

FACTS TECHNOLOGY FOR REACTIVE POWER COMPENSATION AND POWER SYSTEM CONTROL

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Abstract- This paper is on part I of the session and focuses on a summary of the issues and benefits of applying FACTS controllers to AC power systems. The overall process for system studies and analysis associated with FACTS installation projects and the need for FACTS controller models is also discussed. This paper presents control and performance of UPFC intended for installation on that transmission line to control power flow. The performance of the UPFC in real and reactive power flow through the transmission line has been evaluated. Finally, In this paper presents real and reactive power flow control through a transmission line by placing UPFC at the sending end using computer simulation. Simulations were carried out using PSCAD software to validate the performance of the UPFC.

Keywords: Flexible AC Transmission Systems, Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Controller (SSSC), Power System Control.

I. INTRODUCTION

With the ongoing expansion and growth of the electric utility industry, including deregulation in many countries, numerous changes are continuously being introduced to a once predictable business. Thus, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. In the evolving utility environment, financial and market forces are, and will continue to, demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution.

Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. To achieve both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the existing transmission system infrastructure is required. Improved utilization of the existing power system is provided through the application of advanced control technologies. To increase the system efficiency, high efficiency devices based on power electronics equipment have been increasingly used in many applications.

In the late 1980s, the Electric Power Research Institute (EPRI) introduced a new approach to solve the problem of designing and operating power systems; the proposed concept is known as Flexible AC Transmission Systems (FACTS) [3]. The two main objectives of FACTS are to increase the transmission capacity and control power flow over designated transmission routes. Economic factors, such as the high cost of long lines and revenue from the delivery of additional power, give strong incentives to explore all economically and technically feasible means of raising the stability limit. On the other hand, the development of effective ways to use transmission systems at their maximum thermal capability has caught much research attention in recent years.

The ability to control power flow in an electric power system without generation rescheduling or topology changes can improve performance using the power system performance using controllable components. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines. Flexible ac transmission systems (FACTS) technology is the ultimate tool for getting the most out of existing equipment via faster control action and new capabilities. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction.

The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and T&D communities [1]. By providing added flexibility, FACTS controller can enable a line to carry power closer to its thermal rating. The FACTS technology can certainly be used to overcome any to the stability limits, in which case the ultimate limits would be thermal and dielectric.

II. CONTROL OF POWER SYSTEMS

A. Generation, Transmission and Distribution

When discussing the creation, movement, and utilization of electrical power, it can be separated into three areas, which traditionally determined the way in which electric utility companies had been organized. These are illustrated in Figure 1 and are:

- Generation
- Transmission
- Distribution



Figure 1. Illustration of the creation, movement, and utilization of electrical power

Although power electronic based equipment is prevalent in each of these three areas, such as with static excitation systems for generators and Custom Power equipment in distribution systems [2], the focus of this paper and accompanying presentation is on transmission, that is, moving the power from where it is generated to where it is utilized.

B. Power System Constraints

As noted in the introduction, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. The limitations of the transmission system can take many forms and may involve power transfer between areas (referred to here as transmission bottlenecks) or within a single area or region (referred to here as a regional constraint) and may include one or more of the following characteristics:

- Steady-State Power Transfer Limit
- Voltage Stability Limit
- Dynamic Voltage Limit
- Transient Stability Limit
- Power System Oscillation Damping Limit
- Inadvertent Loop Flow Limit
- Thermal Limit
- Short-Circuit Current Limit
- Others

Each transmission bottleneck or regional constraint may have one or more of these system-level problems.

C. Controllability of Power Systems

To illustrate that the power system only has certain variables that can be impacted by control, consider the basic and well-known power-angle curve, shown in Figure 2. Although this is a steady-state curve and the implementation of FACTS is primarily for dynamic issues, this illustration demonstrates the point that there are primarily three main variables that can be directly controlled in the power system to affect its performance. These are:

- Voltage
- Angle
- Impedance

One could also make the point that direct control of power is a fourth variable of controllability in power systems. With the establishment of "what" variables can be controlled in a power system, the next question is "how" these variables can be controlled.

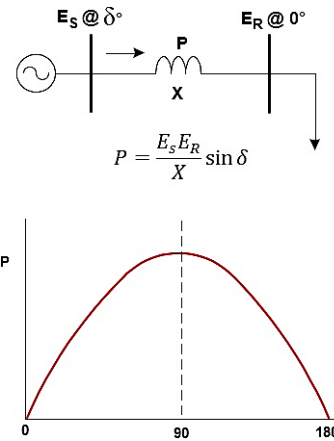


Figure 2. Illustration of controllability of power systems

Example of FACTS Controllers for Enhancing Power System Control:

- Static Synchronous Compensator (STATCOM)
 - Controls voltage
- Static Var Compensator (SVC)
 - Controls voltage
- Unified Power Flow Controller (UPFC)
- Convertible Series Compensator (CSC)
- Inter-phase Power Flow Controller (IPFC)
- Static Synchronous Series Controller (SSSC)
 - Each of the aforementioned (and similar) controllers impact voltage, impedance, and/or angle (and power)
- Thyristor Controlled Series Compensator (TCSC)
 - Controls impedance
- Thyristor Controlled Phase Shifting Transformer (TCPST)
 - Controls angle
- Super Conducting Magnetic Energy Storage (SMES)
 - Controls voltage and power

As mentioned earlier, the key to solving transmission system problems in the most cost-effective and coordinated manner is by thorough systems analysis. This includes comparing the system benefits available by conventional equipment and from FACTS controllers.

D. Benefits of Control of Power Systems

Once power system constraints are identified and through system studies viable solutions options are identified, the benefits of the added power system control must be determined. The following offers a list of such benefits:

- Increased Loading and More Effective Use of Transmission Corridors
- Added Power Flow Control
- Improved Power System Stability
- Increased System Security
- Increased System Reliability
- Added Flexibility in Siting New Generation
- Elimination or Deferral of the Need for New Transmission Lines

III. PHASES OF POWER SYSTEM STUDIES FOR FACTS INSTALLATION PROJECTS

Figure 3 shows the view of the overall process for system studies associated with FACTS installation projects. The presentation will start with initial feasibility studies to determine system constraints and reinforcement needs, typically undertaken by the utility/transmission owners, all the way through to the system studies and modeling issues associated with the every-day operation of an installed FACTS controller in a specific power system.

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Initial Feasibility Studies	Studies to Determine Type of Equipment, Location, and Ratings	Pre-Specification Studies	Pre-Manufacturing and Equipment Design and Verification Studies	Studies for Post-Commissioning system Operation
Typically By Owner or Owner/Consultant		Typically By Owner or Consultant	Typically By Vendor	Typically By Owner

Figure 3. Phases of power system studies for FACTS installation projects

If the analysis of Phase 1 indicates that the system has a problem with voltage, then in Phase 2 it is necessary to identify solution options for system voltage control. These include for Dynamic (fast) Voltage Instability, Consider:

- Shunt capacitor banks
- Static shunt compensators (e.g., STATCOM, SVC)
- Combination

For Voltage Collapse (slow), Consider:

- Shunt capacitor banks
- Series capacitors
- Static shunt compensators (e.g., STATCOM, SVC)
- Static series compensators (e.g., SSSC)
- Combination

If the analysis of Phase 1 indicates that the system has a problem with rotor angle stability, then in Phase 2 it is necessary to identify solution options for this type of problem. These include for Transient Instability, consider:

- Series capacitors
- Static shunt compensators (e.g., STATCOM, SVC)
- Static series compensators (e.g., SSSC)
- Combination

For Oscillatory Instability, Consider:

- Power system stabilizers (PSS)
- Damping controls added to static shunt or series compensators

IV. UPFC CONTROL SYSTEM

The unified power-flow controller (UPFC) is a member of the FACTS family with very attractive features. The UPFC is recently introduced FACTS controller, which has the capability to control all four transmission parameters. Unified Power Flow Controller (UPFC) can provide simultaneous control of all basic power system parameters, viz., transmission voltage, impedance and phase angle. This controller offers advantages in terms of static and dynamic operation of power system [10-11]. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link.

Each of the branches consists of a transformer and power electronic converter. Figure 4 shows the basic circuit for a Unified Power Flow Controller (UPFC) and Figure 5 shows a Static Synchronous Series Compensator (SSSC) [13]. Figure 6 shows the phasor diagrams depicting the UPFC operation and its impact on the power system, and Figure 12 illustrates the control modes of the series compensator (UPFC or SSSC) (the characteristics of the shunt portion of the UPFC is similar to Figure 8) [14].

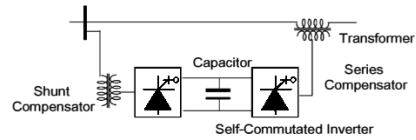


Figure 4. Circuit for a Unified Power Flow Controller (UPFC)

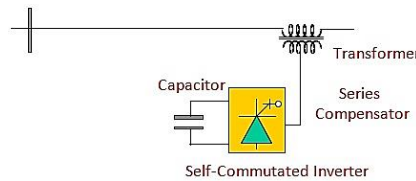


Figure 5. Circuit for a Static Synchronous Series Compensator (SSSC)

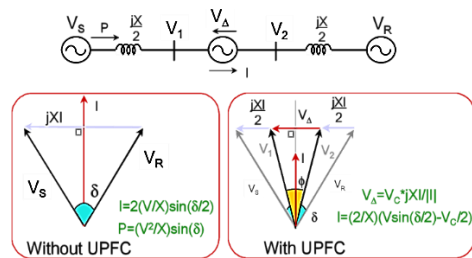


Figure 6. UPFC operation

Figure 7 shows the basic circuit for a Static Synchronous Compensator (STATCOM). Figure 8 shows its voltage current characteristics. In practice, these two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with transmission line through a series transformer, connected to each other by a common dc link including a storage capacitor.

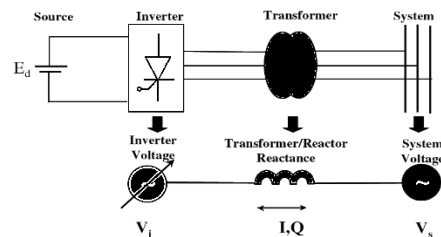


Figure 7. Circuit for a Static Synchronous Compensator (STATCOM)

The two VSI's can work independently of each other by separating the dc side. Therefore, in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flow on the transmission line [9]. The energy storing capacity of this dc capacitor is generally small.

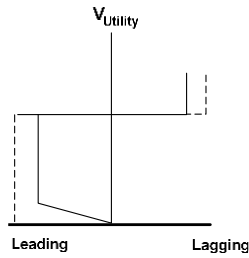


Figure 8. V-I characteristics of a STATCOM

Therefore, active power drawn by the shunt converter should be equal to the active power generated by the series converter. The reactive power in the shunt or series converter can be chosen independently, giving greater flexibility to the power flow control. The coupling transformer is used to connect the device to the system. Figure 9 shows the schematic diagram of the three phase UPFC connected to the transmission line [8].

Control of power flow is achieved by adding the series voltage, V_s with a certain amplitude, $|V_s|$ and phase shift, ϕ to V_1 . This will give a new line voltage V_2 with different magnitude and phase shift. As the angle ϕ varies, the phase shift δ between V_2 and V_3 also varies. Figure 10 shows the single line diagram of the UPFC and phasor diagram of voltage and current. This FACTS topology provides much more flexibility than the SSSC for controlling the line active and reactive power because active power can now be transferred from the shunt converter to the series converter, through the DC bus. Contrary to the SSSC where the injected voltage V_s is constrained to stay in quadrature with line current I , the injected voltage V_s can now have any angle with respect to line current.

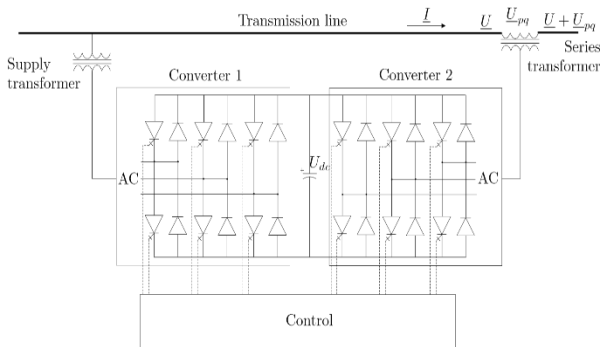


Figure 9. Schematic diagram of three phase UPFC connected to a transmission line

If the magnitude of injected voltage V_s is kept constant and if its phase angle with respect to V_1 is varied from 0 to 360 degrees, the locus described by the end of vector V_2 ($V_2 = V_1 + V_s$) is a circle as shown on the Phasor diagram. As it varies, the phase shift δ between voltages V_2 and V_3 at the two line ends also varies. It follows that both the active power P and the reactive power Q transmitted at one line end can be controlled. The shunt converter operates as a STATCOM. In summary, the shunt converter controls the AC voltage at its terminals and the voltage of DC bus.

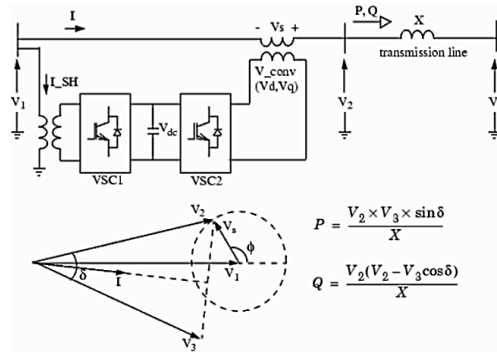


Figure 10. Single line diagram of UPFC and phasor diagram of voltage and current

It uses a dual voltage regulation loop: an inner current control loop and an outer loop regulating AC and DC voltages. Control of the series branch is different from the SSSC. In a SSSC the two degrees of freedom of the series converter are used to control the DC voltage and the reactive power. In case of a UPFC [4] the two degrees of freedom are used to control the active power and the reactive power. The series converter can operate either in power flow control (automatic mode) or in manual voltage injection mod [7]. In this control system, a generalized pulse width modulation technique is used to generate firing pulses for both the converters. It is recognized as the most sophisticated power flow controller currently, and probably the most expensive one.

A Unified Power Flow Controller (UPFC) is an electrical device for providing fast-sensation on high-voltage electricity transmission networks. The Unified Power Flow Controller (UPFC) is the most versatile and complex power electronic equipment that has emerged for the control and optimization of power flow in electrical power transmission system. The UPFC controller mitigates the harmonic distortion that caused by the nonlinear load where all values of THD for voltage and current at all AC buses are decreased to values within allowable limits of IEEE standard.

V. MATHEMATICAL MODEL OF UPFC

The basic structure and operation of the UPFC can be represented through the model shown in Figure 11. The transmission line parameters are as shown in Table 1.

Table 1. System parameters

Line to line voltage	230 kV
Frequency	60 Hz
Transmission rating	100 MVA
Capacitance of DC link Capacitor	2000µF
DC link voltage	45 kV
Length of the transmission line	500 km
Resistance of the line	32 µΩ/m
Inductive reactance of the line	388.3 µΩ/m
Capacitive reactance of the line	241.1 MΩ-m

In this model, we have considered the UPFC is placed at the center of a 100 km transmission line. The equations for sending end active and reactive power can be obtained from the real and imaginary powers of power equation as follows:

$$\begin{aligned}
 Q_s &= I_m (V_s \angle \delta \times I_s^*) = \\
 &= 1.56 - 1.56 \times \cos \delta + 0.25 \times \cos(\delta - \delta_b) + \\
 &+ 0.02 \sin(\delta - \delta_b) - 0.138 \sin \delta
 \end{aligned}
 \tag{1}$$

The variation limits of δ_b and δ are according to the following relation:

$$\begin{cases}
 0 \leq \delta_b \leq 2\pi \\
 0 \leq \delta \leq 0.71 \text{ radians}
 \end{cases}
 \tag{2}$$

The maximum limit of δ is chosen according to the stability margin [5]. The variation of sending end active and reactive powers by varying δ_b and δ is obtained through MATLAB is shown in Figure 12.

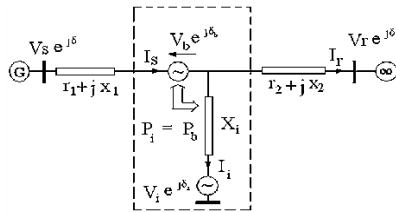


Figure 11. Mathematical model of UPFC

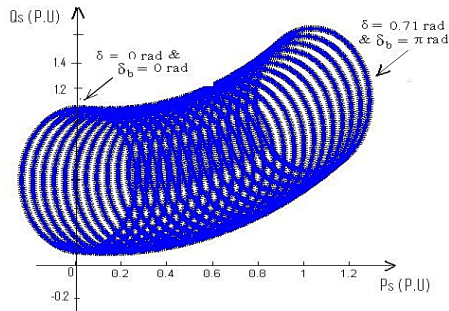


Figure 12. Real power V_s Reactive power with UPFC (100 km Transmission line)

VI. SIMULATION SETUP IN PSCAD

Figure 13 shows the simulation model including a power system with a transmission line. The UPFC installed near the sending end effectively controls the power flow from sending end to the receiving end.

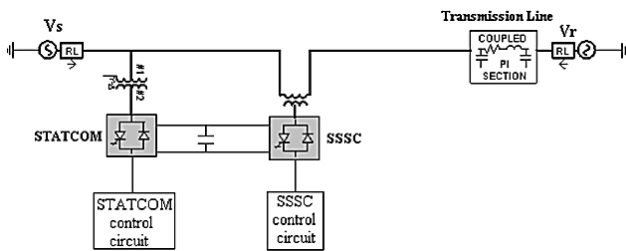


Figure 13. Power system study model

Here, V_s and V_r are assumed to be sending and receiving-end voltages. This model assumes that sending end corresponds to a power plant while the receiving end to an electric power network, i.e., SMIB system. The receiving end voltage may not cause any phase angle change, because V_r is an infinite bus voltage. The phase angle of V_s is adjusted according to the power demand for the power plant. A phase difference of 100 between

sending-end and receiving end voltages is simulated. The circuit parameters are shown in Table 1. Figure 14 shows the circuit of UPFC using IGBTs.

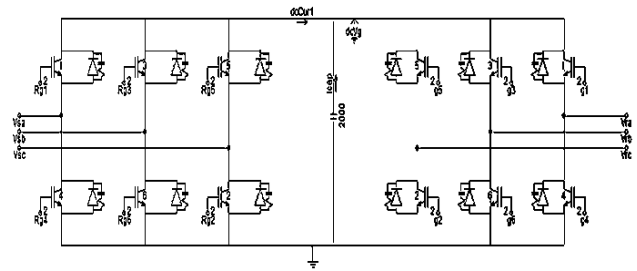


Figure 14. Circuit of UPFC using IGBTs

The main circuit of the series device (SSSC) consists of a three-phase PWM inverter, the ac terminals of which are connected in series to a transmission line through three single phase transformers [12]. The shunt device (STATCOM) consists of a three-phase PWM inverter, the ac terminals of which are connected in parallel with the transmission line via a three phase star-delta transformer.

A. Shunt Inverter Control Circuit

In this simulation, the shunt inverter operates in automatic voltage control mode. Figure 15 shows the DC voltage control circuit for the shunt inverter. DC link voltage is measured (V_{DCm}) and compared with the reference value (V_{DCref}), whose error is fed to PI controller to generate the shift. Similarly, AC voltage from the sending end bus feeding the shunt coupling transformer is measured in p.u. ($V_{p.u.m}$) and compared with the AC voltage set point (here 1.0 p.u), whose error is fed to PI controller to generate modulation index, mi. Figure 16 shows the AC voltage control circuit for the shunt inverter.

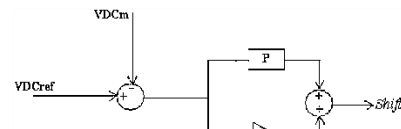


Figure 15. STATCOM DC voltage controller

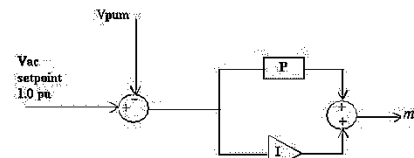


Figure 16. STATCOM AC Voltage controller

Two sets of signals, reference and triangular ones are needed, One set for turning-on and other for turning-off the GTOs. Generated shift and mi signals are used to develop firing pulses for the six GTOs in the inverter, as shown in the Figure 17, in PSCAD environment. A generalized sinusoidal pulse width modulation switching technique is used for pulse generation. H-L (high-low) logic is used to generate firing pulses. Deblock option is available, which is made 0.1 seconds during this simulation.

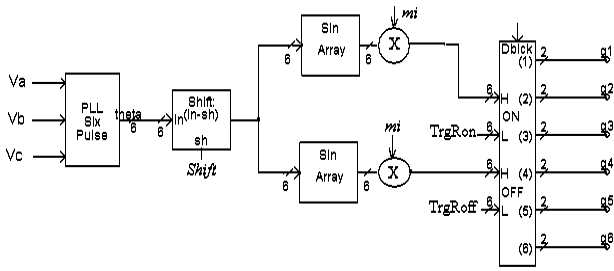


Figure 17. Circuit for firing pulse generation

B. Series Inverter Control Circuit

In this case, the series inverter operates in the direct voltage injection mode. The series inverter simply injects voltage as per the theta order specified. Figure 18 shows the series inverter control circuit, which is an open loop phase angle controller, generates modulation index, mi and shift. The mi and shift signals are used to develop firing pulses as shown in Figure 8.

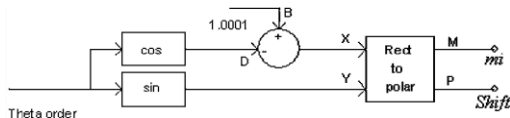
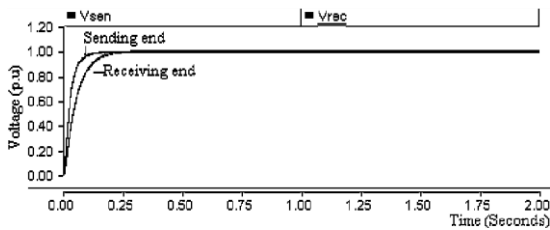


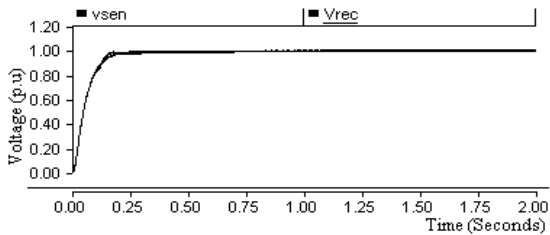
Figure 18. Series inverter open loop phase angle controller

VII. SIMULATION RESULTS

A transmission line of a simple power system with parameters as given in Table 1 is considered. UPFC is placed in series with the transmission line at the sending end. Deblock option blocks the UPFC for the first 0.1 second. Voltage, active power, reactive power and current variations in the transmission line with UPFC and without UPFC are studied and compared. The power system studied is SMIB system, when the transmission line is without UPFC, the sending-end and receiving-end voltages are 1.0 p.u. as shown in Figure 19(a). When UPFC is placed across the same transmission line, the voltage regulation is improved as per Figure 19(b).



(a)



(b)

Figure 19. Sending end and receiving end voltages, (a) Without UPFC (b) With UPFC

In this simulation, the theta order input to the series inverter control circuit is 50. The series inverter injects voltage into the transmission line at point of connection, as shown in Figure 20. By varying the theta order input to the controller the phase and magnitude of the series injected voltage can be varied. When the transmission line is without UPFC, the real and reactive power flow can not be controlled.

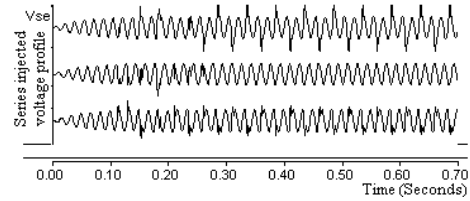
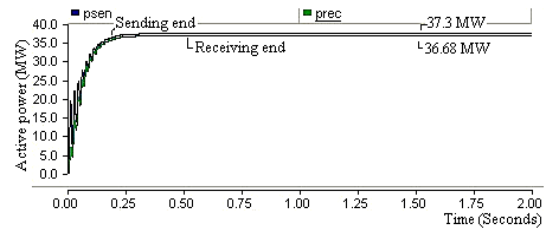
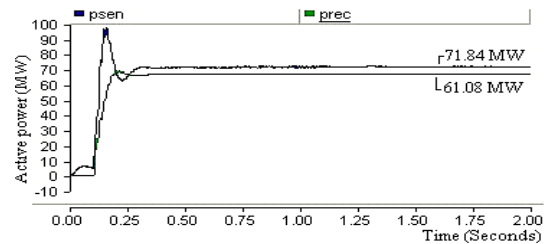


Figure 20. Series injected voltage

Figure 21(a) shows the active power through the line without UPFC. Figure 21(b) shows the active power flow through line, which is controlled by UPFC. Transmission capability of the existing transmission line is highly improved with the presence of UPFC. However, the difference between the sending-end real power and receiving end real power is high in the transmission line with UPFC.



(a)



(b)

Figure 21. sending end and receiving end active power, (a) Without UPFC, (b) With UPFC

This is due to the increase in transmission losses, which include losses in the both converters and coupling transformers. The reactive power flow through the transmission line with and without UPFC is shown in Figure 22. The raise in the transmission capability is noticed from the simulation results. The power transfer capability of long transmission lines is usually limited by their thermal capability. Utilizing the existing transmission line at its maximum thermal capability is possible with UPFC. The variation of current through "A" phase of a transmission line without UPFC is shown in Figure 23(a), whose peak is 0.132 kA.

The current in the same phase is improved to 0.24 kA with the presence of UPFC, shown in Figure 23(b). The performance of the UPFC can be justified by its controller's performance. AC voltage controller tracking its reference values is shown in Figure 19. Similarly, DC voltage controller tracks its reference value, 45 kV is shown in Figure 24.

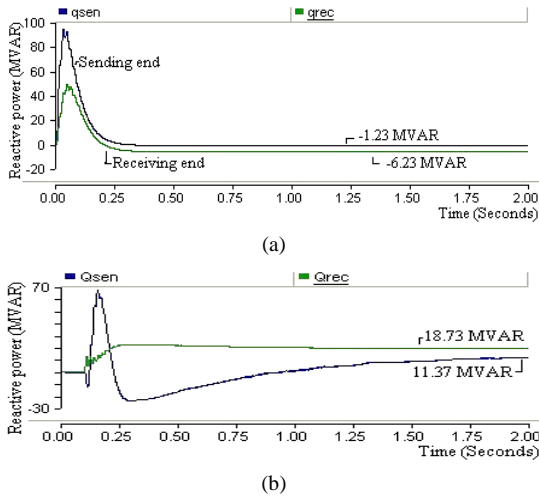


Figure 22. Sending end and receiving end reactive power, (a) Without UPFC, (b) With UPFC

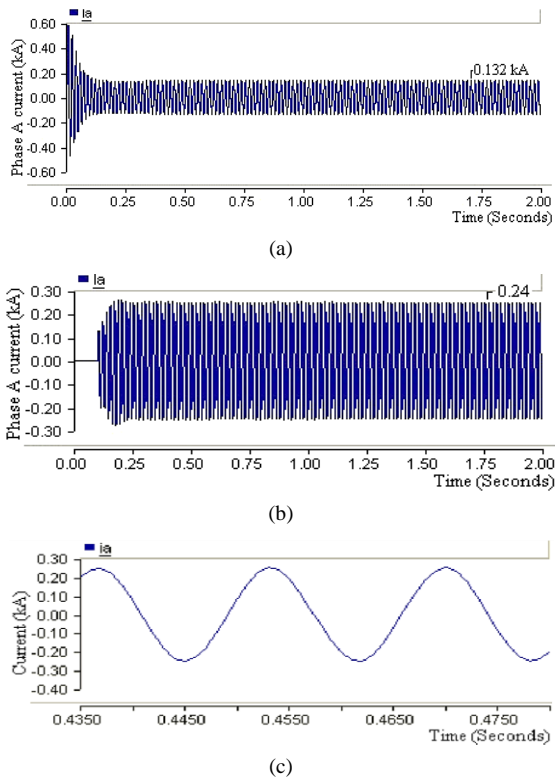


Figure 23. Current through phase 'A' of the transmission line, (a) Without UPFC, (b) With UPFC, (c) Magnified current waveform with UPFC

The function of UPFC can be studied with the help of real power flow through UPFC as shown in Figure 25. The series inverter injects voltage of variable magnitude and phase into the transmission line at the point of its

connection, there by controlling real and reactive power flow through the line. The active power through the line is supplied by SSSC active power (Figures 21(b) and (25)). This real power obtained from the DC source connected to its DC terminals. The shunt inverter provides the required power to the series inverter through the DC-link. This is shown in simulation waveforms of STATCOM and DC-link active power, in Figure 25 [6].

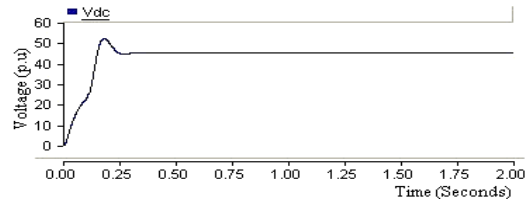


Figure 24. DC-link voltage in UPFC

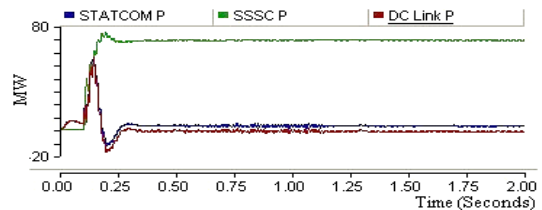


Figure 25. Active power flow through UPFC

VIII. CONCLUSIONS

In this study, the PSCAD environment is used to simulate model of UPFC connected to a three phase-three wire transmission system. The overall process for system studies and analysis associated with FACTS installation projects and the need for FACTS controller models was also discussed. This paper presents control and performance of UPFC intended for installation on a transmission line. In this study, the PSCAD environment is used to simulate the model of UPFC connected to a three phase-three wire transmission system.

A control system is simulated with shunt inverter in AC and DC voltage control mode and series inverter in open loop phase angle control mode. Simulation results show the effectiveness of UPFC in controlling real and reactive power through the line. Due to AC voltage controller, AC voltage regulation is improved. The DC voltage controller maintains DC-link voltage to DC voltage set point, 45 kV.

This paper presents an improvement in the real and reactive power flow through the transmission line with UPFC when compared to the system without UPFC with UPFC in transmission line, results in improvement of transient stability of the system, which is an added advantage along with the power flow control [15], improved Plant Utilization Factor, better Voltage Profile. Also, The real and reactive powers increase with the increase in angle of injection. It is found that there is an improvement in the real and reactive powers through the transmission line when UPFC is introduced.

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