SIMULATION OF POWER QUALITY CONTROLLER USING THREE LEVEL GTO BASED FACTS DEVICE

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Abstract

The importance of quality in power supplied to consumers is increasing as the days are passing due to increase in demand of power .As a solution to this the new control technique that is GTO based controller has been developed by using SSSC ,STATCOM , UPFC for connected reactive power compensation and voltage stabilization of the electrical grid network. This paper examines effective operation of both static synchronous compensator (STATCOM), static synchronous series compensator (SSSC) and unity power factor controller (UPFC) based on a new full model consisting of 48 - pulse gate turn off thyristor voltage source converter. Three controllers of STATCOM, SSSC and UPFC are presented in this paper based on a decoupled with voltage and current control strategy. The performance of STATCOM, SSSC and UPFC is verified by simulation using MATLAB environment. The proposed to ensure the stable operation of the STATCOM under various load conditions. Unified Power Flow Controller (UPFC) has its unique capability to control simultaneously real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected, this device creates a tremendous quality impact on power system stability. The MATLAB simulation results shows that GTO controller has an effective power flow control, less settling time and less overshoot when compared to PI controller in different operating modes.

Introduction

Power Quality

Definition of Power Quality

Power quality has different meanings to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment”. There is a broad range of power quality problems associated with power systems based on time such as long duration variations, short duration variations and other disturbances. All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems.

The main reasons for concern with power quality (PQ) are as following:

- End user devices become more sensitive to PQ due to many microprocessor-based controls.
- Large computer systems in many businesses facilities.

Power electronics equipment used for enhancing system stability, operation and efficiency. These are major sources of bad Power Quality. Continuous development of high-performance equipment: Such equipment is more susceptible to power disturbances.

The users always demand higher power quality. Some basic criterions for power quality are constant RMS value, constant frequency, symmetrical three-phases, pure sinusoidal wave shape and limited THD.

Sources of Poor Power Quality

- Sources of poor Power Quality are listed as follows:
- Adjustable –speed drives
- Switching Power supplies
- Arc furnaces
- Electronic Fluorescent lamp ballasts
- Lightning Strike
- L-G fault
- Non- linear load
- Starting of large motors
- Power electronic devices

Need of Power Quality

There is an increased concern of power quality due to the following reasons:

New-generation loads that use microprocessor and microcontroller-based controls and power electronic devices, are more sensitive to power quality variations than that equipment used in the past.

The demand for increased overall power system efficiency resulted in continued growth of devices such as high-efficiency adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic level on power systems and has many people concerned about the future impact on system capabilities.

End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

Most of the networks are interconnected these days. Integrated processes mean that the failure of any component has much more important consequences.

Classification of Power Quality Problems

Short Duration Voltage Variation

Depending on the fault location and the system conditions, the fault can cause either temporary voltage drops (sags), voltage rises (swells), or a complete loss of voltage (interruptions). The duration of short voltage variations is less than 1minute. These variations are caused by fault conditions, the energization of large loads which require high starting currents, or intermittent loose connections in power wiring.

Voltage Sag

Voltage sag (also called a “dip”) is a brief decrease in the RMS line voltage of 10 to 90 percent of the nominal line-voltage. The duration of a sag is 0.5 cycle to 1 minute. Common sources that contribute to voltage sags are the starting of large induction motors and utility faults.

Voltage Swell

A swell is a brief increase in the RMS line-voltage of 110 to 180 percent of the nominal line-voltage for duration of 0.5 cycle to 1 minute. The main sources of voltage swells are line faults and incorrect tap settings in tap changers in substations.

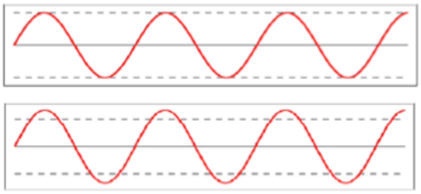

Figure 1 Voltage Swell

Interruption

An interruption is defined as a reduction in line-voltage or current to less than 10 percent of the nominal, not exceeding 60 seconds in length. Interruptions can occur due to power system faults, equipment failures and control malfunctions.

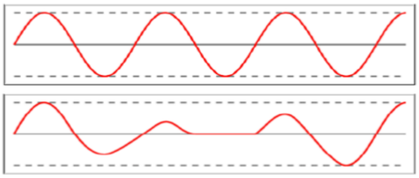

Figure 2 Interruption

Long-Duration Voltage Variation

Long-duration variations can be categorized as over voltages, under voltages or sustained interruptions

Overvoltage

An overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for duration longer than 1 min. Over voltages are usually the results of load switching or incorrect tap settings on transformers.

Under Voltage

An under voltage is decreases in the RMS AC voltage to less than 90 percent at the power frequency for duration longer than 1 min. A load switching on or a capacitor bank switching off can cause an under voltage until voltage regulation equipment on the system can restore the voltage back to within tolerance limits. Also overloaded circuits can result in under voltage.

Sustained Interruptions

When the supply voltage has been zero for a period of time in excess of 1 min the long-duration voltage variation is considered a sustained interruption.

Transients

Impulsive Transient

An impulsive transient is a brief, unidirectional variation in voltage, current, or both on a power line. Lightning strikes, switching of inductive loads, or switching in the power distribution system are the most common causes of impulsive transients. The effects of transients can be mitigated by the use of transient voltage suppressors such as Zener diodes.

Figure 3 Impulsive Transients

Oscillatory Transient

An oscillatory transient is a brief, bidirectional variation in voltage, current, or both on a power line. These are caused due to the switching of power factor correction capacitors.

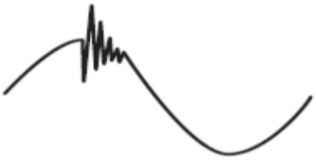

Figure 4 Oscillatory Transients

Voltage Fluctuations

Voltage fluctuations are relatively small (less than 5 percent) variations in the RMS line voltage.

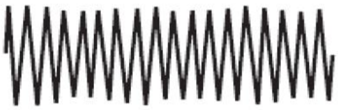

Figure 5 Voltage Fluctuations or Flicker

Cyclo-converters, arc furnaces, and other systems that draw current not in synchronization with the line frequency are the main contributors of these variations.

Voltage Imbalance

A voltage imbalance is a variation in the amplitudes of three-phase voltages, relative to one another. Voltage imbalance can be the result of different loads on the phases, resulting in different voltage drops through the phase-line impedances.

Figure 6 Voltage Imbalances

Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

DC offset: The presence of a dc voltage or current in an AC power system is termed dc offset.

Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate, and that is known as the fundamental frequency which is usually 50 or 60 Hz. The harmonic distortion originates in the nonlinear characteristics of devices and also on loads connected to the power system.

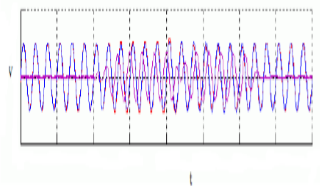

Figure 7 Harmonics

Harmonic distortion levels can be described by the calculating total harmonic distortion (THD) which measures the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. THD is represented as the square-root of the sum of the squares of each individual harmonic. Voltage THD is

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V1}$$

Where *V*1 is the RMS magnitude of the fundamental component, and *Vn* is the RMS magnitude of component *n* where n = 2,....., .∞ The problem with this approach is that THD become infinity if no fundamental is present. A way to avoid this ambiguity is to use an alternate definition that represents the harmonic distortion. This is called the distortion index (DIN) and is defined as

$$\mathrm{DIN} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{\sqrt{\sum_{n=1}^{\infty} V_n^2}}$$

THD and DIN are interrelated by the following equations

$$\mathrm{DIN} = \frac{THD}{\sqrt{1+THD^2}}$$

$$\mathrm{THD} = \frac{DIN}{\sqrt{1-DIN^2}}$$

Sub-Harmonics

Sub harmonics can be defined as frequency components in voltage and current waveforms less than the power system frequency. Cyclo-converters, adjustable speed drives, arc furnaces, wind generators and other loads inject low frequency currents that produce sub harmonic distortion in voltage supply.

Inter-Harmonics

Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (50 or 60 Hz) are called inter-harmonics. Inter-harmonics can appear as discrete frequencies or as a wideband spectrum. The main sources of inter-harmonic waveform distortion are static frequency converters, induction furnaces, cyclo-converters and arcing devices. Power line carrier signals can also be considered as inter-harmonics.

Electrical Noise

Noise is a high frequency distortion of the voltage waveform. Caused by disturbances on the utility system or by equipment such as welders, switchgear and transmitters, noise can frequently go unnoticed. Frequent or high levels of noise can cause equipment malfunction, overheating and premature wear.

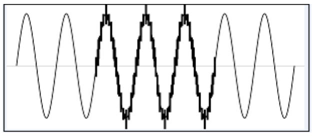

Figure 8 Electrical Noise Waveform

Notching

Notching is a disturbance of opposite polarity to the normal voltage waveform (which is subtracted from the normal waveform) lasting for less than one-half cycle. Notching is usually caused by malfunctioning of electronic switches or power conditioners. While it is generally not a major problem, notching can cause equipment, especially electronics, to operate improperly.

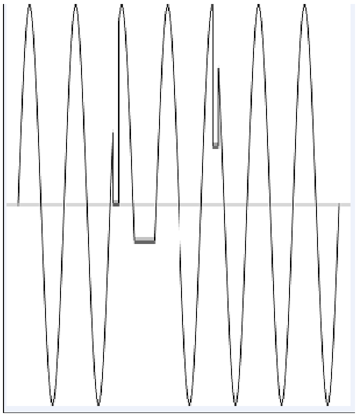

Figure 9 Notching Waveform [3] 14

Three Level GTO based Facts Device

The static series synchronous compensator (SSSC) is able to control active and reactive in a transmission line in a small range via stored energy in capacitor DC-link where static synchronous compensator (STATCOM) with injecting reactive power can control the bus voltage in a transmission line. Unified Power Flow Controller (UPFC) is the most functional and Flexible AC Transmission Systems (FACTS) equipment that has emerged for the control and optimization of power flow in power transmission systems. It has the combining features of both series converter and shunt converter based FACTS devices and is capable of realizing voltage regulation, series compensation and phase angle regulation at the same time. Therefore, the UPFC is capable of independently controlling the active power and reactive power on the compensated transmission line. GTO thyristors are implement the design of the solid-state shunt reactive compensation and active filtering equipment based upon switching convertor technology. These power quality devices (PQ Devices) are power electronic converters connected in parallel or in series with transmission lines and the operation is controlled by digital controllers. The interaction between these compensating devices and the grid network is preferably studied by digital simulation. Flexible alternating current transmission systems (FACTS) devices are usually used for fast dynamic control of voltage, impedance and phase angle of high-voltage AC lines.

Power flow regulated by adjusting the parameters of a system, such as voltage magnitude, line impedance and transmission angle. The device that attempts to vary system parameters to control the power flow can be described as a Power Flow Controlling Device (PFCD) as shown in the following figure.

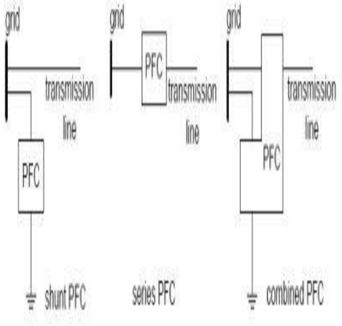

Figure 10 Single Line Diagram of 3 Level FACTS Device

A shunt component is a device that connects between the grid and the ground. Shunt devices generator absorb reactive power at the point of connection thereby controlling the voltage magnitude. Because the bus voltage magnitude can only be varied within certain limits, controlling the power flow in this way is limited and shunt devices mainly serve other purposes. For example, the voltage support provided by a shunt device at the midpoint of a long transmission line can boost the power transmission capacity.

STATCOM, A static synchronous compensator (STATCOM) is basically a Voltage Source Converter (VSC) that is connected between a grid and the ground through a coupling inductance. The STATCOM acts as an AC voltage source and has characteristics similar to a synchronous condenser (a synchronous generator that is running idle and used for reactive compensation). The STATCOM injects an AC current in Quadrature (leading or lagging) with the grid voltage and imitate capacitive or inductive impedance at the point of connection. If the voltage generated by the STATCOM is less than the grid voltage, it will act as an inductive load and withdraw reactive powers from the system. When the STATCOM voltage is higher than the grid voltage, it will act as a capacitor load and provide reactive power to the grid. Compared to the synchronous condenser, the STATCOM is a Power Electronic based device without inertia and therefore has a faster dynamic response. It consists of a three phase current-fed converter, whose outputs are connected to a three-phase full-bridge diode rectifier through a delta-delta wound three-phase transformer. The three-phase current-fed converter is divided into a three-phase full-bridge converter configured as six main MOSFET switches (S1– S6) for three-phase DC/AC conversion, one auxiliary MOSFET switch (SC) and clamp capacitor Cc for the active clamp and a DC boost inductor LDC acting as a current source.

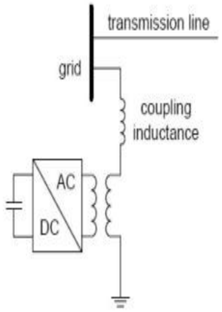

Figure 11 STATCOM Configurations

The DC Voltage Source Converter is the most common type of converter that used for the STATCOM and the DC voltage source can be a capacitor.

By using a multi-level, multi-phase or Pulse-Width Modulated (PWM) converter, the current distortion of the STATCOM outputs can be sufficiently reduced and the STATCOM may even require no filtering. Fig.3 shows the waveforms of a voltage generated by a five-level STATCOM and the corresponding current. Fig. 3. Voltage and current waveforms generated by a five-level STATCOM Unified Power Flow Controller Unified power flow controller (UPFC) is a combination of static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled through a common DC link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC is an angularly unconstrained series voltage injection and control of the transmission line voltage. Impedance and angle in real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. The operation of the UPFC from the standpoint of conventional power transmission based on reactive shunt compensation, series compensation and phase shifting, the UPFC can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage Vinj with appropriate amplitude and phase angle. Fig. 4. UPFC System Fig. 4 shows an combination of Shunt and Series controller action is works as a unified power flow controller (UPFC) is used to control the power flow in a 500 kV transmission system. The SSSC and STATCOM located at the left end of the 75-km line L1, between the 500 kV buses B1 and B2 is used to control the active and reactive powers flowing through bus B2 while controlling voltage at bus B1.

It consists of two 100-MVA, three-level, 48-pulse GTO-based converters, one connected in shunt at bus B1 and one connected in series between buses B1 and B2. The shunt and series converters can exchange power through a DC bus. The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2. This pair of converters can be operated in three modes: Unified Power Flow Controller (UPFC) mode, when the shunt and series converters are interconnected through the DC bus. When the disconnect switches between the DC buses of the shunt and series converter are opened, two additional modes are available. Shunt converter operating as a Static Synchronous Compensator (STATCOM) controlling voltage at bus B1 Series converter operating as a Static Synchronous Series Capacitor (SSSC) controlling injected voltage, while keeping injected voltage in quadrature with current.

Three Level GTO based Facts Device

The Model consists of three-level, 48-pulse GTO-based converters, one connected in shunt at bus B1 and one connected in series between buses B1 and B2. The shunt and series converters can exchange power through a DC bus. The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2.

This pair of converters can be operated in three modes:

Unified Power Flow Controller (UPFC) mode, when the shunt and series converters are interconnected through the DC bus. When the disconnect switches between the DC buses of the shunt and series converter is opened, two additional modes are available:

Shunt converter operating as a Static Synchronous Compensator (STATCOM) controlling voltage at bus B1

Series converter operating as a Static Synchronous Series Capacitor (SSSC) controlling injected voltage, while keeping injected voltage in quadrature with current.

The mode of operation as well as the reference voltage and reference power values can be changed by means of the “UPFC GUI” block.

The principle of operation of the harmonic neutralized converters is explained in another demo entitled “Three-phase 48-pulse GTO converter”. This demo (power_48pulsegtoconverter.mdl) is accessible in the Power Electronics Models library of demos. When the two converters are operated in UPFC mode, the shunt converter operates as a STATCOM. It controls the bus B1 voltage by controlling the absorbed or generated reactive power while also allowing active power transfer to the series converter through the DC bus. The reactive power variation is obtained by varying the DC bus voltage. The four three-level shunt converters operate at a constant conduction angle (Sigma= 180-7.5 = 172.5 degrees), thus generating a quasi-sinusoidal 48-step voltage waveform. The first significant harmonics are the 47th and the 49th.

When operating in UPFC mode, the magnitude of the series injected voltage is varied by varying the Sigma conduction angle, therefore generating higher harmonic contents than the shunt converter. As illustrated in this demo, when the series converter operates in SSSC mode it generates a “true” 48-pulse waveform.

The natural power flow through bus B2 when zero voltage is generated by the series converter (zero voltage on converter side of the four converter transformers) is P=+870 MW and Q=-70 Mvar. In UPFC mode, both the magnitude and phase angle and the series injected voltage can be varied, thus allowing control of P and Q. The UPFC controllable region is obtained by keeping the injected voltage to its maximum value (0.1 pu) and varying its phase angle from zero to 360 degrees. To see the resulting P-Q trajectory, double click the “Show UPFC Controllable Region”. Any point located inside the PQ elliptic region can be obtained in UPFC mode.

Power Control in UPFC Mode

Open the UPFC GUI block menu. The GUI allows you to choose the operation mode (UPFC, STATCOM or SSSC) as well as the Pref / Qref reference powers and/or Vref reference voltage settings. Also, in order to observe the dynamic response of the control system, the GUI allows you to specify a step change of any reference value at a specific time.

Make sure that the operation mode is set to “UPFC (Power Flow Control)”. The reference active and reactive powers are specified in the last two lines of the GUI menu. Initially, Pref= +8.7 pu/100MVA (+870 MW) and Qref=-0.6 pu/100MVA (-60 Mvar). At t=0.25 sec Pref is changed to +10 pu (+1000MW). Then, at t=0.5 sec, Qref is changed to +0.7 pu (+70 Mvar). The reference voltage of the shunt converter (specified in the 2nd line of the GUI) will be kept constant at Vref=1 pu during the whole simulation (Step Time=0.3*100> Simulation stop time (0.8 sec). When the UPFC is in power control mode, the changes in STATCOM reference reactive power and in SSSC injected voltage (specified respectively in 1st and 3rd line of the GUI) as are not used.

Run the simulation for 0.8 sec. Open the “Show Scopes” subsystem. Observe on traces 1 and 2 of the UPFC scope the variations of P and Q. After a transient period lasting approximately 0.15 sec, the steady state is reached (P=+8.7 pu; Q=-0.6 pu). Then P and Q are ramped to the new settings (P=+10 pu Q=+0.7 pu). Observe on traces 3 and 4 the resulting changes in P Q on the three transmission lines. The performance of the shunt and series converters can be observed respectively on the STATCOM and SSSC scopes. If you zoom on the first trace of the STATCOM scope, you can observe the 48-step voltage waveform vs generated on the secondary side of the shunt converter transformers (yellow trace) superimposed with the primary voltage Vp (magenta) and the primary current Ip (cyan). The dc bus voltage (trace 2) varies in the 19kV-21kV range. If you zoom on the first trace of the SSSC scope, you can observe the injected voltage waveforms Vinj measured between buses B1 and B2

Varcontrol in STATCOM Mode

In the GUI block menu, change the operation mode to “STATCOM (Var Control)”. Make sure that the STATCOM references values (1st line of parameters, [T1 T2 Q1 Q2]) are set to [0.3 0.5 +0.8 -0.8]. In this mode, the STATCOM is operated as a variable source of reactive power. Initially, Q is set to zero, then at T1=0.3 sec Q is increased to +0.8 pu (STATCOM absorbing reactive power) and at T2=0.5 sec, Q is reversed to -0.8 pu (STATCOM generating reactive power).

Run the simulation and observe on the STATCOM scope the dynamic response of the STATCOM. Zoom on the first trace around t=0.5 sec when Q is changed from +0.8 pu to -0.8 pu. When Q=+0.8 pu, the current flowing into the STATCOM (cyan trace) is lagging voltage (magenta trace), indicating that STATCOM is absorbing reactive power. When Qref is changed from +0.8 to -0.8, the current phase shift with respect to voltage changes from 90 degrees lagging to 90 degrees leading within one cycle. This control of reactive power is obtained by varying the magnitude of the secondary voltage Vs generated by the shunt converter while keeping it in phase with the bus B1 voltage Vp. This change of Vs magnitude is performed by controlling the dc bus voltage. When Q is changing from +0.8 pu to -0.8 pu, Vdc (trace 3) increases from 17.5 kV to 21 kV.

Series Voltage Injection in SSSC Mode

In the GUI block menu change the operation mode to “SSSC (Voltage injection)”. Make sure that the SSSC references values (3rd line of parameters) [Vinj_Initial Vinj_Final StepTime]) are set to [0.0 0.08 0.3]. The initial voltage is set to 0 pu, then at t=0.3 sec it will be ramped to 0.8 pu.

Run the simulation and observe on the SSSC scope the impact of injected voltage on P and Q flowing in the 3 transmission lines. Contrary to the UPFC mode, in SSCC mode the series inverter operates with a constant conduction angle (Sigma= 172.5 degrees). The magnitude of the injected voltage is controlled by varying the dc voltage which is proportional to Vinj (3rd trace). Also, observe the waveforms of injected voltages (1st trace) and currents flowing through the SSSC (2nd trace). Voltages and currents stay in quadrature so that the SSSC operates as a variable inductance or capacitance.

UPFC P-Q Controllable Region

Now, open the UPFC dialog box and select Show Control parameters (series converter). Select Mode of operation = Manual Voltage injection. In this control mode the voltage generated by the series inverter is controlled by two external signals Vd, Vq multiplexed at the Vdq ref input and generated in the Vdq ref magenta block. For the first five seconds the Bypass breaker stays closed, so that the PQ trajectory stays at the (-27Mvar, 587 MW) point. Then when the breaker opens, the magnitude of the injected series voltage is ramped, from 0.0094 to 0.1 pu. At 10 s, the angle of the injected voltage starts varying at a rate of 45 deg/s.

Run the simulation and look on the UPFC scope the P and Q signals who vary according to the changing phase of the injected voltage. At the end of the simulation, double-click on the blue block labeled "Double click to plot UPFC Controllable Region." The trajectory of the UPFC reactive power as function of its active power, measured at bus B3, is reproduced below. The area located inside the ellipse represents the UPFC controllable region.

IEEE 9 BUS 3 Machines System

This system has three sources. There are three separate buses that connect these sources. Two of these three have been used in the bus, with one being a combination of solar panels and diesel generators. Another option is to use a diesel generator only. Each bus has three loads connected to it, respectively. Matlab/Simulink was used to design this model. MATLAB is used to design the line parameters’ model.

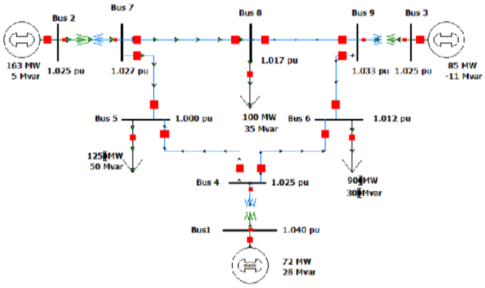

Figure 13 One Line Diagram for IEEE 9BUS 3MACHINES System

Output Result

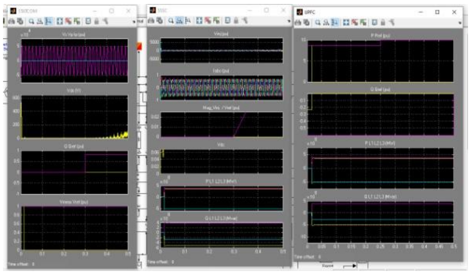

Figure 14 Output Result for 3 Level FACTS Controller

Conclusion

This paper presents 48-pulse GTO voltage source converter of STATCOM, SSSC and UPFC FACTS devices. These full descriptive digital models are validated for voltage stabilization reactive compensation and dynamically power flow control using three novel decoupled current control strategies. The control strategies implemented by current control and auxiliary tracking control based on a pulse width modulation switching technique to ensure fast controllability, minimum oscillatory behavior and minimum inherent phase locked loop time delay as well as system instability reduced impact due to a weak interconnected AC system. Simulation results shows that GTO based controlled slightly increases the power flow control by increasing the damping rate and decreases the amplitude of low frequency oscillations. Results comparison between conventional PI controller and the proposed GTO based controller for UPFC indicates that the proposed GTO based controller has less settling time and less overshoot when compared with the conventional PI controller.

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