UPFC for Enhancing Power System Reliability

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By

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Much of the power system used today is the same one designed and built long ago, without the expectation of the demand and area of operation that they must service today. Upgrades have been introduced where necessary and financially feasible, but expanding the power system itself is subject to both environmental and regulatory concerns.

Research and technology to get the most out of the existing system has been of interest for many years. The first technological implementation were inserting mechanically switched capacitors, reactors, and transformers. This method worked, but the mechanical switches were prone to failure and offered a low control bandwidth. Solid state switching technology was later discovered and used. This allowed the mechanical switches to be upgraded to more reliable alternatives that could be switched at a much higher rate. The latest technology are voltage source converters (VSC). VSCs provide the highest response rate and control resolution. They utilize solid state switching devices which offer the speed
and reliability, but with a variable voltage source that can simulate a wide set of capacitor, reactor, and transformer values.

VSC technology is the core technology for the latest flexible AC transmission system devices. These devices are the STATCOM, the SSSC, and the UPFC. This project reviews both the STATCOM and the SSSC while then focusing on the UPFC.
**Chapter 1: Introduction**

Expansion of electric power transmission facilities are restricted by both environmental and regulatory concerns. These restrictions have caused some power companies to rely on purchasing power from other suppliers and importing it to meet load requirements. Methods to get the most out of the existing architecture’s transmission capacity has been a topic of research for many years.

The capability of importing power is not constrained by transient or dynamic stability of the transmission system, but by facility overloads and reactive power deficiencies. Power losses in transmission lines are governed by the laws of physics, where greater distances between the points of power generation to the load results in reduced efficiency.

Chapter 2 provides an overview of a power electronics technology known as Flexible AC Transmission Systems (FACTS). FACTS are a way to address the above and increase the usable capacity of the existing transmission systems. As outlined in [1], FACTS technology has the advantages of:

- Reducing new transmission lines, capacitors, reactors, etc. from being constructed, which
  - Will reduce environmental and regulatory concerns.
  - Keep the aesthetics of the city.
- Increasing the amount of power that can be wheeled over the existing transmission lines system.
- Providing both dynamic reactive power support and voltage control.
- Improving system stability.
- Controlling real and reactive power flow.
- Mitigating the potential of Sub-Synchronous Resonance problems.
- Allowing for interconnecting renewable and distributed generation and storage.

FACTS devices are split into two categories: Thyristorvalve based and Voltage Source Converter (VSC) based. VSC based FACTS devices are the latest technology and offer a much greater control bandwidth with a much faster dynamic response over its predecessors. The VSC based FACTS technology is based on power converters. Chapter 3 reviews power converters beginning with the 2-level topology which is the simplest, cheapest, and offers time tested reliability. It then focuses on multilevel which is a broad category of different topologies and control methods, each with their own advantages and disadvantages. Multilevel converters offer a more ideal sinusoidal output resulting in lower total harmonic distortion. Multilevel converters are used in VSC based FACTS devices.

The three main VSC based FACTS devices are the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), and the Unified Power Flow Controller (UPFC).

The STATCOM is a shunt connected FACTS device that is used to provide reactive power compensation. Control over the injected current allows the STATCOM to act as a variable shunt capacitor or inductor. Chapter 4 reviews the details of the STATCOM.

The SSSC is a series connected FACTS device which provides power flow control and active power compensation. Injecting a variable series voltage in quadrature with the line current allows it to act as a variable series capacitor or inductor. Chapter 5 reviews the details of the SSSC.
The UPFC is a combination of the STATCOM and the SSSC under a unified control system. This combination gives full control over all the transmission line parameters, allowing it to perform all the functions of the STATCOM and SSSC but with a wider range, allows for independent control of both the active and reactive power, and permits an increase in the maximum transmittable power over a transmission line. Chapter 6 reviews the details of the UPFC.

Simulations of a UPFC model are detailed in chapter 7 followed by the conclusion of the project in chapter 8.
IEEE P1409 has defined flexible AC transmission systems (FACTS) as “Alternating Current Transmission Systems incorporating power electronics-based and other static controllers to enhance controllability and power transfer capability.”

AC transmission lines distribute the flow of power based on the line impedance, the magnitude of both sending and receiving end voltages, and the phase angle between the two end voltages. Control of these parameters have traditionally been done through the use of switched series and shunt reactive compensators, in addition to voltage-regulating and phase-shifting transformers. Before power electronics, the above devices could not adjust quickly enough to handle or control the dynamic behavior of the transmission system, or the transients that occur. Because of this, they were only able to make adjustments for steady state scenarios, and power systems had to be operated below their capacity to account for worst case transients such as faults. The desire to increase the safe operating conditions of the system by controlling the power flow parameters outside of steady state has been discussed and theorized since the 1960s [2].

Advancements made toward power semiconductor switching devices have allowed them to replace their mechanical counterparts and permit dynamic control of the power flow parameters. These semiconductor switches are not only faster, but also without the mechanical switching life limitation [3]. In 1988, the idea to use these semiconductors with series and shunt capacitors for power flow control was proposed [2]. Conceptually, FACTS were proposed at the same time in terms of advanced power electronics-based devices [2]. These power electronic devices were developed to simulate the operation of traditional compensation methods such as transformer tap changers, passive reactive
compensators, synchronous condensers, and more [3]. Since these devices could be used to impact both the active and reactive power flow, system performance could be altered without generation rescheduling or topological changes. More importantly, the thermal limits of the transmission system are not violated, power losses are minimized, and the stability margin is increased.

Power line conditioning devices can be grouped into two main categories. The first would be conventional devices. Conventional devices are fixed, or mechanically switchable components which include resistors, inductors, capacitors, and transformers. The other group would be FACTS devices. FACTS devices can be placed into the two subgroups, static or fast. The term “static” is in reference to the fixed value of the passive components used, while “fast” (also known as dynamic) is in reference to the high speed operation of power electronic controlled voltage source devices that can simulate a variable set of reactors [4]. In consideration of the power electronics that control operation, the two subgroups are thyristor valve based (static) and voltage source converter based (fast). Thyristor valves operate at low switching frequencies resulting in low switching losses. They use semiconductor switches to switch components like resistors, capacitors, and inductors, but in smaller increments. They also use thyristors as a bridge between valve impedances [5]. Voltage source converter (VSC) based FACTS have the ability to generate a controlled output voltage in both magnitude and phase while producing low harmonic content. VSCs operate at high switching frequencies resulting in high switching losses. Figure 1 below provides an overview of the major power line conditioning devices, and the category in which they fall. FACTS technology, compared to the mechanically
switched compensators, is much more expensive, but provides much more flexibility and greater control.

As shown in figure 1, power line conditioning devices can also be categorized into three additional groups based on their placement in the system: shunt, series, or shunt and series. The devices that fall in to the shunt category are used for reactive power compensation, and are used to control the voltage. The static VAR compensator (SVC) is a thyristorvalve shunt device which IEEE defines as “a shunt connected static VAR generator or absorber”. The SVC was developed in the late 1960s as a way to compensate for large fluctuating loads. The thyristor-switched capacitor (TSC), and thyristor-controlled reactor (TCR) are members of the SVC category. SVC devices are able to generate a smooth, precisely controlled output compared to their mechanically switched counterparts; this enhances power grid stability. The output from the SVC is adjustable to be able to exchange either
capacitive or inductive reactive power. While providing reactive power, the SVC can produce a large amount of harmonic current content which must be filtered out with shunt capacitors or special transformer connections. The STATCOM is a VSC based shunt device. STATCOMs are able to provide the same benefits as the SVC with the addition of improving the power quality against fast transients like dips and flickers, and without producing the harmonics.

Series reactive power compensators have the ability to change the effective line impedance, which affects the stability and power flow of the power lines. The thyristor controlled series compensator (TCSC) are a group of thyristorvalve devices used for stability improvements, and are capable of influencing the power flow. TCSCs include the dynamic voltage restorer (DVR) and static voltage restorer (SVR) which are used for series compensation. The thyristorvalve controlled phase shifting transformers (PST) is a series power flow control device that transitions an overloaded transmission line’s power flow to a transmission network that is able to handle a higher load. The SSSC is a VSC based series device. SSSCs are able to provide the same benefits as the other individual series solutions mentioned above with an increased dynamic performance, but are mainly used in distribution systems, to improve power quality.

The hybrid connection of both series and shunt devices provides power flow control along with voltage control. They provide a higher range of compensation that are not achievable independently. These devices have begun to gain popularity, but have the highest expense. Under the thyristorvalve category is the dynamic flow controller (DFC) while the UPFC is the VSC implementation.
The VSC-based compensators are the most well-known families of FACTS devices [5]. The main component in any VSC based FACTS device is the voltage source converter itself. This VSC produces a near sinusoidal AC voltage that can be injected into the power system either as a series voltage or a shunt current. This project focuses on the UPFC, while giving the necessary overview of the STATCOM and SSSC.
Chapter 3: Inverters

3.1: Overview

The IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems defines a power inverter as “a machine, device, or system that changes direct-current power to alternating-current power.” These devices are used in power systems to control the speed of electric motors, as active filters, to tie distributed power systems into the power grid, in flexible AC transmission systems (FACTS), and to convert high voltage DC transmission into high voltage AC transmission.

![Figure 2 - One phase leg of an inverter with different levels](image)

3.2: 2-Level Inverters

For inverters, the number of levels refers to the number of output voltage levels that are able to be generated. The first inverters were a two-level topology; they are still the most commonly used today due to their time tested simple structure and control method. For a given DC voltage source, $V_{DC}$, the output voltage of the two-level topology will be either $V_{DC}$ and 0, or $+V_{DC}/2$ and $-V_{DC}/2$. The switches are driven to produce an output of either
a square wave of the desired frequency, or a pulse width modulated square wave whose integral comes close to a sine wave of the desired frequency.

Both of the switching control methods for the two-level inverter mentioned above have a large number of harmonics in the output waveform. If the application requires these harmonics to be filtered out, the system cost increases with a reduction in efficiency. The pulse width modulated method has the additional disadvantage of high switching losses from the operating frequencies.

3.3: Multilevel Inverters

New power electronic semiconductors such as IGBTs, IGCTs, and MOSFETS have been consistently improved in speed, efficiency, and power ratings. Even as power electronics advance, the limitations of their rated current and voltage prevent individual semiconductor devices from being used in high power or high voltage applications. Multilevel inverters use a series of small voltages that together can provide high power. This concept allows for a rating of each semiconductor switch to have a reduced voltage specification and handle less power. Multilevel inverters began as 3-level inverters and research into new topologies and control methods have increased the number of levels possible. Increasing the number of levels produces a better AC voltage with less distortion, but requires a more complex control algorithm. A three level inverter would have the voltage output of $+V_{DC}/2$, $0$, and $-V_{DC}/2$. The most common three-level inverter output is frequently
referred to as a modified sine wave, where pulse width modulated schemes are available as well.

![Figure 4 - Modified square wave and pulse width modulated modified square wave](image)

Multilevel inverters were conceived in the 1970’s [2] [6]. Out of the multilevel inverters in existence today, there are three that are considered to be fundamental. The first is the cascaded H-Bridge (CHB) that was published in 1975. Second is the neutral-point clamped (NPC), also known as the diode-clamped, inverter published in 1981 by Takashi [2]. The third is the flying-capacitor (FC), also known as the capacitor clamped, inverter published by Menard in 1992 [8].

Within the past decade, new multilevel topologies have been researched and introduced. The concepts behind the new topologies are based on modifications to, or combination of the three fundamental topologies listed above. Each inverter topology has advantages and disadvantages which must be considered while choosing which is best suited for a certain application, and not all of them have been utilized in commercial or industrial applications.

Multilevel inverters have been first utilized in high voltage application by large-scale utilities, but have started to be used for low voltage motor drives as well. Renewable energy generation of different power levels have also begun to implement the multilevel topologies [9]. A pictorial view showing how the different multilevel inverter technology is related is shown below in figure 5 [5].
A main advantage of multilevel inverters over the traditional two-level is that the switching frequency is lower, resulting in lower switching losses, and thus, a possible higher resulting efficiency. In addition, the staircase formation of their output much more closely resembles a sine wave and produces less total harmonic distortion (THD); lower output harmonics can reduce or eliminate the need of output filters. Possible electromagnetic compatibility (EMC) issues reduce as the step size reduces the $dv/dt$. Reduction in step size also puts
less stress on the semiconductor switching devices. Disadvantages are the result of the increased number of components:

- increased possible points of failure,
- possible increased system cost,
- more complicated and critical control schemes, and
- the potential increase in inverter dimensional size.

When a multilevel inverter has a THD much lower than that produced by a modified-sine wave, they are usually termed as pure sine wave inverters; although there is no regulation or approved definition on what the maximum THD allowed is to be able to use this term. A pure sine wave is important, especially for AC motors. AC motors running off of a waveform different than a sine wave can experience higher operating temperatures, a different speed-torque characteristic, and/or produce an audible noise apart from normal running noise.

Ability to control the voltage levels and achieve different shaped output waveforms has led to the introduction of many different modulation schemes, each for a specific purpose that a two-level inverter could not accomplish. Some of the more widely used schemes include sinusoidal pulse width modulation (SPWM), carrier-based pulse width modulation (CPWM), space vector modulation (SVM), selective harmonic elimination (SHE), and optimized harmonic stepped waveform (OHSW) techniques.

When choosing a topology, the three fundamentals are usually looked at first due to their simplicity and time tested performance and reliability. The biggest disadvantage of the cascaded H-bridge topology is that it requires one independent DC source for every level
desired. For the diode clamped topology, it is unable to deliver real power for higher level realizations [10]. The flying capacitor topology is unable to operate in a purely reactive mode, which limits its ability to be used in certain applications.
Chapter 4 – Static Synchronous Compensator (STATCOM)

4.1: Overview

The static synchronous compensator (STATCOM), is also known as an advanced static VAR compensator (ASVC), as a static condenser (STATCON), and as a static synchronous generators (SSG). The STATCOM is a shunt-type, inverter-based compensating device with the ability to generate and absorb reactive power [6].

STATCOMs operate similar to synchronous condensers, where a synchronous condenser is an ideal synchronous machine connected to a power grid, and working in no load conditions. For a synchronous condenser, the flow of reactive power is varied by changing field current. The mechanical nature of a synchronous condenser limits its ability during fast load changes to control reactive power. The term STATCON comes from static synchronous condenser [11].

A switching converter, which is the main component of a STATCOM, is able to supply and receive active power with the AC power system in which it is connected. When it is supplied from a DC energy source, the output voltage can be controlled in terms of magnitude and/or phase angle. This ability is equivalent to that of a rotating synchronous generator, which is why they are also known as static synchronous generators (SSG) [11]. When its energy source is supplied from a DC capacitor, it does not have the capability to adjust the magnitude of the output voltage independently from the phase angle. In this situation, it acts like a static synchronous compensator (STATCOM) [11].

STATCOM devices have been initially developed for transmission systems with typical power ratings of 20-100 MVAR and implemented with low switching frequencies [5].
allows them to use switching devices with high-power and low speed ratings such as integrated gate commutated thyristor (IGCT), gate turn-off thyristor (GTO), and high voltage insulated-gate bipolar transistor (HVIGBT). They are used to perform reactive power compensation and voltage support of the transmission system.

Recent implementations of STATCOMs in distribution systems (D-STATCOM) have a typical power rating of up to 5 MVAR [5]. D-STATCOM are used to provide voltage regulation, voltage control, power factor (PF) correction, improve steady-state power transfer capacity, improve transient stability margin, dampen power system oscillations, dampen sub-synchronous power system oscillations, for flicker control, and to improve power quality. They are designed to provide fast response times and, therefore, use faster switching frequencies; IGBTs or IGCTs are used.

STATCOM devices provide the same power system enhancements of a SVC but with a higher control bandwidth. This, with the addition that the compensating current provided by the STATCOM does not rely on the voltage level at the point of common coupling, gives the STATCOM a performance advantage over thyristor-type SVCs. The second point has a greater benefit due to new standards requiring applications to supply a variable reactive power depending on the voltage and demand of the power grid [5]. Combining of these two advantages gives the capability to increase the transient stability margin of the system [3].

4.2: Main Components of a STATCOM System

A STATCOM system is, at the minimum, made up of a transformer, a VSC with feedback control, and DC link capacitors as shown below in figure 6.
The type of transformer usually used is a step-down transformer, where the secondary is connected to the VSC. This transformer is needed to reduce the grid voltage to one that is suitable for the VSC, and increase the voltage that the VSC outputs so that it is suitable for the grid.

The main component of the STATCOM is the VSC. The VSC must convert the DC voltage to a symmetrical AC voltage with as little harmonic distortion as possible. The VSC is able to provide continuous and independent active and reactive power control due to the combined leakage inductance of the line and transformer. This reactance serves three main purposes:

1. Providing low pass filtering of the output voltage waveform
2. Controlling active and reactive power
3. Limiting short circuit current draw

For grid applications, the low pass filtering is of major importance, and filtering above that provided by the leakage inductance may be necessary. Further filtering can be provided in the form of additional inductance added, or an LC filter combination depending on the
harmonic content of the output voltage. The filter ratings are dependent on the system requirements along with the magnitudes of the harmonics. According to [5], a two-level inverter system needs a filter in the range of 10% to 30% of the rated power. A multilevel inverter produces lower harmonics and therefore, can utilize a lower rated filter.

DC link capacitors are necessary energy support devices for the DC voltage. In addition, these capacitors provide a low-inductance path for the current when the device turns off. While the STATCOM is absorbing power, the DC link capacitors have the function of reducing the ripple voltage on the DC bus.

Additional system components include:

- Buildings to house the STATCOM and possibly energy storage devices
- Heat exchangers and cooling system components
- Various protection systems

4.3: Benefits of Using a STATCOM

Voltage instability is usually due to an inadequate amount of reactive power. Implementing a STATCOM on weak or critical path power buses will help in supporting the load by providing VARs as needed. The primary use of STATCOMs in power systems are:

- to decrease the unnecessary flow of reactive power to reduce power losses
- to improve the power quality in situation with large demand fluctuations
- to improve both the static and transient stability in power transmission and distribution systems
• to increase the maximum amount of power a transmission line can supply by improving the stability margin
• to increase the power factor closer to unity
• to balance an unbalanced three phase system
• to dampen power oscillations

Renewable energy generation, such as wind farms, are utilizing STATCOM devices to balance reactive power levels and maintain the voltage limits within the generation system [5]. Comparing the STATCOM to a thyristor-switched reactive element like an SVC, the STATCOM has the advantages of:

• only requiring a relatively small DC capacitor
• having a smaller footprint in a substation (smaller footprint results in lower cost)
• having a faster dynamic response
• being able to inject current into a network regardless of the network voltage

STATCOMs consist of high speed semiconductor switching devices, which lets them respond to rapidly changing systems. Speed is critical for any VAR supporting device, especially during a fault condition, or after a fault when the voltage has to be raised to stable limits. The amount of reactive power a STATCOM can compensate is linear to the grid voltage; the reactive power a SVC can compensate is quadratic to the grid voltage. This comparison is important since, when the grid voltage drops, it is in the most need of VAR injection, and the SVC is only able to provide a minimal amount.
The performance of a STATCOM when combined with an energy storage system (ESS), significantly improves its capabilities. Stability and voltage fluctuation problems in power systems can be solved by this combination.

Symmetric lead-lag capability of a STATCOM allows for a theoretical transition from full lag to full lead in only a few cycles [3].

4.4: Operating Principles of a STATCOM System

STATCOMs provide reactive power compensation through the injection of a variable magnitude, near-sinusoidal current waveform at the point of its connection. The voltage differential between the output of the STATCOM and its point of connection in the power grid, determines the quantity of reactive power that is transferred. The voltage that the STATCOM inverter can provide is relative to the DC link voltage that supplies it. As the AC voltage generated by the STATCOM increases beyond the grid voltage, the reactive power flows from the inverter into the grid. As the STATCOM voltage falls below that of the grid, reactive power flows from the grid and into the inverter. The STATCOM is designed to simulate the operation of a synchronous generator, where the first case mentioned above would be equivalent to an over-excited condition, and the second to an under-excited condition. Active power transfer from the STATCOM inverter is, additionally, related to the phase angle between the output waveform and the power grid [3]. STATCOMs have two reactive power compensation modes, the first being VAR control, and the second mode being automatic voltage control [5].

The STATCOM VSC contains high speed semiconductor switches that allows for rapid adaptation in the magnitude and phase angle of its output voltage. The main purpose of
the VSC is to generate a symmetric AC voltage with the necessary magnitude and frequency from the DC link voltage. A STATCOM can act as both a source and sink of reactive power through its use of the VSC. Reactive power is compensated by these converters by outputting a controlled voltage and current. Depending on this voltage and current, the STATCOM either operates in capacitive mode, or inductive mode. The V-I characteristics of the STATCOM is shown below in figure 7.

![V-I characteristic of a STATCOM](image)

**Figure 7 - V-I characteristic of a STATCOM**  [11]

Reactive power compensation for a STATCOM is not dependent on supply voltage fluctuations, but rather by the switching power converter.
Chapter 5 – Static Synchronous Series Compensator (SSSC)

5.1: Overview

The first series compensating device ever used in power transmission went into service in 1950 [4]. In general, the use of series compensating devices is for decreasing the reactance of a power line at the transmitting frequency. Originally, this was accomplished by installing series capacitors. These capacitors compensate for reactive power losses that reduces the effective transfer reactance of the line. This reduced impedance, from an electrical standpoint, reduces the length of the line, which improves both angular and voltage stability, as well as increasing the amount of power that can be shared between a set of parallel transmitting lines.

As solid state switching devices advanced, the advent of the Thyristor Controlled Series Compensators (TCSC) emerged. A bank of capacitors could now be connected into and out of a transmission path at a much higher rate without having an impact on the switching life. This allowed for much tighter tolerances on the control structure. A TCSC is modeled as a series impedance [4].

The Static Synchronous Series Compensator (SSSC) is a VSC based FACTS device that is connected in series with the power line in which it operates. The SSSC has a higher control bandwidth then its technological counterparts mentioned above. A SSSC injects a variable reactive power into the power line to compensate for the losses; it is modeled as a series voltage source [4].

No SSSC has been installed independently on the transmission level of a power system do to its high cost, and that its cheaper predecessors are able to meet the needs required. On
the distribution level, the SSSC has been used for power quality purposes; used in this application, it is given the name of Dynamic Voltage Restorer (DVR). The DVR is used to mitigate voltage dips and flickers by keeping the voltage level constant [4].

5.2: Main Components of a SSSC System

A SSSC system is, at the minimum, made up of a transformer, a VSC with feedback control, and DC link capacitors as shown below in figure 8.

From a theoretical standpoint, the SSSC is quite similar in components to the STATCOM. In practice, a SSSC needs Thyristor protection because of the semiconductor switches having a low overload capacity. Additionally, overvoltage protection is critical for the capacitor bank to be able to withstand the current from a fault condition. Overvoltage primary protective equipment will usually include metal-oxide varistors, a spark gap, and a fast bypass switch. Overvoltage secondary protection will include ground mounted electronic devices to act on signals from optical current transducers mounted in the high voltage part of the system. For the SSSC, even the platform that the equipment is mounted on is important. Since it is installed in series with a high voltage power line, the platform needs to be fully insulated [4].
If the SSSR is used as a DVR, the system requires a means to charge the electrical storage device. For both the SSSR and DVR, additional system components include:

- Buildings to house the STATCOM and possibly energy storage devices
- Heat exchangers and cooling system components

5.3: Benefits of Using a SSSC

Series based compensating devices have the ability to [4]:

- keep the voltage constant for the length of a power line in both magnitude and phase angle
- regulate voltage fluctuations within their allowable tolerance as power requirements change
- improves the speed at which oscillations are dampened
- helps limit the short circuit currents

Both the TCSC and SSSR have the advantage over mechanically switched capacitor implementations in reliability. The SSSR has the advantage over the TCSC in its control bandwidth and its ability to maintain tighter tolerances [4] [13].

5.4: Operating Principles of a SSSC System

SSSCs operate through the injection of a variable magnitude, near-sinusoidal voltage waveform in series with the power line. The main operation of a SSSC is to control the flow of power. Control over the phase angle of the injected voltage dictates the flow of active power, while the control over the magnitude dictates the flow of reactive power.
The magnitude must remain positive, so as it tries to cross the zero point, $\pi$ rad gets added to its angle. Controlling of the injected voltage magnitude can also control the voltage magnitude at the bus it is being injected into; this operation is instead of controlling the reactive power [13]. The VSC of the SSSC contains the high speed semiconductor switches that allows for rapid adaptation in the magnitude and phase angle of its output voltage.

Figure 9 – SSSC Phasor relationship between injected voltage [13]

The effect that the injected series voltage has on the overall bus voltage is shown above in figure 9.
Chapter 6 – Unified Power Flow Controller (UPFC)

6.1: Overview

The unified power flow controller (UPFC) is a combination of two inverter based compensating devise, the shunt compensating STATCOM and a series compensating SSSC. The combination of the two allows for control of power flow along with independent control of voltage.

Control over the power flow is utilized to redirect power from overloaded parts of a transmission system to paths with unused capacity. The most widely used method of power flow control is through the use of phase shifting transformers (PST). A PST has a low control bandwidth and has a high maintenance/replacement requirement. As the power flow volatility increases in the market, the need increases for full power flow control with a high bandwidth to be able to utilize the existing transmission system capacity. The UPFC fills this requirement but with a high system setup cost [4].

A UPFC can perform as other FACTS devices, given, that it has sufficient capability for the situation it is to handle. From the UPFC, more advanced systems known as an interline power flow controller (IPFC) and a generalized unified power flow controller (GUPFC) can be derived. The IPFC and GUPFC can control power flow in multiple transmission lines from the same substation.

From the growing restriction on the construction of new power lines, along with the increased volatility of power flow, power flow controllers such as the UPFC have been utilized [4]. The first UPFC installation went into operation on May 1, 1998 at the Inez power station in Kentucky [14].
6.2: Main Components of a UPFC System

A UPFC is a configuration made up of a STATCOM combined with a SSSC. This combination allows for the both real and reactive power compensation simultaneously. The control is possible by injecting a voltage through a series transformer and a reactive current through a shunt transformer. The control voltage is controllable in both phase angle and magnitude and is added with the transmission line voltage. The control current is also controllable in both phase angle and magnitude, and is delivered to or received from the transmission line as needed [15]. The series voltage and shunt current signals are supplied by their own voltage source converters. Both converters share a common DC link capacitor. The shunt converter is responsible for maintaining the voltage on the DC link capacitor so that the active power required by the series converter is available.

The DC link capacitor allows for the exchange between the two converters of active power. There is no reactive power that flows between the two converters, and therefore, are controlled independently by each. This gives three independently controllable parameters for the two UPFC buses that can be controlled at once. Voltage control is handled by the
shunt converter, while control of the flow of active and reactive power is handled by the series converter.

In practice, the series branch will need to be protected through the use of a thyristor bridge.

6.3: Benefits of Using a UPFC

The UPFC has the ability to provide several benefits simultaneously. The first would be local bus voltage regulation which comes from the shunt configuration. The second would be power flow in a transmission line which comes from the series configuration. These are the two control modes that are most notably utilized and studied in the analysis of a UPFC, however, the combination gives the benefits of controlling impedance, voltage angle, and power flow in the system. Additionally, the series aspect may gain the ability to provide direct voltage injection, phase angle shifting, and independent impedance control [4][16][15]. One benefit that a UPFC can provide that no other device before it could offer is that during an emergency, the series converter can control its voltage magnitude to provide voltage support on the other side of the UPFC connection [15].

Advancements in the modeling of the UPFC has led to 13 different control modes [4]:

1. Active and reactive power flow control
2. Power flow control by voltage shifting
3. General Direct Voltage Injection
4. Direct Voltage Injection with $V_{se}$ in phase with $V_i$
5. Direct Voltage Injection with $V_{se}$ in Quadrature with $V_i$ (lead)
6. Direct Voltage Injection with $V_{se}$ in Quadrature with $V_i$ (lag)
7. Direct Voltage Injection with $V_{se}$ in Quadrature with $I_{ij}$ (lead)
8. Direct Voltage Injection with $V_{se}$ in Quadrature with $I_{ij}$ (lag)

9. Voltage Regulation with $V_{se}$ in phase with $V_i$

10. Phase Shifting Regulation

11. Phase shifting and Quadrature Regulation (lead)

12. Phase shifting and Quadrature Regulation (lag)

13. Line Impedance Compensation

6.4: Operating Principles of a UPFC System

A UPFC has the ability to control all of the fundamental power system parameters, to dynamically compensate the AC power requirements, compensate for reactive power through the shunt branch, compensate for real power through the series branch, and perform phase shifting either independently or in combination. The power system parameters mentioned are the transmission voltage, impedance and phase angle.

Figure 11 - Operating principle of a UPFC  [4]

Figure 11 depicts how a UPFC operates [4]. As can be seen, the series converter is coupled to the transmission line through a series transformer, while the shunt converter is coupled to a local bus designated $i$ through a shunt transformer. Both converters are connected
through a common DC link capacitor. The shunt converter is the master converter, being able to both generate and absorb a controllable amount of reactive power, along with providing an active power exchange to the series converter, allowing it to perform as required.

By defining phasor quantities, an equivalent circuit of figure 11 can be obtained where

- $V_{sh}$ is the equivalent shunt voltage injected
- $V_{se}$ is the equivalent series voltage injected
- $Z_{sh}$ is the impedance of the shunt coupling transformer
- $Z_{se}$ is the impedance of the series coupling transformer
- $V_i$ is the voltage at bus $i$
- $V_j$ is the voltage at bus $j$
- $V_k$ is the voltage at bus $k$ at the receiving end of the transmission line
- $I_{sh}$ is the current flowing through the shunt converter
- $Q_{sh}$ is the reactive power flowing through the shunt converter and leaving bus $i$
- $P_{ij}$ is the UPFC series active power flowing out of bus $j$ into $i$
- $Q_{ij}$ is the UPFC series reactive power flowing out of bus $j$ into $i$
- $P_{sh}$ is the active power flowing between the shunt converter and the DC link capacitor and leaving bus $i$
- $P_{se}$ is the active power flowing between the series converter and the DC link capacitor
No leakage current is assumed, so the current flowing from bus $i$ to $j$ is equal and opposite to the current flowing from bus $j$ to $i$:

$$I_{ij} = -I_{ji}$$  \hspace{1cm} \text{Equation 1}

Referring to figure 12, the UPFC has been modeled and analyzed in the implementation of regulating voltage on bus $i$ and controlling both active and reactive power flow in the transmission line linking bus $i$ and bus $j$. These benefits are well defined and are equivalent to that of a combination STATCOM and SSSC that the UPFC is composed of. The UPFC provides additional control that the STATCOM and SSSC would not be able to provide independently such as shifting phase angles, voltage manipulations, and changing equivalent impedances. These parameters can be controlled independently or in combinations [4] [16].
In [4] and [15], the 13 control modes mentioned in section 6.3 are detailed; a synopsis is provided here.

6.4.1: Control Mode 1 – Active and reactive power flow control

Control mode 1 is the independent control of the active and reactive power flow. This mode has a specified active power flow from bus \( j \) to \( i \) termed \( P_{ji}^{\text{Spec}} \), and an equivalent reactive power flow termed \( Q_{ji}^{\text{Spec}} \). \( P_{ji}^{\text{Spec}} \) and \( Q_{ji}^{\text{Spec}} \) are reference values in the control equations where the UPFC adjusts \( P_{ji} \) and \( Q_{ji} \) to meet the following equations:

\[
P_{ji} - P_{ji}^{\text{Spec}} = 0 \quad \text{Equation 2}
\]

\[
Q_{ji} - Q_{ji}^{\text{Spec}} = 0 \quad \text{Equation 3}
\]

6.4.2: Control Mode 2 – Power flow control by voltage shifting

Control mode 2 shifts the voltage between bus \( i \) and \( j \) when the two voltages are equal in order to control the flow of active power. The specified active power flow from bus \( j \) to \( i \) is termed \( P_{ji}^{\text{Spec}} \), and is used to meet the following equations:

\[
P_{ji} - P_{ji}^{\text{Spec}} = 0 \quad \text{Equation 4}
\]

\[
V_i - V_j = 0 \quad \text{Equation 5}
\]

The active power flow that is controlled by this mode is similar to the operation of a phase shifting transformer. Mode 2 is able to be combined with mode 1.
6.4.3: Control Mode 3 – General direct voltage injection

Mode 3 is the injection of a series voltage with a specified magnitude \( (V_{se}^{spec}) \) and phase angle \( (\theta_{se}^{spec}) \). The control of the UPFC is such to meet the following equations:

\[
V_{se} - V_{se}^{spec} = 0 \quad \text{Equation 6}
\]

\[
\theta_{se} - \theta_{se}^{spec} = 0 \quad \text{Equation 7}
\]

6.4.4: Control Mode 4 – Direct voltage injection with \( V_{se} \) in phase with \( V_i \)

Control mode 4 controls the magnitude of the series voltage \( (V_{se}) \) while it is in phase with the voltage at bus \( i \) \( (V_i) \). \( V_{se}^{spec} \) is the specified series voltage magnitude for the control. The following equations are used in this mode:

\[
V_{se} - V_{se}^{spec} = 0 \quad \text{Equation 8}
\]

\[
\theta_{se} - \theta_i = 0 \quad \text{Equation 9}
\]

or

\[
\theta_{se} - \theta_i - 180^\circ = 0 \quad \text{Equation 10}
\]

Mode 4 is similar to the operation of an ideal transformer with a tap ratio equivalent to

\[
\frac{V_i}{V_i + V_{se}} \quad \text{Equation 11}
\]

or

\[
\frac{V_i}{V_i - V_{se}} \quad \text{Equation 12}
\]
The ideal UPFC has the advantage in that it can control the bus voltage to produce an infinite number of taps.

6.4.5: Control Mode 5 – Direct voltage injection with \( V_{se} \) in quadrature with \( V_i \) (lead)

Control mode 5 controls the magnitude of the series voltage \( (V_{se}) \) while it is in quadrature with and leading the voltage at bus \( i \) \( (V_i) \). \( V_{spec} \) is the specified series voltage magnitude for the control. The following equations are used in this mode:

\[
V_{se} - V_{spec} = 0 \quad \text{Equation 13}
\]

\[
\theta_{se} - \theta_i - \frac{\pi}{2} = 0 \quad \text{Equation 14}
\]

Mode 5 is similar in operation to that of a quadrature boosting transformer.

6.4.6: Control Mode 6 – Direct voltage injection with \( V_{se} \) in quadrature with \( V_i \) (lag)

Control mode 6 controls the magnitude of the series voltage \( (V_{se}) \) while it is in quadrature with and lagging the voltage at bus \( i \) \( (V_i) \). \( V_{spec} \) is the specified series voltage magnitude for the control. The following equations are used in this mode:

\[
V_{se} - V_{spec} = 0 \quad \text{Equation 15}
\]

\[
\theta_{se} - \theta_i + \frac{\pi}{2} = 0 \quad \text{Equation 16}
\]

Mode 6 is similar in operation to that of a quadrature boosting transformer.
6.4.7: **Control Mode 7 – Direct voltage injection with \( V_{se} \) in quadrature with \( I_{ij} \) (lead)**

Control mode 7 controls the magnitude of the series voltage \( (V_{se}) \) while it is in quadrature with and leading the current flowing from bus \( i \) to \( j \) \( (I_{ij}) \). \( V_{se}^{Spec} \) is the specified series voltage magnitude for the control. The following equations are used in this mode:

\[
V_{se} - V_{se}^{Spec} = 0 \\
Im(V_{se}I_{ij}e^{j}) = 0
\]

Equation 17

Equation 18

6.4.8: **Control Mode 8 – Direct voltage injection with \( V_{se} \) in quadrature with \( I_{ij} \) (lag)**

Control mode 8 controls the magnitude of the series voltage \( (V_{se}) \) while it is in quadrature with and lagging the current flowing from bus \( i \) to \( j \) \( (I_{ij}) \). \( V_{se}^{Spec} \) is the specified series voltage magnitude for the control. The following equations are used in this mode:

\[
V_{se} - V_{se}^{Spec} = 0 \\
Im(V_{se}I_{ij}e^{-j}) = 0
\]

Equation 19

Equation 20

6.4.9: **Control Mode 9 – Voltage regulation with \( V_{se} \) in phase with \( V_{i} \)**

Control mode 9 controls the magnitude of the voltage at bus \( i \) \( (V_{i}) \) while keeping the series branch voltage \( V_{se} \) in phase. \( V_{j}^{Spec} \) is the specified voltage magnitude of bus \( j \) for the control. The following equations are used in this mode:

\[
V_{j} - V_{j}^{Spec} = 0 \\
\theta_{se} - \theta_{i} = 0
\]

Equation 21

Equation 22
6.4.10: Control Mode 10 –Phase shifting regulation

Control mode 10 regulates the magnitude of the series voltage \( (V_{se}) \) in order to control the difference between the voltage magnitudes at bus \( i \) \( (V_i) \) and \( j \) \( (V_j) \) to be zero. The phase difference between \( V_i \) and \( V_j \) is also controlled to a specified angle \( \theta_{ij}^{Spec} \). The following equations are used in this mode:

\[
V_i - V_j = 0 \quad \text{Equation 23}
\]

\[
\theta_i - \theta_j - \theta_{ij}^{Spec} = 0 \quad \text{Equation 24}
\]

Mode 10 is similar in operation to that of a phase shifting transformer.

6.4.11: Control Mode 11 –Phase shifting and quadrature regulation (lead)

Control mode 11 regulates the magnitude of the series voltage \( (V_{se}) \) in order to control the difference between the voltage magnitudes at bus \( i \) \( (V_i) \) and \( j \) \( (V_j) \) to be zero. The phase of \( V_{se} \) leads \( V_i \) and is in quadrature. The following equations are used in this mode:

\[
V_i - V_j = 0 \quad \text{Equation 25}
\]

\[
\theta_{se} - \theta_i - \frac{\pi}{2} = 0 \quad \text{Equation 26}
\]

6.4.12: Control Mode 12 –Phase shifting and quadrature regulation (lag)

Control mode 11 regulates the magnitude of the series voltage \( (V_{se}) \) in order to control the difference between the voltage magnitudes at bus \( i \) \( (V_i) \) and \( j \) \( (V_j) \) to be zero. The phase of \( V_{se} \) lags \( V_i \) and is in quadrature. The following equations are used in this mode:

\[
V_i - V_j = 0 \quad \text{Equation 27}
\]
\[ \theta_{se} - \theta_l + \frac{\pi}{2} = 0 \]  

Equation 28

6.4.13: Control Mode 13 – Line impedance compensation

Control mode 11 regulates both the magnitude and phase of the series voltage \( V_{se} \) in order to control the series impedance of the series UPFC voltage source. The equivalent impedance of the series voltage source is designated \( R_{se} + jX_{se} \) while specified impedance to control to is designated as \( Z_{se}^{Spec} \). The following equations are used in this mode:

\[ R_{se} - Z_{se}^{Spec} \cos \gamma_{se}^{Spec} = 0 \]  

Equation 29

\[ X_{se} - Z_{se}^{Spec} \sin \gamma_{se}^{Spec} = 0 \]  

Equation 30

This mode allows for the UPFC impedance to be purely capacitive or purely inductive which simulates compensation through adding a capacitor or reactor to the line. Besides quickly and easily being able to change the reactance, the UPFC is also able to compensate for resistance.

6.5: Power Flow in a UPFC System

The amount of power flow possible in a UPFC is constrained in both the shunt and series branches. For analyzing the maximum limitation in the UPFC shunt branch, the shunt voltage is set to

\[ V_{sh} = V_{sh} \angle \theta_{sh} \]  

Equation 31

with defining

\[ z_{sh} + jb_{sh} = \frac{1}{Z_{sh}} \]  

Equation 32

results in
\[ P_{sh} = V_i^2 g_{sh} - V_i V_{sh} (g_{sh} \cos(\theta_i - \theta_{sh}) + b_{sh} \sin(\theta_i - \theta_{sh})) \]  
Equation 33

\[ Q_{sh} = -V_i^2 b_{sh} \]  
Equation 34

\[ -V_i V_{sh} (g_{sh} \sin(\theta_i - \theta_{sh}) - b_{sh} \cos(\theta_i - \theta_{sh})) \]

For the series branch, the maximum limitation can be analyzed by setting

\[ V_{se} = V_{se} \angle \theta_{se} \]  
Equation 35

\[ V_i = V_i \angle \theta_i \]  
Equation 36

\[ V_j = V_j \angle \theta_j \]  
Equation 37

and defining

\[ g_{ij} + j b_{ij} = \frac{1}{Z_{se}} \]  
Equation 38

\[ \theta_{ij} = \theta_i - \theta_j \]  
Equation 39

\[ \theta_{ji} = \theta_j - \theta_i \]  
Equation 40

This results in a constrained power flow as follows:

\[ p_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos(\theta_{ij}) + b_{ij} \sin(\theta_{ij})) \]  
Equation 41

\[ -V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) \]  

\[ + b_{ij} \sin(\theta_i - \theta_{se})) \]
\[ Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij} \sin(\theta_{ij}) + b_{ij} \cos(\theta_{ij})) \]  \hspace{1cm} \text{Equation 42}

\[ -V_i V_{se} (g_{ij} \sin(\theta_i - \theta_{se})) \]

\[ -b_{ij} \cos(\theta_i - \theta_{se}) \]

\[ P_{ji} = V_j^2 g_{ij} - V_i V_j (g_{ij} \cos(\theta_{ji}) + b_{ij} \sin(\theta_{ji})) \]  \hspace{1cm} \text{Equation 43}

\[ + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se})) \]

\[ + b_{ij} \sin(\theta_j - \theta_{se}) \]

\[ Q_{ji} = -V_j^2 b_{ij} - V_i V_j (g_{ij} \sin(\theta_{ji}) - b_{ij} \cos(\theta_{ji})) \]  \hspace{1cm} \text{Equation 44}

\[ + V_j V_{se} (g_{ij} \sin(\theta_j - \theta_{se})) \]

\[ -b_{ij} \cos(\theta_j - \theta_{se}) \]

Additionally, the power balancing, or operating, constraint of the UPFC is defined as the amount of active power that can be exchanged between the shunt and series converters through the DC link.

The power exchange equation for the shunt converter is defined as

\[ P_{E_{sh}} = \text{Re}(V_{sh} l_{sh}^*) \]  \hspace{1cm} \text{Equation 45}

The power exchange equation for the series converter is defined as

\[ P_{E_{se}} = \text{Re}(V_{se} l_{ji}^*) \]  \hspace{1cm} \text{Equation 46}

Assuming an ideal system, this results in a power balancing constraint of

\[ \Delta P_{\Sigma} = P_{E_{sh}} - P_{E_{se}} = 0 \]  \hspace{1cm} \text{Equation 47}
6.6: *Modeling of a UPFC (The Injection Model)*

Figure 13 below shows an equivalent electronic schematic of a 2 bus transmission line with a UPFC connected. This schematic is the functional representation that the UPFC injection model is derived from [15].

![Figure 13 - The UPFC electric circuit arrangement][15]

In this diagram, the series converter is represented by a series voltage source ($\bar{V}_{se}$) that is injected into bus $i$, while the shunt converter is represented by the active power $P_{sh}$ and reactive power $Q_{sh}$. $X_{se}$ denotes the reactance that is seen from the series transformer terminals. The value of $X_{se}$ is calculated by:

$$X_{se} = X_k r_{max}^2 \frac{S_B}{S_{se,n}}$$  \[\text{Equation 48}\]

where

- $X_k$ is the reactance of the series transformer,
- $r_{max}$ is the maximum magnitude of the injected voltage in per unit,
- $S_B$ is the system power base value, and
- $S_{se,n}$ is the nominal power rating of the series converter.
The current, \( \tilde{I}_{ij} \), is the current that flows in the transmission line through the equivalent voltage source in the direction of bus \( i \) to bus \( j \). The nominal power rating of \( S_{se,n} \) is calculated by multiplying the maximum injected voltage with the maximum line current in the range that power flow is controlled. Active power of the series converter is exchanged with the shunt converter. The reactive power of the shunt converter, \( Q_{sh} \), is independently controlled up to that that is remaining after supplying what is needed by the active power control.

The injection model of the UPFC is based on simultaneously being able to control the shunt reactive power (\( Q_{sh} \)), and the magnitude (\( r \)) and phase angle (\( \gamma \)) of the injected voltage \( \tilde{V}_{se} \) [15]. The steady state vector diagram of a UPFC showing how \( \tilde{V}_{se} \) is added to the shunt side bus voltage (\( \tilde{V}_i \)) is shown below.

![Figure 14 - General vector diagram of the UPFC steady state operation](image)

The series injected voltage, \( \tilde{V}_{se} \), is defined as

\[
\tilde{V}_{se} = r\tilde{V}_i e^{j\gamma} = rV_i e^{j(\phi_i+\gamma)} = V_{se} e^{j(\phi_i+\gamma)}
\]

Equation 49

While the voltage at bus \( i \) controlled by the shunt converter, \( \tilde{V}_i \), is defined as
\[
\bar{V}_i = V_i e^{j\Theta_i} \quad \text{Equation 50}
\]

Since the magnitude of \( V_{se} \) is defined as
\[
V_{se} = rV_i \quad \text{Equation 51}
\]

The injected voltage magnitude \((r)\) is calculated by
\[
r = \frac{V_{se}}{V_i} \quad \text{Equation 52}
\]

Parameter \( r \) is limited to \( 0 \leq r \leq r_{\text{max}} \), and the angle \( \gamma \) has the full range of \( 0 \leq \gamma \leq 2\pi \).

The derivation of the UPFC injection model starts with consideration of the series voltage source shown below.

![Series voltage source](image)

From the diagram, it can be seen that the voltage \( \bar{V}'_i \) is calculated by
\[
\bar{V}'_i = \bar{V}_i + \bar{V}_{se} \quad \text{Equation 53}
\]

and the current \( \bar{I}_{ij} \) by
\[
\bar{I}_{ij} = \frac{\bar{V}'_i - \bar{V}_j}{jX_{se}} \quad \text{Equation 54}
\]

A vector representation of the series voltage is shown below.
Conversion of the series voltage circuit into its Norton equivalent is shown below.

Where the current is $\bar{I}_{se}$ and susceptance $b_{se}$ replace the voltage $\bar{V}_{se}$ and reactance $X_{se}$. $\bar{I}_{se}$ is calculated from

$$\bar{I}_{se} = \frac{\bar{V}_{se}}{jX_{se}} = jb_{se}\bar{V}_{se}$$

Equation 55

and $b_{se}$ being defined in the range $b_{se} \leq 0$, is calculated by

$$b_{se} = -\frac{1}{X_{se}}$$

Equation 56

The transformation shows how the series voltage source is able to inject power into the buses as shown in the figure below.
The injected power is based on the current $\bar{I}_{se}$ and the associated voltage at the corresponding bus, $\bar{V}_i$ and $\bar{V}_j$, resulting in

$$\bar{S}_{iS} = \bar{V}_i(-\bar{I}_{se})^*$$

Equation 57

$$\bar{S}_{jS} = \bar{V}_j(\bar{I}_{se})^*$$

Equation 58

The resulting power will be positive for the sourcing bus and negative for the loaded bus.

Equation 57 and equation 58 can be expanded into

$$\bar{S}_{iS} = \bar{V}_i(-j b_{se} \bar{V}_{se})^* = \bar{V}_i(-j b_{se} r \bar{V}_i e^{j\gamma})^*$$

Equation 59

$$\bar{S}_{jS} = \bar{V}_j(j b_{se} \bar{V}_{se})^* = \bar{V}_j(j b_{se} r \bar{V}_i e^{j\gamma})^*$$

Equation 60

$$= r b_{se} V_i^2 \sin \gamma + j r b_{se} V_i^2 \cos \gamma$$

$$= -r b_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma)$$

$$- j r b_{se} V_i V_j \cos(\theta_i - \theta_j + \gamma)$$

The model continues with the coupling of the UPFC shunt converter to produce figure 19.
The power injected by the UPFC can be calculated as

\[ P_{IS} = -\text{Re}(\vec{S}_{IS}) + \text{Re}(\vec{S}_{sh}) \]  
Equation 61

\[ Q_{IS} = -\text{Im}(\vec{S}_{IS}) + \text{Im}(\vec{S}_{sh}) \]  
Equation 62

\[ P_{Sj} = -\text{Re}(\vec{S}_{Sj}) \]  
Equation 63

\[ Q_{Sj} = -\text{Im}(\vec{S}_{Sj}) \]  
Equation 64

And the equivalent UPFC model can be redrawn as shown below.

In order to determine the UPFC injected power at bus \( i \), the apparent power of the shunt converter \((\vec{S}_{sh})\) needs to be known.

In the operation of the UPFC, active power is exchanged between both the series and shunt converters, but the reactive power is controlled independently as expressed by:
\[ P_{sh} = P_{se} \]  \hspace{1cm} \text{Equation 65}

and where \( Q_{sh} \) is independently controlled.

The active power of the shunt converter (\( P_{sh} \)) can be calculated from the apparent power of the series converter (\( \tilde{S}_{se} \)).

\[
\tilde{S}_{se} = \bar{V}_{se}(\bar{t}_{ij})' = r \bar{V}_i e^{j \gamma} \left( \frac{\bar{V}'_i - \bar{V}_j}{jX_{se}} \right)
\]

\[
= -r b_{se} V_i V_j \sin(\theta_{ij} + \gamma)
\]

\[
+ r b_{se} V_i^2 \sin \gamma
\]

\[
+ j r b_{se} V_i V_j \cos(\theta_{ij} + \gamma)
\]

\[
- r b_{se} V_i^2 \cos \gamma - r^2 b_{se} V_i^2
\]

\hspace{1cm} \text{Equation 66}

From this, the set of equations that define the power injected by the UPFC into bus \( i \) and \( j \) are:

\[ P_{Si} = -r b_{se} V_i V_j \sin(\theta_{ij} + \gamma) \]  \hspace{1cm} \text{Equation 67}

\[ Q_{Si} = -r b_{se} V_i^2 \cos(\gamma) + Q_{sh} \]  \hspace{1cm} \text{Equation 68}

\[ P_{Sj} = r b_{se} V_i V_j \sin(\theta_{ij} + \gamma) \]  \hspace{1cm} \text{Equation 69}

\[ Q_{Sj} = r b_{se} V_i V_j \cos(\theta_{ij} + \gamma) \]  \hspace{1cm} \text{Equation 70}

The complete injection model of the UPFC is shown below in figure 21.
The power flow from the UPFC shunt side \( i \) is defined by

\[
P_{i1} = -r b_{se} V_i V_j \sin(\theta_{ij} + \gamma) - b_{se} V_i V_j \sin(\theta_{ij})
\]

Equation 71

\[
Q_{i1} = -r b_{se} V_i^2 \cos(\gamma) + Q_{sh} - b_{se} V_i^2
\]

\[
+ b_{se} V_i V_j \cos(\theta_{ij})
\]

Equation 72

And for the UPFC series side \( j \), the power flow is defined by

\[
P_{j2} = r b_{se} V_i V_j \sin(\theta_{ij} + \gamma) + b_{se} V_i V_j \sin(\theta_{ij})
\]

Equation 73

\[
Q_{j2} = r b_{se} V_i V_j \cos(\theta_{ij} + \gamma) - b_{se} V_j^2
\]

\[
+ b_{se} V_i V_j \cos(\theta_{ij})
\]

Equation 74

It can be seen that the UPFC injection model simplifies the system into a series branch susceptance \( b_{se} \), which is part of the system bus admittance matrix \([B]\), and the injected bus quantities \( P_{Si}, Q_{Si}, P_{Sj}, \) and \( Q_{Sj} \). Through this model, control is achieved by modifying the parameters \( r, \gamma, \) and \( Q_{sh} \) as needed [15] [17].

The most widely used control system for the UPFC is a de-coupled single-input, single-output proportional-integral system [15] [17]. The input and output signals that are used in the control system vary depending on which mode the injection model is in.
By changing the three parameters of the model, the external power system parameters are changed as follows:

- changing $Q_{sh}$ results in
  - changing the shunt side bus voltage magnitude, $V_i$

- changing $r$ results in
  - changing the series side bus voltage magnitude, $V_j$
  - changing the reactive power flow into series side bus, $Q_{j2}$
  - changing the reactive power requirement of the series side converter, $Q_{se}$, or
  - changing the compensating voltage magnitude, $V_{comp}$

- changing $\gamma$ results in
  - changing the active power flow into the series side bus, $P_{j2}$
  - changing the active power requirement of the series side converter, $P_{se}$
  - changing the bus voltage angle difference, $\Theta_{ij}$, or
  - changing the compensating voltage angle, $\varphi_{comp}$

The shunt side is only able to be controlled in voltage mode, where $V_i$ is related to $Q_{sh}$ and the shunt converter controls reactive power [15].

The series converter can be controlled by the $r$ - $\gamma$ pair that results in several unique modes:

- bus voltage magnitude and active power flow, $V_j$ and $P_{j2}$
- reactive and active power flows, $Q_{j2}$ and $P_{j2}$
- series compensation, $Q_{se}$ and $P_{se}(=0)$
• phase shifting of Phase Angle Regulator (PAR) type, $V_j(= V_i)$ and $\Theta_{ij}$

• phase shifting of Quadrature Booster Transformer (QBT) type, $V_{comp}$ and $Q_{comp}(= \frac{\pi}{2})$

The choice of how the variables are used is to satisfy the $V - Q$ and $\Theta - P$ de-coupling relationship [15].
Chapter 7 – Simulations

7.1: The System for Simulation

Figure 22 shows the system for simulation. The system modeled is located at the end of a 75km line labeled L2, and between busses B1 and B2 with a voltage of 500 kV [18] [19]. It shows the shunt converter connected to bus B1 and the series converter connected between buses B1 and B2. Each converter is a 100MVA, three-level, 48 pulse GTO-based converter with a modulation scheme designed for harmonic neutralization [20]. The common DC link shared between the two converters are made up of four 2.5mF capacitors, two on the positive leg, and two on the negative. In between the capacitor bank is a block labeled Sw, which contains switches to connect the 2 banks based on the mode of operation chosen. Three modes are simulated in this project:

1. In STATCOM mode, the switch is open and the shunt converter operates to control the voltage at bus B1. The series converter is not operating.

2. In SSSC mode, the switch is open and the series converter operates to control the injected voltage, while keeping it in quadrature with the current. The shunt converter is not in operation.

3. In the UPFC mode, the switch is closed to connect the shunt and series converters by a common DC bus. Both the shunt and series converters are in operation. The shunt converter operates as a STATCOM to maintain the DC bus so that the series converter can provide active power. The voltage at bus B1 is then maintained with reactive power getting absorbed or generated.
7.2: Simulation of a STATCOM

With the system set to operate in a STATCOM VAR control mode, the STATCOM operates as a variable reactive power source. The injected reference value for $Q$ starts at $0\, VAR_{pu}$ at time 0 seconds. At time equal to 0.3 seconds, the STATCOM starts to absorb reactive power from the transmission line by setting its reference value to $+0.8\, VAR_{pu}$. At time equal to 0.5 seconds, $Q$ is changed to $-0.8\, VAR_{pu}$ which causes the STATCOM to generate reactive power.
The 1st trace shows the current flowing to/from the STATCOM (green) and its relationship to the voltage (red). At the time between 0.3 and 0.5 seconds, the current is lagging the voltage, which is the inductive mode where the STATCOM absorbs the reactive power. At the time of 0.5 seconds, the current leads the voltage, which is the capacitive mode where the STATCOM supplies reactive power. Whether leading or lagging, the current is always in quadrature with the voltage.

To control the amount of reactive power absorbed or supplied, the STATCOM varies the magnitude of the voltage generated by its converter. The 2nd trace shows the magnitude of the voltage is changed by effectively changing the DC bus voltage.
Figure 24 - STATCOM simulation traces focused on changes
7.3: *Simulation of a SSSC*

With the system set to operate in an SSSC voltage injection mode, the injected voltage magnitude begins at $0 \ V_{pu}$ at time 0. After 0.3 seconds have past, the injected voltage magnitude is increased to $0.8 \ V_{pu}$.

![SSSC simulation traces](image)

The waveforms show how injecting voltage onto the line effects the value of the active ($5^{th}$ trace) and reactive power ($6^{th}$ trace) flowing through the transmission lines. In this mode, the series converter of the SSSC is operated with a constant conduction angle. The magnitude of the injected voltage is changed through control over the DC voltage which is proportional to the $3^{rd}$ trace on the oscilloscope ($V_{inj}$). The $1^{st}$ trace shows the injected voltage. The $2^{nd}$ shows the current flowing through the SSSC. The voltages and currents
are operated in quadrature to simulate a variable inductance or capacitance. An image showing the zoomed in the time frame surrounding 0.3 seconds is shown below.

Figure 26 - SSSC simulation traces focused on changes
7.4: Simulation of an UPFC

With the system set to operate in an UPFC power flow control mode, the active power ($P_{ref}$) is defined at +8.7 $W_{pu}$ and the reactive power ($Q_{ref}$) as +0.6 $VAR_{pu}$. These values are held until the time reaches 0.25 seconds. At that time, $P_{ref}$ changes to +10 $W_{pu}$. At a time of 0.5 seconds, $Q_{ref}$ goes to +0.7 $VAR_{pu}$. The reference voltage of the shunt converter ($V_{ref}$) is kept constant at +1 $V_{pu}$ for the duration of the simulation (0.8 seconds).

![Figure 27 - UPFC simulation traces](image)

The traces above show the variations of $P$ and $Q$. There is a transient that lasts from startup to a time of 0.15 seconds. The steady state is then reached with $P$ and $Q$ reaching their respective set points before being increased to their new settings. The 3rd and 4th traces show the effects that changing $P$ and $Q$ have on the transmission lines.

The STATCOM and SSSC traces during this simulation are shown below in figure 28 and figure 29 respectively.
Figure 28 - UPFC simulation traces of the STATCOM

Figure 29 - UPFC simulation traces of the SSSC
Chapter 8 – Conclusion

Compensating devices in power systems are now a critical part of the system in maintaining quality and reliability. These devices have been implemented to maintain the current power grid structure, while allowing for the increased demand and service areas that they were not designed for.

The technology has advanced from mechanically switched reactors, capacitors, and transformers, to solid state switched implementations that have dramatically increased reliability and control. The latest advent is VSC based technology which provides the reliability with an increased precision and faster reaction times.

The UPFC is an advanced compensating device based on VSC technology that is able to dynamically change between independent compensating modes, as well as provide combined ones, to mimic all of the previous technological implementations. The UPFC also adds the ability to provide double ended voltage support that has not been possible by a single device in the past.

As system monitoring techniques advance from power station and substation implementations into multi-region wide implementations, fast, reliable, and precise control will be necessary to maintain a safe, reliable, and efficient system. The UPFC provides the necessary features needed in the current power system, along with those being implemented for the future.
References


