Module-1

Subject: Flexible AC Transmission System (FACTS)

Content: Conventional controlled systems, such as automatic governor control and excitation control employed at generating stations. Transformer tap-changer control is another control feature generally available in transmission networks. Arising from the transformer combinations and the use of on-load tap changers, phase-shifting transformers are realized, which are primarily used to mitigate circulating power on network tie-lines. introduction and the recognition of limited controllability provide the basis for introducing the concept of the Flexible Ac Transmission System (FACTS), operating principles of new FACTS devices.

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1. The Conventional Power Grid

The power sources in conventional power systems must operate at exactly the same frequency and in perfect synchronism. Each generator controls the magnitude of its terminal voltage by the excitation current and the phase angle of this voltage by means of the mechanical torque developed by the turbine. The generators are designed to produce relatively low voltages, and thus the generated power undergoes a number of voltage transformations, from low to high voltage (for efficient power transmission) and from high to medium and low voltage (for economic and safe power distribution). These changes are implemented by power transformers. Within a national grid, the use of a fully interconnected primary transmission system, to which the new power stations are connected, has traditionally been the generally accepted philosophy behind the development of an efficient power system.

The expansion of the primary transmission system was normally continued until the rated switchgear fault level was exceeded. Beyond that point a new primary transmission system, of higher voltage and fault levels, was created, while the previous one continued expanding into several separate (secondary) systems. Each of these secondary transmission systems in turn supplied a number of distribution (normally radial) feeders. So the conventional power grid has traditionally been grouped into three separate parts, i.e. generation, transmission and distribution, all of them inflexibly tied by the synchronous constraints.

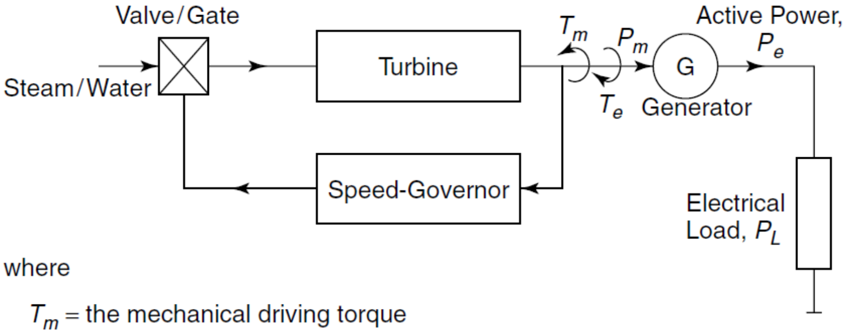
1.1 Conventional Control Mechanisms

In the foregoing discussion, a lack of control on active- and reactive-power flow on a given line, embedded in an interconnected ac transmission network, was stated. Also, to maintain steady-state voltages and, in selected cases, to alter the power-transmission capacity of lines, traditional use of shunt and series impedances was hinted.

In a conventional ac power system, however, most of the controllability exists at generating stations. For example, generators called spinning reserves maintain an instantaneous balance between power demand and power supply. These generators, in fact, are purposely operated at reduced power. Also, to regulate the system frequency and for maintaining the system at the rated voltage, controls are exercised on selected generators.

1.1.1 Automatic Generation Control (AGC)

The megawatt (MW) output of a generator is regulated by controlling the driving torque, T_m, provided by a prime-mover turbine. In a conventional electromechanical system, it could be a steam or a hydraulic turbine. The needed change in the turbine-output torque is achieved by controlling the steam □□water input into the turbine. Therefore, in situations where the output exceeds or falls below the input, a speed-governing system senses the deviation in the generator speed because of the load-generation mismatch, adjusts the mechanical driving torque to restore the power balance, and returns the operating speed to its rated value. The speed-governor output is invariably taken through several stages of mechanical amplification for controlling the inlet (steam□□water) valve□ □gate of the driving turbine. Figure 1.1 shows the basic speed-governing system of a generator supplying an isolated load. The operation of this basic feedback-control system is enhanced by adding further control inputs to help control the frequency of a large interconnection. In that role, the control system becomes an Automatic Generation Control (AGC) with supplementary signals.



where

T_m = the mechanical driving torque
T_e = the mechanical load torque from the generator electrical output
P_m = the mechanical power input to the generator

Fig 1.1 A speed-governor system.

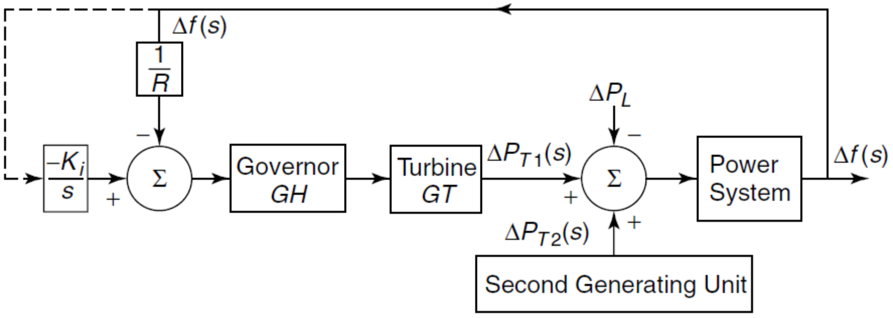


Fig 1.2 An AGC with supplementary control on the principal generating unit.

To avoid competing control actions, in a multigenerator unit station each speed-governor system is provided with droop (R) characteristics through a proportional feedback loop. Figure.2 shows an AGC on the principal generating unit with supplementary control. In contrast, the second, third, and remaining generating units in a multiunit station operate with their basic AGCs. In a complex interconnected system, the supplementary control signal may be determined by a load-dispatch center.

1.1.2 Excitation Control

The basic function of an exciter is to provide a dc source for field excitation of a synchronous generator. A control on exciter voltage results in controlling the field current, which, in turn, controls the generated voltage. When a synchronous generator is connected to a large system where the operating frequency and the terminal voltages are largely unaffected by a generator, its excitation control causes its reactive power output to change.

In older power plants, a dc generator, also called an exciter, was mounted on the main generator shaft. A control of the field excitation of the dc generator provided a controlled excitation source for the main generator. In contrast, modern stations employ either a brushless exciter (an inverted 3-phase alternator with a solid-state rectifier connecting the resulting dc source directly through the shaft to the field windings of the main generator) or a static exciter (the use of a station supply with static rectifiers).

An excitation-control system employs a voltage controller to control the excitation voltage. This operation is typically recognized as an Automatic Voltage Regulator (AVR). However, because an excitation control operates quickly, several stabilizing and protective signals are invariably added to the basic voltage regulator. A Power System Stabilizer (PSS) is implemented by adding auxiliary damping signals derived from the shaft speed, or the terminal frequency, or the power—an effective and frequently used technique for enhancing small-signal stability of the connected system. Figure 1.3 shows the functionality of an excitation-control system.

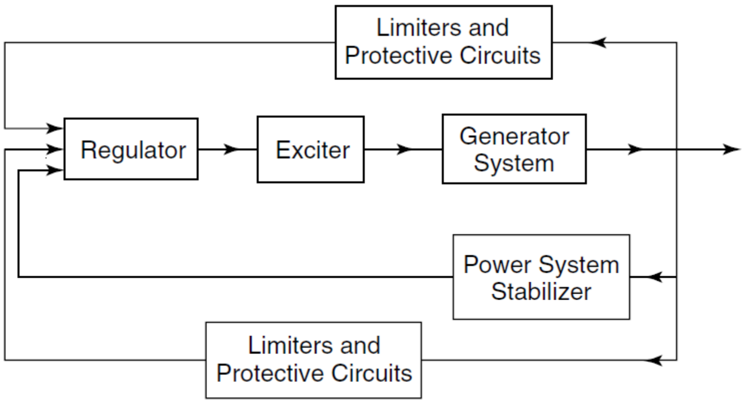


Figure 1.3 A conceptual block diagram of a modern excitation controller.

1.1.3 Transformer Tap-Changer Control

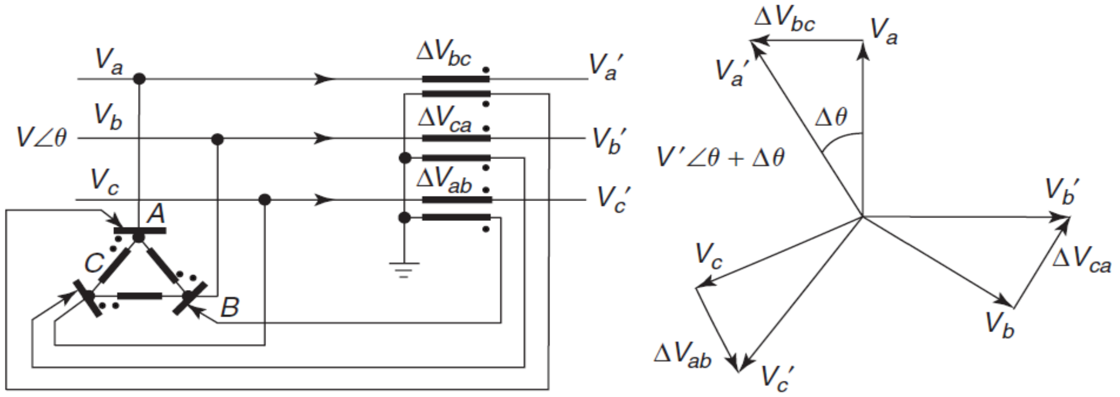
Next to the generating units, transformers constitute the second family of major power-transmission-system apparatus. In addition to increasing and decreasing nominal voltages, many transformers are equipped with tap-changers to realize a limited range of voltage control. This tap control can be carried out manually or automatically. Two types of tap changers are usually available: offload tap changers, which perform adjustments when deenergized, and on-load tap changers, which are equipped with current-commutation capacity and are operated under load. Tap changers may be provided on one of the two transformer windings as well as on autotransformers.

Because tap-changing transformers vary voltages and, therefore, the reactive power flow, these transformers may be used as reactive power control devices. On-load tap-changing transformers are usually employed to correct voltage profiles on an hourly or daily basis to accommodate load variations. Their speed of operation is generally slow, and frequent operations result in electrical and mechanical wear and tear.

1.1.4 Phase-Shifting Transformers

A special form of a 3-phase–regulating transformer is realized by combining a transformer that is connected in series with a line to a voltage transformer equipped with a tap changer. The windings of the voltage transformer are so connected that on its secondary side, phase-quadrature voltages are generated and fed into the secondary windings of the series transformer. Thus the addition of small, phase-quadrature voltage components to the phase voltages of the line creates phase-shifted output voltages without any appreciable change in magnitude. A phase-shifting transformer is therefore able to introduce a phase shift in a line. Figure 1.4 shows such an arrangement together with a phasor diagram. The phasor diagram shows the phase shift realized without an appreciable change in magnitude by the injection of phase-quadrature voltage components in a 3-phase system. When a phase-shifting transformer employs an on-load tap changer, controllable phase-shifting is achieved. The interesting aspect of such phase shifters is that despite their low MVA capacity, by controlling the phase shift they exercise a significant real-power control. Therefore, they are used to mitigate circulating power flows in interconnected utilities. A promising application of these devices is in creating active-power regulation on selected lines and securing active-power damping through the incorporation of auxiliary signals in their feedback controllers. From this description, it is easy to visualize that an incremental in-phase component can also be added in lines to alter only their voltage magnitudes, not their phase. The modification of voltage magnitudes and/or their phase by adding a control voltage is an important concept. It forms the basis of some of the new

FACTS devices discussed in this book. The injected voltage need not be realized through electromagnetic transformer–winding arrangements; instead, by using high-speed semiconductor switches such as Gate Turn-Off (GTO) thyristors, Voltage Source Inverters (VSIs) synchronized with the system frequency are produced. The application of a VSI to compensate the line voltage drop yields a new, fast, controllable reactive-power compensator: the Static Synchronous Series Compensator (SSSC). The application of a VSI to inject a phase-quadrature voltage in lines yields a new, fast, controllable phase shifter for active-power control. Once a synchronized VSI is produced, it is indeed easy to regulate both the magnitude and the phase angle of the injected voltages to yield a new, Unified Power Flow Controller (UPFC).



(b)

Figure 1.4 A phase-shifting transformer: (a) a schematic diagram and (b) a phasor diagram.

1.2 Towards a More Flexible Power Grid

A variety of technical, economical and environmental reasons affecting the generation, transmission and utilization of power are forcing a rethink on the conventional power system development philosophy. The dilemma is that, on the one hand, there is growing opposition to the acceptance of new transmission lines and ever-increasing primary transmission voltages. On the other hand, there is the realization that power system interconnections bring undisputable benefits, such as economies of scale, wider choices of generating plant, reductions in reserve capacity, diversity in demand, supply reliability, pooling opportunities, etc. Clearly an important factor in the solution is the possibility of increasing the power carrying capability of the transmission lines. In this respect conventional AC transmission is severely restricted by the need to keep the two systems interconnected by the line in synchronism following disturbances (i.e. when the phase difference between the terminal voltages increases rapidly), a condition referred to as transient stability. Therefore increases in the steady-state power carrying capability are linked to improvements in the transient stability levels, which in turn require faster controllability. Controllability and flexibility are used in power transmission as synonymous terms; in other words, greater flexibility implies greater and faster controllability. The latter has been made possible by the development of power semiconductors and their application to the control of power apparatus and systems, commonly referred to as power electronics.

1.3 Limitations of Transmission Systems

The characteristics of a given power system evolve with time, as load grows and generation is added. If the transmission facilities are not upgraded sufficiently the power system becomes vulnerable to steady-state and transient stability problems, as stability margins become narrower (Hingorani and Gyugyi, 2000).

The ability of the transmission system to transmit power becomes impaired by one or more of the following steady-state and dynamic limitations (Song and Johns, 1999):

_ angular stability;
_ voltage magnitude;
_ thermal limits;
_ transient stability;
_ dynamic stability.

These limits define the maximum electrical power to be transmitted without causing damage to transmission lines and electric equipment. In principle, limitations on power transfer can always be relieved by the addition of new transmission and generation facilities. Alternatively, FACTS controllers can enable the same objectives to be met with no major alterations to system layout. The potential benefits brought about by FACTS controllers include reduction of operation and transmission investment cost, increased system security and reliability, increased power transfer capabilities, and an overall enhancement of the quality of the electric energy delivered to customers (IEEE/CIGRE´ , 1995).

1.4 Power Electronics

Power electronics have a widely spread range of applications from electrical machine drives to excitation systems, industrial high current rectifiers for metal smelters, frequency controllers or electrical trains. FACTS-devices are just one application beside others, but use the same technology trends. It has started with the first thyristor rectifiers in 1965 and goes to the nowadays modularized IGBT or IGCT voltage source converters.

Without repeating lectures in Semiconductors or Converters, the following sections provide some basic information.

1.4.1 Semiconductors

Since the first development of a Thyristor by General Electric in 1957, the targets for power semiconductors are low switching losses for high switching rates and minimal conduction losses. The innovation in the FACTS area is mainly driven by these developments. Today, there are thyristor and transistor technologies available. Figure 1.4 shows the ranges of power and voltage for the applications of the specific semiconductors.

The Thyristor is a device, which can be triggered with a pulse at the gate and remains in the on-stage until the next current zero crossing. Therefore only one switching per half-cycle is possible, which limits the controllability. Thyristors have the highest current and blocking voltage. This means that fewer semiconductors need to be used for an application. Thyristors are used as switches for capacities or inductances, in converters for reactive power compensators or as protection switches for less robust power converters.

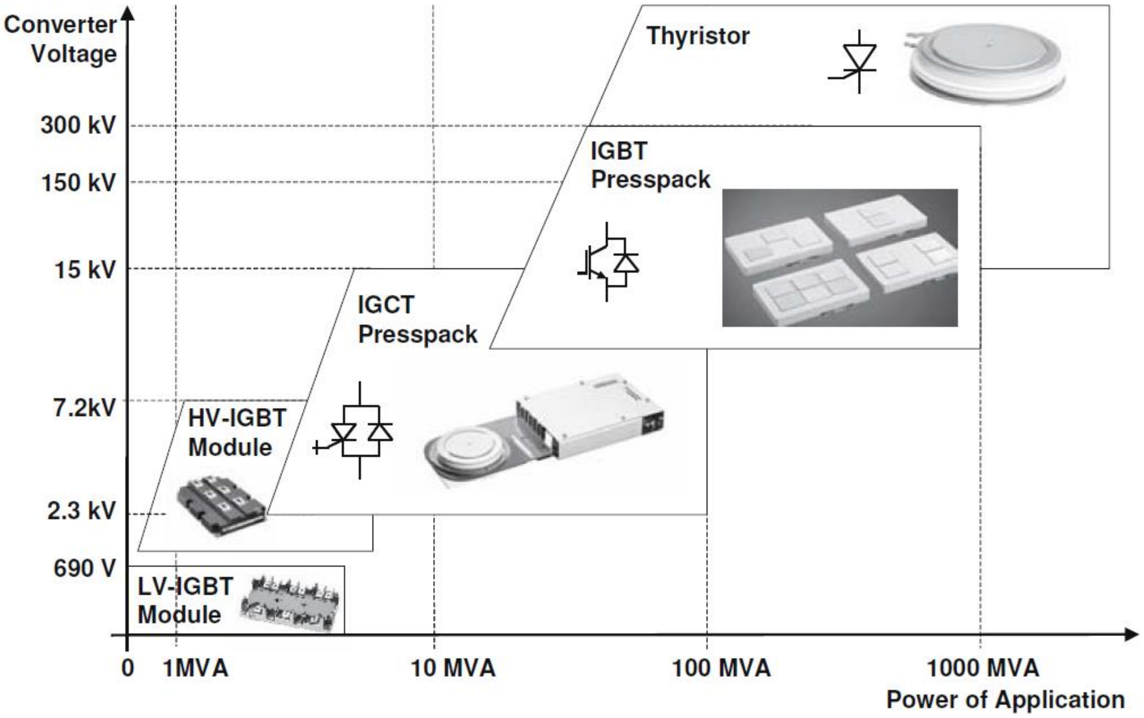


Fig. 1.4. Ranges of converter voltages and power of applications for power semiconductors

The Thyristors are still the devices for applications with the highest voltage and power levels. They are part of the mostly used FACTS-devices up to the biggest HVDC-Transmissions with a voltage level above 500 kV and power above 3000 MVA. To increase the controllability, GTO-Thyristors have been developed, which can be switched off with a voltage peak at the gate. These devices are nowadays replaced by Insulated Gate Commutated Thyristors (IGCT), which combine the advantage of the Thyristor, the low on stage losses, with low switching losses. These semiconductors are used in smaller FACTS-devices and drive applications. The Insulated Gate Bipolar Transistor (IGBT) is getting more and more importance in the FACTS area. An IGBT can be switched on with a positive voltage and switched off with a zero voltage. This allows a very simple gate drive unit to control the IGBT. The voltage and power level of the applications is on the way to grow up to 300 kV and 1000 MVA for HVDC with Voltage Source Converters.

The IGBT capability covers nowadays the whole range of power system applications. An important issue for power semiconductors is the packaging to ensure a reliable connection to the gate drive unit. This electronic circuit ensures beside the control of the semiconductor as well its supervision and protection. A development in the Thyristor area tries to trigger the Thyristor with a light signal through an optical fiber. This allows the decoupling of the Semiconductor and the gate drive unit. The advantage is that the electronic circuit can be taken out of the high electromagnetic field close to the thyristor. The disadvantage is, that the protection of the thyristor has to be implemented in the thyristor itself, which leads to an extremely complex component. A supervision of the thyristor by the gate drive unit is as well impossible in this case, which leads to disadvantages for the entire converter.

A second issue for the packing is the stacking of the semiconductor devices. A number of devices need to be stacked to achieve the required voltage level for the power system application. A mechanically stable packaging needs to ensure an equal current distribution in the semiconductor.

1.4.2 Power Converters

Starting with the Thyristor, it can be used most simply as a switch. Thyristor switched capacities or inductances are possible applications. In this half-bridge the Thyristors can be triggered once in a half-cycle. The next zero crossing will block the Thyristor. In an ideal case, where the feeding inductance on the DC side is infinity, the output AC current is rectangular, which means it has a high harmonic content. But due the small number of switchings, the switching losses are low. The operational diagram is a half cycle, which means, that the active power flow can be controlled, but the reactive power is fixed with a certain ratio.

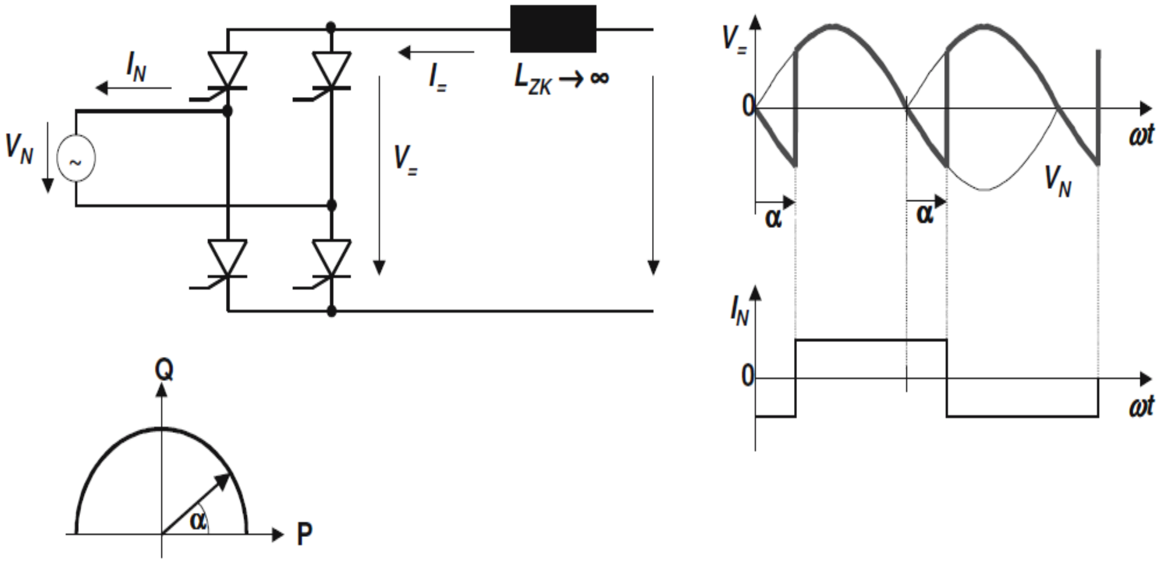


Fig. 1.5. Thyristor half-bridge converter and operational diagram

To overcome these disadvantages for FACTS-applications, where the controllability as well of reactive power is a prime target, on and off switchable devices must be used. Figure 1.5 (a) shows a half bridge with IGBTs. The same setup is valid as well for GTO-Thyristors or IGCTs.

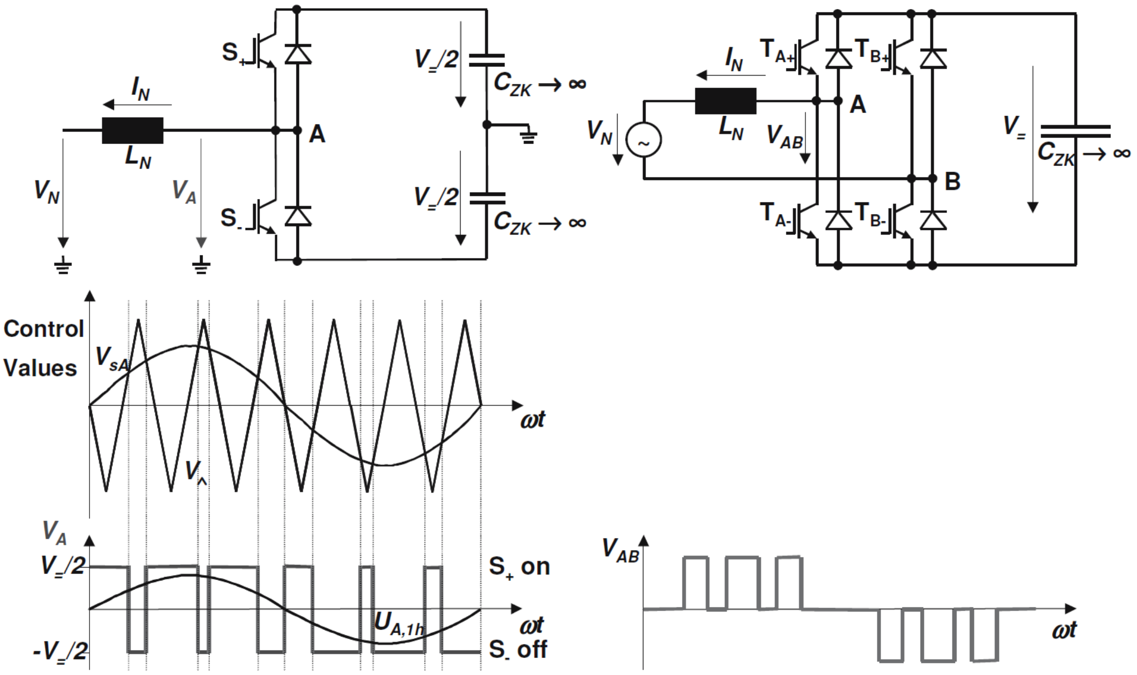


Fig. 1.6. 2-Level voltage source converter with pulse width modulation,
a) Half-bridge, b) TWIN-circuit

A suitable switching pattern must be defined for the switch-on-and-off capability. The simplest solution is the combination of a triangular voltage with a reference voltage as control values. The changing sign of the difference of both signals triggers the IGBTs alternately. The output voltage is jumping between both maximums. With an increasing number of switchings the harmonic content is decreasing. Fig 1.6 (b) shows a TWIN converter uses two IGBT bridges. The output is the voltage between the midpoints. Three stages, plus, minus and zero, are now possible and reducing the harmonics further. This pattern can be achieved as well with a three level converter, where four IGBT and six diodes are used in the simple bridge. While the increasing number of switching reduces the harmonics, the switching losses are increasing. For practical applications a compromise between harmonics, which means output filtering, and losses must be found. For HVDC converters, the losses of one converter station are around 1% for Thyristor converters and a little above 2% for IGBT Voltage Source Converters. A switching pattern of an IGBT 2-level converter is shown in Figure 1.7. A special switching scheme, called harmonic cancellation, is applied here. During some time intervals the switching is interrupted to reduce harmonics.

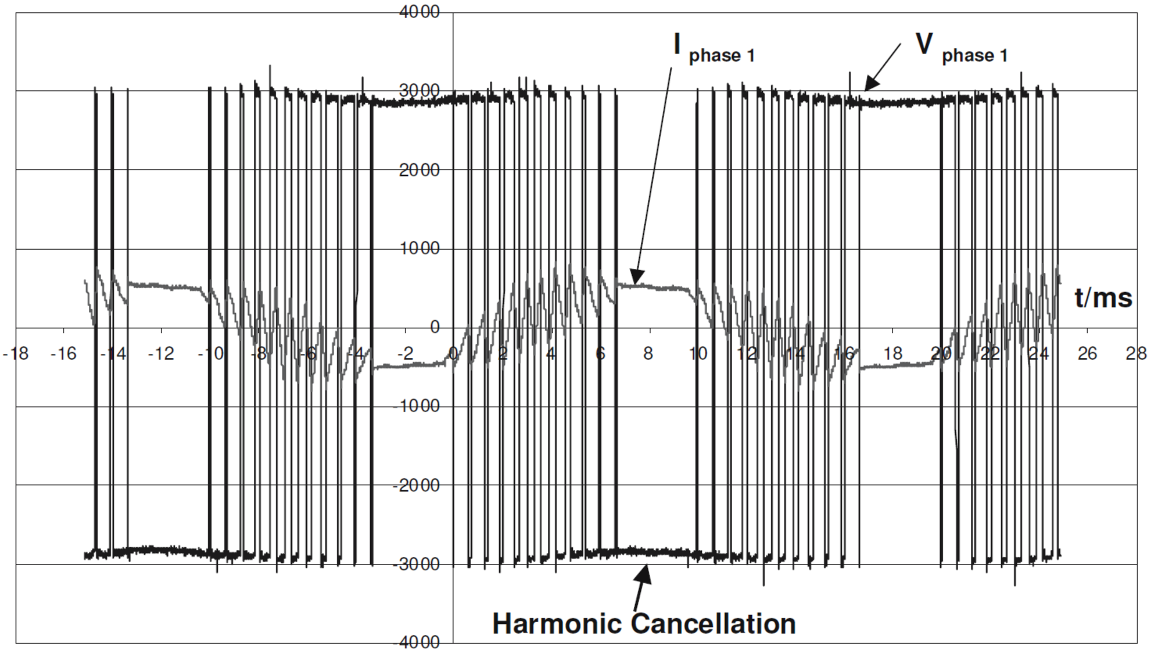


Fig. 1.7. Output current and voltage of 2-level voltage source converter with pulse width modulation and harmonic cancellation, modulation frequency 21 f

More complex converters are proposed in the literature, but the number of semiconductor elements increases the cost more than loss or harmonic reduction would justify.

1.5 Introduction of FACTS devices

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. Particularly with the deregulation of the electricity market, there is an increasing interest in using FACTS devices in the operation and control of power systems with new loading and power flow conditions. A better utilization of the existing power systems to increase their capacities and controllability by installing FACTS devices becomes imperative. Due to the present situation, there are two main aspects that should be considered in using FACTS devices: The first aspect is the flexible power system operation according to the power flow control capability of FACTS devices. The other aspect is the improvement of transient and steady-state stability of power systems.

Definition of FACTS

Flexible AC Transmission Systems (FACTS) is a technology that responds to needs of dynamic control of voltage, impedance and phase angle of high voltage AC lines.

The ability to accommodate changes in the electric transmission Systems or operating conditions while maintaining sufficient steady state and transient margins

Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.

1.5.1 Types of FACTS Devices

The various types of FACTS devices are listed below:

- Static Shunt Compensators
- Static Series Compensators
- Combined Compensators

Static Shunt Compensators

- Static Var Compensator (SVC)
- Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR)
- Thyristor-Switched Capacitor (TSC)
- STATCOM

Static Series Compensators

- Thyristor-Switched Series Capacitor (TSSC)
- Thyristor-Controlled Series Capacitor (TCSC)
- GTO Thyristor-Controlled Series Capacitor (GCSC)
- Static Synchronous Series Compensator (SSSC)
- Phase Angle Regulator (PAR)

Combined Compensators

- Interline Power Flow Controller (IPFC)
- Unified Power Flow Controller (UPFC)

FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations.The basic applications of FACTS-devices are:

- power flow control
- increase of transmission capability
- voltage control
- reactive power compensation
- stability improvement
- power quality improvement
- power conditioning
- flicker mitigation
- interconnection of renewable and distributed generation and storages.

In all applications the practical requirements, needs and benefits have to be considered carefully to justify the investment into a complex new device. Fig 1.9 shows the basic idea of FACTS for transmission systems. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different FACTS devices. It can be seen that with growing line length, the opportunity for FACTS devices gets more and more important.

The influence of FACTS-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction times down to far below one second.

In the following a structured overview on FACTS-devices is given. These devices are mapped to their different fields of applications.

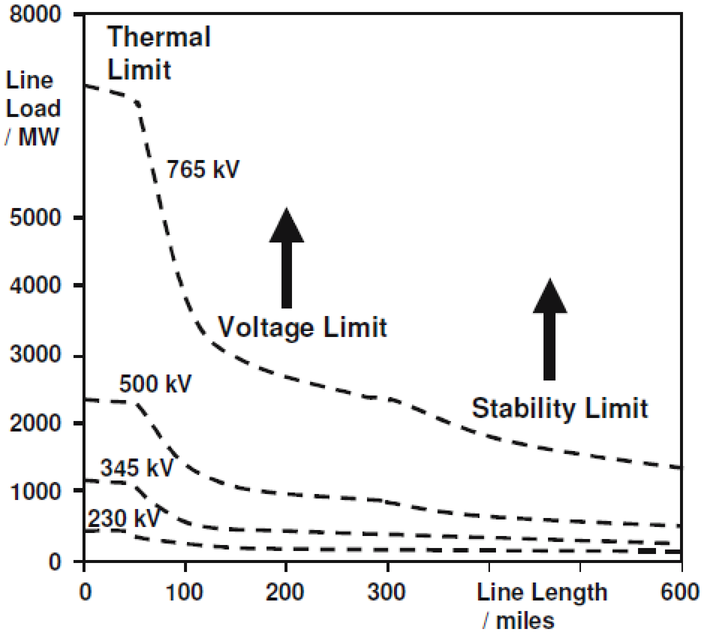


Fig. 1.8 Operational limits of transmission lines for different voltage levels

1.5.2 Overview of FACTS

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. Figure 1.9 shows a number of basic devices separated into the conventional ones and the FACTS-devices.

For the FACTS side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of FACTS-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS devices can equally be static and dynamic.
Figure 1.9 contains the conventional devices build out of fixed or mechanically switchable components like resistance, inductance or capacitance together with transformers. The FACTS-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of FACTS-devices uses Thyristor valves or converters. These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the Thyristors to simply bridge impedances in the valves.

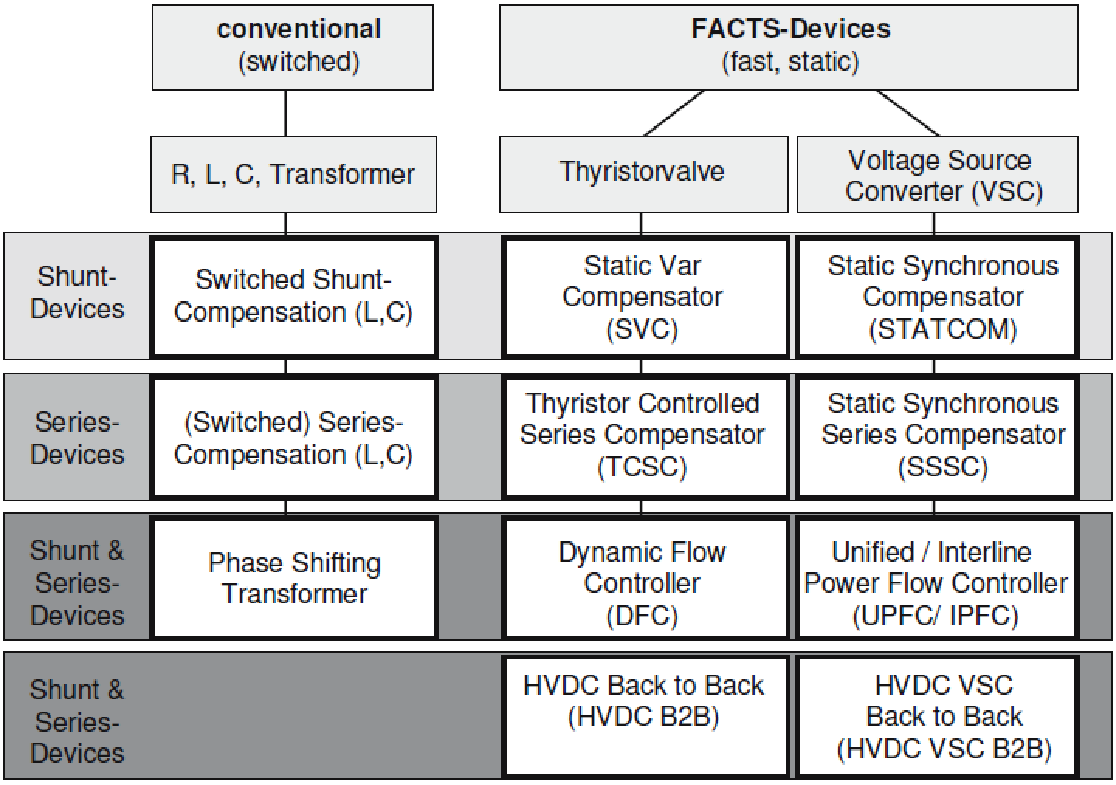


Fig. 1.9. Overview of major FACTS-Devices

FACTS-devices contains more advanced technology of voltage source converters based today mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the IGBTs or IGCTs. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore special designs of the converters are required to compensate this.

In each column the elements can be structured according to their connection to the power system. The shunt devices are primarily for reactive power compensation and therefore voltage control. The SVC provides in comparison to the mechanically switched compensation a smoother and more precise control. It improves the stability of the network and it can be adapted instantaneously to new situations. The STATCOM goes one step further and is capable of improving the power quality against dips and flickers.

The series devices are compensating reactive power. With their influence on the effective impedance on the line they have an influence on stability and power flow. These devices are installed on platforms in series to the line. Most manufacturers count series compensation, which is usually used in a fixed configuration, as a FACTS-device. The reason is, that most parts and the system setup require the same knowledge as for the other FACTS-devices. In some cases the series compensator is protected with a thyristor-bridge. The application of the TCSC is primarily for damping the inter-area oscillations and therefore stability improvement, but it has as well a certain influence on the power flow.

The SSSC is a device which has so far not been build on transmission level because Series Compensation and TCSC are fulfilling all the today's requirements more cost efficient. But series applications of Voltage Source Converters have been implemented for power quality applications on distribution level for instance to secure factory infeeds against dips and flicker. These devices are called Dynamic Voltage Restorer (DVR) or Static Voltage Restorer (SVR).

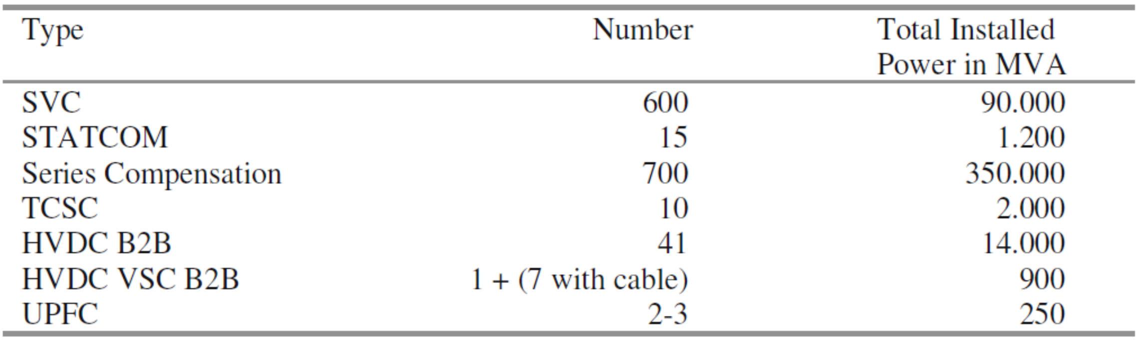
More and more growing importance are getting the FACTS-devices in shunt and series configuration. These devices are used for power flow controllability. The higher volatility of power flows due to the energy market activities requires a more flexible usage of the transmission capacity. Power flow control devices shift power flows from overloaded parts of the power system to areas with free transmission capability.

Phase Shifting Transformers (PST) are the most common device in this sector. Their limitation is the low control speed together with a high wearing and maintenance for frequent operation. As an alternative with full and fast controllability, the Unified Power Flow Controller (UPFC) is known since several years mainly in the literature and but as well in some test installations. The UPFC provides power flow control together with independent voltage control. The main disadvantage of this device is the high cost level due to the complex system setup. The relevance of this device is given especially for studies and research to figure out the requirements and benefits for a new FACTS-installation. All simpler devices can be derived from the UPFC if their capability is sufficient for a given situation. Derived from the UPFC there are even more complex devices called Interline Power Flow Controller (IPFC) and Generalized Unified Power Flow Controller (GUPFC) which provide power flow controllability in more than one line starting from the same substation. Between the UPFC and the PST there was a gap for a device with dynamic power flow capability but with a simpler setup than the UPFC. The Dynamic Power Flow Controller (DFC) was introduced recently to fill this gap. The combination of a small PST with Thyristor switched capacitors and inductances provide the dynamic controllability over parts of the control range. The practical requirements are fulfilled good enough to shift power flows in market situations and as well during contingencies.

The last line of HVDC is added to this overview, because such installations are fulfilling all criteria to be a FACTS-device, which is mainly the full dynamic controllability. HVDC Back-to-Back systems allow power flow controllability while additionally decoupling the frequency of both sides. While the HVDC Back-to- Back with Thyristors only controls the active power, the version with Voltage Source Converters allows additionally a full independent controllability of reactive power on both sides. Such a device ideally improves voltage control and stability together with the dynamic power flow control. For sure HVDC with Thyristor or Voltage Source Converters together with lines or cables provide the same functionality and can be seen as very long FACTS-devices.

FACTS-devices are usually perceived as new technology, but hundreds of installations worldwide, especially of SVC since early 1970s with a total installed power of 90.000 MVAr, show the acceptance of this kind of technology. Table 1.1 shows the estimated number of worldwide installed FACTS devices and the estimated total installed power. Even the newer developments like STATCOM or TCSC show a quick growth rate in their specific application areas.

Table 1.1. Estimated number of worldwide installed FACTS-devices and their estimated total installed power



Type	Number	Total Installed Power in MVA
SVC	600	90.000
STATCOM	15	1.200
Series Compensation	700	350.000
TCSC	10	2.000
HVDC B2B	41	14.000
HVDC VSC B2B	1 + (7 with cable)	900
UPFC	2-3	250

1.6 Configurations of FACTS-Devices

1.6.1 Shunt Devices

The most used FACTS-device is the SVC or the version with Voltage Source Converter called STATCOM. These shunt devices are operating as reactive power compensators.

The main applications in transmission, distribution and industrial networks are

- reduction of unwanted reactive power flows and therefore reduced network losses,
- keeping of contractual power exchanges with balanced reactive power
- compensation of consumers and improvement of power quality especially with huge demand fluctuations like industrial machines, metal melting plants, railway or underground train systems
- compensation of Thyristor converters e.g. in conventional HVDC lines
- improvement of static or transient stability.

Almost half of the SVC and more than half of the STATCOMs are used for industrial applications. Industry as well as commercial and domestic groups of users require power quality. Flickering lamps are no longer accepted, nor are interruptions of industrial processes due to insufficient power quality. For example demands for increased steel production and rules for network disturbances have, together with increasing cost of energy, made reactive power compensation a requirement in the steel industry. A special attention is given to weak network connections with severe voltage support problems.

A steel melting process demands a stable and steady voltage support for the electric arc furnace. With dynamic reactive power compensation, the random voltage variations characterized by an arc furnace are minimized. The minimized voltage variations are achieved by continuously compensating the reactive power consumption from the arc furnace. The result is an overall improvement of the furnace operation, which leads to better process and production economy.

Railway or underground systems with huge load variations require SVCs or STATCOMs similar to the application above. SVC or STATCOM for even stricter requirements on power quality are used in other kinds of critical factory processes, like electronic or semiconductor productions.

A growing area of application is the renewable or distributed energy sector. Especially offshore wind farms with its production fluctuation have to provide a balanced reactive power level and keep the voltage limitations within the wind farm, but as well on the interconnection point with the main grid. A lot distributed generation devices are interconnected with the grid through a voltage source converter similar to the STATCOM fulfilling all requirements on a stable network operation.

16.1.1 SVC

Electrical loads both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations or even a voltage depression, at the extreme a voltage collapse. A rapidly operating Static Var Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system conditions and thereby improve the power system transmission and distribution stability. Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. In addition an SVC can mitigate active power oscillations through voltage amplitude modulation.
SVC installations consist of a number of building blocks. The most important is the Thyristor valve, i.e. stack assemblies of series connected anti-parallel Thyristors to provide controllability. Air core reactors and high voltage AC capacitors are the reactive power elements used together with the Thyristor valves. The stepup connection of this equipment to the transmission voltage is achieved through a power transformer. The Thyristor valves together with auxiliary systems are located indoors in an SVC building, while the air core reactors and capacitors, together with the power transformer are located outdoors.

In principle the SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR / TCR). The coordinated control of a combination of these branches varies the reactive power as shown in Figure 1.10. The first commercial SVC was installed in 1972 for an electric arc furnace. On transmission level the first SVC was used in 1979. Since then it is widely used and the most accepted FACTS-device.

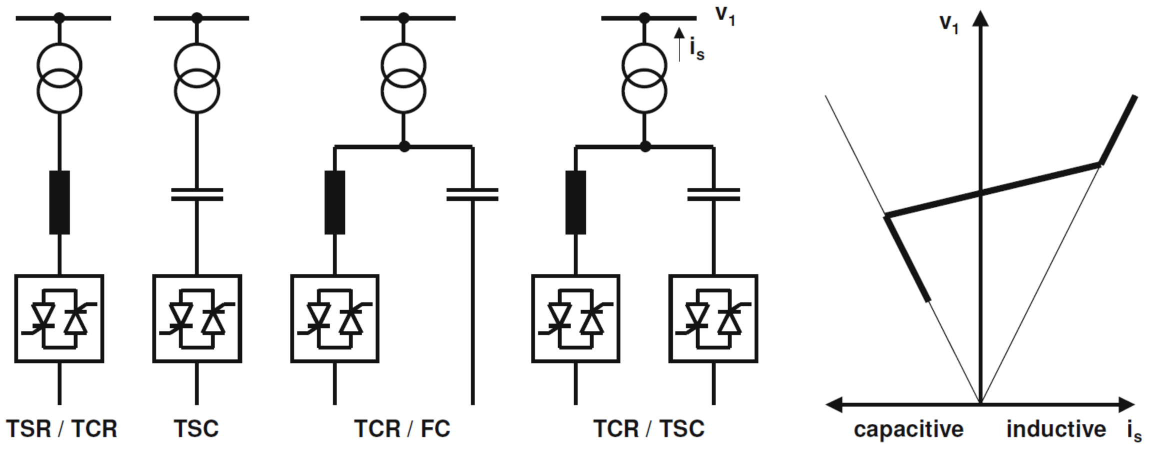


Fig. 1.10. SVC building blocks and voltage / current characteristic

1.6.1.2 STATCOM

In 1999, the first SVC with Voltage Source Converter called STATCOM (STATic COMpensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs.

A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The structure and operational characteristic is shown in Figure 1.11. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage. The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC in Figure 1.10. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

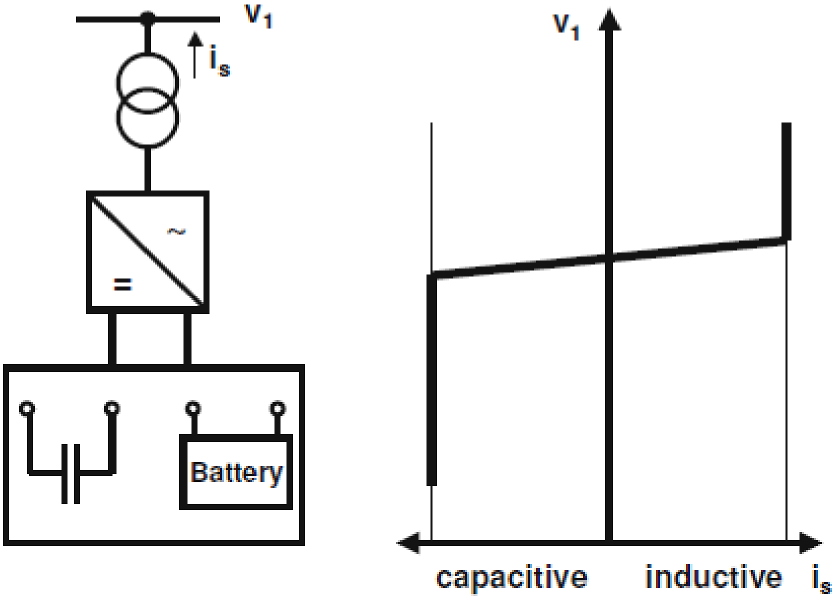


Fig. 1.11. STATCOM structure and voltage / current characteristic

In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

1.6.2. Series Devices

Series devices have been further developed from fixed or mechanically switched compensations to the Thyristor Controlled Series Compensation (TCSC) or even Voltage Source Converter based devices. The main applications are:

- reduction of series voltage decline in magnitude and angle over a power line
- reduction of voltage fluctuations within defined limits during changing power transmissions
- improvement of system damping
- limitation of short circuit currents in networks or substations
- avoidance of loop flows

1.6.2.1 Series Compensation

The world's first series compensation on transmission level, counted nowadays by the manufacturers as a FACTS-device, went into operation in 1950. Series Compensation is used in order to decrease the transfer reactance of a power line at rated frequency. A series capacitor installation generates reactive power that in a self-regulating manner balances a fraction of the line's transfer reactance. The result is that the line is electrically shortened, which improves angular stability, voltage stability and power sharing between parallel lines.

Series Capacitors are installed in series with a transmission line, which means that all the equipment has to be installed on a fully insulated platform. On this steel platform the main capacitor is located together with the overvoltage protection circuits. The overvoltage protection is a key design factor, as the capacitor bank has to withstand the throughput fault current, even at a severe nearby fault. The primary overvoltage protection typically involves non-linear varistors of metal-oxide type, a spark gap and a fast bypass switch. Secondary protection is achieved with ground mounted electronics acting on signals from optical current transducers in the high voltage circuit. Even if the device is known since several years, improvements are ongoing. One recent achievement is the usage of dry capacitors with a higher energy density and higher environmental friendliness. As a primary protection Thyristor switches can be used, but cheaper alternatives with almost the same capability based on triggered spark gaps and special breakers without power electronics have recently been developed.

A special application of Series Compensation can be achieved by combining it with a series reactance to get a fault current limiter. Both components are neutralizing each other in normal operation. In the case of a fault, die Series Compensation is bridged with a fast protection device or a Thyristor bridge. The remaining reactance is limiting the fault current.

1.6.2.2 TCSC

Thyristor Controlled Series Capacitors (TCSC) address specific dynamical problems in transmission systems. Firstly it increases damping when large electrical systems are interconnected. Secondly it can overcome the problem of Sub- Synchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems.

The TCSC's high speed switching capability provides a mechanism for controlling line power flow, which permits increased loading of existing transmission lines, and allows for rapid readjustment of line power flow in response to various contingencies. The TCSC also can regulate steady-state power flow within its rating limits.

From a principal technology point of view, the TCSC resembles the conventional series capacitor. All the power equipment is located on an isolated steel platform, including the Thyristor valve that is used to control the behavior of the main capacitor bank. Likewise the control and protection is located on ground potential together with other auxiliary systems. Figure 1.12 shows the principle setup of a TCSC and its operational diagram. The firing angle and the thermal limits of the Thyristors determine the boundaries of the operational diagram.

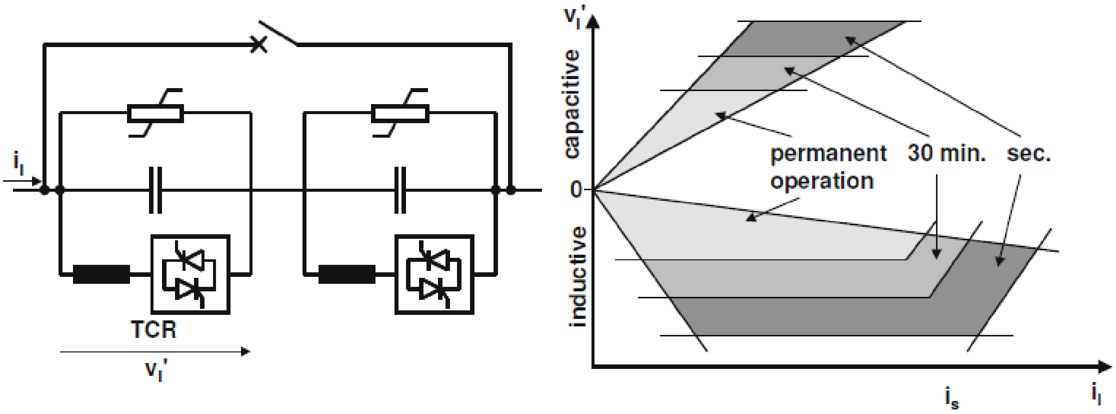


Fig. 1.12. Principle setup and operational diagram of a Thyristor Controlled Series Compensation (TCSC)

The main principles of the TCSC concept are two; firstly, to provide electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line, i.e. the TCSC will provide a variable capacitive reactance. Secondly, the TCSC shall change its apparent impedance (as seen by the line current) for sub-synchronous frequencies, such that a prospective subsynchronous resonance is avoided. Both objectives are achieved with the TCSC, using control algorithms that work concurrently. The controls will function on the Thyristor circuit in parallel to the main capacitor bank such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency but a “virtual inductor” at sub-synchronous frequencies.

16.2.3 SSSC

While the TCSC can be modeled as a series impedance, the SSSC is a series voltage source. The principle configuration is shown in Figure 1.13, which looks basically the same as the STATCOM. But in reality this device is more complicated because of the platform mounting and the protection. A Thyristor protection is absolutely necessary, because of the low overload capacity of the semiconductors, especially when IGBTs are used.

The voltage source converter plus the Thyristor protection makes the device much more costly, while the better performance cannot be used on transmission level. The picture is quite different if we look into power quality applications. This device is then called Dynamic Voltage Restorer (DVR). The DVR is used to keep the voltage level constant, for example in a factory infeed. Voltage dips and flicker can be mitigated. The duration of the action is limited by the energy stored in the DC capacitor. With a charging mechanism or battery on the DC side, the device could work as an uninterruptible power supply.

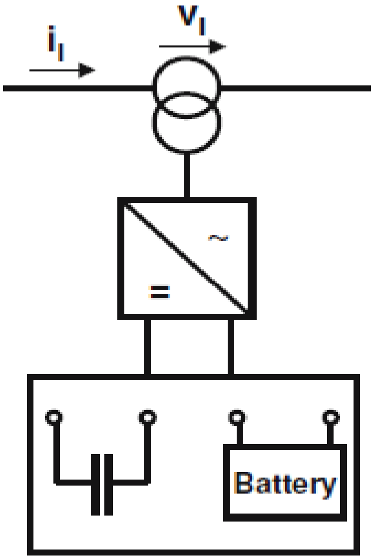


Fig. 1.13. Principle setup of SSSC

1.7 Shunt and Series Devices

Power flow capability is getting more and more importance with the growing restrictions for new power lines and the more volatile power flow due to the energy market activities.

1.7.1 Dynamic Flow Controller

A new device in the area of power flow control is the Dynamic Power Flow Controller (DFC). The DFC is a hybrid device between a Phase Shifting Transformer (PST) and switched series compensation. A functional single line diagram of the Dynamic Flow Controller is shown in Figure 1.14. The Dynamic Flow Controller consists of the following components:

- a standard phase shifting transformer with tap-changer (PST)
- series-connected Thyristor Switched Capacitors and Reactors (TSC / TSR)
- A mechanically switched shunt capacitor (MSC). (This is optional depending on the system reactive power requirements)

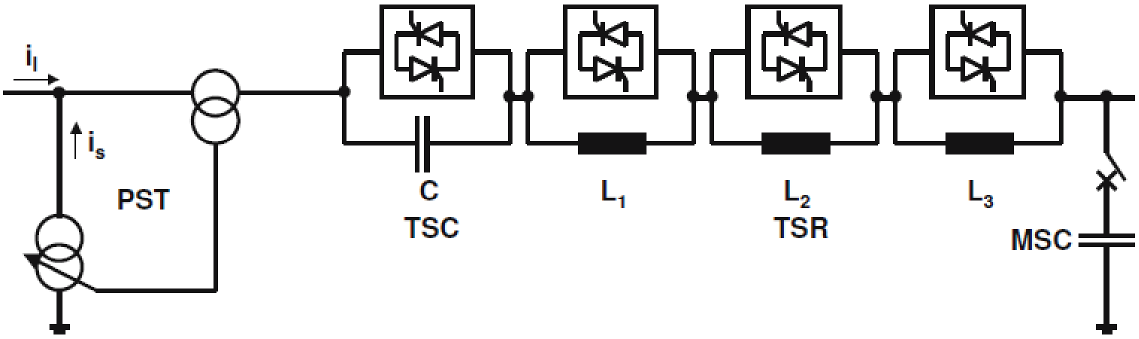


Fig. 1.14. Principle configuration of DFC

Based on the system requirements, a DFC might consist of a number of series TSC or TSR. The mechanically switched shunt capacitor (MSC) will provide voltage support in case of overload and other conditions. Normally the reactances of reactors and the capacitors are selected based on a binary basis to result in a desired stepped reactance variation. If a higher power flow resolution is needed, a reactance equivalent to the half of the smallest one can be added.

The switching of series reactors occurs at zero current to avoid any harmonics. However, in general, the principle of phase-angle control used in TCSC can be applied for a continuous control as well. The operation of a DFC is based on the following rules:

- TSC / TSR are switched when a fast response is required.
- The relieve of overload and work in stressed situations is handled by the TSC / TSR.
- The switching of the PST tap-changer should be minimized particularly for the currents higher than normal loading.

The total reactive power consumption of the device can be optimized by the operation of the MSC, tap changer and the switched capacitors and reactors. In order to visualize the steady state operating range of the DFC, we assume an inductance in parallel representing parallel transmission paths. The overall control objective in steady state would be to control the distribution of power flow between the branch with the DFC and the parallel path. This control is accomplished by control of the injected series voltage.

The PST (assuming a quadrature booster) will inject a voltage in quadrature with the node voltage. The controllable reactance will inject a voltage in quadrature with the current. Assuming that the power flow has a load factor close to one, the two parts of the series voltage will be close to linear. However, in terms of speed control, influence on reactive power balance and effectiveness at high/low loading the two parts of the series voltage has quite different characteristics. The steady state control range for loadings up to rated current is illustrated in Figure 1.15, where the x-axis corresponds to the throughput current and the y-axis corresponds to the injected series voltage.

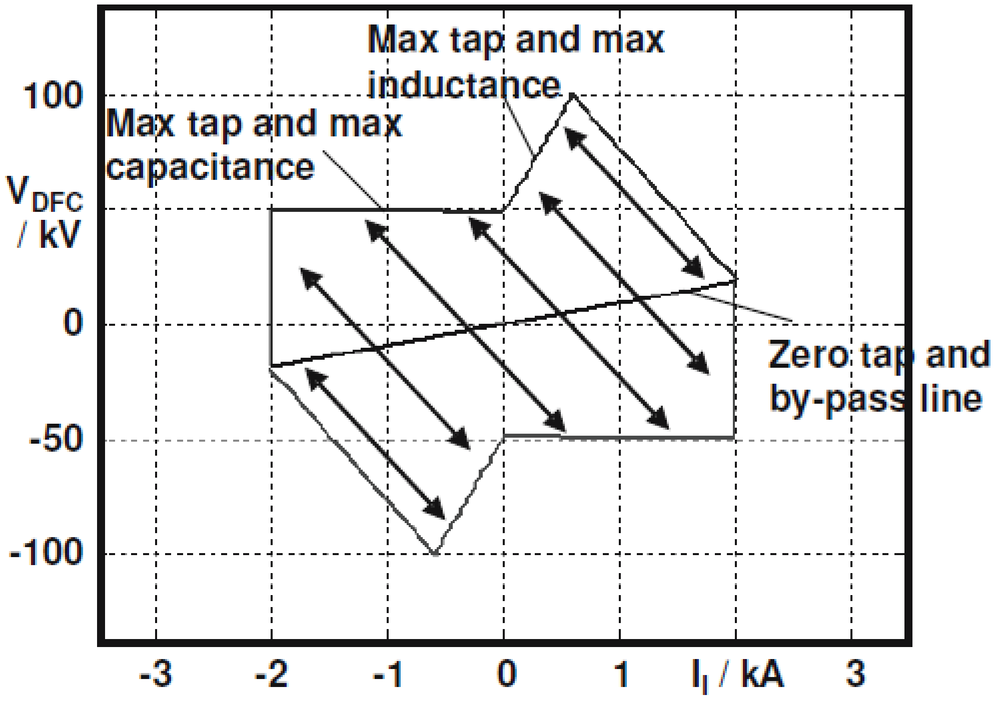


Fig. 1.15. Operational diagram of a DFC

Operation in the first and third quadrants corresponds to reduction of power through the DFC, whereas operation in the second and fourth quadrants corresponds to increasing the power flow through the DFC. The slope of the line passing through the origin (at which the tap is at zero and TSC / TSR are bypassed) depends on the short circuit reactance of the PST.

Starting at rated current (2 kA) the short circuit reactance by itself provides an injected voltage (approximately 20 kV in this case). If more inductance is switched in and/or the tap is increased, the series voltage increases and the current through the DFC decreases (and the flow on parallel branches increases). The operating point moves along lines parallel to the arrows in the figure. The slope of these arrows depends on the size of the parallel reactance. The maximum series voltage in the first quadrant is obtained when all inductive steps are switched in and the tap is at its maximum.

Now, assuming maximum tap and inductance, if the throughput current decreases (due e.g. to changing loading of the system) the series voltage will decrease. At zero current, it will not matter whether the TSC / TSR steps are in or out, they will not contribute to the series voltage. Consequently, the series voltage at zero current corresponds to rated PST series voltage. Next, moving into the second quadrant, the operating range will be limited by the line corresponding to maximum tap and the capacitive step being switched in (and the inductive steps by-passed). In this case, the capacitive step is approximately as large as the short circuit reactance of the PST, giving an almost constant maximum voltage in the second quadrant.

1.7.2 Unified Power Flow Controller

The UPFC is a combination of a static compensator and static series compensation. It acts as a shunt compensating and a phase shifting device simultaneously.

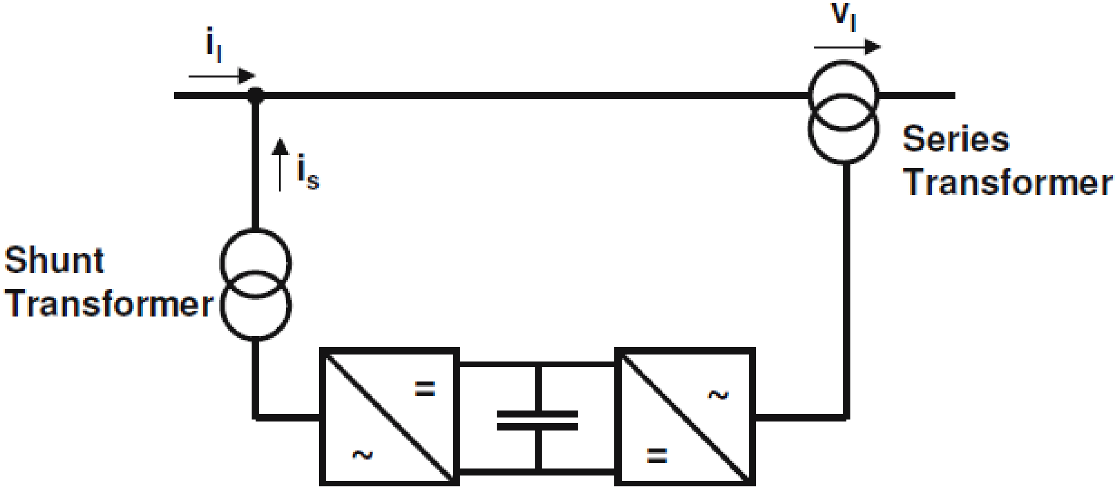


Fig. 1.16. Principle configuration of an UPFC

The UPFC consists of a shunt and a series transformer, which are connected via two voltage source converters with a common DC-capacitor. The DC-circuit allows the active power exchange between shunt and series transformer to control the phase shift of the series voltage. This setup, as shown in Figure 1.16, provides the full controllability for voltage and power flow. The series converter needs to be protected with a Thyristor bridge. Due to the high efforts for the Voltage Source Converters and the protection, an UPFC is getting quite expensive, which limits the practical applications where the voltage and power flow control is required simultaneously.

1.7.3 Interline Power Flow Controller

One of the latest FACTS-devices is named Convertible Static Compensator (CSC) and was recently installed as a pilot by the New York Power Authority (NYPA). The CSC-project shall increase power transfer capability and maximise the use of the existing transmission network. Within the general conceptual framework of the CSC, two multi-converter FACTS-devices, the Interline Power Flow Controller (IPFC) and the Generalized Unified Power Flow Controller (GUPFC), are among many possible configurations. The target is to control power flows of multi-lines or a subnetwork rather than control the power flow of a single line by for instance DFC or UPFC. The IPFC combines two or more series converters and the GUPFC combines one shunt converter and two or more series converters. The current NYPA's CSC installation is a two converter one and can operate as an IPFC but not as a GUPFC.

When the power flows of two lines starting in one substation need to be controlled, an Interline Power Flow Controller (IPFC) can be used. The IPFC consists of two series VSCs whose DC capacitors are coupled. This allows active power to circulate between the VSCs. Figure 1.17 shows the principle configuration of an IPFC. With this configuration two lines can be controlled simultaneously to optimize the network utilization. In general, due to its complex setup, specific application cases need to be identified justifying the investment.

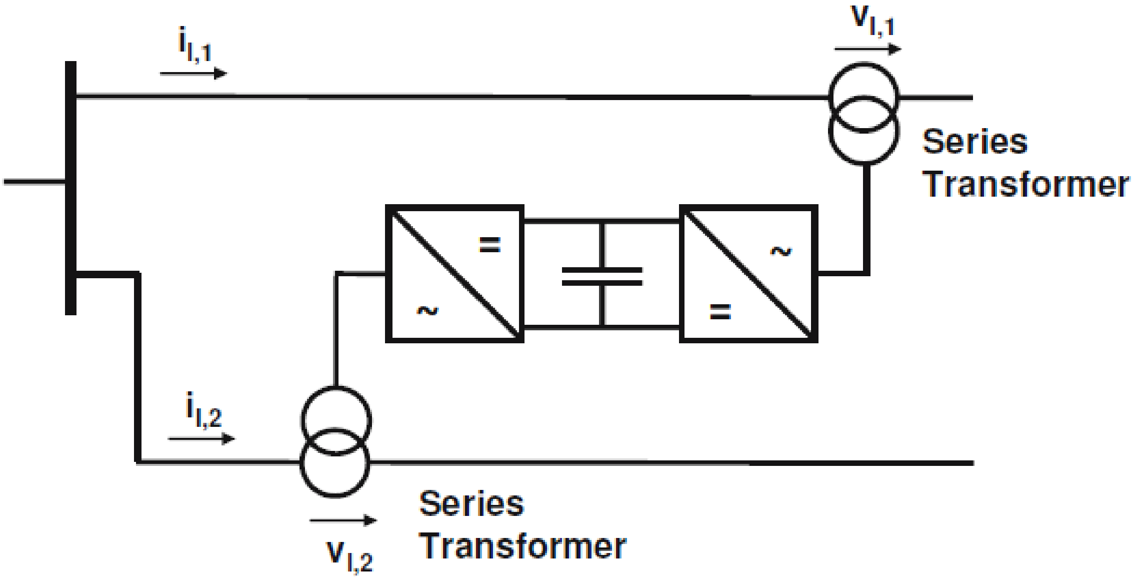


Fig. 1.17. Principle configuration of an IPFC

1.7.4 Generalized Unified Power Flow Controller

The GUPFC combines three or more shunt and series converters. It extends the concept of voltage and power flow control beyond what is achievable with the known two-converter UPFC. The simplest GUPFC consists of three converters, one connected in shunt and the other two in series with two transmission lines in a substation. Figure 1.18 shows the principle configuration. The basic GUPFC can control total five power system quantities such as a bus voltage and independent active and reactive power flows of two lines.

The concept of GUPFC can be extended for more lines if necessary. The device may be installed in some central substations to manage power flows of multi-lines or a group of lines and provide voltage support as well. By using GUPFC-devices, the transfer capability of transmission lines can be increased significantly. Further more, by using the multi-line management capability of the GUPFC, active power flows on lines can not only be increased, but also be decreased with respect to operating and market transaction requirements. In general the GUPFC can be used to increase transfer capability and relieve congestions in a flexible way. The complexity of its configuration and control scheme needs specific applications cases.

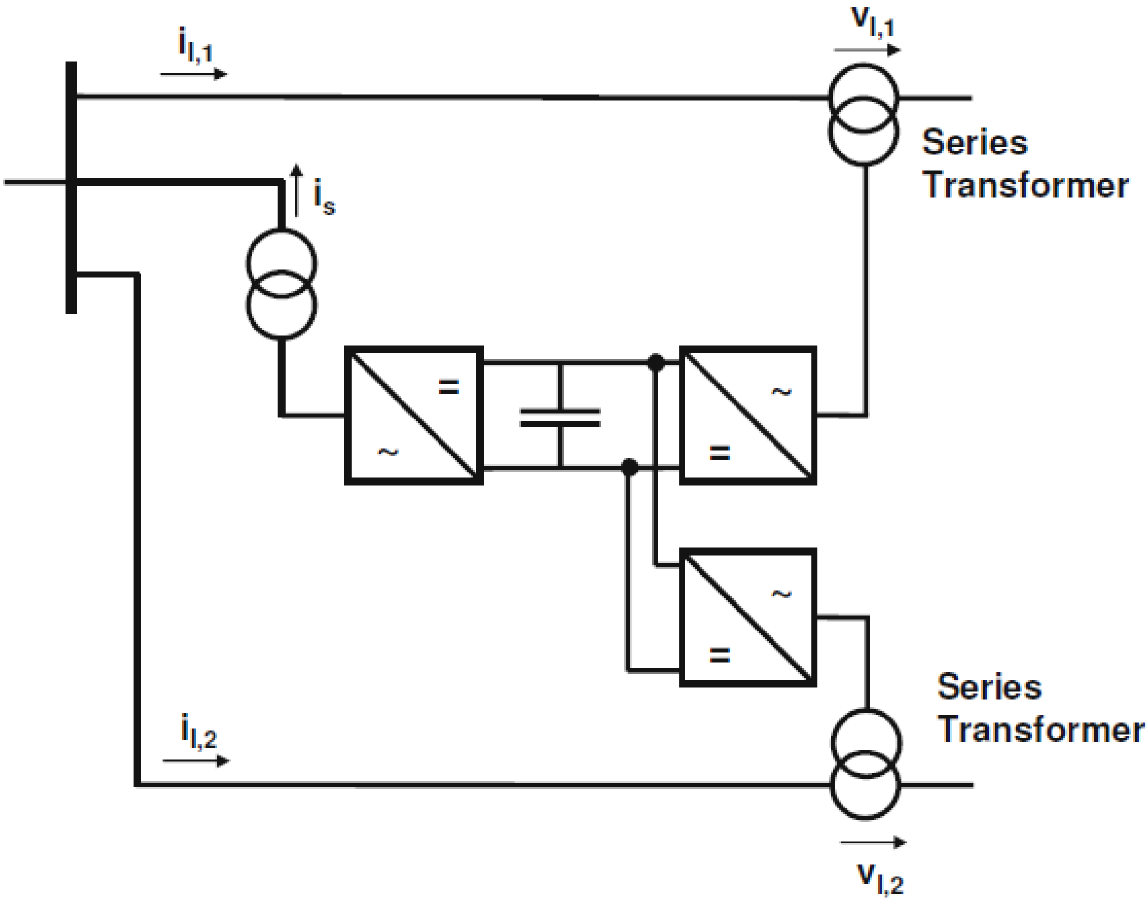


Fig. 1.18. Principle configuration of a GUPFC

1.8 Back-to-Back Devices

The Back-to-Back devices provide in general a full power flow controllability and power flow limitation. An overload of these devices is therefore impossible. They can resist cascading outages, which might occur due to line outages when one line after the other is overloaded. This gives a great benefit even if the frequency decoupling characteristic is not needed.

Conventional HVDC Back-to-Back systems with Thyristor converters need space consuming filters to reduce the harmonic distortion. The reactive power is not controllable. These devices are mainly used when two asynchronous networks need to be coupled or in the usual application as power transmission line over long distances.

The HVDC with voltage source converters instead provides benefits as well within synchronous operated networks. It has a much smaller footprint and provides the full voltage controllability to the network on both ends. Therefore it can be operated in addition to the power flow control as two STATCOMS. On both ends a full four quadrant circular operational diagram is provided. This reactive power provision can be used to increase the transmission capability of surrounding transmission lines in addition to balancing the power flow. Figure 1.24 shows the principle configuration of a HVDC Back-to-Back with Voltage Source Converters. A practical implementation is shown in Figure 1.19, which is based on the design of two STATCOM converters with IGBTs.

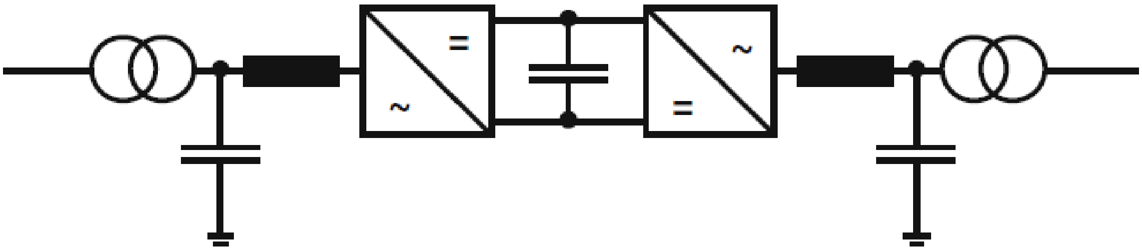


Fig. 1.19. Schematic configuration of a HVDC Back-to-Back with Voltage Source Converters

1.9 Converter Based FACTS

The purpose of this section is to briefly describe and define various converter-based FACTS devices (voltage and current injection systems). It is worthy of mention here that for converter-based devices there are two principal types of converters, these are Voltage Source Converters and Current Source Converters. However, the first one seems to be more favored from an overall point of view and therefore will form the basis for presentation of the entire converter-based FACTS devices. Generally, FACTS devices can be divided into three major categories:
series devices;
shunt devices;
combined devices

As a series device a variable impedance (capacitor, reactor etc.) or power electronics based variable source which injects voltage in series with the line, could be utilized. When injected voltage is in phase quadrature with the line current, the series source exchanges (supplies or consumes) only reactive power and thus predominantly affects the active power in the line. From the other side if injected voltage is in phase with the line current, the series source handles (supplies or consumes) active power but predominantly affects the reactive power in the line. However, in the last case an external source of the active power is needed (it could be an Energy Storage System (ESS) or shunt connected variable source). As a shunt device the variable impedance (capacitor, reactor etc.) or variable source which injects current into the system at the point of common coupling may be utilized. As in the case of series devices, if injected current is in phase quadrature with the line voltage, the shunt device exchanges only reactive power with the line. Other phase relationships will also cause active power exchange. But this time there is no need for an extra source, because a shunt connected source can produce active power itself.

As a combined device unified series and shunt variable sources may be utilized (UPFC). In this type of device current is injected into the system with the shunt part, and voltage with the series part. Because both parts are unified, there can be a real power exchange between parts through the power link. As combined devices also unified series-series and unified series-series-shunt variable sources which are connected to a multilane transmission system could be utilized (IPFC). In these configurations it is possible to balance both real and reactive power flows in the lines.

However, the FACTS family is very extensive, and in this part of the book the major attention will be paid to the converter-based arrangements that represent the basic approaches to overcome the transmission system limitations by series (SSSC), shunt (STATCOM) and combined (UPFC) compensation. To gain a wide view of the transmission control arrangements, this chapter ends with the mature technology of HVDC systems.

19 Benefits of FACTS technology

Within the basic system security guidelines, the FACTS devices enable the transmission system to obtain one or more of the following benefits:

1. Control of power flow as ordered. This is the main function of FACTS devices. The use of power flow control may be to follow a contract, meet the utilities' own needs, ensure optimum power flow, ride through emergency conditions, or a combination of them.
2. Increase utilization of lowest cost generation. One of the principal reasons for transmission interconnections is to utilize the lowest cost generation. When this cannot be done, it follows that there is not enough cost-effective transmission capacity. Cost-effective enhancement of capacity will therefore allow increased use of lowest cost generation.
3. Dynamic stability enhancement. This FACTS additional function includes the transient stability improvement, power oscillation damping and voltage stability control.
4. Increase the loading capability of lines to their thermal capabilities, including short term and seasonal demands.
5. Provide secure tie-line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
6. Upgrade of transmission lines.
7. Reduce reactive power flows, thus allowing the lines to carry more active power.
8. Loop flows control.

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