactive power of bus that given by STATCOM. The controlling operation can be done by generating the trigger signals of the current and voltage signals which is taken as output signals of the converter (Song and Johns, 1999; Dirik and Özdemir, 2008).

4.3.2. Controller Configuration PSCAD/EMTDC

The control used in the simulation is AC voltage control or reactive power control. This control is divided into two parts, that is, the sinusoidal pulse width

modulation (SPWM) and reactive power control. Figure 4.17 shows that the PI controller regulates the AC side voltage sourced converter (VSC) or alternatively, reactive power into or out of the VSC. The output of PI controller is the angle order, which is used to maintain the phase shift. The reactive power flow from the system is compared to the reference per-unit voltage that contributes to a change of the phase shift. The difference in phase shift will provide the needed reactive power from the DC capacitor (Masdi et al.)

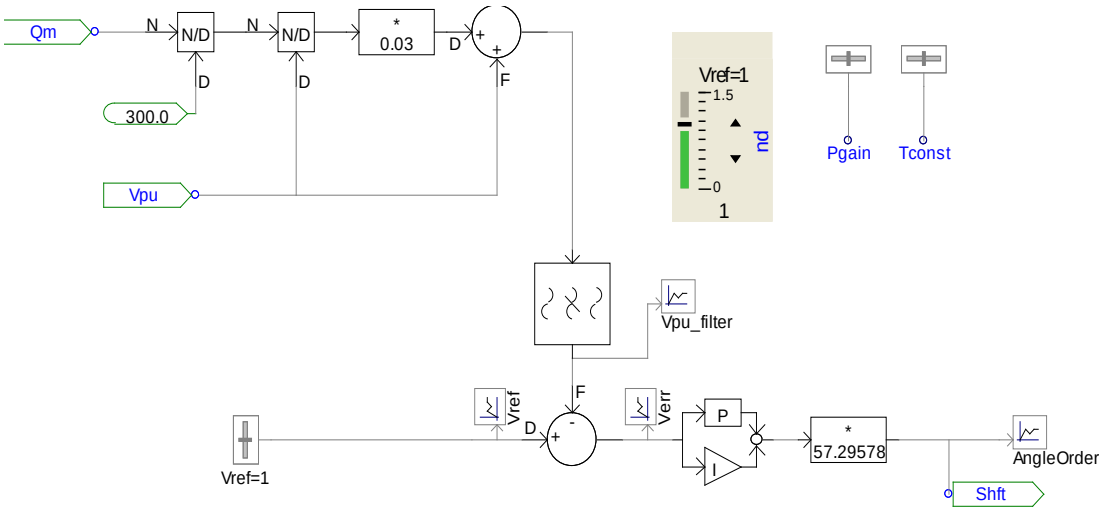


Figure 4.17. Reactive power control loop (PSCAD/EMTDC)

Measured reactive power and root mean square (RMS) voltage (in per unit) is given as the input. The measured reactive power is divided with the rated reactive power of the circuit. This output is divided with the measured RMS voltage (in per unit). After allowing a drop of about 3% the output of this block is summed up again with the Measured RMS voltage. This summed output is passed through filters. The reference voltage (in per unit), is summed with the output signal of the filters. This is given as input to the PI controller. The output of PI controller is the angle order. It represents the required shift between system voltage and voltage generated by shunt converter (STATCOM). This shift determines the output angle order is converted to degrees. Firing signals are generated by pulse width modulation technique. The instantaneous voltage measured is split into its 3-phase components. This is given as input to the 3-phase PI controlled phase locked loop. It generates a ramp signal that

is synchronized in phase to the input voltage signal. This is then multiplied with a real constant to obtain the necessary carrier frequency. From this triangular waveforms synchronized with system AC voltage are generated. Now sinusoidal waveforms synchronized with system AC voltage and shifted by the angle order are to be generated. Again, the instantaneous voltage split into its 3-phase components is given as input to the 3-phase PI controlled phase locked loop. The generated signal that is synchronized in phase to the input voltage signal is shifted by the obtained angle order. Then, this output signal is sent to the sinusoidal function block to generate the required sinusoidal waveforms. The generated triangular and sinusoidal waveforms are sent to the interpolated firing pulse generation block. Two sets of input signals (reference and triangular ones) are needed; one set for turning on and the second one (a negation of the first set of signals) for turning off. Firing pulses are generated using comparison of sinusoidal signals to triangular signals. The output signals generated are of two element arrays. The first element determines the firing signals which indicate the gate turn-off (GTOs) to turn-on and turn-off. The second element determines the exact moment of switching which is used by interpolation procedure for switching between time steps (Nandi et al., 2013).

4.3.3. Generation of the Firing Pulse

PWM technique requires mixing the carrier signal with the fundamental frequency signal defining AC wave shape. In this case, a sine wave is used to make it simplest signal to apply. Therefore, the PWM carrier signal is compared with the sine wave signal and both turn-on and turn-off pulses are generated for interpolated switching (Kim et al,. 2009).

4.3.3.1. Carrier Signal Generation

Figure 4.18 shows the EMTDC model for generating carrier signal. In this figure, phase locked oscillator synchronized to three phase AC system volts, one ramp output synchronized to phase A, ramping between 0° and 360° over one cycle

of the fundamental frequency. The phase A 0°~360° ramp is converted to PWM frequency, then to triangular signal between -1 and +1, and finally allocated to each valve for both interpolated switching turn-on and turn-off. The carrier signal generation process is as follows:

- Increases PLL ramp slope to the level required by carrier frequency.
- Restrains ramps between 0° and 360° at carrier frequency.
- Convert carriers ramps to carrier signals (Kim et al. 2009).

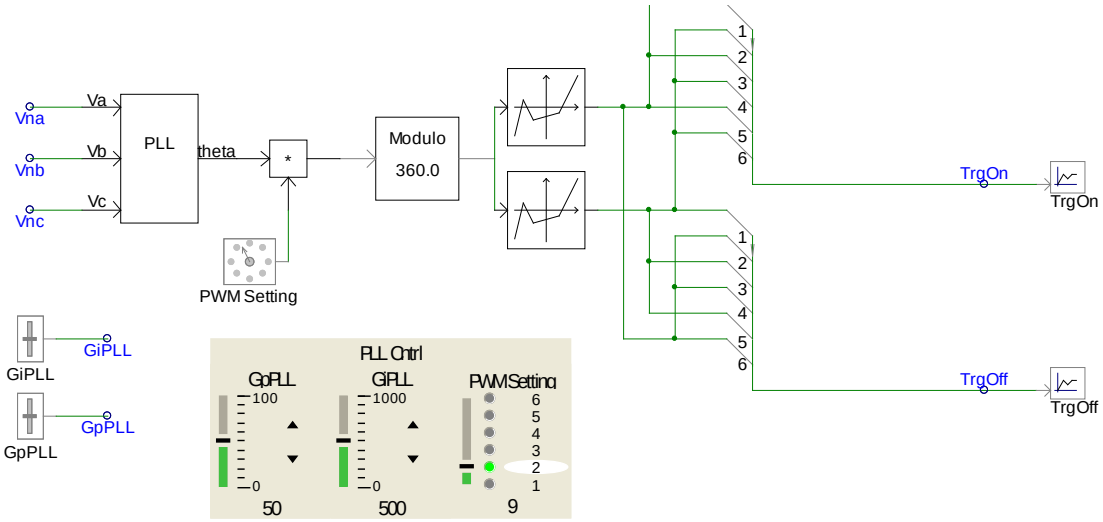


Figure 4.18. Generation carrier signal model (PSCAD/EMTDC)

4.3.3.2. Sine Wave Signal Generation

Figure 4.19 shows an EMTDC model for generating sine wave signal. As in the carrier signal generation, phase locked oscillator synchronized to three phase AC system volts. But, output are six ramps, 60° apart, ramping between 0° and 360° over one cycle of the fundamental frequency. The input ramp array signals from the PLL are phase-shifted 30° as well as by control input signal "shift". The ramps are converted to sine waves (Kim et al. 2009).

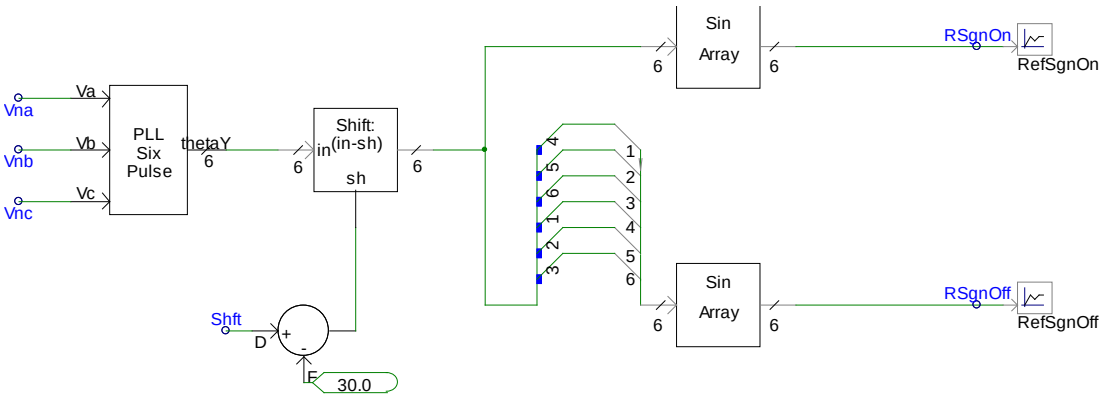


Figure 4.19. Generating sine wave signal model (PSCAD/ EMTDC)

4.3.3.3. Firing Pulses Generation Module

Carrier signal and sine waves are compared and at crossover points, and generate turn-on and turn-off pulses for each GTO valve. Figure 4.20 presents an EMTDC module for generating firing pulses of GTO valve (Kim et al. 2009).

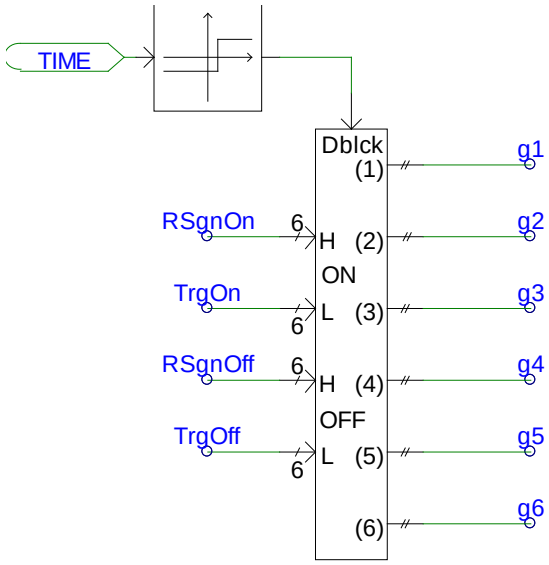


Figure 4.20. Generating firing pulses of GTO valve module (PSCAD / EMTDC)

5. MODELING OF TRANSMISSION LINE IN PSCAD/EMTDC

5.1. Turkish Electricity Transmission System

In Türkiye, if electrical energy's voltage level is over the 36 kV, it is named transmission line. There are 66 kV, 154 kV and 380 kV voltage level transmission lines in Turkey.

5.1.1. National Power Quality Monitoring Network and Assesment Center for the Turkish Electricity Transmission System

The National Power Quality Monitoring System is developed for monitoring the power quality (PQ) of the Turkish Electricity Transmission System. The National PQ Monitoring System consists of three main parts:

- PQ monitors, which are installed all over the country,
- A monitoring center, which collects the data sent by the power quality monitors in a database and provides assessment facilities,
- A client software for remote connection to the center and analysis of the collected PQ data.

PQ monitors compute the PQ parameters according to the IEC-Standard 61000- 4-30. The PQ monitoring center is located in the TEİAŞ Ankara Bahçelievler campus and it has a huge digital light processing (DLP) display to observe the PQ events on the map of Turkey as soon as the event occurs. The client software provides remote connection from universities, research institutes and TEİAŞ offices to the monitoring center to analyse the collected PQ data (Demirci at al., 2008)

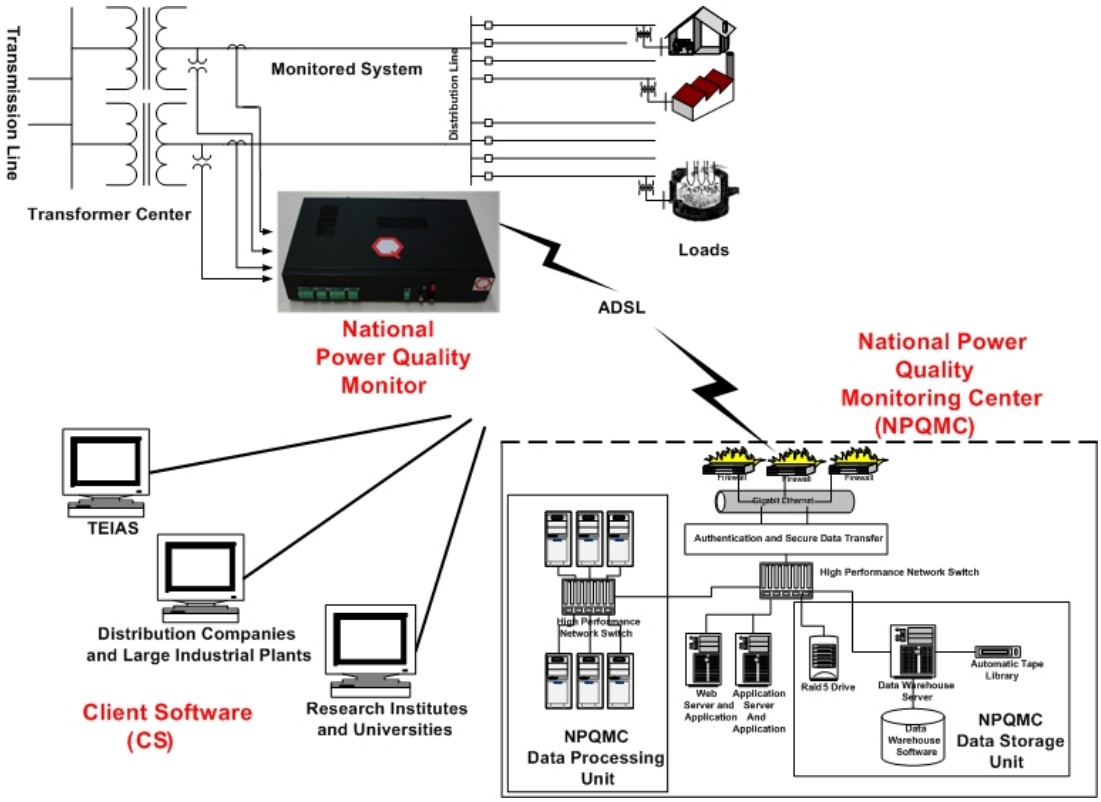


Figure 5.1. National Power Quality Monitoring Project and Operation Department (Demirci at al., 2008)

5.1.2. Turkish Electricity Transmission System Power Quality Monitoring Project

Under this project, by connecting the National Power Quality Monitors to most critical points that selected in Transmission System of Turkey and Power Quality Components (such as: Frequency, Magnitude of the Source Voltage, Flickering, Sags and Swells of the Source Votage, Voltage Interruptions, Transient Voltage Components, Instability of the Source Voltage, Voltage Harmonics, Voltage Sub-Harmonics, Main Signal Voltage of the Source Voltage, Instantenous Voltage Changes, Upper and Lower Change Parameters of Measurement) changes where is selected critical points at the system and active-reactive power flows are measured and analysed at the real time. The software and hardware of the National Power Quality Monitors are designed to be improved, developed, updated in based on experiences in the field and the needs may change in the future (Akkaya and Gök).

Within the scope of the this thesis, from 23.01.2015 / 19:18:34 to 26.01.2015 / 19:18:14 the frequency, voltage, current, powers (active, reactive, apperant powers) and power factor components' real time measurement results of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line, which is operated by TEİAŞ 1. Transmission Installation and Operation Group Management in İstanbul district are obtained from National Power Quality Monitor.

From Figure 5.2 and Figure 5.3 graphs that obtained by National Power Quality Monitor:

- Voltage irregularity is observed at 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line. Also, imbalance case that is seen between phase voltages is caused by unbalanced supply voltage of the network.
- 154 kV double circuit overhead transmission line is fed by İkitelli Substation. However National Power Quality Monitor's measuring point is in Yenibosna Substation. That's why the active power is observed at negative direction.
- Observed that the power factor is under 1 and 154 kV double circuit overhead transmission line is to be inductive.

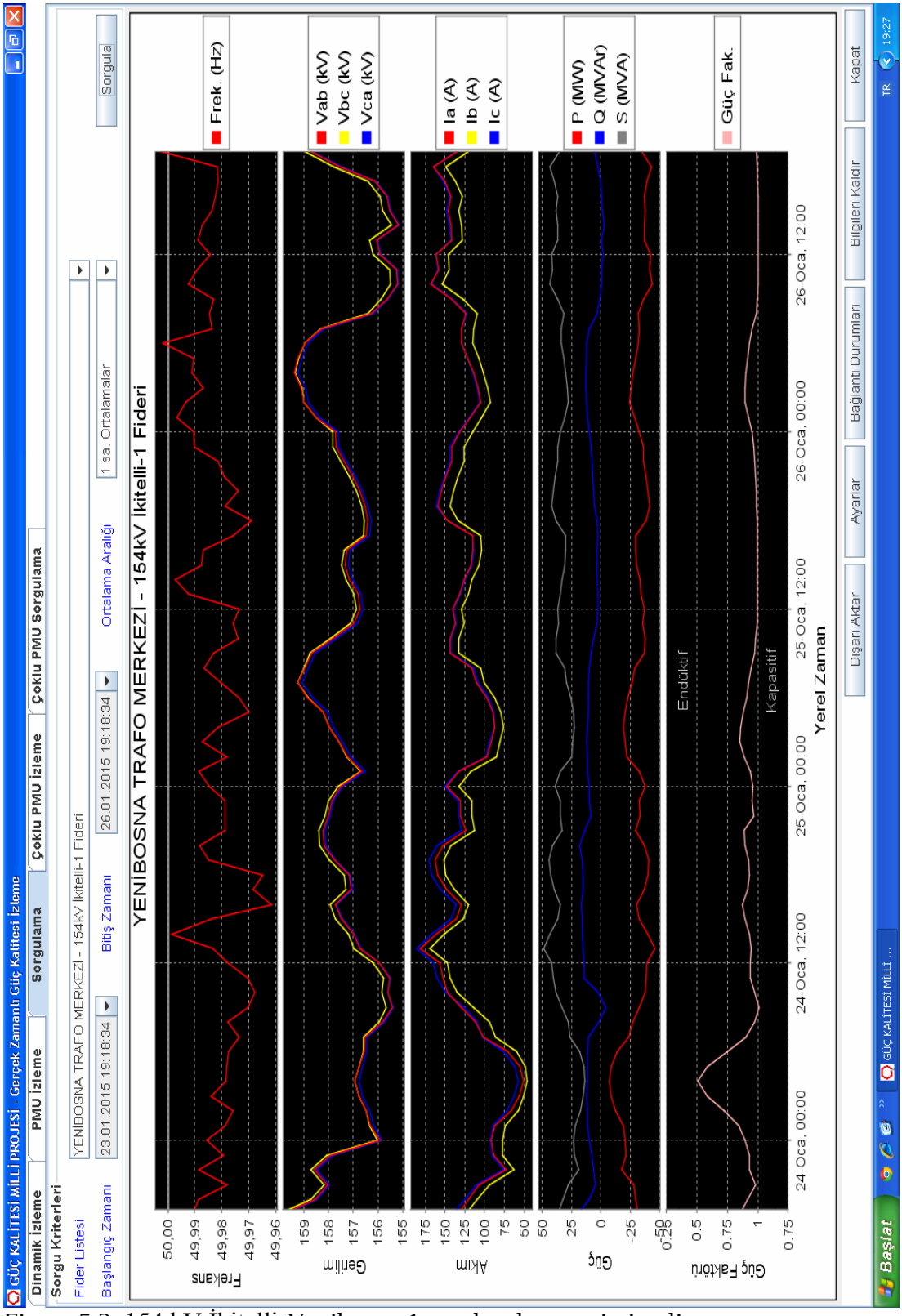


Figure 5.2. 154 kV İkitelli-Yenibosna-1 overhead transmission line

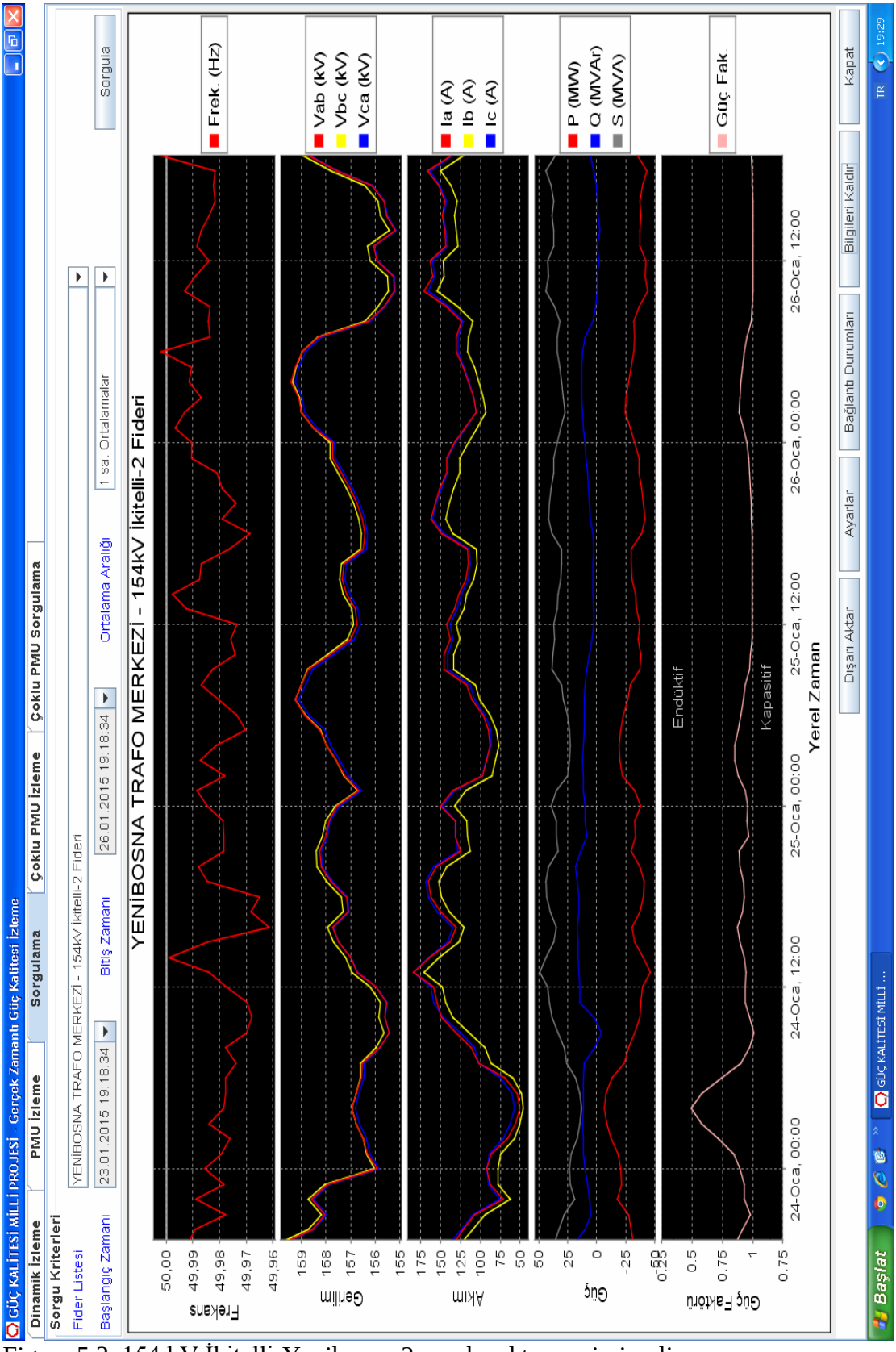


Figure 5.3. 154 kV İkitelli-Yenibosna-2 overhead transmission line

In this case study, as it can be seen from the Figure 5.2 and Figure 5.3, the voltage irregularity problem of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line must be solved. For preventing the voltage irregularity problem, it is done the modeling by placing STATCOM at İkitelli Substation where the line is fed from there.

In the first step, for the modeling the 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line in the PSCAD/EMTDC, line constants are needed. The constants of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line are given in Table 5.1, that's obtained from Ankara Gölbaşı National Load Dispatch Center.

Table 5.1. İkitelli-Yenibosna 1-2 double circuit overhead transmission line conductor constants

Voltage Base Value (U_B)	154 kV
Appearent Power Base Value (S_B)	100 MVA
Resistance (r')	0,003068 pu
Inductive Reactance (x')	0,014399 pu
Admittance (y')	0,006167 pu

In the second step, for the modeling of the overhead line and tower of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line in the PSCAD/EMTDC, the project of line is needed. The line profile project of the 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line is obtained from TEİAŞ 1. Transmission Installation and Operation Group Manegement. The length of the line: 8,852 km and 28 towers have been used at the line. RA1+15 type tower which is the majoerities type of towers in the line is modeled at PSCAD/EMTDC. RA1+15 type tower that is used in 154 kV double circuits overhead transmission line is the bearing type of towers. The main part dimensions of RA1+15 type tower are given in Appendix-1 and the photo of the tower that has used in the line is given Appendix-5.

For the third step, after modeling of the 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line and tower, STATCOM with 3 phases, 6-pulse, voltage source device is placed at İkitelli Substation. In result of committed modeling, the dynamic answer of STATCOM is observed by using PSCAD/EMTDC and graphical based model which located in PSCAD/EMTDC's model library.

5.2. PSCAD/EMTDC Transmission Models

Generally in electromagnetic transient simulations, there are two basic methods to represent transmission systems. The first is the π-section approach, where multi–phase systems can be characterized by a circuit of lumped passive elements. The second and more acknowledged method is a distributed parameter representation. Both π-sections and distributed systems can be modeled with EMTDC (Anonymous, 2010).

5.2.1. π-Sections

A π-section model will give the correct fundamental impedance, but cannot accurately represent other frequencies unless many sections are used (which is inefficient). It is suitable for very short lines where the traveling wave models cannot be used, due to time step constraints. In EMTDC, π-sections are not considered a very elegant means of transmission line modeling for the following reasons:

- Greater computational time and increased EMTDC conductance matrix sizes.
- Do not represent propagation delay.
- Not practical with a large number of mutually coupled conductors.
- Frequency dependent attenuation of the traveling waves is not easily or accurately incorporated (Anonymous, 2010).

5.2.2. The Bergeron Model

The Bergeron model is the simplest, oldest and least accurate of the distributed branch models in PSCAD – mainly due to the fact that it is not frequency-dependent (calculates at a single frequency).

The Bergeron model represents the system L and C in a distributed manner (as opposed to lumped elements as in π-sections). In fact, it is roughly equivalent to using an infinite number of series-connected π-sections except that the total system resistance R is lumped (½ in the middle of the line, ¼ at each end). As with π-sections, the Bergeron model accurately represents system parameters at the fundamental frequency. However, it can also be used to approximate higher frequency attenuation by choosing an additional frequency for calculation.

The Bergeron model is suitable for studies where frequencies other than the fundamental are of little or no concern (i.e. many load flow and protection studies). Situations where this model should be chosen over the more accurate frequency dependent models include; when a lack of frequency dependent input data exists (such as when only +, -, and 0 sequence data is known), and/or when computational speed over accuracy is more important (Anonymous, 2010).

5.2.3. Frequency Dependent Models

The frequency dependent models strive to represent the full frequency dependence of a transmission system. This is accomplished by solving the line parameters at many frequency points within a user-defined scope. As such, the frequency dependent models will take longer to solve than the Bergeron model, but are necessary for studies requiring a very detailed representation of the system over a wide frequency range. Unlike the Bergeron model, these models also represent the total system resistance R as a distributed parameter (along with a distributed system L and C), providing a much more accurate representation of attenuation.

PSCAD offers two frequency dependent models:

- The Frequency Dependent (Mode) model
- The Frequency Dependent (Phase) model

For all new studies involving transmission lines or cables, it is recommended that the Frequency Dependent (Phase) model be used. This model is the newest of the two (c. 1998) and was added to PSCAD specifically to replace the Frequency Dependent (Mode) model, which has been carried over from PSCAD V2 to allow for compatibility with older projects. The Frequency Dependent (Phase) model can represent any type of transmission system (i.e. aerial and underground, symmetrical and non-symmetrical) and is more accurate and more stable than its predecessor. The Frequency Dependent (Phase) model should normally be the model of choice for most studies (Anonymous, 2010).

5.3. 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 Double Circuit Overhead Transmission Line Modeling in PSCAD/EMTDC

In this chart of the thesis, the modeling of the conductor and designing tower of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line are presented. In the modeling of the conductor and the tower that are being designed in PSCAD/EMTDC and its model library with using the data of 154 kV İkitelli-Yenibosna-1 and İkitelli-Yenibosna-2 double circuit overhead transmission line which has been operated by TEİAŞ 1. Transmission Installation and Operation Group Manegement in İstanbul district. The length of the line is 8,852 km, the voltage is 154 kV, the frequency is 50 Hz and the conductor type is 795 MCM Drake. For the line is double circuit system, there are 6 conductors. The majority of the towers in the line are RA1+15 bearing type tower. Additionally there has been used also 24xG652 type OPGW (Optical Ground Wire) for line protection and communication for between the substations.

In Figure 5.4, it is seen of the basic scheme that generated by PSCAD/EMTDC of the double circuit transmission line between İkitelli Substation and Yenibosna Substation.

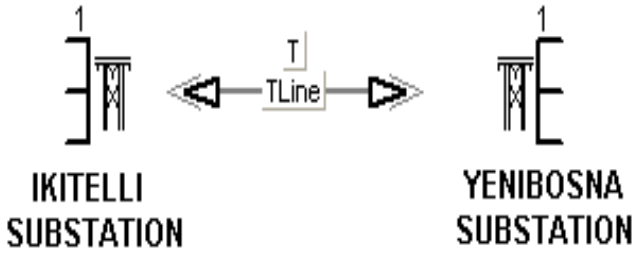


Figure 5.4. İkitelli Substation and Yenibosna Substation basic scheme in PSCAD/EMTDC

The main part dimensions of RA1+15 type tower are given in Table 5.2., the data of the 795 MCM Drake are given in Table 5.3, the data of the 24xG652 type OPGW (Optical Ground Wire) are given in Table 5.4.

Table 5.2. RA1+15 tower main part dimensions

Height of Lowest Conductors	31,182 m
Vertical Offset of Conductors	4,2 m
Horiz. Spacing Between Lower Cond's	8 m
Horizontal Dist. Of Outside Cond's from Inner Cond's	1,3 m

The data which are been in Table 5.2 are added the sub-section of " Tower Data" chapter which is been in "Frequency Dependent (Phase) Model Options" of PSCAD/EMTDC model library as shown in Figure 5.5.

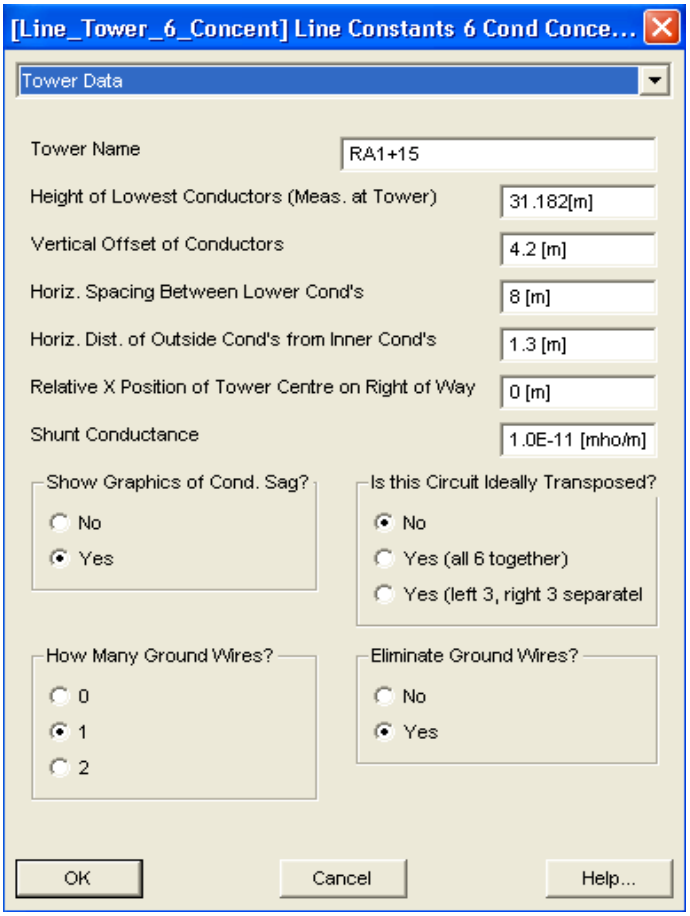


Figure 5.5. RA1+15 tower main part dimensions

Table 5.3. 795 MCM Drake conductor data

Conductor Geometric Mean Radius	0,014055 m
Conductor DC Resistance	0,0715 ohm/km
SAG for all Conductors	9 m
Number of Sub-Conductors in a Bundle	1

The data which are been in Table 5.3 are added the sub-section of “Conductor Data” chapter which is been in “Frequency Dependent (Phase) Model Options” of PSCAD/EMTDC model library as shown in Figure 5.6.

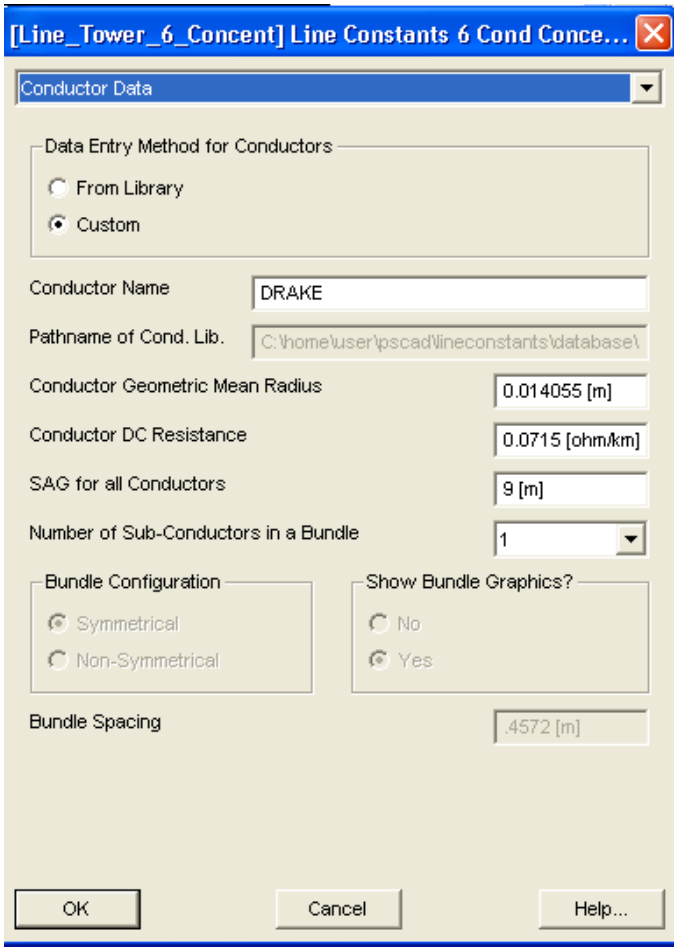


Figure 5.6. 795 MCM Drake conductor data

Table 5.4. 24xG652 OPGW conductor data

Ground Wire Radius	0,0076 m
Ground Wire DC Resistance	0,43 ohm/km
SAG for all Ground Wires	6 m
Height of Ground Wires Above Lowest Conductor	14,45 m

The data which are been in Table 5.4 are added the sub-section of “Ground Wire Data” chapter which is been in “Frequency Dependent (Phase) Model Options” of PSCAD/EMTDC model library as shown in Figure 5.7.

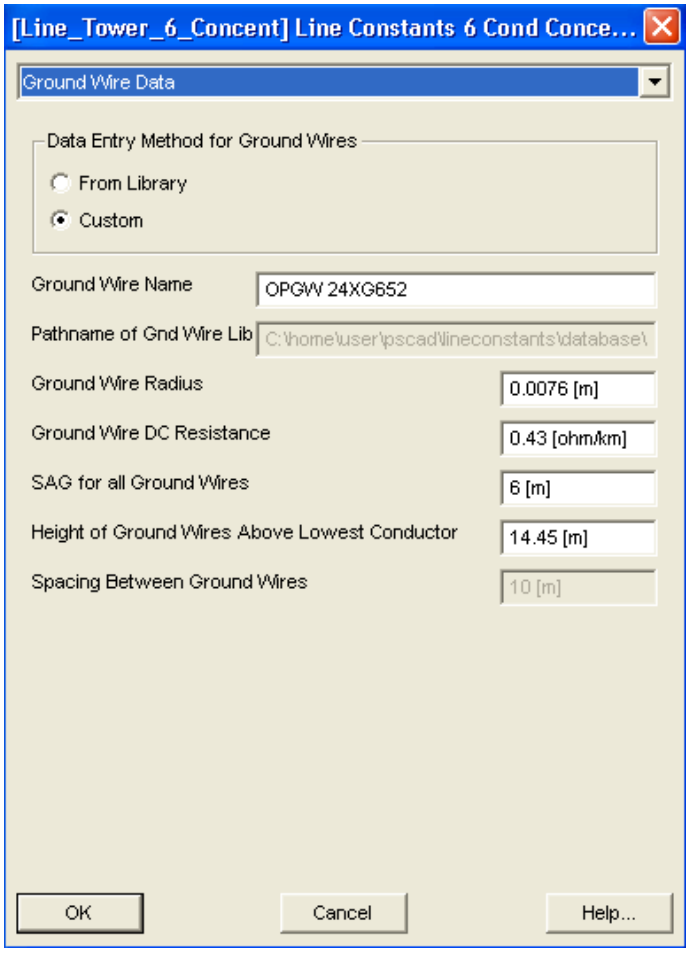


Figure 5.7. 24xG652 OPGW conductor data

In this study, the modeling of overhead transmission line and tower is done by using the PSCAD/EMTDC and graphical based model which located in PSCAD/EMTDC' s model library with data that obtained from Table 5.1, Table 5.2, Table 5.3 and Table 5.4. The Frequency Dependent (Phase) Model that located in PSCAD/EMTDC of İkitelli-Yenibosna 1-2 double circuit overhead transmission line is formed by using sub-section data of Figure 5.5, Figure 5.6 and Figure 5.7 as shown in Figure 5.8.

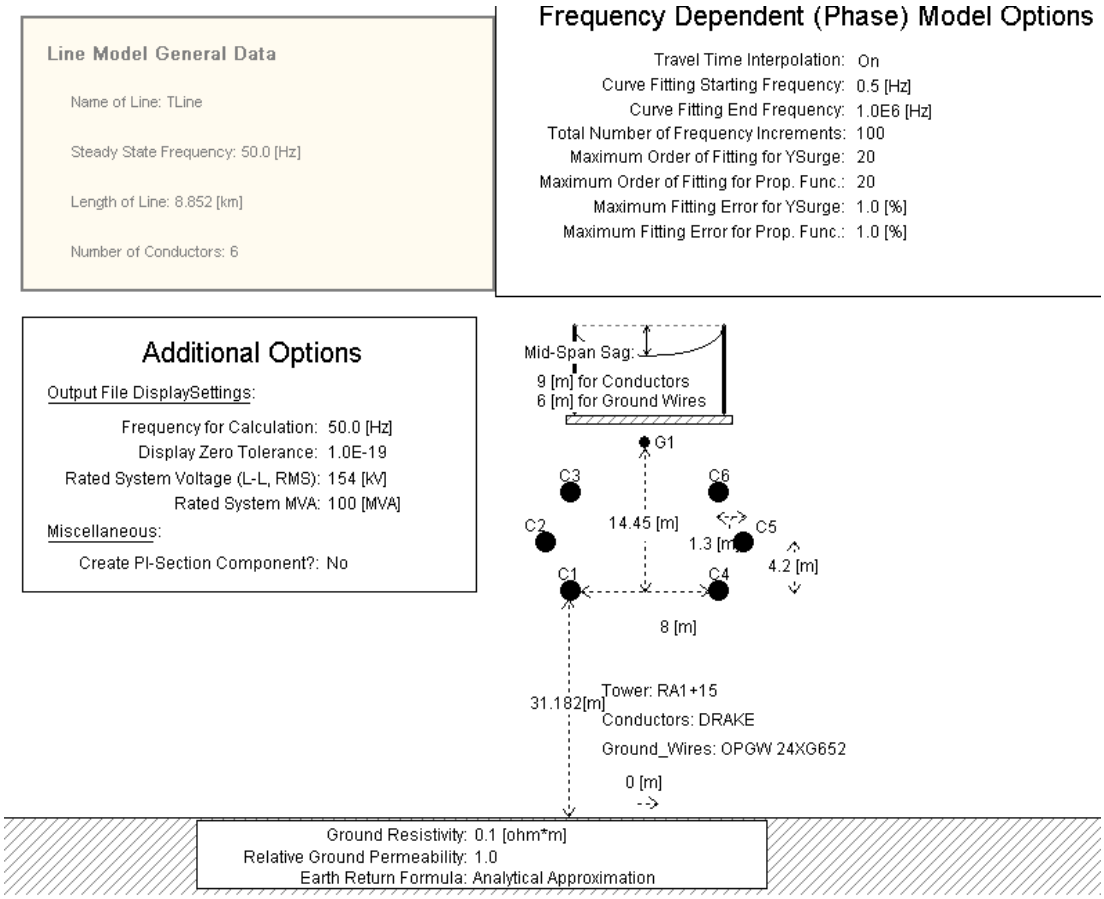


Figure 5.8. 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line Frequncy Dependent (Phase) Model

According to base values given by TEİAŞ Ankara National Power Dispatch Center regarding İkitelli-Yenibosna 1-2 double circuit overhead transmission line: S_B = 100 MVA, U_B = 154 kV and positive component constants of the all transmission line are r' = 0.003068 pu, x'=0.014399 pu ve y' = 0.006167 pu. These pu values are converted to unit long belonging to line constants with the aid of Eq. (5.1) – Eq. (5.3). Obtained results are shown in Table 5.5. These values are obtained in 50 Hz frequency of the line.

$$R = \frac{r' U_B^2}{S_B} \qquad (5.1)$$

$$X = \frac{x' U_B^2}{S_B} \tag{5.2}$$

$$Y = \frac{y' S_B}{U_B^2} \tag{5.3}$$

Table 5.5. İkitelli-Yenibosna 1-2 double circuit overhead transmission line conductor constants which obtained from TEİAŞ data

	TEİAŞ
Resistance (R)	0,08219689E-03 ohm/m
Inductive Reactance (X_L)	0,38577347E-03 ohm/m
Admittance (Y)	0,29375800E-08 ohm/m

The data obtained through the result of the inverting process are used for comparing with the line constants that provided after modeling of conductor and tower which shown in Figure 5.8. The parameters of that conductor's model are calculated by using the settings of "Frequncy Dependent (Phase) Model Options" and "Additional Options" of the PSCAD/EMTDC Transmission Line program. Obtained results are shown in Table 5.6 along with the data of TEİAŞ.

Table 5.6. Conductor constants which calculated by PSCAD/EMTDC and obtained from TEİAŞ data

	TEİAŞ	**PSCAD/EMTDC**
Resistance (R)	0,08219689E-03 ohm/m	0,096296953E-03 ohm /m
Inductive Reactance (X_L)	0,38577347E-03 ohm/m	0,541153422E-03 ohm/m
Admittance (Y)	0,29375800E-08 ohm/m	0,251065040E-08 ohm/m

$$Z = R + jX_L \tag{5.4}$$

$$Y = G + jB \tag{5.5}$$

Calculated admittance (Y) value has been accepted equal to capacitive susceptance (B) value, because of conductance (G) value which placed at admittance (Y) formula in Eq. (5.5) is so small (like 0,1E-10).

As it can be seen at the Table 5.6, the line constants of TEİAŞ and PSCAD/EMTDC are very close to each other. The differences seen between the line constants of operator's (TEİAŞ) data and PSCAD/EMTDC's data, because of:

- The conductor geometry and material properties of the 795 MCM and 24xG652 conductor system which are obtained from the manufacturer firms are used for calculating the line parameters with sub-program of conductor constants in PSCAD/EMTDC. But 795 MCM and 24xG652 conductors' material properties which are imputed by manufacturer firms are not one-to-one 795 MCM and 24xG652 conductors' material properties which are in operating time.
- In the sub-program of the PSCAD/EMTDC conductor constants, the all towers' main part dimensions of the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line are not been used and just only RA1+15 type tower's main part dimensions are considered.
- RA1+15 tower's main part diemonsions are calculated based on single hanger team chain insulator height (1,950 m) in PSCAD/EMTDC. However couple hanger team chain insulators (2,077 m) are used at RA1+15 towers of 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line at the same time. And couple hanger team chain insulators' heights are different from single hanger team chain insulators' heights.
- Each manufacturer firm insulators' chain heights are different from each others.
- The ground resistivity value of the line is accepted 0,1 ohm*m. However the length of the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line is 8,852 km. Ground resistivity is not constant along the distance.

5.4. Voltage Source 6-Pulse STATCOM

The STATCOM is essentially consisting of six-pulse VSC units, DC side of which is connected to a DC capacitor to be used as an energy storage device, interfacing magnetics (main coupling transformer) that form the electrical coupling between converter AC output voltage (V_C) and system voltage (V_S) and a controller. An elementary six-pulse VSC which consists of three legs (phases) with two valves per leg and an electrostatic capacitor on the DC bus is illustrated in Figure 5.9. Each valve consists of a self-commutating switch (GTO) with a reverse diode connected in parallel (Singh et al., 2009).

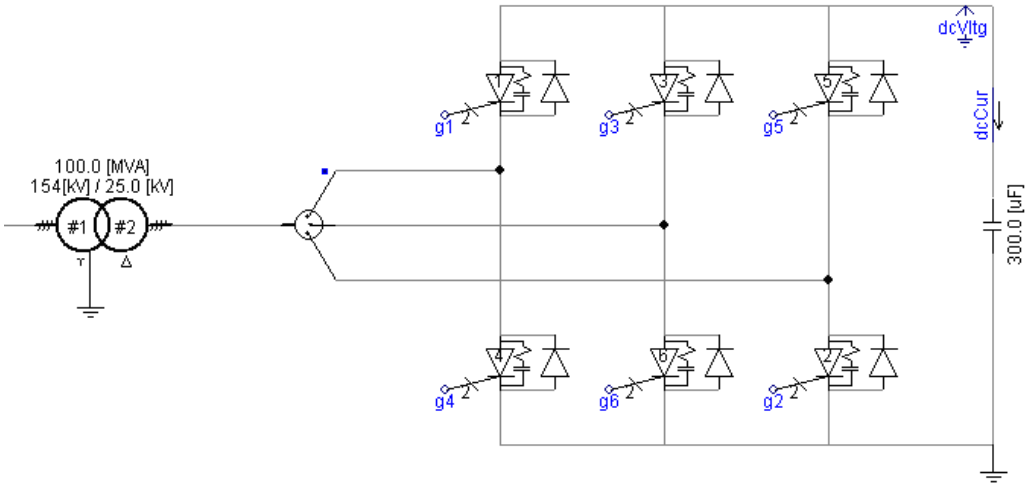


Figure 5.9. Voltage source 6-pulse STATCOM

5.5. PSCAD/EMTDC Simulation Tool

PSCAD/EMTDC is an industry standard simulation tool for studying the transient behavior of electrical networks. Its graphical user interface enables all aspects of the simulation to be conducted within a single integrated environment including circuit assembly, run-time control, analysis of results, and reporting. Its comprehensive library of models supports most ac and dc of power plant components and controls, in such a way that FACTS, custom power, and HVDC systems can be modeled with speed and precision. It provides a powerful resource for assessing the

impact of new power technologies in the power network.

Simplicity of use is one of the outstanding features of PSCAD/EMTDC. It's great many modeling capabilities and highly complex algorithms and methods are transparent to the user, leaving him free to concentrate his efforts on the analysis of results rather than on mathematical modeling. For the purpose of system assembling, the user can either use the large base of built-in components available in PSCAD/EMTDC or to its own user-defined models (Jibhkate et al, 2013).

6. SIMULATION RESULTS AND CASE STUDIES

In this chapter, for the first step, a basic transmission line that contains only voltage source and load is modeled. At the side of source and load, after connecting STATCOM, for examining the developments occurring, selected an ideal voltage source.

For the second step, a basic transmission line that contains a non-ideal voltage source and load is modeled.

For the third step, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line, that modeled by using PSCAD/EMTDC Frequency Dependent (Phase) Model is added between non-ideal voltage source and load.

For the fourth step, in order to obtain voltage dip, the timed fault logic is connected to the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line, which was modeled at third step.

At last step, STATCOM is connected to the modeled transmission line.

In this study, it is achieved voltage dip by using Time Fault Logic. In the study, for modeling to be close to the actual data, since the second step non-ideal voltage source is used.

According to data that obtained from İstanbul Trakya Load Dispatch Management, the average load values of the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line are P=100 MW and Q= 10 MVAR.

6.1. Case 1: Single Line Circuit (Ideal Source)

The basic transmission line circuit which is generated by using graphical interface of PSCAD/EMTDC is shown in Figure 6.1. The modeled overhead transmission line is tested by using an ideal voltage source. The voltage of this basic line circuit is 154 kV, the frequency is 50 Hz. The values of the 3 phase load that at the end of the line are P=100 MW and Q=10 MVAR.

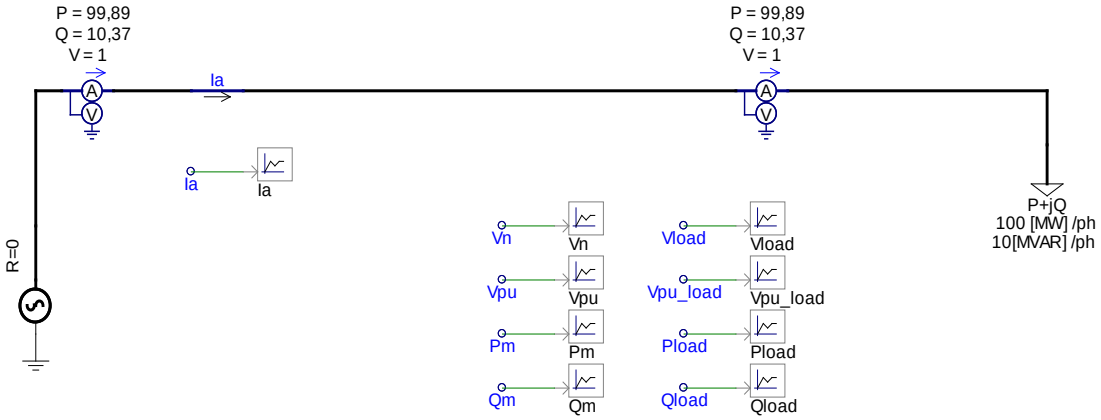


Figure 6.1. Single line circuit (ideal source)

In this case study, as it can be seen in Figure 6.1, the measuring devices are placed at the source side and load side. The measured values at the source side and load side of the basic line are as such; active power is 99, 89 MW, reactive power is 10, 37 MVAR and voltage is 1 pu. For selected ideal source, it is not observed for anything that affecting the active power, reactive power and voltage of the line. Just 10 MVAR reactive power that is available at the load side causes very slight decreasing at active power and increasing at reactive power.

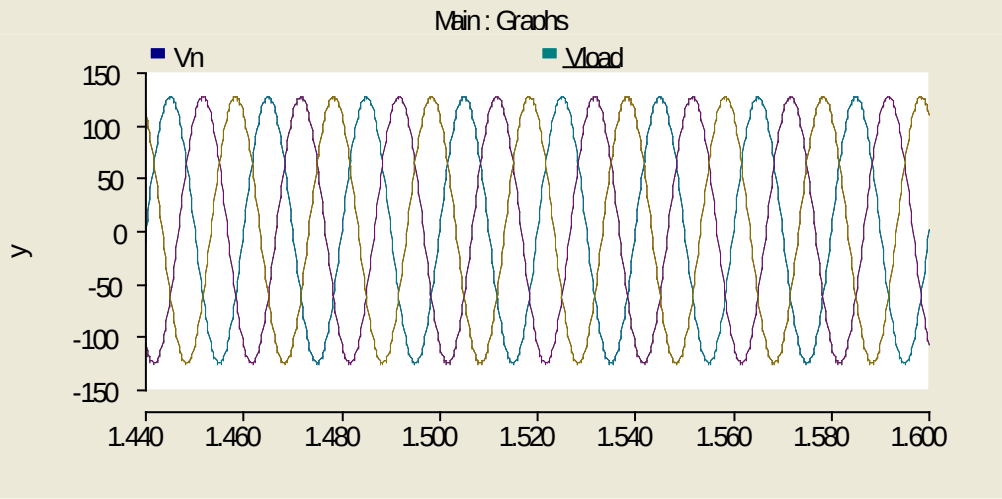


Figure 6.2. Single line circuit source and load voltage (ideal source)

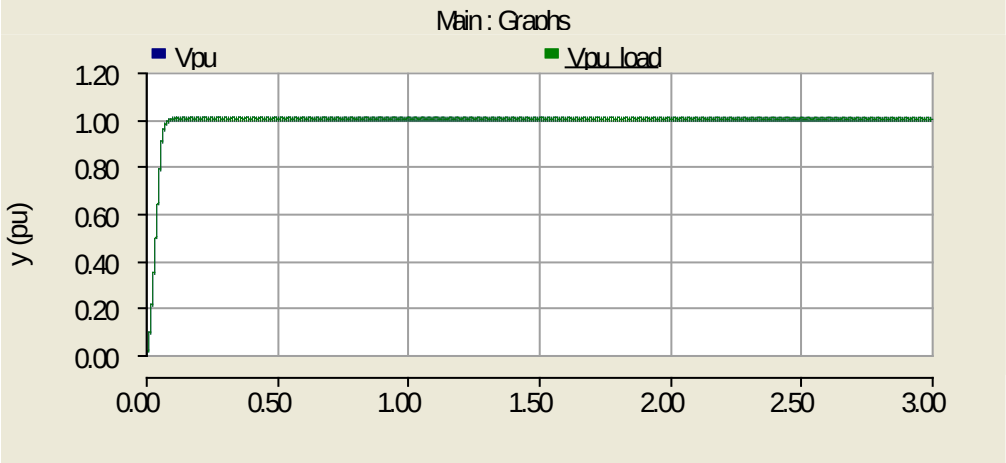


Figure 6.3. Single line circuit source and load pu voltage (ideal source)

System is working under the normal conditions and the simulation is run for no fault (or voltage sag) introduced in the system, then the three phase source and load voltage are obtained as shown Figure 6.2. In this condition, the fault current is zero for all the three phases. The per unit of source and load voltage is also constant at 1.0 pu during the whole simulation time which is in the voltage stable zone in Figure 6.3.

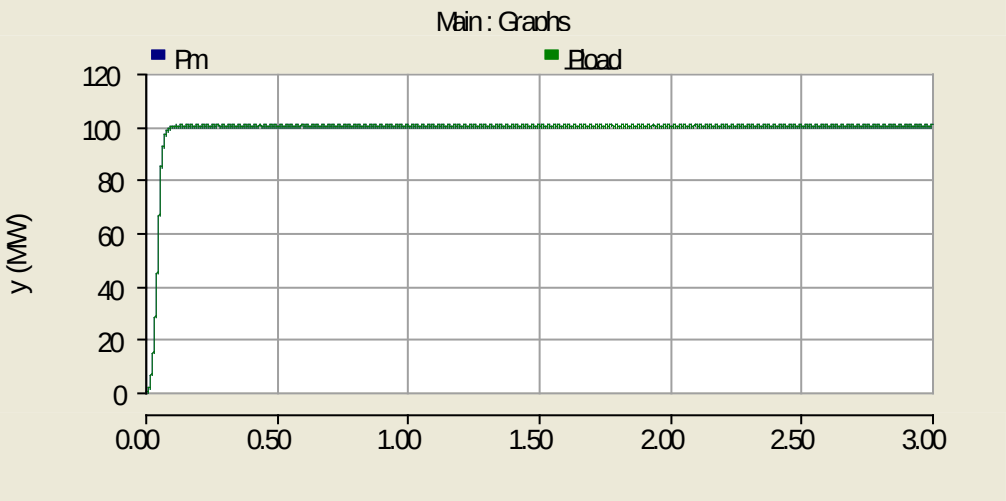


Figure 6.4. Single line circuit source and load active power (ideal source)

Measured P_m =99, 89 MW at the source side and measured P_{load} =99, 89 MW at the load side are seen in Figure 6.4.

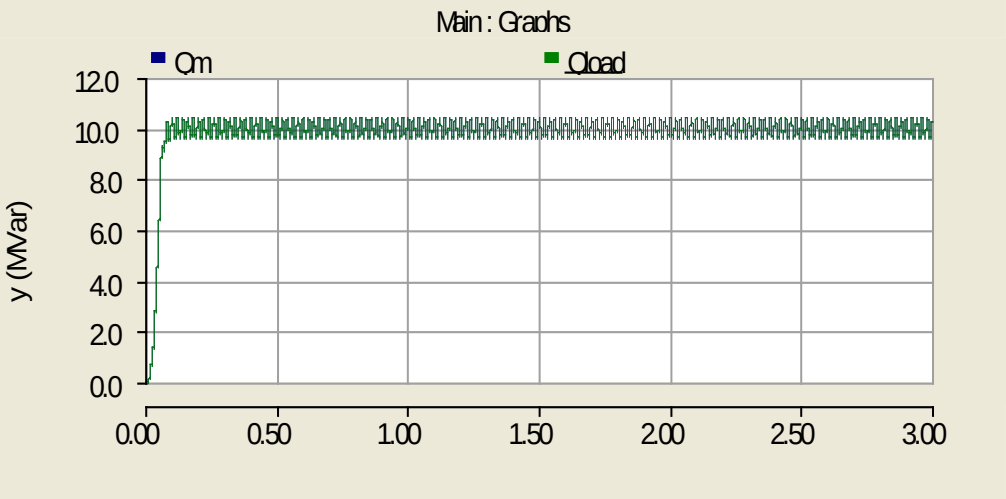


Figure 6.5. Single line circuit source and load reactive power (ideal source)

Measured Q_m =10, 37 MVAR at the source side and measured Q_{load} =10, 37 MVAR at the load side are seen in Figure 6.5.

6.2. Case 2 : Single Line Circuit (Non-Ideal Source)

The basic transmission line circuit which is generated by using graphical interface of PSCAD/EMTDC is shown in Figure 6.6. The modeled overhead transmission line is tested by using a non-ideal voltage source. The voltage of this basic line circuit is 154 kV, the frequency is 50 Hz. The values of the 3 phase load that at the end of the line are P=100 MW and Q=10 MVAR.

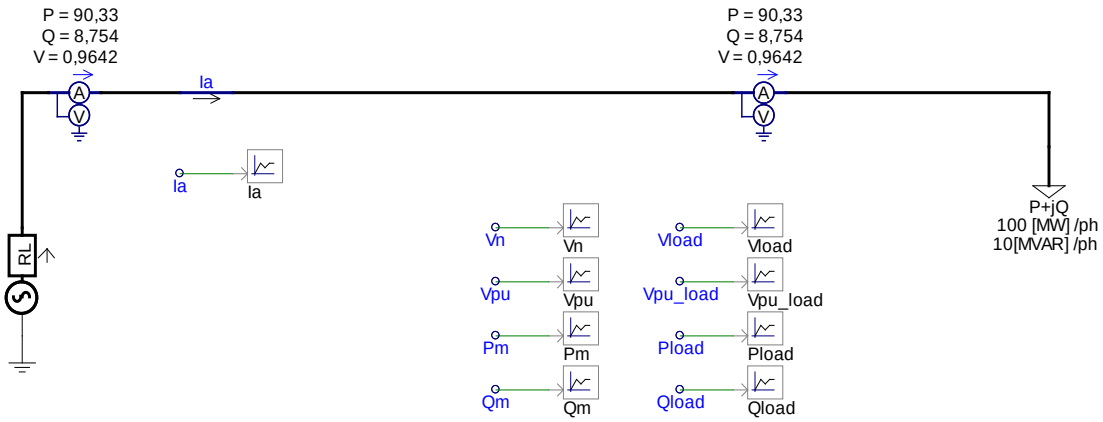


Figure 6.6. Single line circuit (non-ideal source)

In this case study, RL type source is chosen for the basic line circuit. The positive sequence impedance value is determined 26,45 ohm. This determined value is the same as the positive sequence impedance value of the 6-pulse STATCOM, which is available as ready module in the PSCAD/EMTDC. The RL type non-ideal source causes decreasing of active power, reactive power and voltage values at the source side and load side.

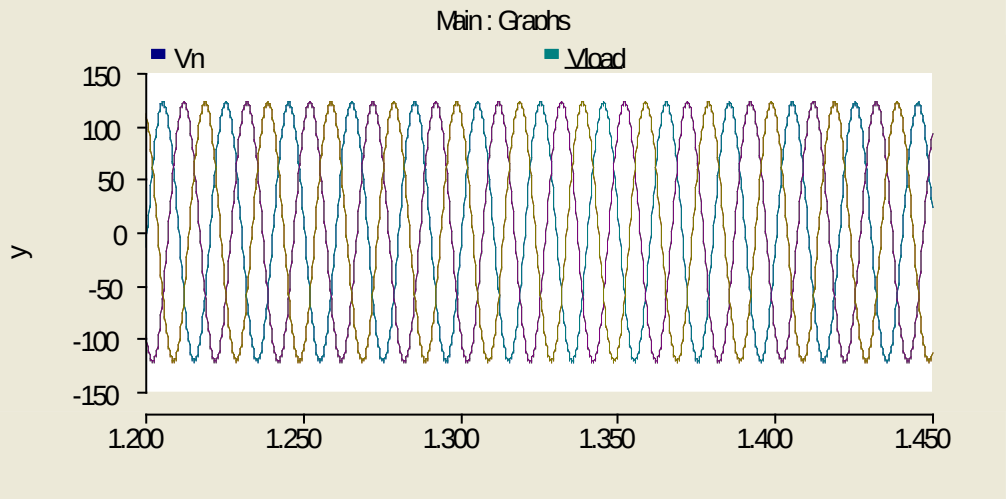


Figure 6.7. Single line circuit source and load voltage (non-ideal source)

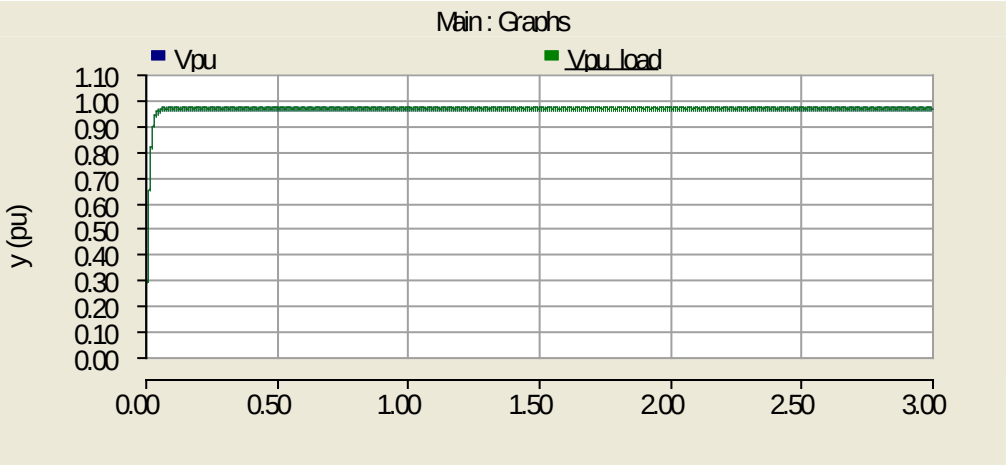


Figure 6.8. Single line circuit source and load pu voltage (non-ideal source)

System is working under the normal conditions and the simulation is run for no fault (or voltage sag) introduced in the system, then the three phase source and load voltage are obtained as shown Figure 6.7. In this condition, the fault current is

zero for all the three phases. The per unit voltage of source and load are also constant at 0, 9642 pu during the whole simulation time which is in the voltage stable zone in Figure 6.8. System voltage is dropped from 1, 00 pu to 0, 9642 pu because of non-ideal source.

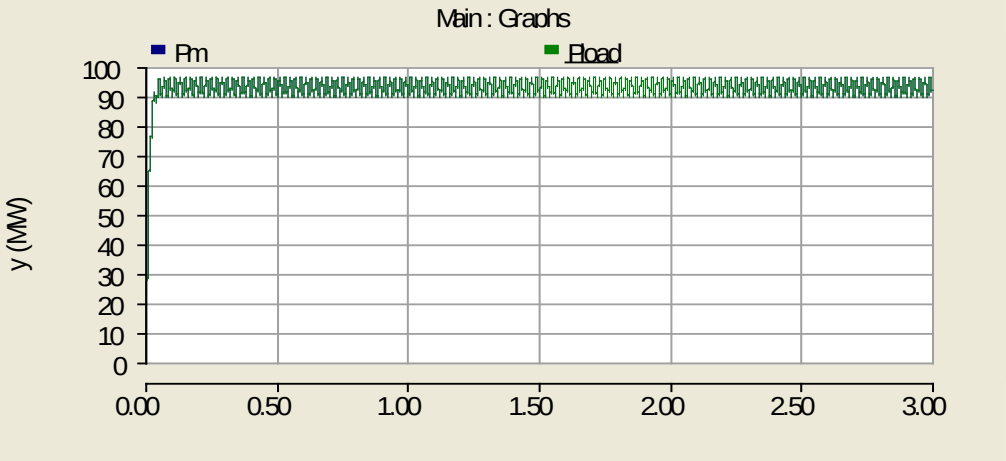


Figure 6.9. Single line circuit source and load active power (non-ideal source)

Measured P_m =90, 33 MW at the source side and measured P_{load} =90, 33 MW at the load side are seen in Figure 6.9. Active powers of source and load are dropped from 99, 89 MW to 90, 33 MW because of non-ideal source.

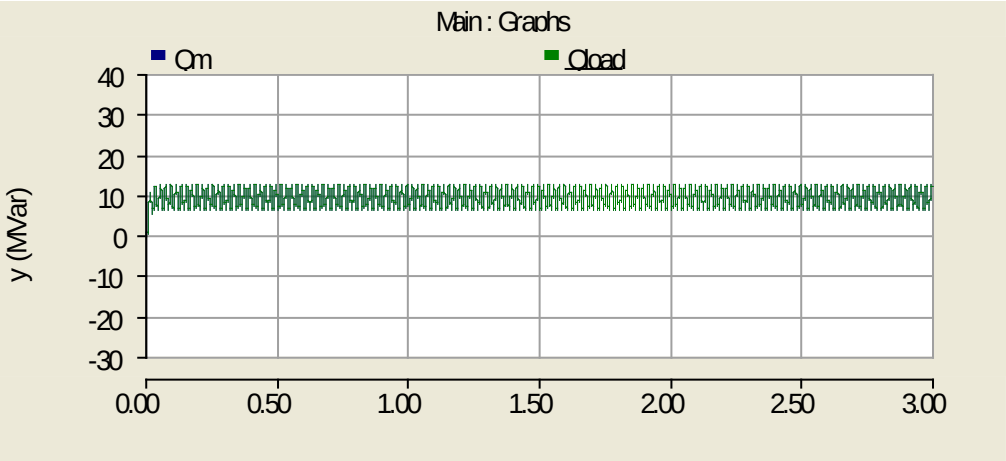


Figure 6.10. Single line circuit source and load reactive power (non-ideal source)

Measured Q_m =8,754 MVAR at the source side and measured Q_{load} =8,754 MVAR at the load side are seen in Figure 6.10. Reactive powers of source and load are dropped from 10, 37 MVAR to 8,754 MVAR because of non-ideal source.

6.3. Case 3: İkitelli-Yenibosna 1-2 Double Circuit Overhead Transmission Line Frequncy Phase Model

154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line model which is generated by using graphical interface of PSCAD/EMTDC is shown in Figure 6.11. The modeled overhead transmission line is tested by using a non-ideal voltage source. The voltage of transmission line is 154 kV, the frequency is 50 Hz. The values of the 3 phase load that at the end of the line are P=100 MW and Q=10 MVAR.

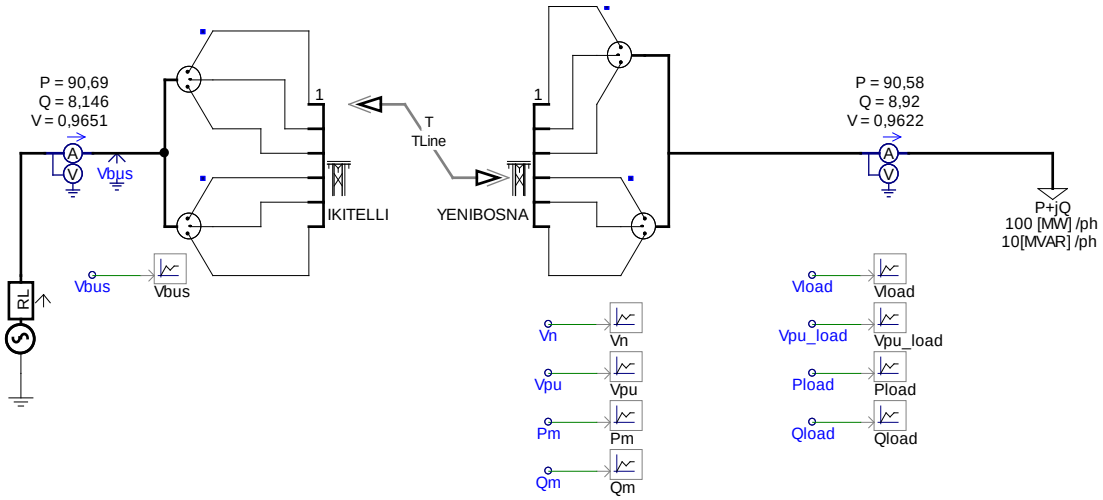


Figure 6.11. İkitelli-Yenibosna double circuit overhead transmission line Frequncy Phase Model

In this case study, by adding the İkitelli-Yenibosna 1-2 double circuit overhead transmission line to the basic line circuit, it is seen that the active power, reactive power and voltage values which are measured at the source side and the load side of the transmission line are not equal to each other. The reason of that slight difference is the resistance and the reactance values and line's distance of modeled the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line.

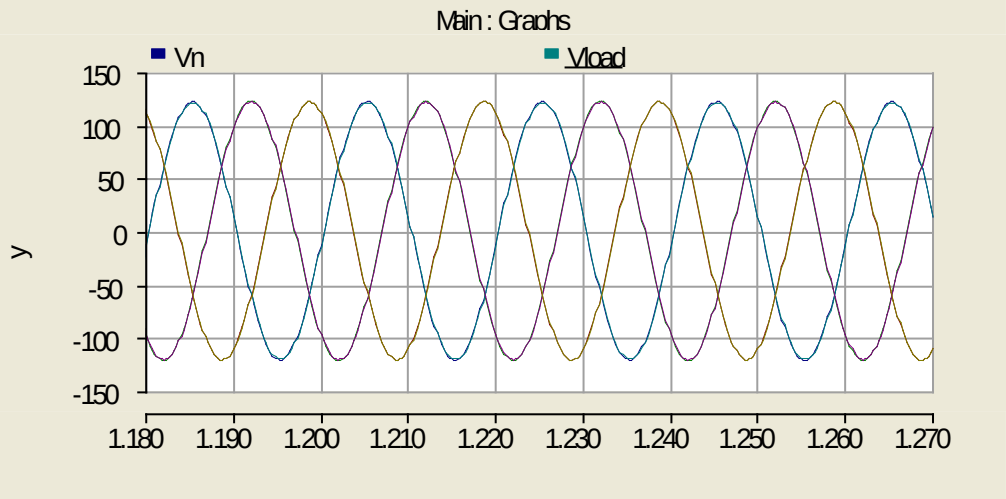


Figure 6.12. İkitelli-Yenibosna double circuit overhead transmission line source and load voltage (non-ideal source)

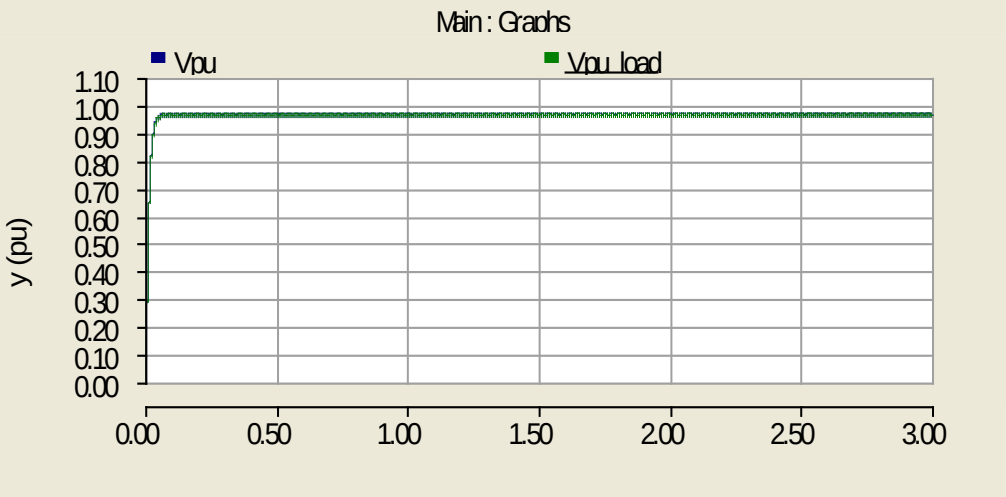


Figure 6.13. İkitelli-Yenibosna double circuit overhead transmission line source and load pu voltage (non-ideal source)

System is working under the normal conditions and the simulation is run for no fault (or voltage sag) introduced in the system, then the three phase source and load voltage are obtained as shown Figure 6.12. In this condition, the fault current is zero for all the three phases. The per unit source voltage is constant at 0,9651 pu and load voltage is 0,9622 pu during the whole simulation time which is in the voltage stable zone in Figure 6.13. System values are different from each other in the source and load because of 154 kV İkitelli-Yenibosna double circuit overhead transmission line' s resistance and reactance values and line's distance.

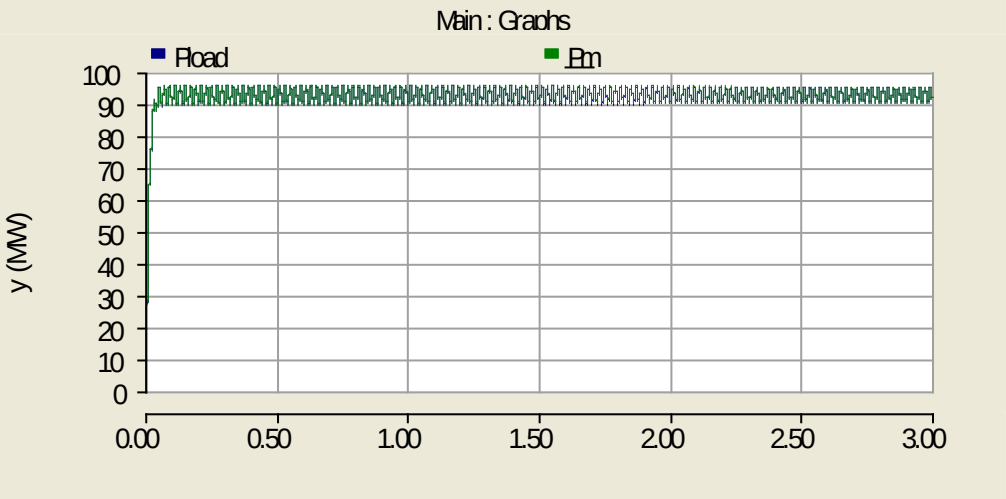


Figure 6.14. İkitelli-Yenibosna double circuit overhead transmission line source and load active power (non-ideal source)

Measured P_m =90, 69 MW at the source side and measured P_{load} =90, 58 MW at the load side are seen in Figure 6.14. Active power of source is incresed from 90, 33 MW to 90, 69 MW and active power of load is incresed from 90, 33 MW to 90, 58 MW because of 154 kV Ikıtelli-Yenibosna double circuit overhead transmission line's resistance and reactance values and line's distance.

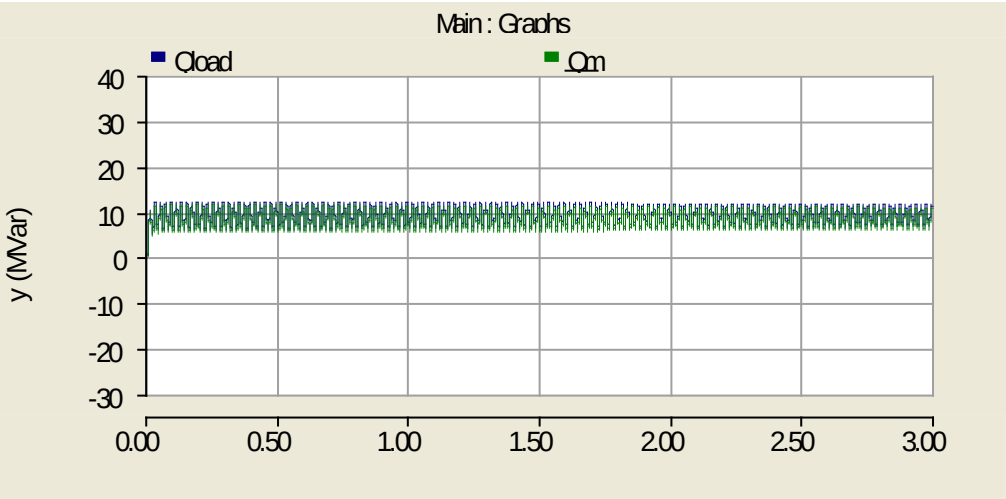


Figure 6.15. İkitelli-Yenibosna double circuit overhead transmission line source and load reactive power (non-ideal source)

Measured Q_m =8, 146 MVAR at the source side and measured Q_{load} =8, 92 MVAR at the load side are seen in Figure 6.15. Reactive power of source is dropped

from 8,754 MVAR to 8,146 MVAR and reactive power of load is incresed from 8,754 MVAR to 8, 92 MVAR because of 154 kV İkitelli-Yenibosna double circuit overhead transmission line's resistance and reactance values.

6.4. Case 4: İkitelli-Yenibosna 1-2 Double Circuit Overhead Transmission Lines Frequncy Phase Model with Timed Fault Logic

154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line model which is generated by using graphical interface of PSCAD/EMTDC is shown in Figure 6.16. The modeled overhead transmission line is tested by using a non-ideal voltage source. The voltage of transmission line is 154 kV, the frequency is 50 Hz. The values of the 3 phase load that at the end of the line are P=100 MW and Q=10 MVAR.

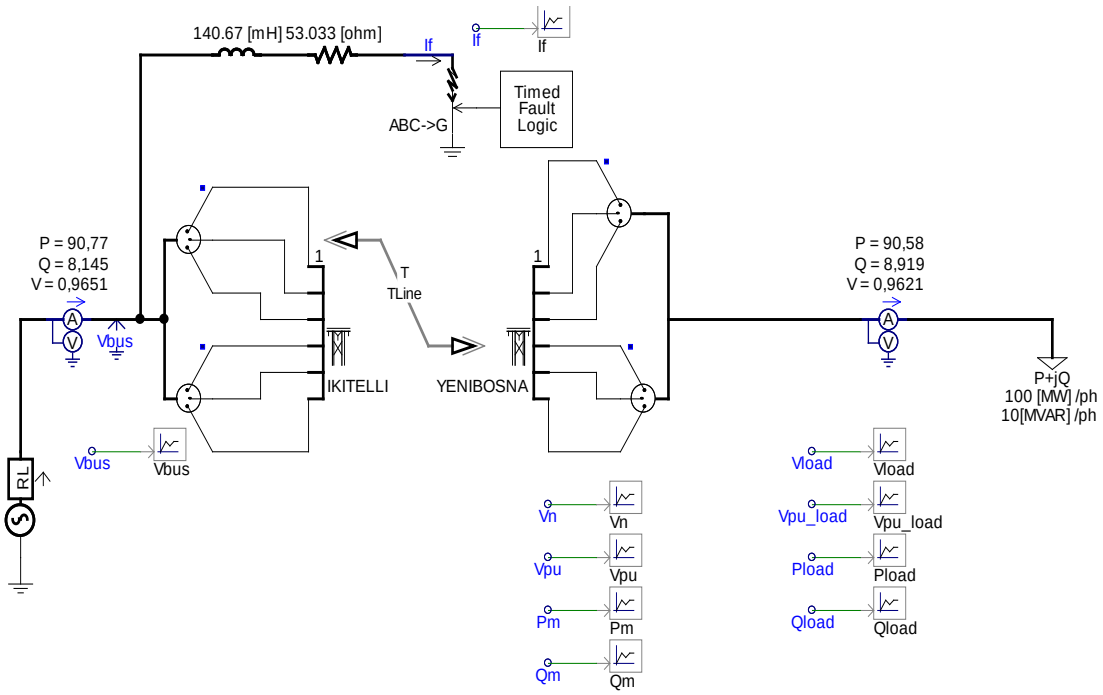


Figure 6.16. İkitelli-Yenibosna double circuit overhead Frequncy Phase Model with Timed Fault Logic

In this case study, to gain the voltage dip between 1.5 and 2.25 seconds at 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line, the timed fault

logic with additinol resistance and inductance fault component is connected at the system' s PCC (Point of Common Coupling).

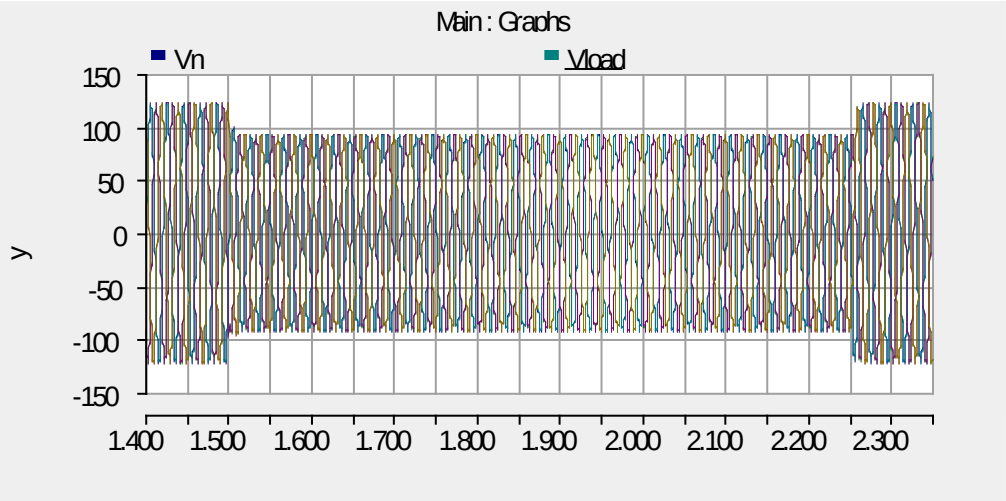


Figure 6.17. PCC and load voltage (without STATCOM)

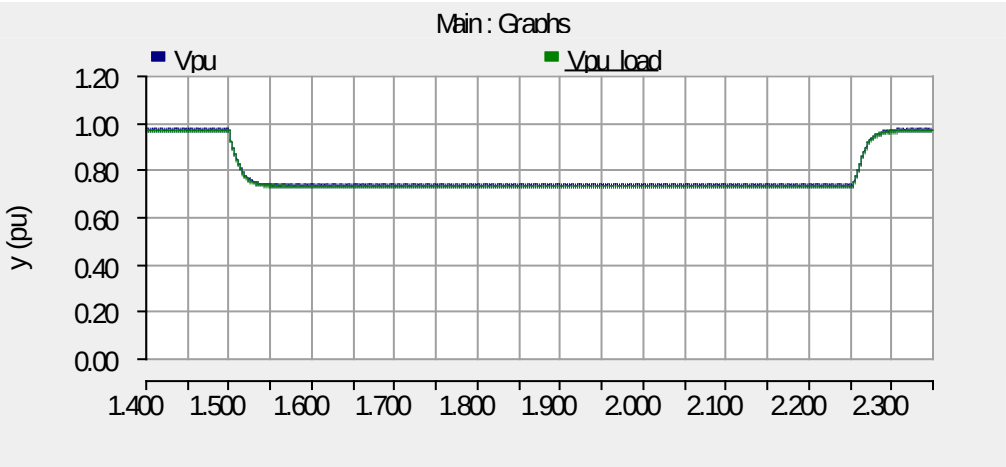


Figure 6.18. PCC and load pu voltage (without STATCOM)

A Time Fault Logic is connected to the system. From the simulation results as shown in Figure 6.17 and Figure 6.18, it is observed that there is dip in the system voltage level. PCC voltage drops from its nominal value 0,9651 pu to 0,731 pu and load voltage drops from its nominal value 0, 9621 pu to 0,729 pu. This is a voltage sag condition which is due to a three- phase fault created at time t = 1.5 sec. for a duration of 0.75 sec. in Figure 6.17 and 6.18.

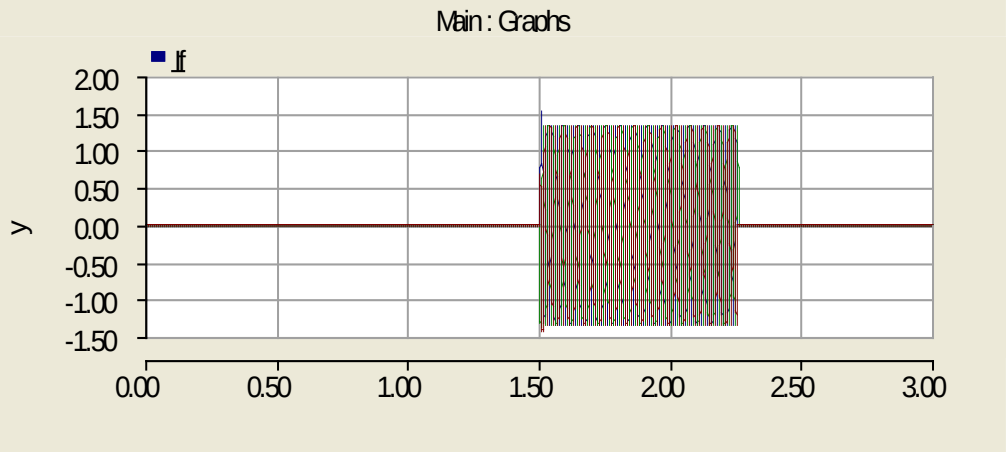


Figure 6.19. Three phase timed fault logic current

During the same interval (from 1.5 second to 2.25 second), a fault current is flowing in all the three phases i.e. Ifa, Ifb, Ifc is not zero for 0.75 sec. in Figure 6.19.

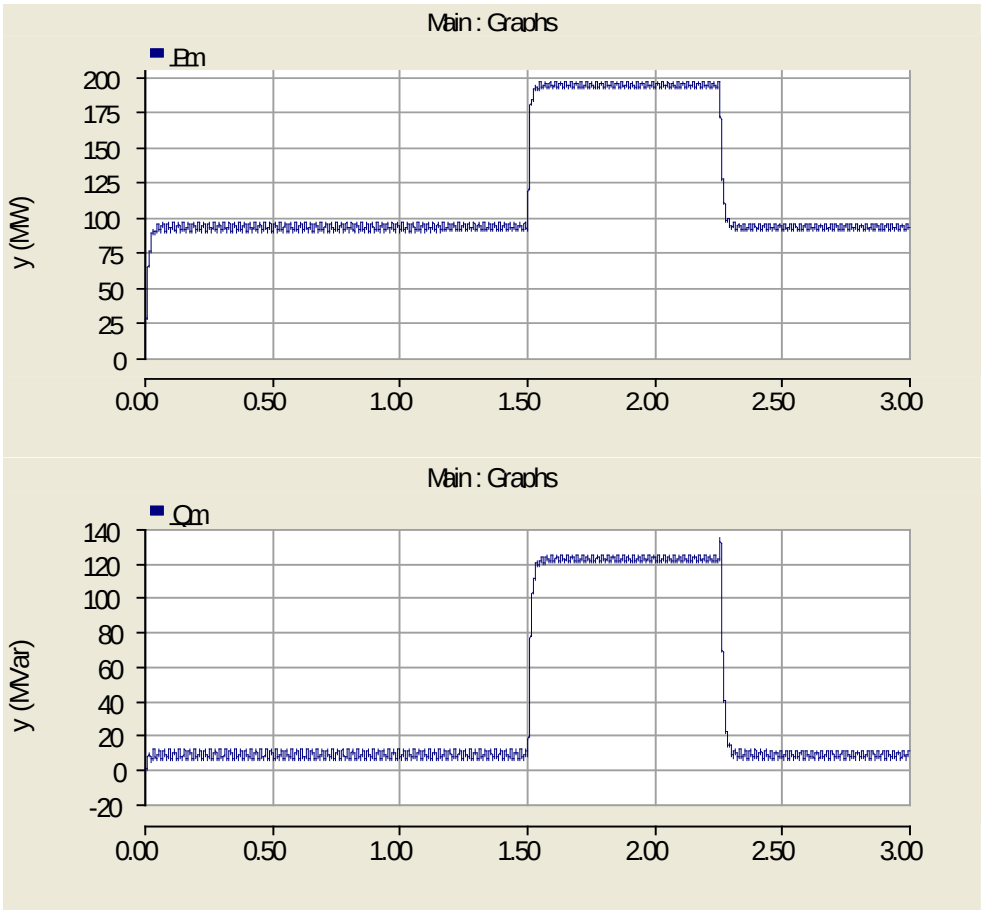


Figure 6.20. PCC active and reactive power (without STATCOM)

The time fault logic' s resistance and inductance values which is added to the system from source side cause increasing of the measured P_m and Q_m values between 1.5 and 2.25 seconds as shown in Figure 6.20.

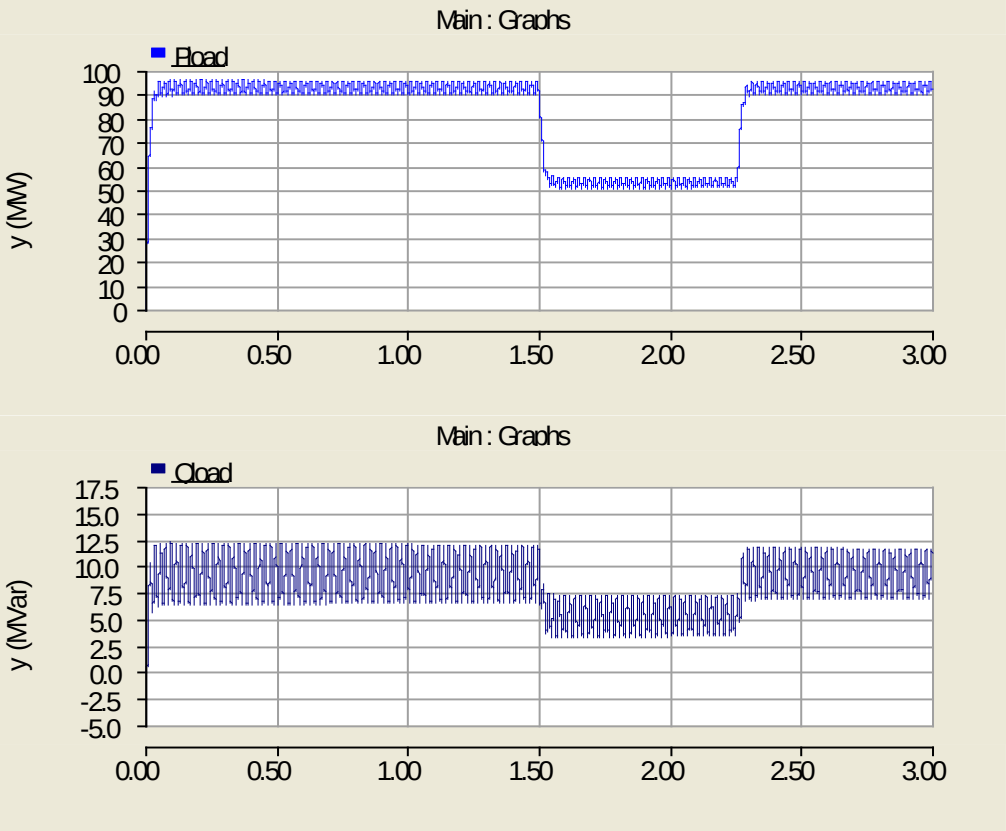


Figure 6.21. Load active and reactive power (without STATCOM)

The time fault logic' s resistance and inductance values which is added to the system from source side cause decreasing of the measured P_{load} and Q_{load} values between 1.5 and 2.25 seconds as shown in Figure 6.21.

6.5. Case 5: İkitelli-Yenibosna 1-2 Double Circuit Overhead Transmission Line Using STATCOM PSCAD/EMTDC Model

In this case study, STATCOM which is regulated voltage and power compensation of power systems and ones shunt FACTS device is simulated by using the PSCAD/EMTDC.

In the simulation program, 6-pulse STATCOM device is connected to the PCC (Point of Common Coupling) of the system with the aid of Y − Δ connection transformer that chosen 154/25 kV voltage and 100 MVA power. Simulated power system and STATCOM circuit is shown in Figure 6.22. As shown the STATCOM circuit consists of the connection transformer, two-level VSC and a capacitor that provides the required DC voltage for VSC. In simulation program, the best performance is gained for the system by using the optimum PI parameters.

In order to providing the reactive power to the system by Voltage-Source convertor, the AC output voltage of the STATCOM must be greater than the AC voltage of the system. The output voltage which is greater than the source voltage is stored in DC capacitor of the STATCOM. For the value of DC capacitor, it is determined 300 μF. Before starting STATCOM, firstly DC capacitors shall be charged over the reverse parallel diodes of the GTO switches that are on the inverter bridges.

Timed Fault Logic in the diagram in the 154 kV PCC bus of the system with additional resistance and inductance fault component available in PSCAD/EMTDC software library. This will create the effect of voltage sag. To mitigate this voltage sag, STATCOM is connected to the same bus via a transformer.

The model which is added STATCOM to 154 kV Ikıtelli-Yenibosna 1-2 double circuit overhead transmission line system' s PCC bus is generated by using graphical interface of the PSCAD/EMTDC as shown in Figure 6.22. The modeled overhead transmission line is tested by using a non-ideal voltage source. The voltage of this transmission line is 154 kV, the frequency is 50 Hz. The values of the 3 phase load that at the end of the line are P=100 MW and Q= 10 MVAR.

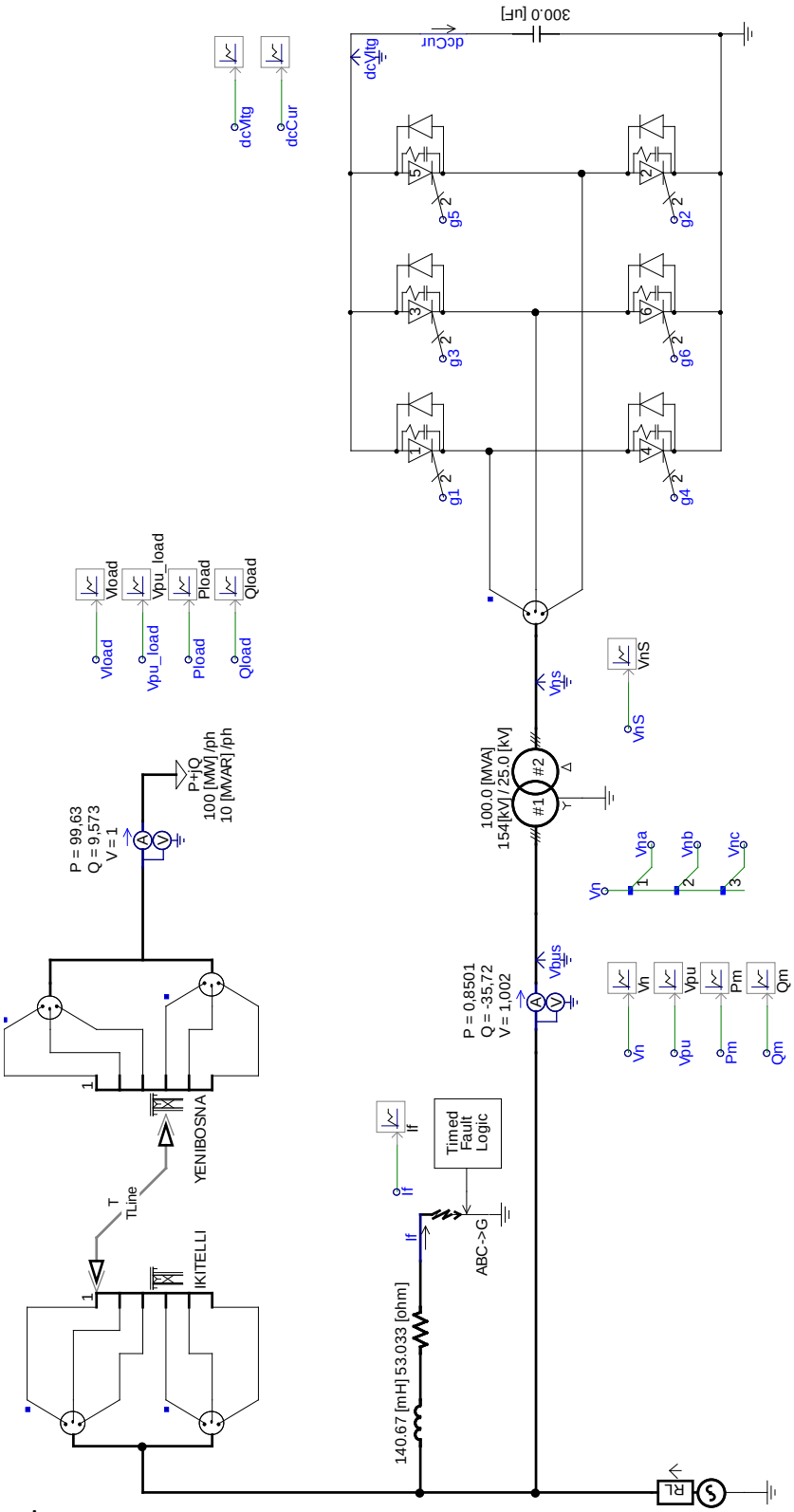


Figure 6.22. İkitelli-Yenibosna 1-2 double circuit overhead transmission line using STACOM PSCAD/EMTDC Model

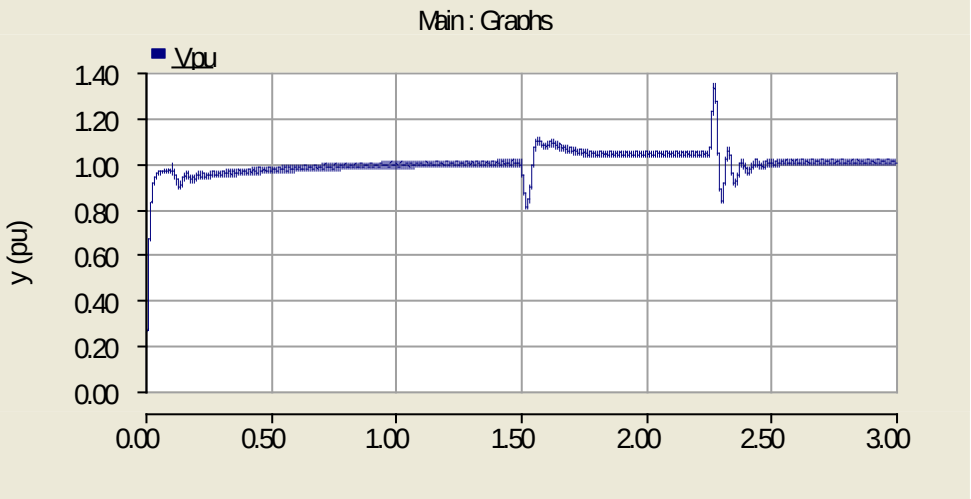


Figure 6.23. PCC pu voltage (with STATCOM)

The simulation is now carried out with STATCOM. The simulation result for PCC voltage level compensation is shown in Figure 6.23. It is clear from Figure 6.23 that the severity of voltage drop as observed due to addition of timed fault logic between 1.5 sec. and at 2.25 sec. has been prevented.

When the fault is created, STATCOM boosts the voltage by injecting the reactive power and than system voltage variations are dynamically mitigated. The compensated PCC voltage is shown in Figure 6.23. Voltage can come back the pre-defined rating value (1,002 pu).

Figure 6.23 shows the system voltage response for the system with the STATCOM, in which the PCC voltage is increased from 0,731 pu to 1,002 pu. Thus the system voltage returns to its rated voltage due to the voltage sag mitigation capability of the STATCOM with a capacitance value of 300 microfarads. Figure 6.23 also shows that the ripple voltage at the starting and the ending of compensation are due to the charging and discharging of the STATCOM capacitor.

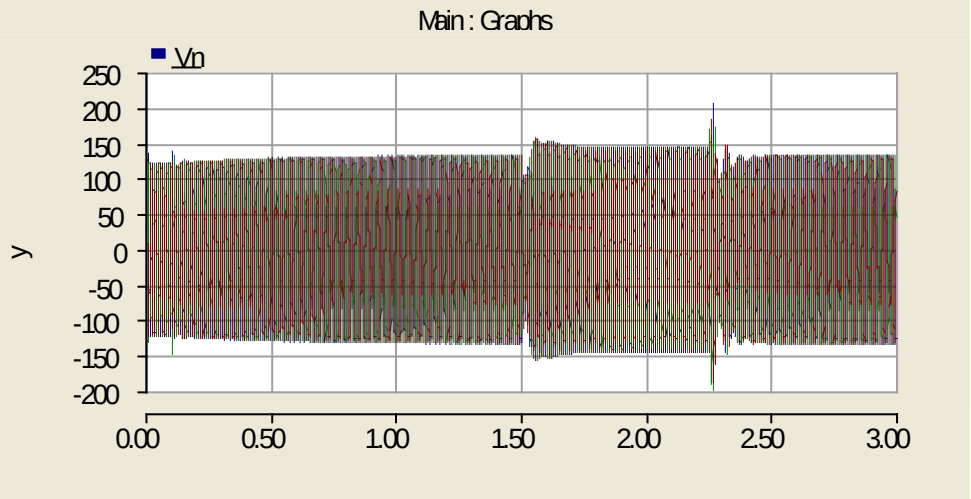


Figure 6. 24. PCC three phase voltage (with STATCOM)

STATCOM is connected in the 154 kV PCC bus, and run the simulation with the voltage sag created for 0.75 sec., we observe that as soon as voltage sag is produced at 1.5 sec., it is mitigated by the effect of STATCOM as it injects the voltage during the whole voltage dip of 0.75 sec. The results are shown in Figure 6.24, where the very effective voltage regulation provided by the STATCOM can be clearly appreciated.

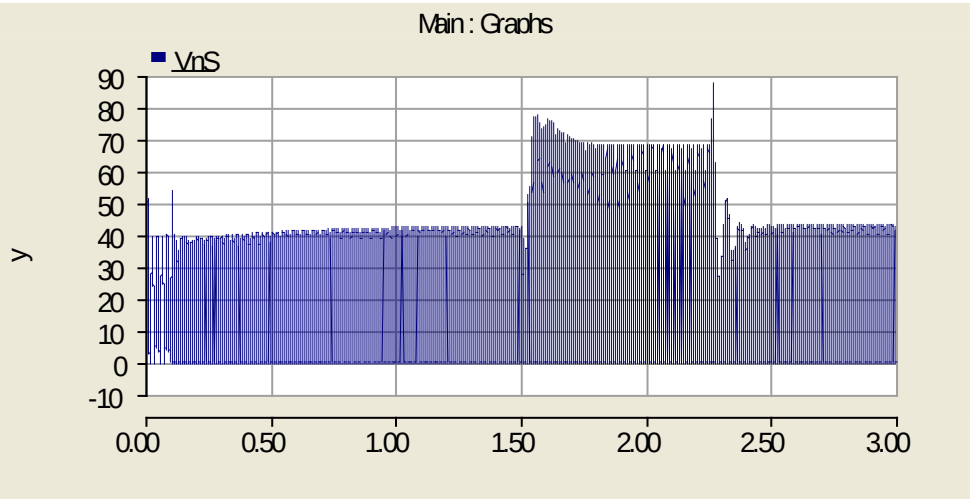


Figure 6.25. STATCOM's voltage

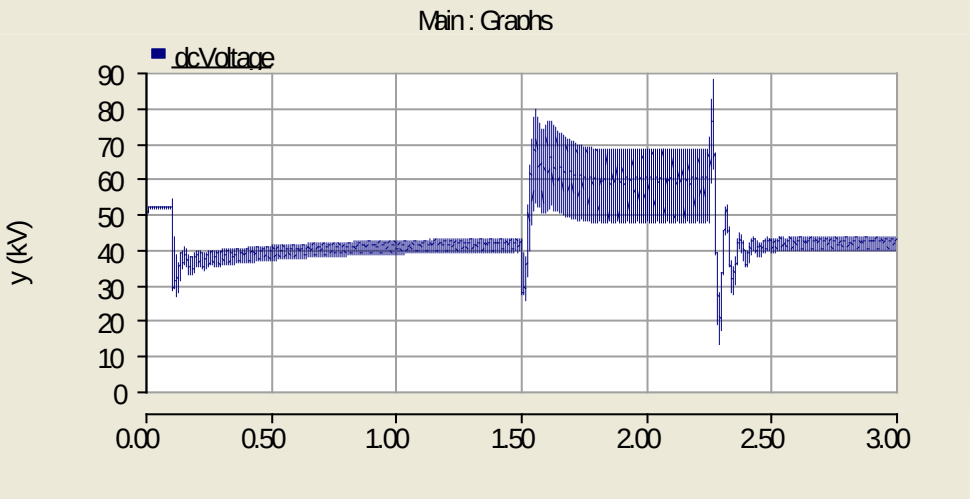


Figure 6.26. DC voltage

As it seen in Figure 6.25, the output voltage value of the STATCOM is increased when Timed Fault Logic is activated at the time t=1.5-2.25 sec. This situation shows that reactive power is supplied to the system.

The Figure 6.18 shows that the PCC voltage is stabile until the fault occurs. When the fault is run between 1.5 sec. and 2.25 sec., the voltage drops, and the STACOM is delivering reactive power. The DC voltage should be higher than the AC side inverter voltage in order to produce reactive power.

Figure 6.26 depicts the voltage of the dc-side capacitor. When STATCOM is full in operation Figure 6.26 shows that the reactive power is generated by the STATCOM and that the dc voltage is increased so as to increase the PCC voltage from 0,731 pu to 1,002 p.u. This shows that the STATCOM helps to stabilize the voltage with reactive power compensation.

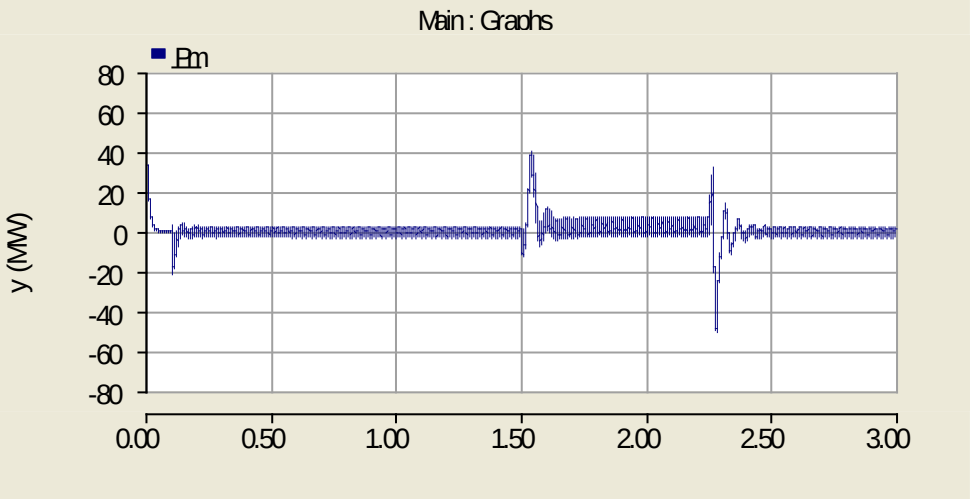


Figure 6.27. PCC active power (with STATCOM)

Figure 6.27 shows the active power of the system. The active power is kept at a minimal level close to zero, which is desired of a STATCOM device.

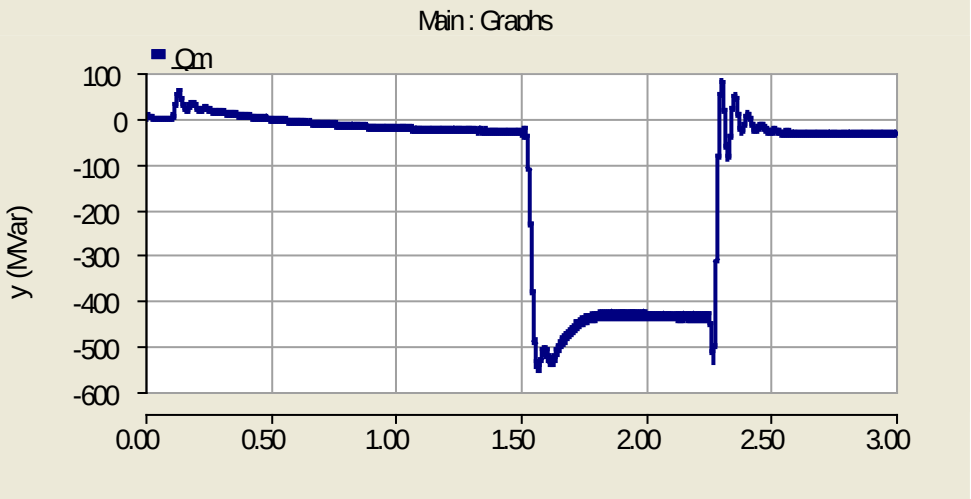


Figure 6.28. PCC reactive power (with STATCOM)

The reactive power simulation of the line without connecting STATCOM is shown in Figure 6.20. By activated of Timed Fault Logic, the reactive power consumption is increasing between 1.5-2.25 sec. during 0.75 sec. at the PCC.

By the connection of the STATCOM, the reactive power becomes negative as shown Figure 6.28. The explanation is that; the DC voltage starts to increase for

providing voltage regulation and it starts to supply reactive power to the system from STATCOM.

Figure 6.28 shows the STATCOM's response of the output reactive power. When the three phase fault occurs in the system, the voltage is reduced. From the theory it is stated that when the system voltage is lower than the reference voltage from the converter, the STATCOM should produce reactive power to the system and so STATCOM is capacitive mode.

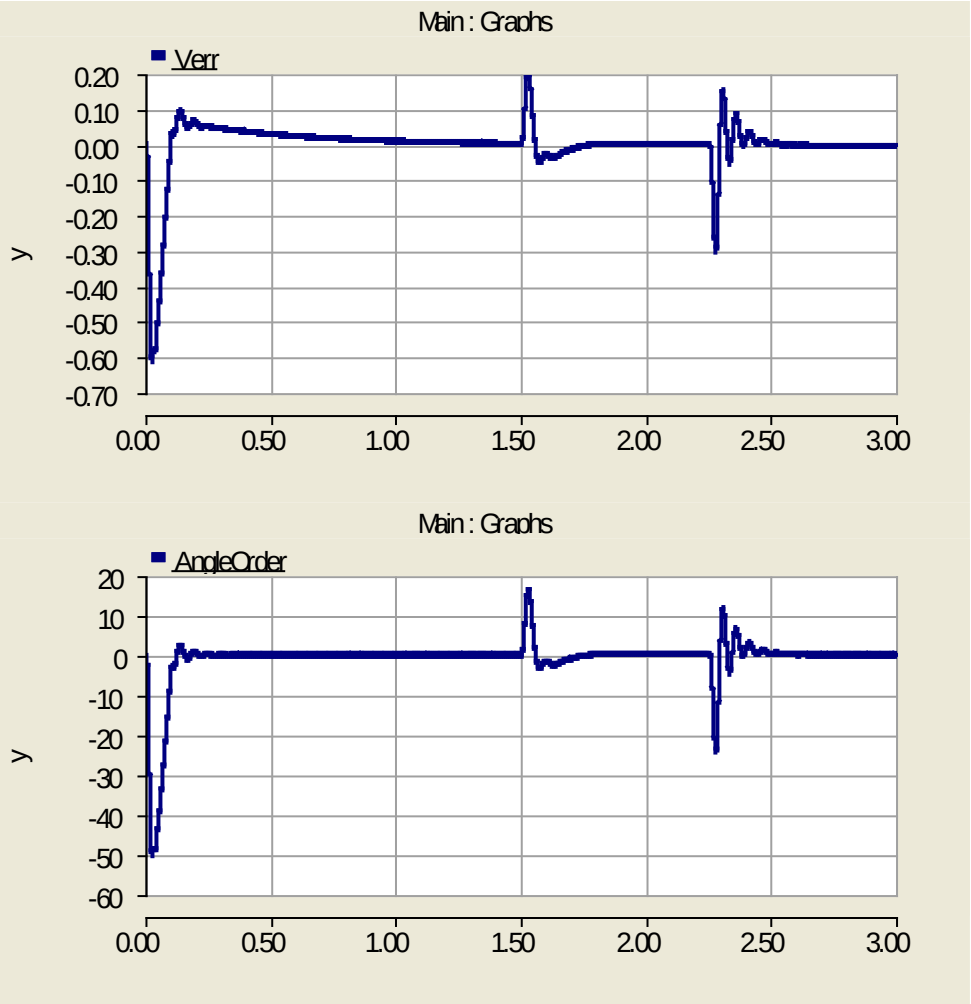


Figure 6.29. Verr Signal and Angle Order Signal

The PI controller processes the error signal and generates the required angle δ to drive the error to zero in Figure 6.29.

The PWM control circuit generates the firing signal of the GTO by comparing the triangular wave carrier signals with the sine wave reference signals. The zero crossings of the voltage ramps fire/block the GTOs depending on the displacement angle δ. If, δ=0, the resulting output voltage is said to be in phase with the ac system voltage. However, if there is an error between the reference voltage and the system voltage in per unit i.e. $V_{pu} < V_{ref}$, then the displacement angle δ>0 and the STATCOM voltage lags the ac voltage thus causing a real power flow into the devices. Consequently, the dc bus voltage will increase, causing an increase of the ac output voltage of the devices. The increasing output voltages causes the capacitive reactive current to increase and reduces the error voltage until $V_{pu} = V_{ref}$. The inverse occurs, if $V_{pu} > V_{ref}$.

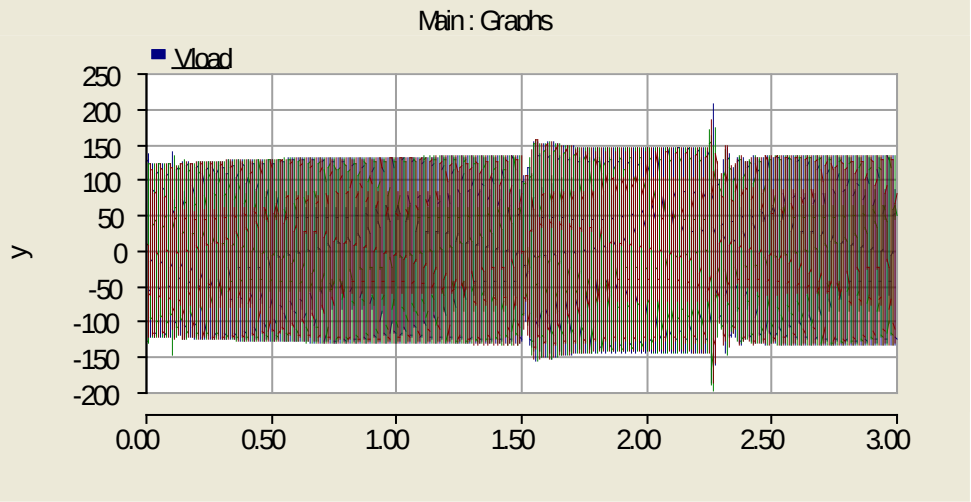


Figure 6.30. Load three phase voltage (with STATCOM)

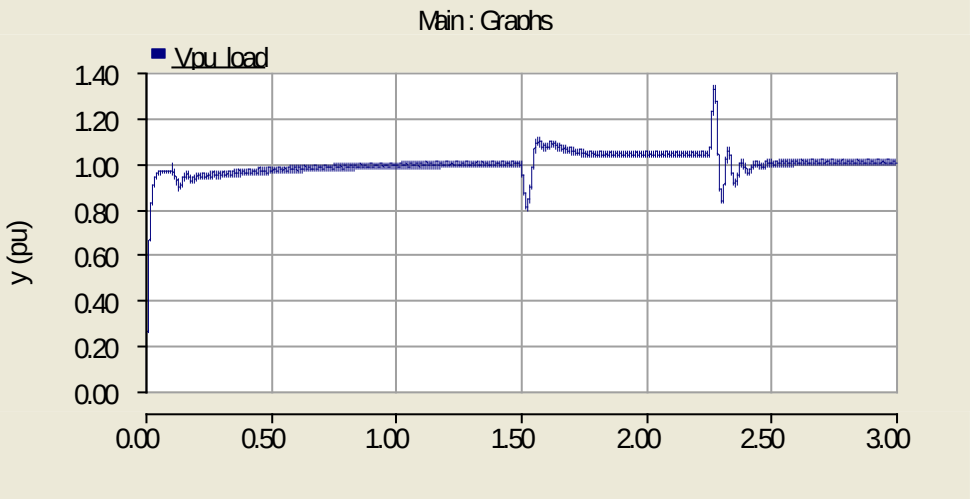


Figure 6.31. Load pu voltage (with STATCOM)

The effect of the STATCOM on the load terminal voltage shows that the voltage sag is eliminated and it proves that the STATCOM is capable of mitigating voltage sag in Figure 6.30 and 6.31.

When the fault is created, STATCOM boosts the voltage by injecting the reactive power and than load voltage variations are dynamically mitigated. The compensated load voltage is shown in Figure 6.30 and 6.31. Load Voltage can come back the pre-defined rating value (1.0 pu).

As it seen in Figure 6.31, the value of voltage at the transmission line's load side is the same as the voltage value of the V_{pu_load} =1 pu as it seen in Figure 6.3. It is seen in Figure 6.31 that STATCOM can stabilize even the voltage drops that caused by non-ideal source of transmission line. Also the voltage dip that caused by Timed Fault Logic between 1.5 sec. and 2.25 sec. is regulated by STATCOM.

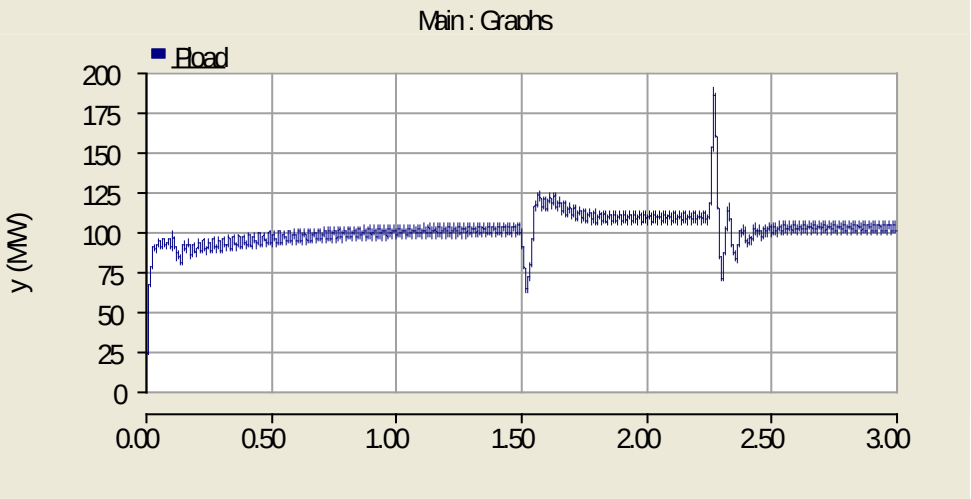


Figure 6.32. Load active power (with STATCOM)

As it seen in Figure 6.32, the active power at the transmission line's load side P_{load} =99, 63 MW and the active power P_{load} =99, 89 MW that is seen in Figure 6.4 are about the same. Also, the drop of active power at the load side that was caused by timed fault logic between 1.5 sec. and 2.25 sec. is prevented by STATCOM. Thus, increasing of the transmitted active power is provided.

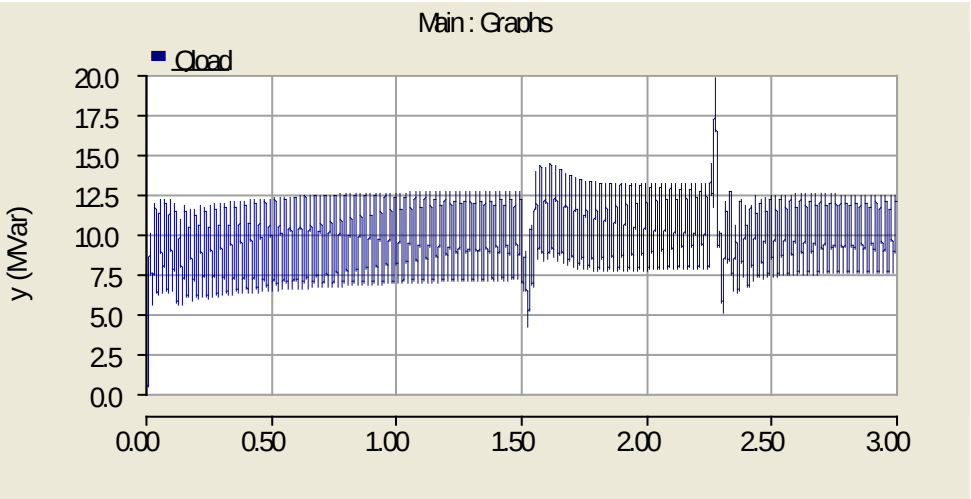


Figure 6.33. Load reactive power (with STATCOM)

As it seen in Figure 6.33, the reactive power at the transmission line's load side Q_{load} =9,573 MVAR and the reactive power Q_{load} =10, 37 MVAR that is seen in Figure 6.5 are about the same. Also, the drop of the reactive power at the load side

that caused by timed fault logic between 1.5 sec. and 2.25 sec. is prevented by STATCOM. So STATCOM is doing reactive power compensation as it seen in Figure 6.33.

In simulation program, STATCOM with the aid of a transformer is connected parallel to the bus that wanted to be controlled. The between phase relationship of STATCOM's the current and voltage is dependent on workout conditions (inductive or capacitive) of the power system. That means, in this case when the system is inductive, then STATCOM generates capacitive reactive current and when the system is capacitive, then STATCOM generates inductive reactive current. In order to STATCOM's working capacitive, the amplitude of the STATCOM's output voltage amplitude must be greater than the bus voltage amplitude and for achieving that it is needed to increase the voltage of the capacitor.

As it can be seen from the simulation results, STATCOM provides voltage support to the bus which is connected to and STATCOM gives answer to the reactive power demand of the load in very short time. STATCOM's this ability is very important for the voltage regulations of the transmission lines and especially so effective at compensation of the critical loads and increases transmitted active power. Also STATCOM can manage to provide required voltage and compensation current, within its inductive and capacitive current boundaries, while staying independently from the load increases and decreases.

7. CONCLUSIONS AND SUGGESTIONS

7.1. Conclusions

The need for more efficient electric power generation and transmission bring with new technologies. Transmission systems are changing continuously and being restructured at the all over the world. With increasing number of the users, more shoulder to the transmission systems.

Ensuring a high level of power quality in generation, transmission and distribution is important for the efficient and reliable operation for the working devices which are connected to the system. Also, to come into question necessity quality power with increasing of used voltage-sensitive electronic devices. Therefore for developing the countermeasures, the power quality should be monitored regularly and properly at certain points of electrical system. Power quality is measured by evaluating the real-time field data. Many new and powerful devices that detect power quality distortion is produced. In Ankara TEİAŞ, a laboratory has been established for monitoring the power quality parameters by using power monitoring devices for 24 hours.

At TEİAŞ energy transmission lines:

- **Serial Capacitor:** It represents capacitor group. When it is serially connected to line, it decreases impedance and increases system stability.
- **Serial Reactor**: It represents the used coil which is connected to feeder to constraint the current.
- **Shunt Capacitor:** It represents condenser group that is connected parallel to the system generating reactive power.
- **Shunt Reactor:** It represents coil that is used to consume reactive power from connected line, transformer or bus, and used to decrease the voltage.

If need be, the serial capacitors are used to reduce inductive reactance of the line at 380 kV long transmission lines. At cable transmission lines, unless

establishing shunt reactors at proper points, cable is charged by its own charge current and active power capacity is reduced.

The shunt compensation is made by using shunt reactors and shunt capacitor at the system. Shunt reactors are to connect to line feeders, buses and 380/154 kV autotransformer's tertiary coil. The connections of shunt reactors which are to be connected to the line feeders are designed to allow taking into service both on the line and only on the bus. Shunt capacitors are able to designed to be connected to only the bus. Shunt reactors and capacitors are connected to the junction points via on circuit breaker and seperator.

Shunt reactors are designed to work continuously on system voltages of 420 and 170 kV. Shunt capacitor groups are established to secondary side bus of 154 kV substations for correcting power factor when they are necessary. Shunt capacitors are designed to link to separate feeders as double capacitor group if necessary and limiting %20 capacities of the transformer.

In İstanbul district, shunt capacitor and shunt reactor are used for voltage regulation and reactive power compensation. Shunt capacitors have been assembled to medium-voltage bus in TEİAŞ substations. Only one shunt reactor has been used till today in İstanbul. Shunt reactor is established 1. Transmission Installation and Operation Group Management's switchyard and it was put into use in 2014 years. Its photograph is shown Appendix-6.

The main reason for voltage instability, power system can not respond the load demand. Voltage instability is affecting from medium-voltage side to 154 kV and 380 kV bus. Instability voltage problem has negative effects on lines between Turkey and European Network of Transmission System Operators of Electricity (ENTSO-E). A system that is suggested solution in literature and also approximately for TEİAŞ of Turkey and able to reactive power compensation must be used for voltage instability. STATCOM technology which exists in the world and also our country that has been before built on base transmission system in Ankara Sincan Substation since 2010 by TUBITAK (Turkey Science and Research Center) is the most suitable option.

For this purpose, STATCOM must be used to get over voltage instability problem and stabilizing transmission system for voltage regulation and reactive power compensation.

In this case study, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line which is operated by TEİAŞ 1. Transmission Installation and Operation Group Management in İstanbul district is modeled by used "Frequency Dependent (Phase) Model" sub-program of PSCAD/EMTDC with operating data.

In order to evaluate the performance of the STATCOM model, different case studies are investigated.

In the first case, a basic transmission line that contains only voltage source and load is modeled. In this case, for selected ideal source, nothing is observed to affect to active power, reactive power and voltage of the line. Just 10 MVAR reactive power that is available at the load side causes very slight decreasing at active power, increasing at reactive power in the basic transmission system.

In the second case, a basic transmission line that contains a non-ideal voltage source and load is modeled. Therefore selected non-ideal source and source' s positive sequence impedance value that is chosen 26,45 ohm for equalizing with positive sequence impedance value of 6-pulse STATCOM which is available as ready module in the PSCAD/EMTDC causes decreasing of active power, reactive power and voltage values at the source side and load side.

In the third case, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line, that modeled by using PSCAD /EMTDC Frequency Dependent (Phase) Model is added between non-ideal voltage source and load. It is observed active power, reactive power and voltage values which are measured source side and load side of the transmission line are not equal to each other. The reason of that slight difference is the resistance and reactance values and line's distance of modeled the 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line.

In the fourth case, in order to obtain voltage dip, the timed fault logic is connected to the Point of Common Coupling (PCC) of transmission line, which was modeled at the third case.

In the fifth case, 6-pulse STATCOM is added to the PCC of the line which was modeled at the fourth case. In simulations results shows that STATCOM supplies voltage to its connected bus and responds the load's necessity reactive power immediately. In this thesis, modeled STATCOM provide to reguate voltage and damp transient regime event and control reactive power flow connected to TEİAŞ bus that has power flow problem from the voltage fluctuations.

7.2. Suggestions

Voltage regulations and instability problems of transmission system are important elements to affect the system quality. In recent years, mention elements are controlled by using dynamical and flexible (FACTS) base power semi-conductor devices for being both more economic and more efficient. Therefore in this case study, 154 kV İkitelli-Yenibosna 1-2 double circuit overhead transmission line which is located TEİAŞ system is modeled in PSCAD/EMTDC with adding to 6-pulse STATCOM for being solution of Turkish Electricity Transmission System's voltage regulation, power compensation and voltage stability problems.

Excessive current rising are occurred when the coil or reactor groups changed step by step at the reactive power controlling which is carried out by switched condenser or reactor coils available in TEİAŞ system. This state causes underground cables to heat and/or defect cable to be destroyed isolation. If STATCOM is used to for controlling reactive power, excessive current increments just occurred in preliminary charge instant of DC bus condenser. To get over this condition, if the capacitance value of condenser increases, the response time of STATCOM would decrease. For this reason, the best control method can be development to control DC voltage side in future studies.

Output voltage and current of 6-pulse STATCOM has high-level harmonic value. Phase shifting feature of STATCOM belonging to coupling transformers is not enough to decrease amplitude of high-level harmonic components. VSC's output voltage can be filter before it connects to the linked transformer for reducing harmonics' frequency which is generating by VSC (Voltage Source Converter). Or

pulse numbers of VSC can be increased for example 48-pulse to eliminate high-level harmonics or designed can be improved by using of different modulated techniques.

If STATCOM system is connected to TEİAŞ bus, it will be directly placed in transformer center and will not need to nationalization. On the other hand, STATCOM can be put into near to load or middle of transmission line to make efficient for reactive power compensation.

The reactive power that is necessary for line can be more economical to supply rather medium voltage than transmission system. If this is done, power factor will rise to 1.0 value and thereby active power will be able to increase not being caused voltage instability at the line.

STATCOM can be design modular system. By the way, in the case of elimination of the needs at the one point, it will be easily taken apart and connected to the other point requiring it; as a result, it can be a relocatable.

STATCOM structures have commonly had a feature of multi-pulse structures until now. In the studies of the literature, multi-pulse structures will replace with multi-level structures. Multi-level STATCOMs which have full bridge structure are score over others due to using modular structure and concurred valued elements. Therefore, multi-level STATCOM can be designed in the further studies.

10-20% losses in transmission and distribution systems have been eliminated by STATCOM. Therefore, TEİAŞ can transmit electricity more efficient such as corporation funds used in other important areas and electricity dispatched urgent needs or efficient areas. The loss in transmission system because of power quality will be minimized.

Can be joined ENTSO-E as a full member when voltage instability problems are solved in TEİAŞ system. In addition to this, export/import limits is going to increase, so it can be obtained enlargement of energy marketing bulk.

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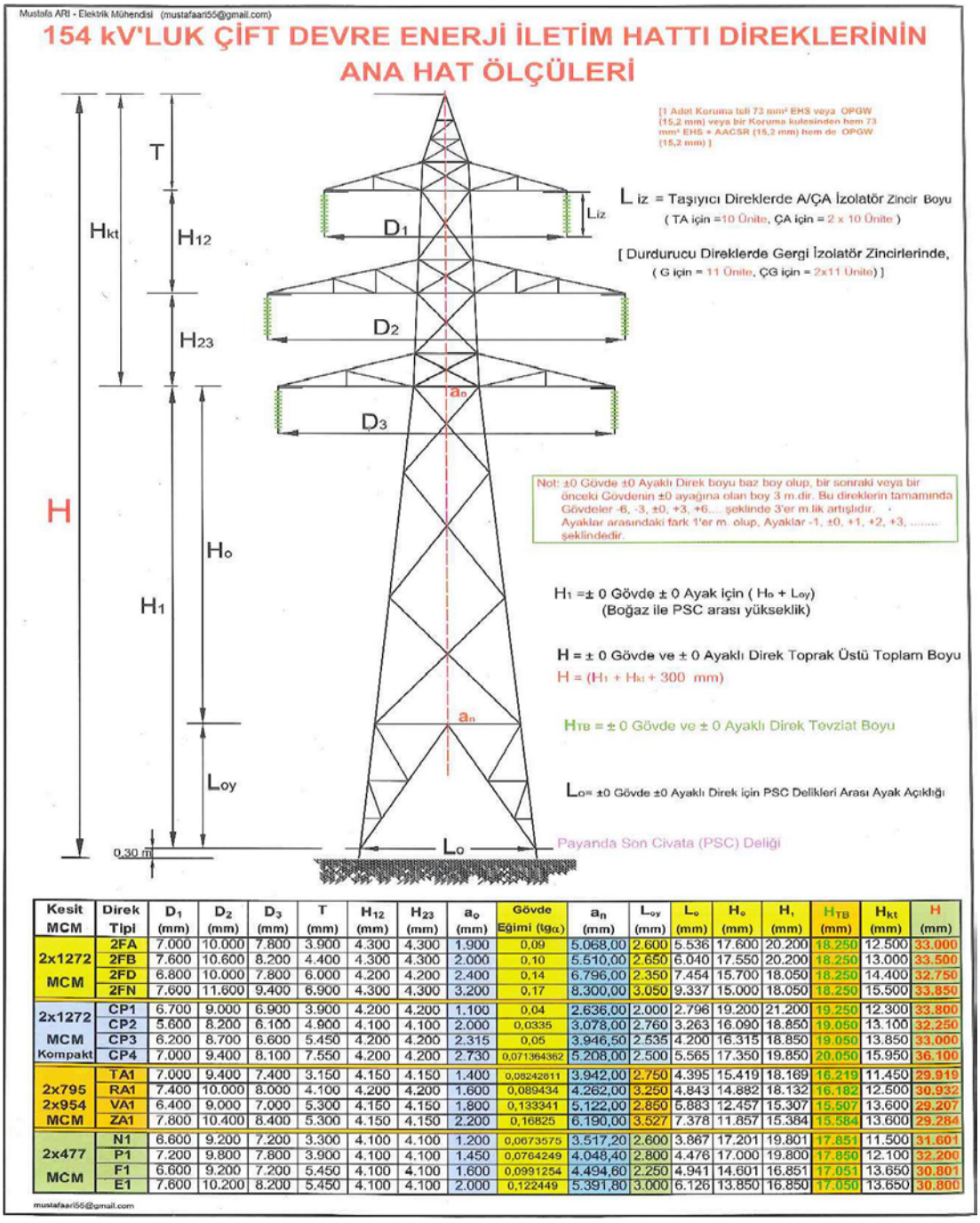
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Meral AY was born in Adana in 1983. She completed his elementary education at Barbaros Primary School in Adana. She went to high school at 19 Mayıs Super High School. She graduated from Niğde University Department of Electrical and Electronics Engineering in 2005. She worked as a R&D and Project Engineer at TEDAŞ in Adana between 2007-2011 years. Then she is working as an Installation&Cotrol Engineer at TEİAŞ in İstanbul.

APPENDIX

APPENDIX–1: 154 kV Double Circuit Overhead Transmission Line Towers' Main Part Diemensions



Kesit MCM	Direk Tipi	D_1 (mm)	D_2 (mm)	D_3 (mm)	T (mm)	H_{12} (mm)	H_{23} (mm)	a_o (mm)	Gövde Eğimi ($tg\alpha$)	a_n (mm)	L_{oy} (mm)	L_o (mm)	H_o (mm)	H_1 (mm)	H_{TB} (mm)	H_{kt} (mm)	H (mm)
2x1272 MCM	2FA	7.000	10.000	7.800	3.900	4.300	4.300	1.900	0,09	5.068,00	2.600	5.536	17.600	20.200	18.250	12.500	33.000
	2FB	7.600	10.600	8.200	4.400	4.300	4.300	2.000	0,10	5.510,00	2.650	6.040	17.550	20.200	18.250	13.000	33.500
	2FD	6.800	10.000	7.800	6.000	4.200	4.200	2.400	0,14	6.796,00	2.350	7.454	15.700	18.050	18.250	14.400	32.750
	2FN	7.600	11.600	9.400	6.900	4.300	4.300	3.200	0,17	8.300,00	3.050	9.337	15.000	18.050	18.250	15.500	33.850
2x1272 MCM Kompakt	CP1	6.700	9.000	6.900	3.900	4.200	4.200	1.100	0,04	2.636,00	2.000	2.796	19.200	21.200	19.250	12.300	33.800
	CP2	5.600	8.200	6.100	4.900	4.100	4.100	2.000	0,0335	3.078,00	2.760	3.263	16.090	18.850	19.050	13.100	32.250
	CP3	6.200	8.700	6.600	5.450	4.200	4.200	2.315	0,05	3.946,50	2.535	4.200	16.315	18.850	19.050	13.850	33.000
	CP4	7.000	9.400	8.100	7.550	4.200	4.200	2.730	0,071364362	5.208,00	2.500	5.565	17.350	19.850	20.050	15.950	36.100
2x795 2x954 MCM	TA1	7.000	9.400	7.400	3.150	4.150	4.150	1.400	0,08242811	3.942,00	2.750	4.395	15.419	18.169	16.219	11.450	29.919
	RA1	7.400	10.000	8.000	4.100	4.200	4.200	1.600	0,089434	4.262,00	3.250	4.843	14.882	18.132	16.182	12.500	30.932
	VA1	6.400	9.000	7.000	5.300	4.150	4.150	1.800	0,133341	5.122,00	2.850	5.883	12.457	15.307	15.507	13.600	29.207
	ZA1	7.800	10.400	8.400	5.300	4.150	4.150	2.200	0,16825	6.190,00	3.527	7.378	11.857	15.384	15.584	13.600	29.284
2x477 MCM	N1	6.600	9.200	7.200	3.300	4.100	4.100	1.200	0,0673575	3.517,20	2.600	3.867	17.201	19.801	17.851	11.500	31.601
	P1	7.200	9.800	7.800	3.900	4.100	4.100	1.450	0,0764249	4.048,40	2.800	4.476	17.000	19.800	17.850	12.100	32.200
	F1	6.600	9.200	7.200	5.450	4.100	4.100	1.600	0,0991254	4.494,60	2.250	4.941	14.601	16.851	17.051	13.650	30.801
	E1	7.600	10.200	8.200	5.450	4.100	4.100	2.000	0,122449	5.391,80	3.000	6.126	13.850	16.850	17.050	13.650	30.800

APPENDIX–2: Characteristics of Aluminium Conductor Steel Core

ÇELİK ÖZLÜ ALÜMİNYUM İLETKENLERİN KARAKTERİSTİKLERİ						
İLETKEN ACSR	**Anma Kesit MCM**	**477**	**795**	**954**	**954**	**1272**
	Kod İsmi	**HAWK**	**DRAKE**	**RAIL**	**CARDINAL**	**PHEASANT**
STANDART KESİT(mm^2)	**Alüminyum**	241,65	402,56	484,40	484,53	645,08
	Çelik	39,19	65,44	33,60	62,81	81,71
	Toplam	280,84	468,00	517,00	547,34	726,79
KATMAN SAYISI		3	3	4	4	5
KATMANLARDAKİ TEL SAYISI		1/6/10/16	1/6/10/16	1/6/9/15/21	1/6/12/18/24	1/6/12/12/18/24
ÖRGÜDEKİ ALÜMİNYUM TELİN	**Adedi**	26	26	45	54	54
	Çapı(mm)	3,44	4,44	3,70	3,38	3,90
ÖRGÜDEKİ ÇELİK TELİN	**Adedi**	7	7	7	7	19
	Çapı(mm)	2,67	3,45	2,48	3,38	2,34
STANDART ÇAP(mm)	**Komple İletken**	21,77	28,11	29,60	30,42	35,10
	Çelik Nüve	8,01	10,36	7,4	10,14	11,70
ANMA KOPMA KUVVETİ(kgf)		8798	14165	11864	15589	20357
BİRİM AĞIRLIK (kg/km)		973	1624	1600,2	1829	2423,5
NİHAİEL ASTİSİTE MODÜLÜ (kg/mm^2)		7700	7700	6700	7000	6800
ORTALAMA ISIL UZAMA KATSAYISI ($1/^0CX10^{-6}$)		18,9	18,9	19,5	19,3	19,4
BİR MAKARADA ALÜMİNYUM TELLERDEKİ İZİN VERİLEN EKLERİN SAYISI		4	4	5	5	5
20 ^{0}C' de DC Direnci Ω/km		0,1194	0,0715	0,0599	0,0597	0,0449

APPENDIX–3: 24XG652 OPGW Protection Conductor Test Report

QUALITY TEST CERTIFICATE
KALİTE TEST SERTİFİKASI

AFTER STRANDING
BÜKMEDEN SONRA

Type/*Tip* : OPGW AA/Galv. Steel 88/44 24xG 652
Standard/*Standart* : TEİAŞ ŞARTNAMESİ VE İLGİLİ STANDARTLAR (IEC 888,104)
Customer /*Müşteri* : ERŞA ELEKTRİK

Drum no / *Makara no* : 24

Gross Weight/*Brüt Ağırlık*	:	2583	kg
Tare/*Dara*	:	186	kg
Net Weight/*Net Ağırlık*	:	2397	kg
Length/*Uzunluk*	:	3860	m

Weight (g/m) *Ağırlık*	Stipulated *Standart*	Measured *Ölçülen*
Conductor/*İletken*	: 612g/m (± 3 %)	605,81 g/m
Aluminium	: 242 g/m (± 3 %)	242,15 g/m
Steel/*Çelik*	: 348 g/m (± 3 %)	343,65 g/m
St. Tube/Çelik tub	: 22 g/m	20,01 g/m

Layers / *Katlar*	Overall / *Dışçap(mm)* Nominal *Nominal*	Measured *Ölçülen*	Lay Length / *Hatve (mm)* Design Value *Dizayn Değeri*	Measured *Ölçülen*	Lay Ratio / *Hatve Oranı* (L/D) Design Value *Dizayn Değeri*	Measured *Ölçülen*
1. Steel Layer/Çelik Katları (s)	9,15	9,12	91,5 - 146,5	120	10 - 16	13,15
2. Al. Alloy Layer/Al. Alaşım Katları (z)	15,20	15,22	152,5 - 213,5	188	10 - 14	12,35

Complete Conductor Tensile Test	Standard Tensile Load , kN	Calculated Value , kN
Breaking Load	89,5	96,5

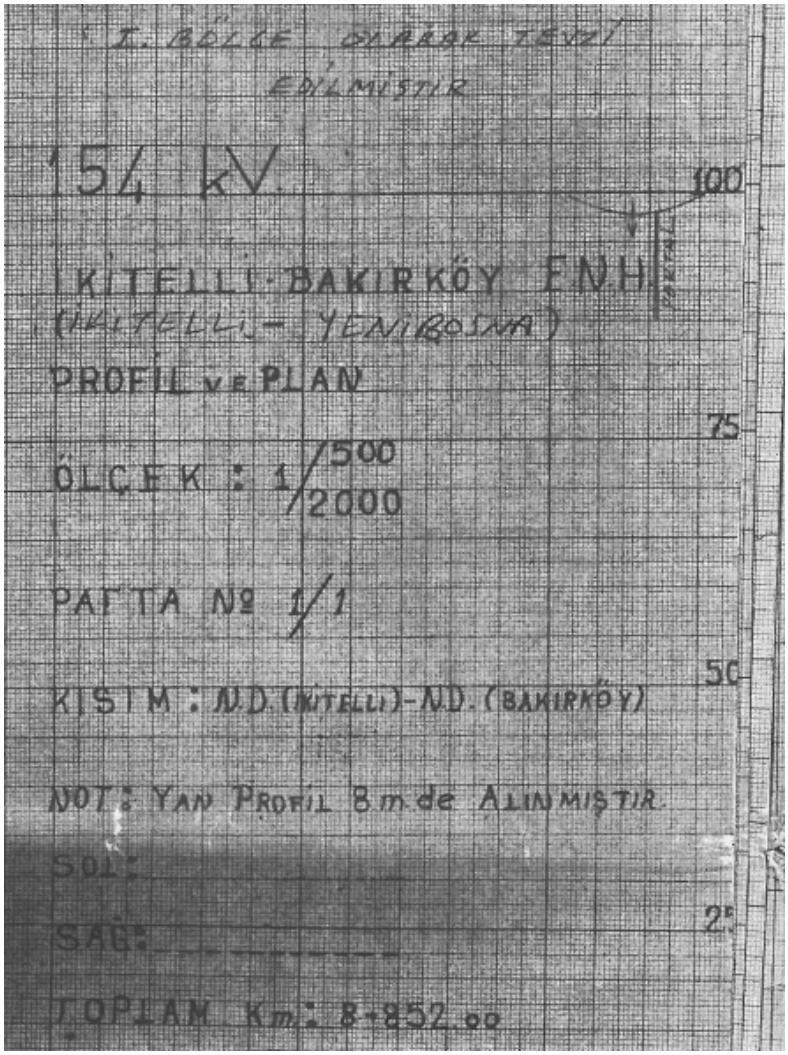
Complete Conductor	Standard Resistance Value , ohm/km	Calculated Resistance Value , ohm/km
Resistance ohm per km	0,334	0,327

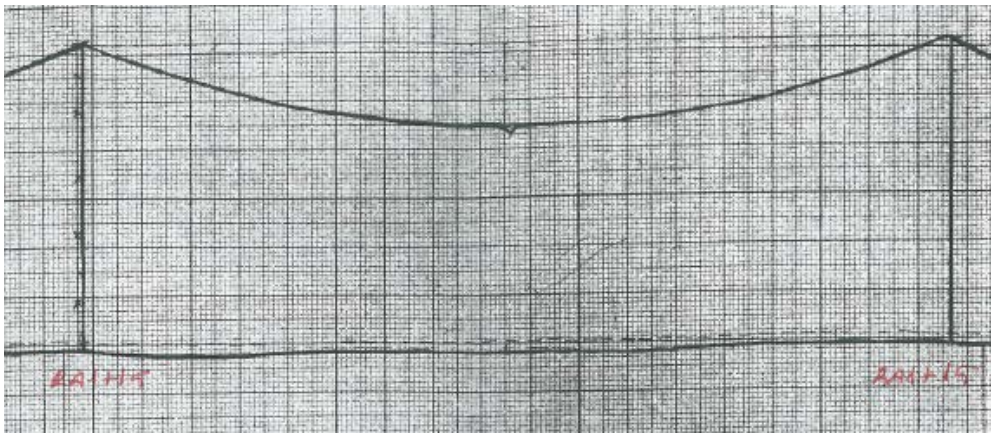
The tested conductor comply with above-mentioned stipulations.
İletken testi standart değerleri sağlamaktadır.

DATE : 05.06.2009

pector / *Testi Yapan* : F.Ş.

APPENDIX–4: 154 kV İkitelli-Yenibosna 1-2 Double Circuit Overhead Transmission Line RA1+15 Profile Project





APPENDIX–5: 154 kV İkitelli-Yenibosna 1-2 Double Circuit Overhead Transmission Line RA1+15 Tower Photography



APPENDIX–6: İstanbul Davutpaşa Substation Reactor Feeder

