

*Introducción a las Aplicaciones de Electrónica de
Potencia en Sistemas Eléctricos de Potencia –
Generación, Transmisión y Distribución*

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IEEE Sección

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*Introduction to Power Electronics –
Applications in Electrical Power Systems and
Generation*

- *Introducing the subject*
- *Power electronics in high-voltage transmission, low-voltage distribution and distributed renewable generation*
 - High-Voltage Transmission*
 - *Inherent limitations of high-voltage transmission and compensation principles*
- *FACTS equipment Characteristics*

Introduction to Power Electronics – Applications in Electrical Power Systems and Generation

Low-Voltage Distribution

- *Power Quality phenomena in low-voltage distribution systems*
- *Custom Power equipment characteristics*

Distributed Renewable Generation

- *Types of distributed renewable generation, extent of deployment and markets*
- *Wind Generation*

Course Objectives

- *To gain a good understanding of the basic concepts associated with the Flexible AC Transmission System (FACTS) technology and the Custom Power technology and to be able to appreciate their potential roles in overcoming intrinsic shortcomings exhibited by the high-voltage transmission system and the low-voltage distribution system, respectively*
- *To have an appreciation of the main solid-state devices used in electric power applications and the control techniques used to make them perform useful work*
- *To look at the power electronic topology of the most popular FACTS equipment and Custom Power equipment and to learn about their range of applicability and undesirable, adverse effects that they may introduce into the power system*
- *To discuss suitable representations of FACTS equipment and Custom Power equipment suitable for carrying out basic power systems studies*
- *To gain a basic understanding of the key role that reactive power compensation plays in wind generation*

Background

- *The electricity supply industry is undergoing profound transformation world-wide*
- *Market forces, scarcer natural resources, and an ever increasing demand for electricity are some of the drivers responsible for such an unprecedented change*
- *Against this background of rapid evolution, the expansion programmes of many utilities are being thwarted by a variety of well-founded, environmental, land-use and regulatory pressures, which prevent the licensing and building of new transmission lines and electricity generating plants*
- *An in-depth analysis of the options available for maximising existing transmission assets, with high levels of reliability and stability, has pointed in the direction of power electronics*

Background

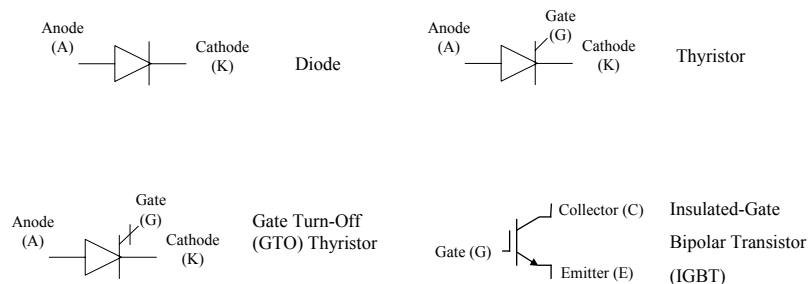
- *There is general agreement that novel power electronics equipment and techniques are potential substitutes for conventional solutions, which are normally based on electro-mechanical technologies which have slow response times and high maintenance cost*
- *Independently of the structure of a power system, the power flows throughout the network are largely distributed as a function of transmission line impedance: a transmission line with low impedance enables larger power flows through it than a transmission line with high impedance*
- *This is not always the most desirable outcome because quite often it gives rise to a myriad of operational problems; and the job of the system operator is to intervene to try to achieve power flow re-distribution, but with limited success*
- *Examples of operating problems, which unregulated active and reactive power flows may give rise to are: loss of system stability; power flow loops; high transmission losses; voltage limits violations; inability to fully utilise transmission lines capability up to their thermal limits; and cascade tripping*

Background

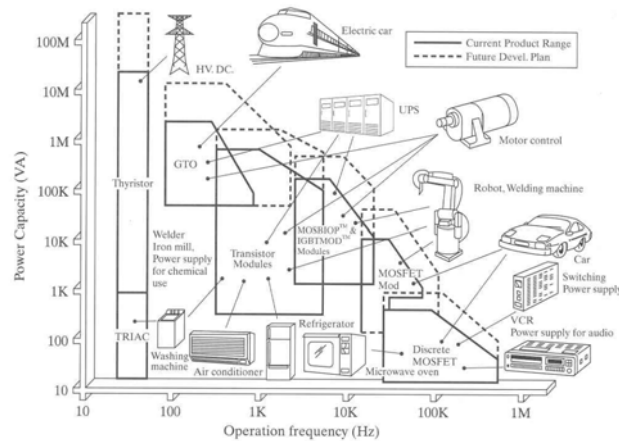
- *In the long term, such problems have traditionally been solved by building new power plants and transmission lines; a solution which is costly to implement and carries long construction times and opposition from pressure groups*
- *It is envisaged that a new solution to such operational problems will rely on the upgrading of existing transmission corridors using the latest power electronic equipment and methods; a new technological thinking that comes under the generic title of FACTS – an acronym for Flexible AC Transmission Systems*

Background

Electronic symbols of semiconductor devices used in high-voltage, high-power applications:



Background



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What is FACTS?

- *In its most general expression, the FACTS concept is based on the substantial incorporation of power electronic devices and methods into the high-voltage side of the network, to make it electronically controllable*
- *Many of the ideas upon which the foundation of FACTS rests, evolved over a period of many decades. Nevertheless, FACTS, an integrated philosophy, is a relatively new concept that was brought to fruition during the eighties at EPRI*
- *FACTS looks at ways of capitalising on the many breakthroughs taking place in the area of high-voltage and high-current power electronics, aiming at increasing the control of power flows in the high-voltage side of the network during both steady-state and transient conditions.*
- *The new reality of making the power network electronically controllable, has begun to alter the way power plant equipment is designed and built, as well as the thinking and procedures that go into the planning and operation of transmission and distribution networks*
- *These developments may also affect the way energy transactions are conducted, since high-speed control of the path of the energy flow is now feasible*

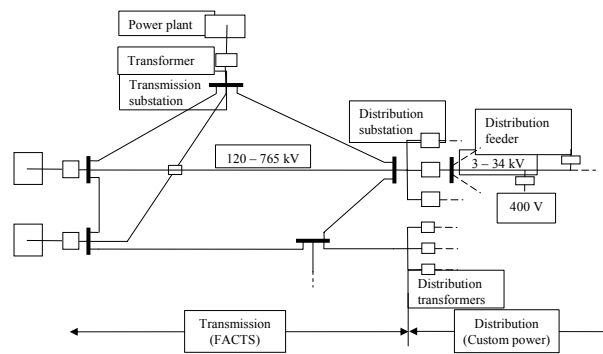
What is FACTS?

- *Owing to the many economical and technical benefits it promised, FACTS received the support of electrical equipment manufacturers, utilities and research organisations around the world*
- Two kinds of emerging power electronics applications in power systems are already well defined:
 - Bulk active and reactive power control
 - Power quality improvement
- The first application area is known as FACTS; where the latest power electronic devices and methods are used to electronically control the high-voltage side of the network
- The second application area is custom power; which focuses on low voltage distribution, and is a technology created in response to reports of poor power quality and reliability of supply affecting factories, offices and homes.
- It is expected that when widespread deployment of the technology takes place, the end-user will see tighter voltage regulation, minimum power interruptions, low harmonic voltages, and acceptance of rapidly fluctuating and other non-linear loads in the vicinity

What is FACTS?

- *It is expected that when widespread deployment of the technology takes place, the end-user will see tighter voltage regulation, minimum power interruptions, low harmonic voltages, and acceptance of rapidly fluctuating and other non-linear loads in the vicinity*

- *High Voltage transmission benefits from the installation of FACTS equipment*
- *Low voltage distribution benefits from the installation of custom power equipment*



What is FACTS?

- Several kinds of FACTS controllers have been commissioned or are in the planning stage in various parts of the world, e.g. USA, Sweden, Japan, UK, Brazil, USA/Mexico, Australia, China.
- The most popular FACTS equipment is:
 - Thyristor-based
 - Tap changer
 - Phase angle regulator
 - Static VAR compensator (SVC)
 - Thyristor-controlled series compensator (TCSC)
 - Sub-synchronous resonance damper (Hingorani's scheme)
 - Inter-phase power controller (IPC)
 - GTO-based (Switched at the fundamental frequency: 60/50 Hz)
 - Static compensator (STATCOM)
 - Solid state series controller (SSSC)
 - Unified power flow controller (UPFC)
 -
 - IGBT-based (Switched at higher frequencies)
 - STATCOM (shunt and series connected)
 - High-voltage direct current based on voltage source converters (HVDC-VSC)

What is FACTS?

- An example of power electronics-based plant components and where they may be installed in the electrical power network:
 - Transmission level: TCSC
HVDC(conventional)
SVC
STATCOM
 - Distribution level: VSC
D-STATCOM
- Two quite distinct kinds of generators are illustrated in this figure:
 - Conventional generation: Coal
Hydro
Nuclear
 - Dispersed generation: Wind
Bio-mass
Fuel cells
Micro-hydro

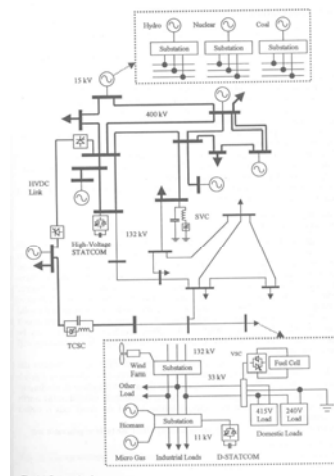


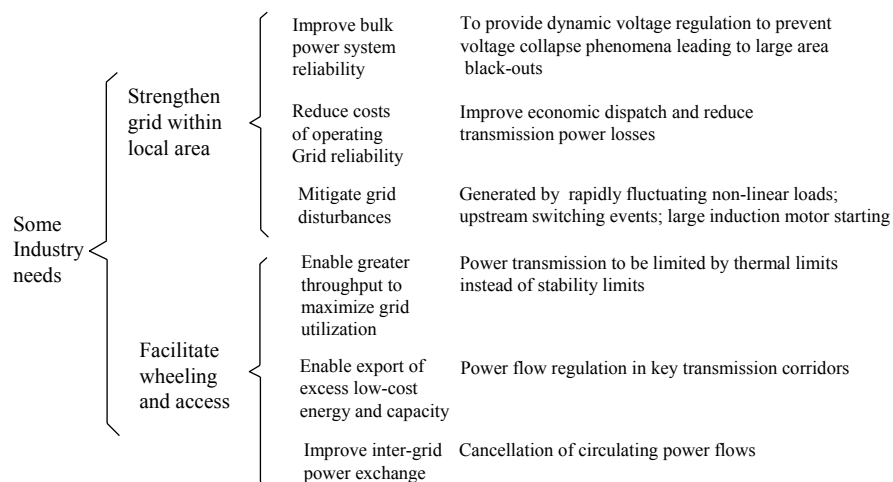
Fig. 1.1 Power network.

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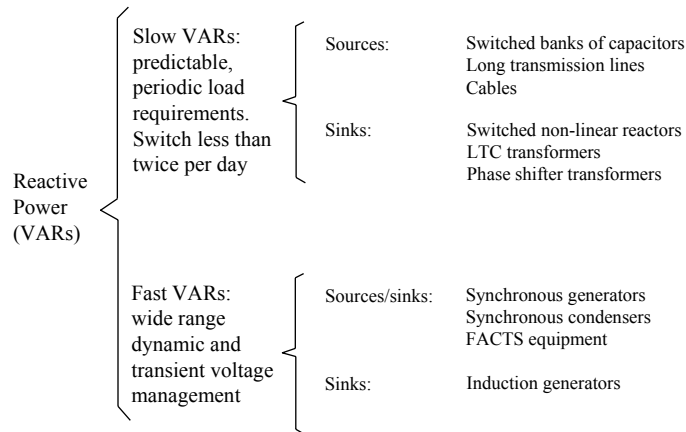
What is FACTS?

- *It was recognised quite early on the development programme of the FACTS technology that in order to determine the effectiveness of such controllers, on a network-wide basis, it would be necessary to upgrade most of the system analysis tools with which power engineers plan and operate their systems, e.g.*
 - Positive sequence power flows
 - Three-phase power flows
 - Optimal power flows
 - State estimation
 - Transient stability
 - Dynamic stability
 - Electromagnetic transients
 - Power quality

Industry Needs for Dynamic Reactive Power



Optimum Mix of Reactive Power Sources/Sinks Maximises Grid Utilization



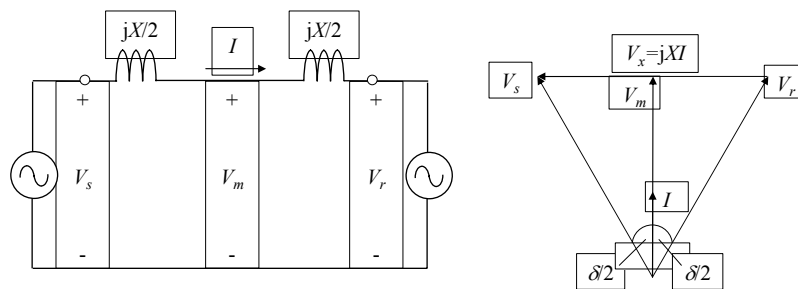
Inherent Limitations of Transmission Systems

- *The ability of the transmission system to transmit power becomes impaired by one or more of the following steady-state and dynamic limitations:*
 - 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 would enable the same objectives to be met with no major alterations to system layout*

Inherent Limitations of Transmission Systems

- Proponents of the technology argue that 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 in the quality of the electric energy delivered to customers
- Compensated transmission lines with suitable FACTS controllers may be able to increase their power-carrying capability up to values that approach their thermal ratings
- Most FACTS controllers are capable of contributing fast acting, dynamic reactive power at the point of connection, hence, enhancing network security
- At the distribution system level, they should increase the reliability of supply, with improved waveform quality

Principle of Power Transmission



The voltage and current relations are:

$$\left. \begin{aligned} V_s &= V e^{j\delta/2} = V(\cos \delta/2 + j \sin \delta/2) \\ V_r &= V e^{-j\delta/2} = V(\cos \delta/2 - j \sin \delta/2) \end{aligned} \right\} \Rightarrow V_m = \frac{V_s + V_r}{2} = V \cos \delta/2$$

$$I = \frac{V_s - V_r}{jX} = \frac{2V}{X} \cdot \sin \delta/2$$

Principle of Power Transmission

Active and reactive power relations:

$$S_s = V_s I^* = V (\cos \delta/2 + j \sin \delta/2) \cdot \frac{2V}{X} \sin \delta/2$$

$$= \frac{2V^2}{X} \cdot (\cos \delta/2 \cdot \sin \delta/2 + j \sin^2 \delta/2)$$

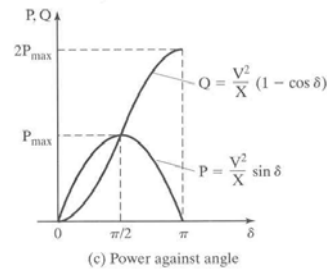
$$P_s = \frac{V^2}{X} \cdot \sin \delta$$

$$Q_s = \frac{V^2}{X} \cdot (1 - \cos \delta)$$

Maximum powers:

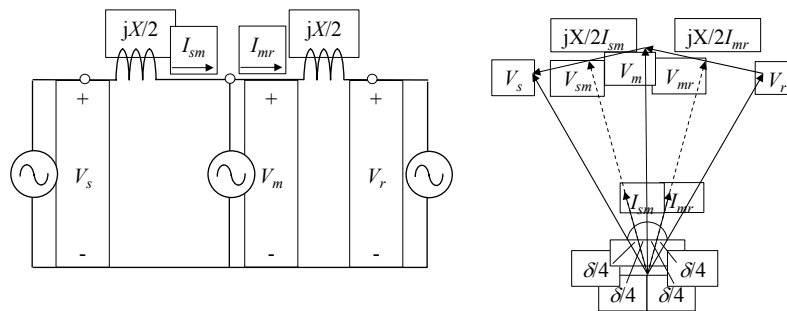
$$P_{\max} = \frac{V^2}{X} \quad \text{at } \delta = \pi/2$$

$$Q_{\max} = \frac{2V^2}{X} \quad \text{at } \delta = \pi$$



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Principle of Shunt Compensation



The voltage and current relations are:

$$\left. \begin{aligned} V_s &= V e^{j\delta/2} = V (\cos \delta/2 + j \sin \delta/2) \\ V_m &= V \end{aligned} \right\} \quad I_{sm} = \frac{V_s - V_m}{jX/2} = \frac{2V}{X} \cdot [\sin \delta/2 + j(1 - \cos \delta/2)]$$

Principle of Shunt Compensation

Active and reactive power relations:

$$S_{sm} = V_{sm} I_{sm}^* = V (\cos \delta/2 + j \sin \delta/2) \cdot \frac{2V}{X} [\sin \delta/2 - j(1 - \cos \delta/2)]$$

$$= \frac{2V^2}{X} \cdot [\sin \delta/2 + j(1 - \cos \delta/2)]$$

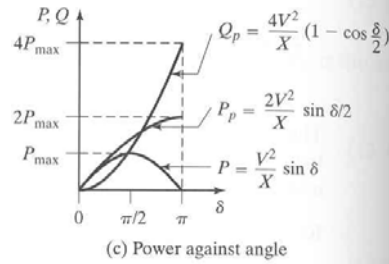
$$P_{sm} = \frac{2V^2}{X} \cdot \sin \delta/2$$

$$Q_{sm} = \frac{2V^2}{X} \cdot (1 - \cos \delta/2)$$

Maximum powers:

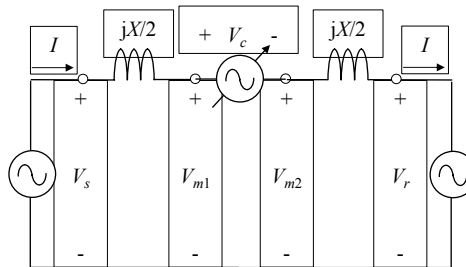
$$P_{\max} = \frac{2V^2}{X} \quad \text{at } \delta = \pi$$

$$Q_{\max} = \frac{4V^2}{X} \quad \text{at } \delta = 2\pi$$



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Principle of Series Compensation



The voltage and current relations are:

$$\left. \begin{aligned} V_s &= V e^{j\delta/2} = V (\cos \delta/2 + j \sin \delta/2) \\ V_r &= V e^{-j\delta/2} = V (\cos \delta/2 - j \sin \delta/2) \\ V_c &= V e^{j\sigma/2} = V (\cos \sigma/2 + j \sin \sigma/2) \end{aligned} \right\} I = \frac{V_s - V_r - V_c}{jX}$$

Principle of Series Compensation

If the series applied voltage V_c is in quadrature with respect to the line current, the series compensator cannot supply or absorb active power, hence, the source may be replaced by an equivalent reactance:

$$X_{eq} = X - X_c = X(1-r)$$

where $r = \frac{X_c}{X}$ is the degree of series compensation ($0 < r < 1$)

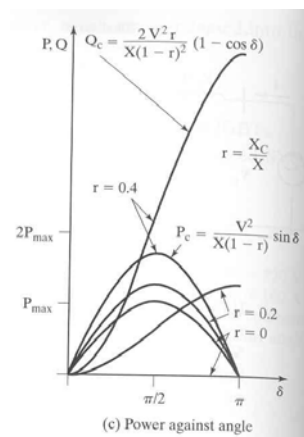
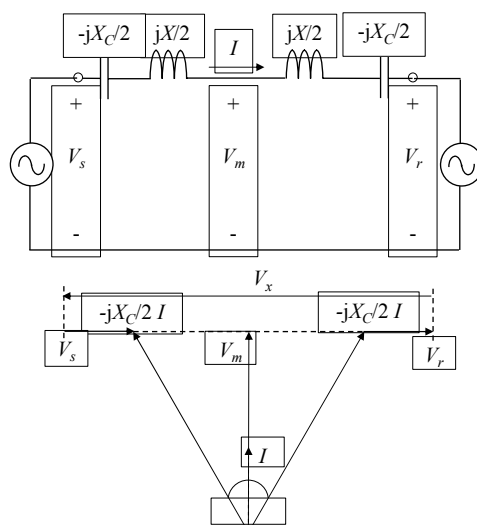
Current and active and reactive power relations:

$$I = \frac{2V}{(1-r)X} \cdot \sin \delta / 2$$

$$P_c = \text{Re}(V_c I^*) = \frac{V^2}{(1-r)X} \cdot \sin \delta$$

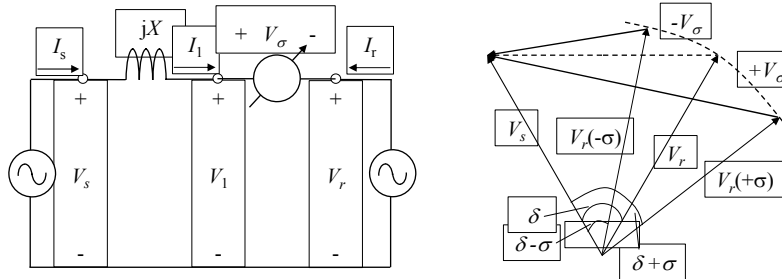
$$Q_c = I^2 X_c = \frac{2V^2}{X} \cdot \frac{r}{(1-r)^2} \cdot (1 - \cos \delta)$$

Principle of Series Compensation



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Principle of Phase-Angle Compensation



$$\frac{V_1}{V_r} = T_V = (\cos \sigma + j \sin \sigma) \quad ; \quad \frac{I_r}{I_1} = -T_I = -(\cos \sigma - j \sin \sigma)$$

The voltage and current relations are:

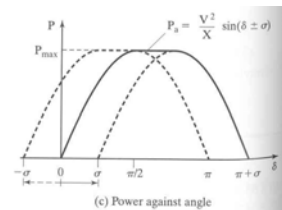
$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \frac{1}{jX} \begin{bmatrix} 1 & -(\cos \sigma + j \sin \sigma) \\ -(\cos \sigma - j \sin \sigma) & 1 \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix}$$

Principle of Phase-Angle Compensation

Active and reactive power relations:

$$P_\sigma = \frac{V^2}{X} \cdot \sin(\delta - \sigma)$$

$$Q_\sigma = \frac{V^2}{X} [1 - \cos(\delta - \sigma)]$$

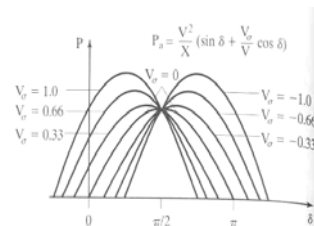


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Quadrature booster:

- If the phasor V_σ relative to phasor V_s is maintained fixed at $\pm 90^\circ$, the phase compensator becomes a quadrature booster

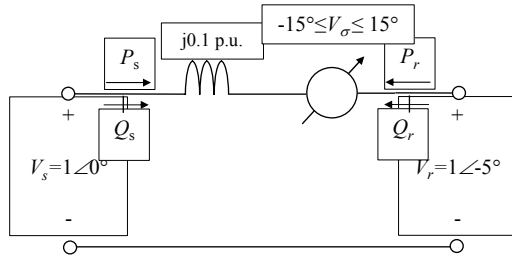
$$P_\sigma = \frac{V^2}{X} \left[\sin \delta + \frac{V_\sigma}{V} \cdot \cos \delta \right]$$



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Principle of Phase-Angle Compensation

Numerical example:

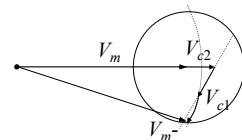
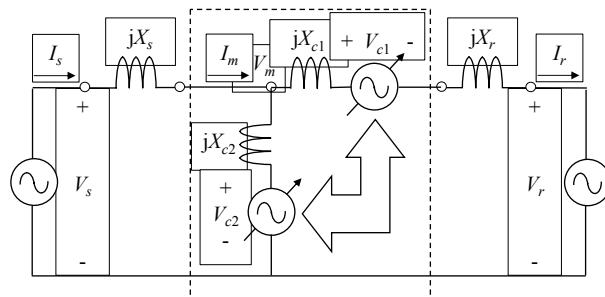


Matlab® code:

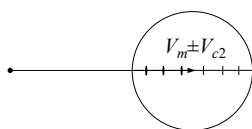
```
sigma = -15*pi/180;
V = [ 1 ; (cos(-5*pi/180 + i*sin(-5*pi/180)) )];
Y = -i*10*[ 1 -(cos(sigma)+i*sin(sigma)) ; -(cos(sigma)+i*sin(sigma)) 1 ];
S = diag(V)*conj(Y*V)
```

σ	S_s (p.u.)	S_r (p.u.)	S_{Loss} (p.u.)
-15°	3.4202 +j0.6031	-3.4202 +j0.6031	0 +j1.206
-10°	2.5882 +j0.3407	-2.5882 +j0.3407	0 +j0.6815
-5°	1.7365 +j0.1519	-1.7365 +j0.1519	0 +j0.3038
0°	0.8716 +j0.0381	-0.8716 +j0.0381	0 +j0.0761
+5°	-	-	-
+10°	-0.8716 +j0.0381	0.8716 +j0.0381	0 +j0.0761
+15°	-1.7365 +j0.1519	1.7365 +j0.1519	0 +j0.3038

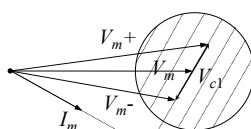
Principle of Combined Compensation



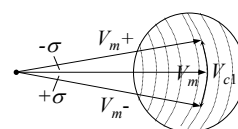
Combined compensation



Shunt compensation



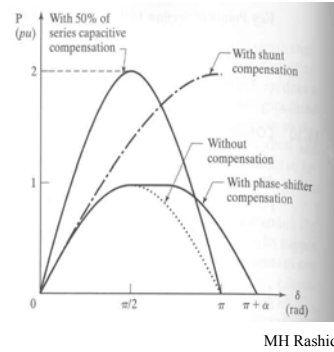
Series compensation



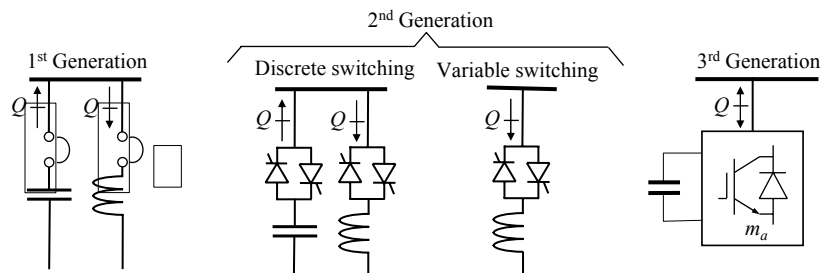
Phase angle compensation

Comparisons of Compensators

- *The ideal shunt controller acts like a voltage source, which draws or injects current into the network. It enables tight voltage control at the point of connection. It is also quite effective in damping voltage oscillations*
- *The series controller impacts directly the driving voltage and, hence, the current and power flow. If the aim is to control current or power flow and damp oscillations, the series controller is several times more powerful than the shunt controller, for the same MVA*
- *The phase shifter does not increase the transmittable power of the uncompensated transmission line. The flat-topped curve indicates the range of the action of the phase compensation*
- *A combined, single compensator which provides all three functions do exist in practice. It is termed Unified Power Flow Controller (UPFC)*



Evolution of Transmission Controls for Shunt VAR Compensation

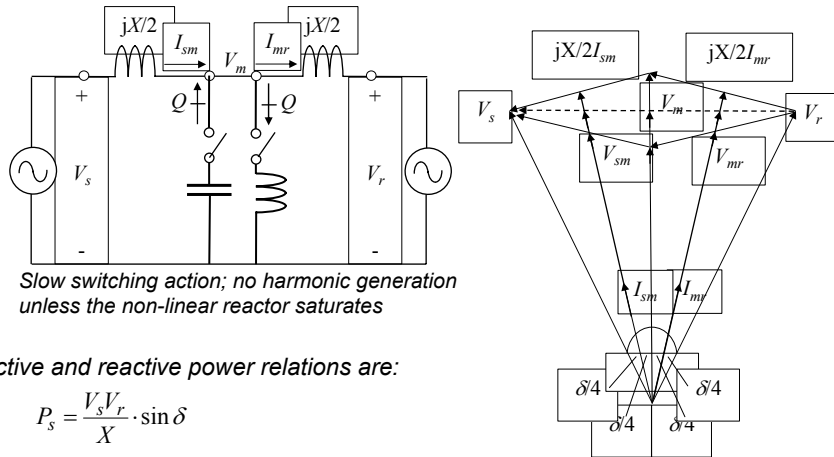


1st Generation
 Mechanically switched components:
 - Capacitor introduces no harmonic distortion
 - Reactor uses an iron core. It causes harmonic distortion if the core saturates

2nd Generation
 Thyristor switched components:
 - Reactor uses an air core
 - Discrete switching introduces no harmonic distortion
 - Variable switching, based on phase control, normally causes harmonic distortion

3rd Generation
 Fully controlled switched components:
 - Multi-level, Fundamental frequency switching introduces manageable harmonic distortion
 - In future, high frequency PWM switching will introduce manageable harmonic distortion

Principle of Shunt Compensation – Discrete, Fixed-value Compensation



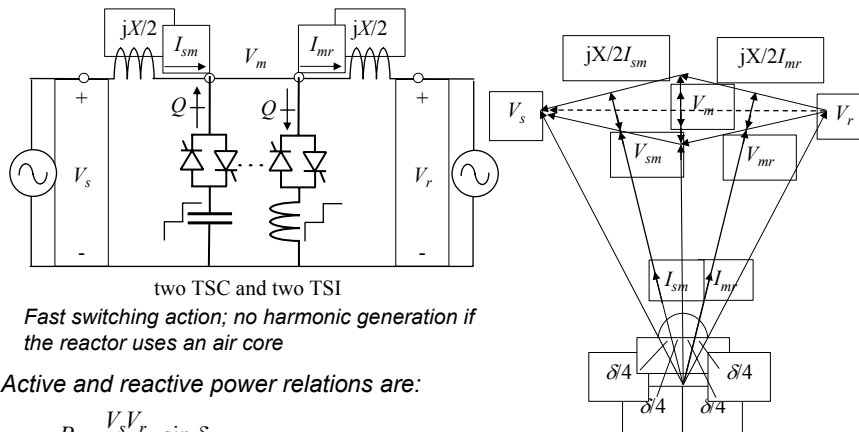
Slow switching action; no harmonic generation unless the non-linear reactor saturates

Active and reactive power relations are:

$$P_s = \frac{V_s V_r}{X} \cdot \sin \delta$$

$$Q_s = \frac{V_s V_r}{X} \cdot (1 - \cos \delta)$$

Principle of Shunt Compensation – Discrete, Variable Compensation



two TSC and two TSI

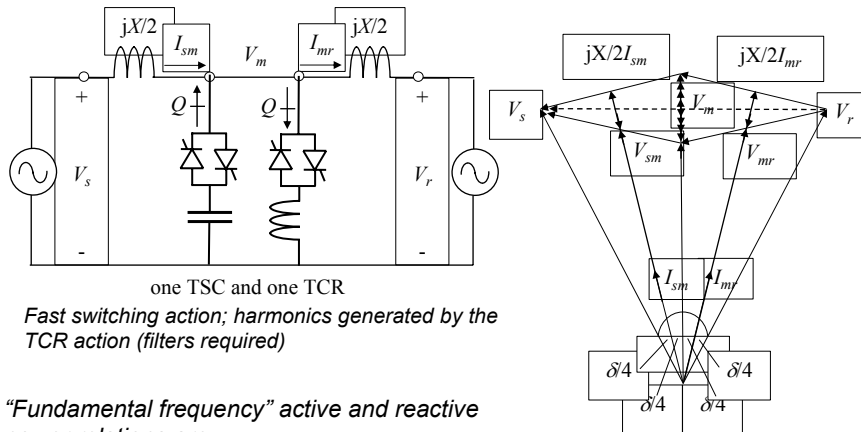
Fast switching action; no harmonic generation if the reactor uses an air core

Active and reactive power relations are:

$$P_s = \frac{V_s V_r}{X} \cdot \sin \delta$$

$$Q_s = \frac{V_s V_r}{X} \cdot (1 - \cos \delta)$$

Principle of Shunt Compensation – Smooth, Variable Compensation With SVC



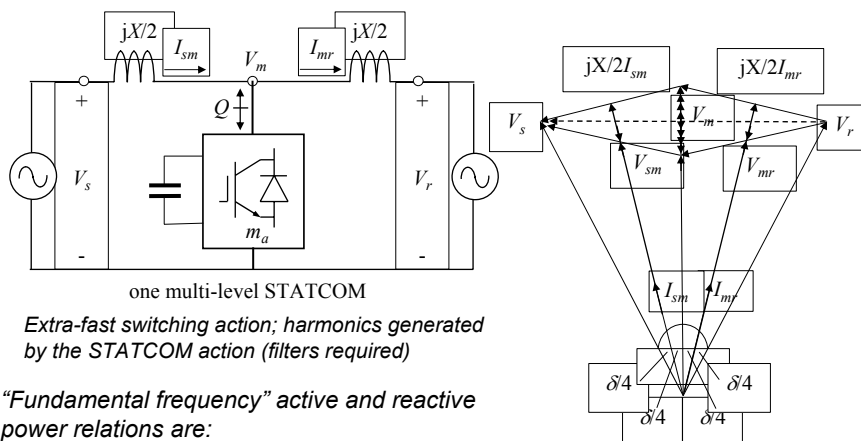
one TSC and one TCR

Fast switching action; harmonics generated by the TCR action (filters required)

“Fundamental frequency” active and reactive power relations are:

$$P_s = \frac{V_s V_r}{X} \cdot \sin \delta \quad \text{and} \quad Q_s = \frac{V_s V_r}{X} \cdot (1 - \cos \delta)$$

Principle of Shunt Compensation – Smooth, Variable Compensation With STATCOM



one multi-level STATCOM

Extra-fast switching action; harmonics generated by the STATCOM action (filters required)

“Fundamental frequency” active and reactive power relations are:

$$P_s = \frac{V_s V_r}{X} \cdot \sin \delta \quad \text{and} \quad Q_s = \frac{V_s V_r}{X} \cdot (1 - \cos \delta)$$

FACTS Equipment – Based on Conventional Thyristors

- Power electronic circuits using conventional thyristors have been widely used in power transmission applications since the early seventies
- The first applications took place in the area of HVDC transmission but shunt reactive power compensation using fast controllable inductors and capacitors soon gained general acceptance
- More recently, fast acting series compensators using thyristors are being used to vary the electrical length of key transmission lines, with almost no delay, instead of the classical series capacitor, which is mechanically controlled
- In distribution system applications, solid-state transfer switches using thyristors are being used to enhance reliability of supply to critical customer loads

FACTS Equipment – Electronic Components

- The diode is the simplest of the family of semiconductor devices. It consists of the assembly of a p-type material and an n-type material.
- The diode enables the flow of current, from Anode to Cathode, when a forward voltage is applied. Conversely, it blocks the flow of current when a reverse voltage is applied
- It is an uncontrolled device whose turn-on and turn-off capabilities are entirely dependent on the external circuit conditions
- The actual and the idealised characteristics are shown in the figure opposite. The operation of the latter resembles very much a switch

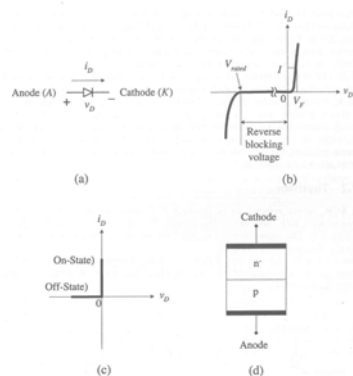


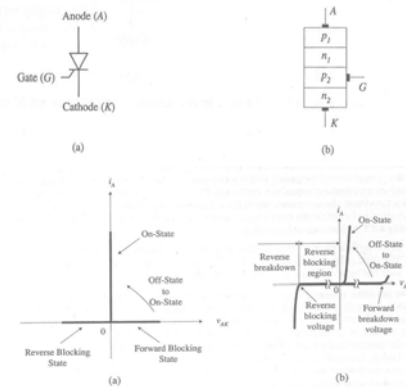
Fig. 5.1 Diode: (a) circuit symbol, (b) typical i - v characteristics, (c) ideal i - v characteristics, and (d) typical structure.

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Basic Semiconductor Junction - Diode

FACTS Equipment – Electronic Components

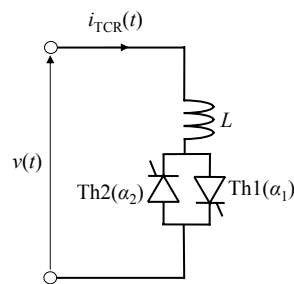
- The thyristor is a four layer (p-n-p-n), three-junction semiconductor device. It contains three electrodes, namely Anode, Cathode and Gate
- When a voltage of reverse polarity is applied between Anode and Cathode, with no current injected through the Gate, the thyristor behaves similarly to the diode
- Unlike the diode, when a voltage in the forward direction is applied, the thyristor does not immediately start conduction. It requires a relatively large amount of voltage to take it to the point of forward break-down voltage and into the on-state
- If current pulses are applied through the gate, the point of forward break-down voltage reduces and the on-state takes place at reduced forward voltages, in a controlled manner. The thyristor is a semi-controlled, semiconductor device



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The Silicon-Controlled Rectifier (SCR) - Thyristor

FACTS Equipment - TCR

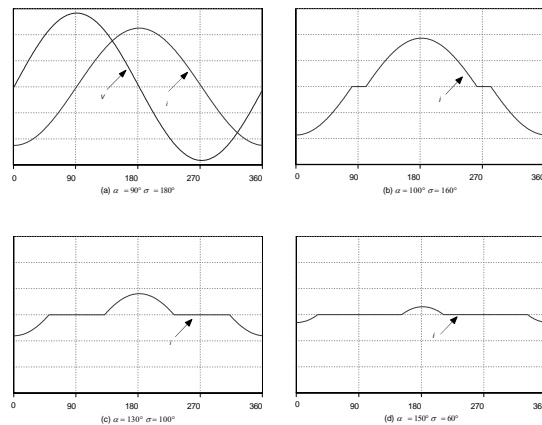


Basic TCR Circuit

$$\sigma = 2(\pi - \alpha)$$

$$\pi/2 < \alpha < \pi$$

$$0 < \sigma < \pi$$



Voltage and current waveforms in the basic TCR

FACTS Equipment - TCR

- Increasing α above $\pi/2$ causes the TCR current waveform to become non-sinusoidal, with its fundamental frequency component reducing in magnitude
- This is equivalent to an increase in the inductance of the reactor, reducing its ability to draw reactive power from the network at the point of connection

The TCR instantaneous current is

$$i_{\text{TCR}}(t) = \begin{cases} \frac{1}{L} \int_{\alpha}^{\omega t} \sqrt{2} V \sin \omega t \, dt = \frac{\sqrt{2} V}{\omega L} (\cos \alpha - \cos \omega t) & \text{if } \alpha \leq \omega t \leq \alpha + \sigma \\ 0 & \text{otherwise} \end{cases}$$

Using Fourier analysis yields

$$I_{\text{TCR},f1} = \frac{V}{j\omega L \pi} [2(\pi - \alpha) + \sin 2\alpha]$$

$$I_{\text{TCR},h} = \frac{4V}{j\omega L \pi} \left[\frac{\sin(h+1)\alpha}{2(h+1)} + \frac{\sin(h-1)\alpha}{2(h-1)} - \cos \alpha \frac{\sin h\alpha}{h} \right] \quad \text{where } h = 3, 5, 7, 9, 11, 13, \dots$$

FACTS Equipment - TCR

- The fundamental frequency expression of the TCR may be interpreted in terms of an equivalent susceptance, which is a function of the controllable parameter α

$$I_{\text{TCR}} = -jB_{\text{TCR}} V$$

$$\text{where } B_{\text{TCR}} = \frac{1}{\omega L} \cdot \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi}$$

Alternatively

$$B_L = \frac{\sigma - \sin \sigma}{\pi X_L}$$

$$\text{where } X_L = \omega L$$

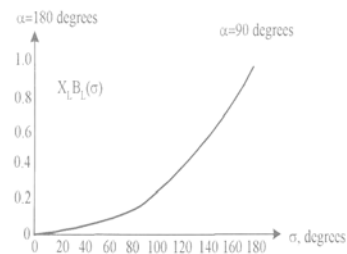


Fig. 6.3 Control law of a basic TCR.

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Control characteristic of a basic TCR

FACTS Equipment - TCR

- Increasing the firing angle α above 90° has the effect of making the current waveform less sinusoidal
- The TCR achieves its fundamental frequency operating point at the expense of generating harmonic distortion
- The figure opposite shows the variation of the amplitudes of the dominant harmonics against the conduction angle. It also shows the variation of the total harmonic content
- If the firing angles of the thyristor pairs are equal, $\sigma_1 = \sigma_2$, only odd harmonics are generated. Also, under balanced conditions, the triplen line harmonics do not exist

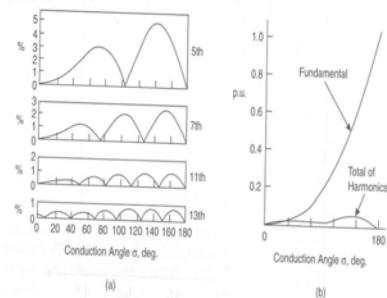


Fig. 6.5 TCR Harmonics. (a) major harmonic current components of TCR. Each is shown as a percentage of the fundamental component at full conduction. The percentages are the same for both phase and line currents; and (b) total harmonic content of TCR current, as a fraction of the fundamental component at full conduction. The percentages are the same for both phase and line currents.

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TCR harmonics

FACTS Equipment - TCR

- In three-phase installations the TCR is delta-connected to prevent the triplen harmonic phase currents from reaching the TCR transformer
- Filters are normally used to prevent the 5th, 7th, 11th and 13th harmonic currents from reaching the power network
- An alternative is to use two smaller three-phase TCRs, connected in the arrangement shown in the figure opposite. Under balanced conditions, this has the effect of removing the 5th and 7th harmonic current at the primary side of the TCR transformer
- The TCR transformer has two secondary windings, one connected in star and the other in delta

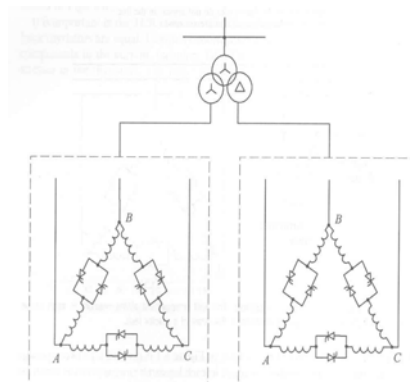


Fig. 6.8 Arrangement of 12-pulse TCR configuration with double-secondary transformer.

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Arrangement of a 12-pulse TCR

FACTS Equipment - TCR

- The TCR has a control system that determines the firing instants α and, hence, the conduction periods σ
- In some designs the control system responds to a signal that directly represents the desired susceptance B_c . In some others, the aim is to control directly the voltage magnitude at the point of connection
- In either case, the result is a voltage/current characteristic of the form shown in the opposite figure
- Steady-state operation is shown at the point of intersection with the system load line, e.g. 130°

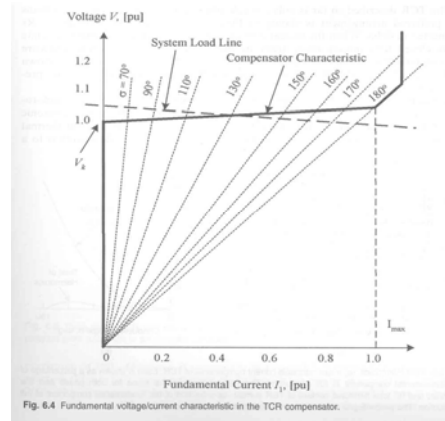


Fig. 6.4 Fundamental voltage/current characteristic in the TCR compensator.

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Voltage/current characteristic of a TCR

FACTS Equipment - TCR

- For the purpose of fundamental frequency analysis it is assumed that suitable harmonic cancellation measures are in place
- Hence, the nodal admittance matrix representation of a delta-connected, three-phase TCR is

$$\begin{bmatrix} I_{TCR a} \\ I_{TCR b} \\ I_{TCR c} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} -j(B_{TCR1} + B_{TCR3}) & jB_{TCR1} & jB_{TCR3} \\ jB_{TCR1} & -j(B_{TCR1} + B_{TCR2}) & jB_{TCR2} \\ jB_{TCR3} & jB_{TCR2} & -j(B_{TCR2} + B_{TCR3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

- As special condition, if all three branches in the three-phase TCR have equal susceptances, i.e. $B_{TCR1} = B_{TCR2} = B_{TCR3} = B_{TCR}$

$$\begin{bmatrix} I_{TCR a} \\ I_{TCR b} \\ I_{TCR c} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} -j2B_{TCR} & jB_{TCR} & jB_{TCR} \\ jB_{TCR} & -j2B_{TCR} & jB_{TCR} \\ jB_{TCR} & jB_{TCR} & -j2B_{TCR} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{where } B_{TCR} = \frac{1}{\omega L} \cdot \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi}$$

FACTS Equipment - TSC

- The TSC is a shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction of the thyristor valve
- The susceptance is adjusted by controlling the number of parallel capacitors in conduction. Each capacitor always conducts for an integral number of half-cycles
- Two alternative arrangements are shown in the figure opposite, with little difference between them since the TSC generates no harmonic distortion - ignoring switching transients, the current is sinusoidal

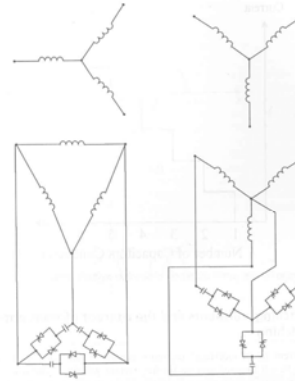


Fig. 6.12 Alternative arrangements of three-phase thyristor-switched capacitor. (a) delta-connected secondary, Delta-connected TSC; and (b) wye-connected secondary, wye-connected TSC (four-wire system).

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Arrangements of three-phase TCSC

FACTS Equipment - TSC

- Each phase of the TSC comprises several switched capacitors in parallel, as illustrated in the figure opposite
- The relationship between the compensator current and the number of capacitors conducting, for a constant terminal voltage, are also shown
- The total susceptance varies in a step-wise manner. In principle, a very fine susceptance control can be achieved, by having a large number of capacitors in parallel, but this is not practical because of economic reasons and added control complexity

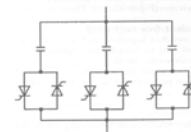


Fig. 6.13 Principles of operation of TSC. Each phase of Figure 6.12 comprises of parallel combinations of switched capacitors of this type.

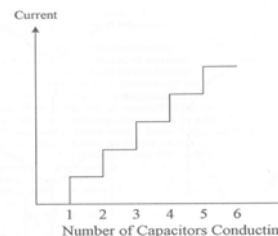
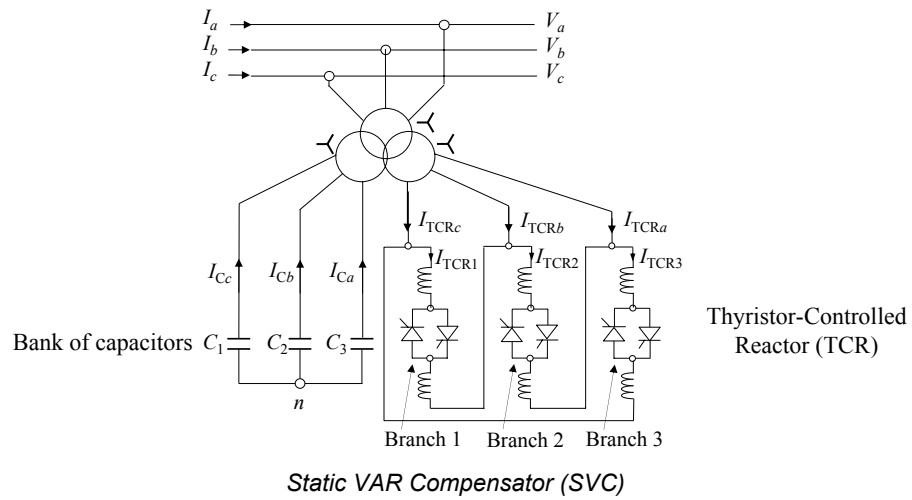


Fig. 6.14 Relationship between current and number of capacitors conducting in the TSC.

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Principle of operation of a TSC

FACTS Equipment – SVC



FACTS Equipment – SVC

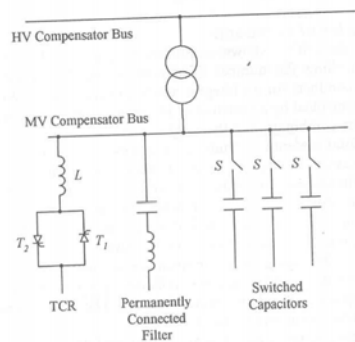


Fig. 6.11 Hybrid compensator with switched capacitors and 'interpolating' TCR. The switches S may be mechanical circuit breakers or thyristor switches.

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One line diagram of a SVC with filter

FACTS Equipment - SVC

- In its simplest form, the SVC consists of a TCR in parallel with a bank of switched capacitors, either mechanically or electronically controlled. Filters may be required to prevent TCR harmonics from reaching the high-voltage side of the network
- From the operational point of view, the SVC behaves like a shunt-connected variable reactance, up to its operating limits, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network
- The SVC is used extensively to provide not only fast reactive power and voltage regulation support but also to increase stability margins

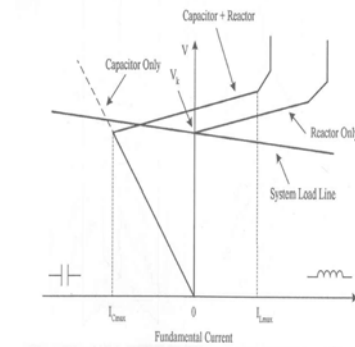
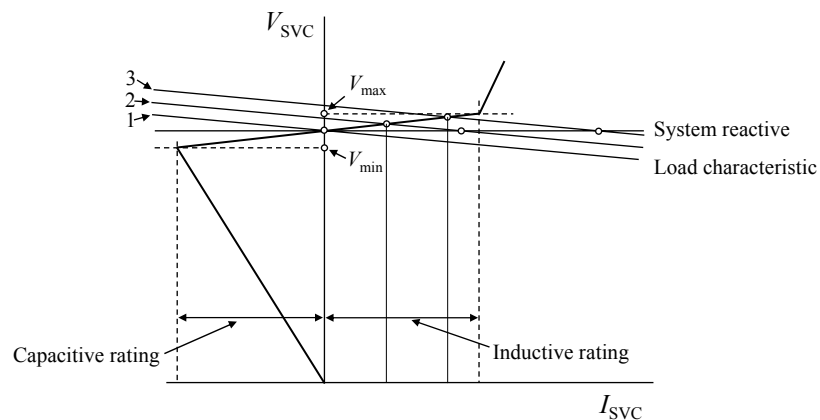


Fig. 6.10 Voltage/current characteristics of TCR.

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SVC voltage/current characteristic

FACTS Equipment - SVC



SVC voltage/current characteristic with varying system load

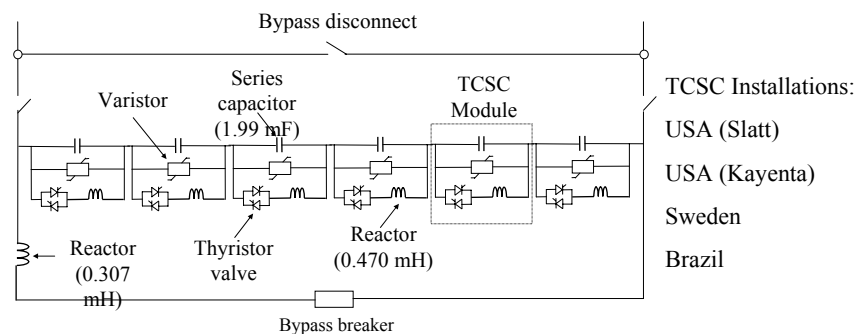
FACTS Equipment - SVC

- The nodal admittance of the capacitor bank, in phase co-ordinates, may be expressed with explicit representation of the star point. However, it is more advantageous to perform a Kron's reduction to obtain a reduced equivalent,

$$\begin{bmatrix} I_{SVCa} \\ I_{SVCb} \\ I_{SVCc} \end{bmatrix} = \begin{bmatrix} I_{Ca} \\ I_{Cb} \\ I_{Cc} \end{bmatrix} + \begin{bmatrix} I_{TCRa} \\ I_{TCRb} \\ I_{TCRc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} j2(B_C - B_{TCR}) & -j(B_C - B_{TCR}) & -j(B_C - B_{TCR}) \\ -j(B_C - B_{TCR}) & j2(B_C - B_{TCR}) & -j(B_C - B_{TCR}) \\ -j(B_C - B_{TCR}) & -j(B_C - B_{TCR}) & j2(B_C - B_{TCR}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Further to the simplifying assumptions in the TCR representation, this representation assumes that $B_{C1}=B_{C2}=B_{C3}=B_C$ with $B_C=\omega C$

FACTS Equipment - TCSC



Thyristor-Controlled Series Compensator (TCSC) - layout of one phase of the TCSC installed in the Slatt substation

FACTS Equipment -TCSC

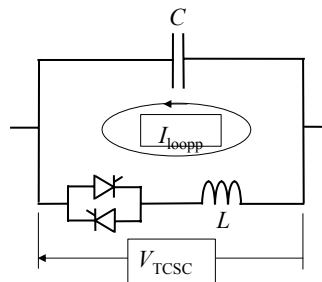
- *The TCSC varies the electrical length of the compensated transmission line with little delay. This characteristic enables the TCSC to be used to provide fast active power flow regulation. It also increases the stability margin of the system and has proved very effective in damping SSR and power oscillations*
- *The steady-state response of the TCSC may be calculated by solving the differential equations that describes its electrical performance. This approach involves the integration of the differential equations over many cycles until the transient response dies out. This solution method is rich in information since the full evolution of the response is captured, from transient inception to steady-state operation*
- *Alternatively, the TCSC differential equations may be expressed in algebraic form and then a phasorial method used to solve them. One option is to use fundamental and harmonic frequency phasors, neatly arranged in the harmonic domain frame-of-reference. The method yields full information for the fundamental and harmonic frequency TCSC parameters but no transient information is available*

FACTS Equipment - TCSC

- *A second option is to use a non-linear equivalent impedance expression, which is solved by iteration. The solution method is accurate and converges very robustly towards the solution, but it only yields information for the fundamental frequency, steady-state solution*
- *The TCR achieves its fundamental frequency operating state at the expense of generating harmonic currents, which are a function of the thyristor's conduction angle*
- *Contrary to the SVC application where the harmonic currents generated by the TCR tend to escape towards the network, in the TCSC application the TCR harmonic currents are trapped inside the TCSC due to the low impedance of the capacitor, compared to the network equivalent impedance*
- *Measurements conducted in both the Slatt and the Kayenta TCSC systems support this observation. For instance, the Kayenta system generates at its terminals, a maximum THD voltage of 1.5% when operated in capacitive mode and firing at an angle of 147°*

FACTS Equipment - TCSC

- For the purpose of fundamental frequency power system studies, a complex TCSC topology, such as the single-phase branch shown above, may be taken to consist of one equivalent TCR paralleled by one equivalent capacitor
- The surge arrester is not represented since this is a representation intended for steady-state operation, but the existence of a loop current is emphasised



FACTS Equipment - TCSC

- As illustrated by the TCSC waveforms shown above, they are non-sinusoidal but periodic - They contain harmonic distortion
- If the interest is the study of the TCSC at only the fundamental frequency then it becomes necessary to apply Fourier analysis to a full period of the waveforms, in order to obtain an expression for the impedance at the fundamental frequency
- The TCSC equivalent reactance is as a function of its capacitive and inductive parameters, and firing angle:

$$X_{TCSC(1)} = -X_C + C_1 \left\{ 2(\pi - \alpha) + \sin[2(\pi - \alpha)] \right\} \\ + C_2 \cos^2(\pi - \alpha) \left\{ \varpi \tan[\varpi(\pi - \alpha)] - \tan(\pi - \alpha) \right\}$$

where

$$X_{LC} = \frac{X_C X_L}{X_C - X_L} \quad C_1 = \frac{X_C + X_{LC}}{\pi} \quad C_2 = -\frac{4X_{LC}^2}{X_L \pi}$$

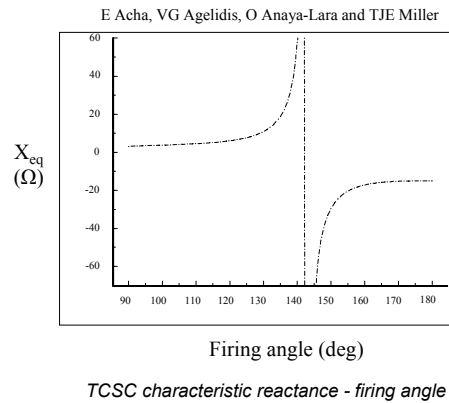
FACTS Equipment - TCSC

The poles of the TCSC impedance equation are given by

$$\alpha = \pi - \frac{(2n-1)\sqrt{LC}\pi\omega}{2}$$

for $n = 1, 2, 3, \dots$

The TCSC capacitive and inductive reactance values should be chosen carefully in order to ensure that just one resonant point is present in the range of 90° - 180°



FACTS Equipment - TCSC

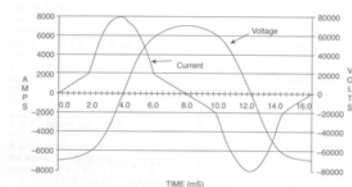


Fig. 7.11 Voltage and current waveforms in the TCSC capacitor.

Typical voltage and current waveforms in the various elements of the TCSC: Capacitor, inductor and thyristors

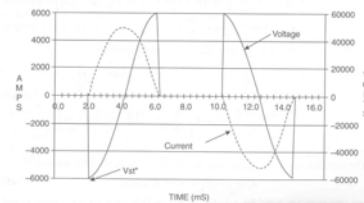


Fig. 7.12 Voltage and current waveforms in the TCSC inductor.

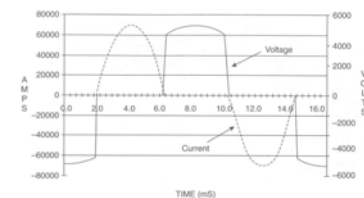


Fig. 7.13 Voltage and current waveforms in the bidirectional thyristors.

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FACTS Equipment - TCSC

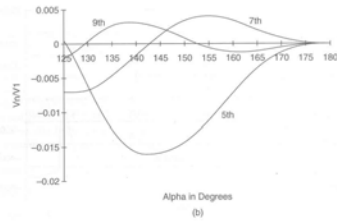
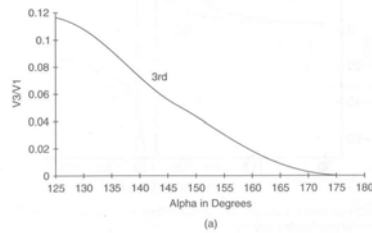


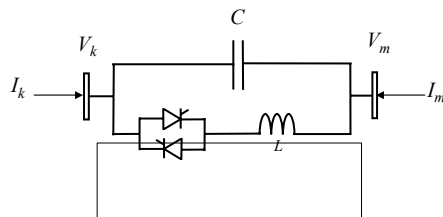
Fig. 7.14 Harmonic generation in per unit of fundamental frequency voltage as a function of firing angle.

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TCSC harmonic generation as a function firing angle

FACTS Equipment - TCSC

- For the purpose of fundamental frequency, positive sequence studies (power flows), the TCSC may be adequately represented by the equivalent, reactance expression given above, which enables a straightforward representation of the TCSC in the form of a nodal transfer admittance matrix
- This is derived with reference to the equivalent circuit shown below, where it is assumed that the TCSC is connected between buses k and m



$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} \frac{1}{jX_{TCSC}} & \frac{1}{jX_{TCSC}} \\ \frac{1}{jX_{TCSC}} & -\frac{1}{jX_{TCSC}} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix}$$

FACTS Equipment - TCSC

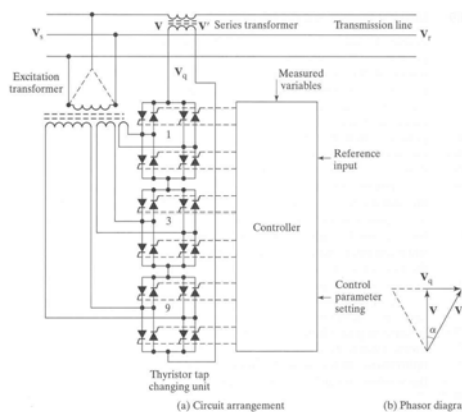
- In three-phase TCSC installations, three independent modules, possibly of the form shown above, may be used, one for each phase
- For modelling and simulation purposes, it is assumed that no electromagnetic couplings exist between the TCSC units making up the three-phase module

$$\begin{bmatrix} I_{TCSCak} \\ I_{TCSCbk} \\ I_{TCSCck} \\ I_{TCSCam} \\ I_{TCSCbm} \\ I_{TCSCcm} \end{bmatrix} = \begin{bmatrix} \frac{1}{jX_{TCSC1}} & 0 & 0 & \frac{1}{jX_{TCSC1}} & 0 & 0 \\ 0 & -\frac{1}{jX_{TCSC2}} & 0 & 0 & \frac{1}{jX_{TCSC2}} & 0 \\ 0 & 0 & -\frac{1}{jX_{TCSC3}} & 0 & 0 & \frac{1}{jX_{TCSC3}} \\ \frac{1}{jX_{TCSC1}} & 0 & 0 & -\frac{1}{jX_{TCSC1}} & 0 & 0 \\ 0 & \frac{1}{jX_{TCSC2}} & 0 & 0 & -\frac{1}{jX_{TCSC2}} & 0 \\ 0 & 0 & \frac{1}{jX_{TCSC3}} & 0 & 0 & -\frac{1}{jX_{TCSC3}} \end{bmatrix} \begin{bmatrix} V_{TCSCak} \\ V_{TCSCbk} \\ V_{TCSCck} \\ V_{TCSCam} \\ V_{TCSCbm} \\ V_{TCSCcm} \end{bmatrix}$$

FACTS Equipment – Phase Shifter

- This phase shifter arrangement introduces little harmonic distortion
- The phase angle control is carried out in discrete steps
- It injects a voltage V_q in quadrature with voltage V at one end of the series-connected transformer to give V' at the other end

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \frac{1}{jX} \begin{bmatrix} 1 & -(\cos\alpha + j\sin\alpha) \\ -(\cos\alpha - j\sin\alpha) & 1 \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix}$$



Solid State Phase Shifter

MH Rashid

FACTS Equipment - SSS

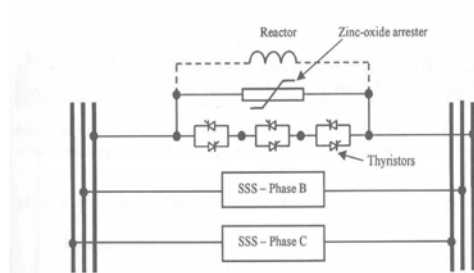


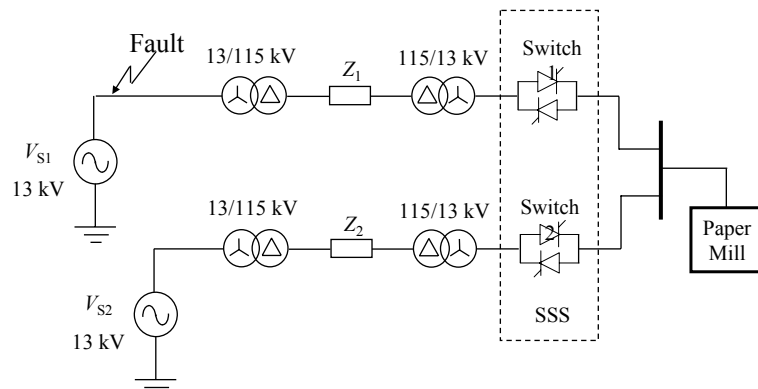
Fig. 1.15 Thyristor-based solid state switch.

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Solid State Switch (SSS)

- American Electric Power
- Baltimore Gas & Electric
- Commonwealth Edison Co.
- Detroit Edison Co.
- PG & E Energy Services
- Chuba Electric Corp.
- Kyushu Electric Corp.
- Tokyo Oil Industry Co.

FACTS Equipment - SSS



Main and back-up feeders used to supply a sensitive load with increased reliability – The SSS play a pivotal role in switching supply onto the load following an unscheduled event in the main feeder, even very short duration events in the range of milliseconds

FACTS Equipment – Based on Fully Controlled Electronic Valves

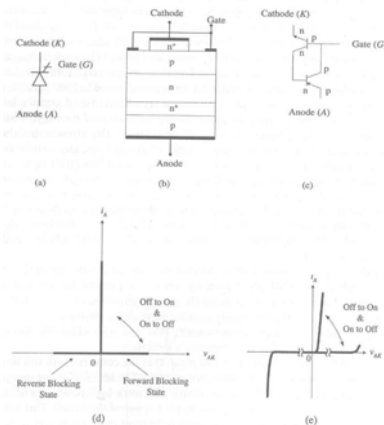
- *Power converters aimed at power systems applications are beginning to make use of IGBTs owing to their increasing power handling capability and relatively low conduction losses. Further progress is expected in IGBT and GTO technology and applications*
- *In DC-AC converters that use fully controlled semiconductors, the DC input can be either a voltage source (typically a capacitor) or a current source (typically a voltage source in series with an inductor). Hence, converters can be classified as either voltage source converters (VSC) or current source converters (CSC)*
- *For economic and performance reasons, most reactive power controllers are based on the VSC topology. The availability of modern semiconductors with relatively high-voltage and current ratings, such as GTOs or IGBTs, has made the concepts of reactive compensation based on switching converters a certainty*

FACTS Equipment – Based on Fully Controlled Electronic Valves

- *Modern power system controllers based on power electronic converters are capable of generating reactive power with no need for large reactive energy storage elements, such as in SVC systems*
- *The semiconductor devices employed in the new generation of power electronic converters are of the fully controlled type, such as the IGBT and the GTO*
- *The GTO is a more advanced version of the conventional thyristor, with a similar switched on characteristic but with the ability to switch off at a time different from when the forward current falls naturally below the holding current level*
- *There is room for improvement in GTO construction and design, where still large negative pulses are required to turn it off. At present, the maximum switching frequency attainable is in the order of 1 kHz*

Electronic Components – GTO

- A Gate Turn-Off (GTO) thyristor is like a conventional thyristor but in one very important respect, the GTO can also be turned off by applying a negative gate signal
- The circuit symbol together with the layers structure and equivalent circuit are shown in the figure opposite. Its ideal and non-ideal v-i characteristics are also shown
- This device became commercially available in the late 1980s. It has undergone a number of improvements and it is likely to replace the conventional thyristor in all high power applications
- The control technique used to drive the GTO is known as Pulse Width Modulation (PWM) and it is fundamentally different from the phase control technique used to drive the conventional thyristor

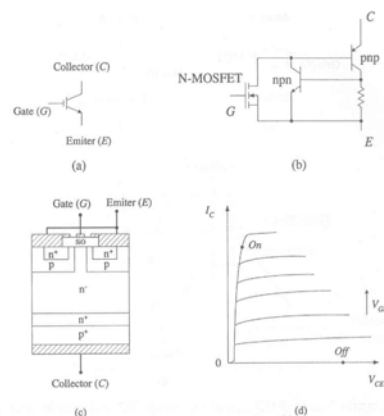


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Gate Turn-Off Thyristor (GTO)

Electronic Components– IGBT

- The Insulated-Gate Bipolar Transistor (IGBT) is the most popular device for AC and DC motor drives reaching a few hundred kW. It has also started to make its way into the high-voltage converter technology for power system applications
- The circuit symbol together with the equivalent circuit and layers structure are shown in the figure opposite. Its v-i characteristics is also shown
- Similarly to the GTO, the control technique used to drive the IGBT is also the PWM technique
- The IGBT is a faster switching device than the GTO which is limited to the order of 1 kHz. The IGBT switches up to 10 kHz and also incurs lower switching losses. The higher the switching frequency the higher the harmonic order present

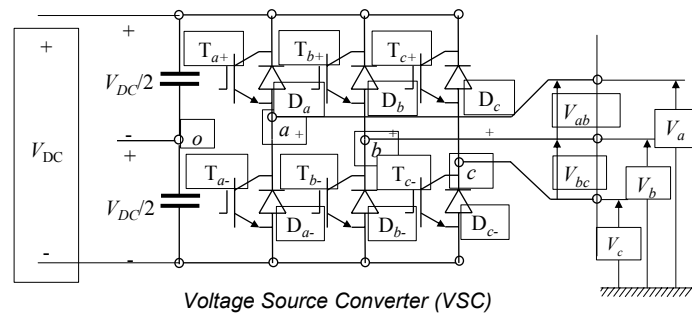


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Insulated Gate Bipolar Transistor (IGBT)

FACTS Equipment - VSC

- There are several VSC topologies currently in use in actual power systems operation. Common aims of these topologies are: (i) to minimise the switching losses of the semiconductors inside the VSC; (ii) to produce a high-quality sinusoidal voltage waveform with minimum or no filtering requirements
- By way of example, the topology of a conventional two-level VSC using IGBT switches is illustrated below



FACTS Equipment - VSC

- The VSC shown above comprises six IGBTs, with two IGBTs placed on each leg. Moreover, each IGBT is provided with a diode connected in anti-parallel to make provisions for possible voltage reversals due to external circuit conditions. Two equally sized capacitors are placed on the DC side to provide a source of reactive power
- Although not shown in the VSC circuit, the switching control module is an integral component of the VSC. Its task is to control the switching sequence of the various semiconductor devices in the VSC, aiming at producing an output voltage waveform, which is as near to a sinusoidal waveform as possible, with high power controllability and minimum switching loss
- Current VSC switching strategies aimed at utility applications may be classified into two main categories:
 - Fundamental frequency switching: The switching of each semiconductor device is limited to one turn-on and one turn-off per power cycle
 - Pulse-width modulation (PWM): This control technique enables the switches to be turn on and off at a rate considerably higher than the fundamental frequency

FACTS Equipment - VSC

- *The basic VSC topology, with fundamental frequency switching; yields a quasi-square-wave output, which has an unacceptable high harmonic content. It is normal to use several six-pulse VSCs, arranged to form a multi-pulse structure, to achieve better waveform quality and higher power ratings*
- *With PWM control, the output waveform is chopped and the width of the resulting pulses is modulated. Undesirable harmonics in the output waveform are shifted to the higher frequencies, and filtering requirements are much reduced*
- *From the viewpoint of utility applications, both switching techniques are far from perfect. The fundamental frequency switching technique requires of complex transformer arrangements to achieve an acceptable level of waveform distortion. Such a drawback is offset by its high semiconductor switch utilization and low switching losses; and it is, at present, the switching technique used in high-voltage, high-power applications*
- *The PWM technique incurs high switching loss, but it is envisaged that future semiconductor devices would reduce this by a significant margin; making PWM the universally preferred switching technique, even at high and extra-high-voltage transmission applications*

FACTS Equipment – PWM Control

- *This is a case of linear voltage control, where $m_a < 1$, but this is not the only possibility. Two other forms of voltage control exist, namely over-modulation and square-wave. The former takes place in the region $1 < m_a < 3.24$ and the latter applies when $m_a > 3.24$*
- *To determine the magnitude and frequency of the resulting fundamental and harmonic terms, it is useful to use the concept of amplitude modulation ratio, m_a , and frequency modulation ratio, m_f*

$$m_a = \frac{\hat{V}_{\text{control}}}{\hat{V}_{\text{tri}}}$$

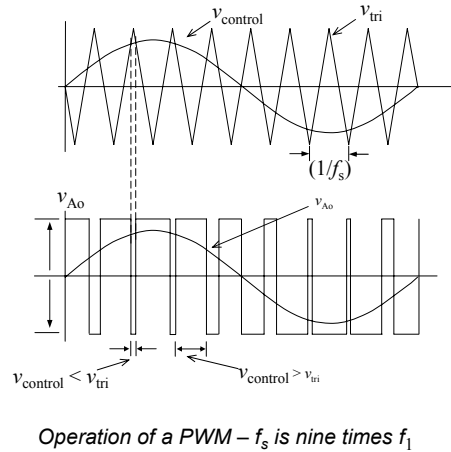
$$m_f = \frac{f_s}{f_1}$$

- *With reference to one leg of the three-phase converter, the switches T_{a+} and T_{a-} are controlled by straightforward comparison of v_{control} and v_{tri} , resulting in the following output voltages:*

$$v_{Ao} = \begin{cases} \frac{1}{2}V_{\text{DC}} & \text{when } T_{a+} \text{ is on in response to } v_{\text{control}} > v_{\text{tri}} \\ -\frac{1}{2}V_{\text{DC}} & \text{when } T_{a-} \text{ is on in response to } v_{\text{control}} < v_{\text{tri}} \end{cases}$$

FACTS Equipment – PWM Control

- In the basic PWM method a sinusoidal, fundamental frequency signal is compared against a high-frequency triangular signal; producing a square-wave signal, which controls the firing of the converter valves
- The sinusoidal and triangular signals, and their associated frequencies, are termed reference and carrier signals and frequencies
- By varying the amplitude of the sinusoidal signal against the fixed amplitude of the carrier signal, which is normally kept at 1 p.u., the amplitude of the fundamental component of the resulting control signal varies linearly



FACTS Equipment – PWM Control

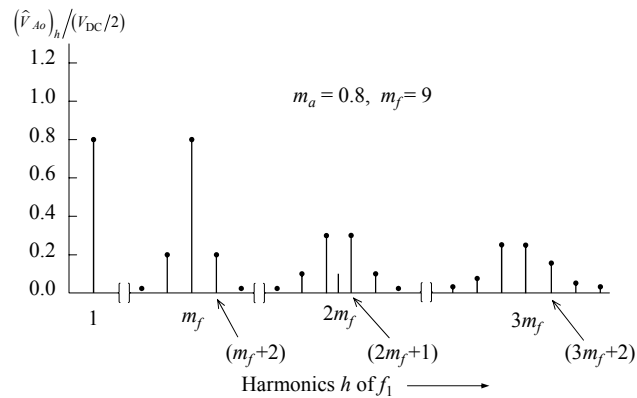
- The case of linear voltage control ($m_a < 1$) is of most interest. The peak amplitude of the fundamental frequency component is m_a times $V_{DC}/2$; and the harmonics appear as sidebands, centred around the switching frequency and its multiples, following a well defined pattern given by:

$$f_h = (\beta m_f \pm \kappa) f_1$$

- Harmonic terms exist only for odd values of β with even values of κ . Conversely, even values of β combine with odd values of κ . Moreover, the harmonic m_f should be an odd integer in order to prevent the appearance of even harmonic terms in v_{ao} .

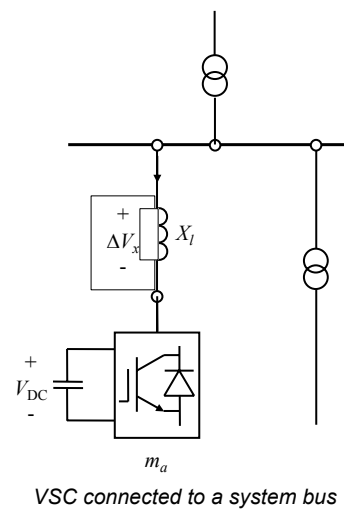
FACTS Equipment – PWM Control

- The fundamental frequency component is shown in the previous figure for the case of $m_f=9$ and $m_s=0.8$. The corresponding harmonic voltage spectrum, in normalised form, is shown in the figure below



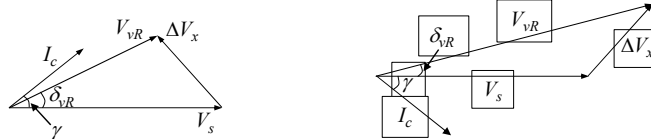
Principle of VSC Operation

- The interaction between the VSC and the power system may be explained in simple terms, by considering a VSC connected to the AC mains through a loss-less reactor, as illustrated in the single-line diagram shown opposite
- The premise is that the amplitude and the phase angle of the voltage drop, ΔV_x , across the reactor, X_l , can be controlled; defining the amount and direction of active and reactive power flows through X_l . The voltage at the supply bus is taken to be sinusoidal, of value $V_s \angle 0^\circ$, and the fundamental frequency component of the SVC's AC voltage is taken to be $V_{VR} \angle \delta_{VR}$



Principle of VSC Operation

- The positive sequence, fundamental frequency vector representation is shown in the figures below for leading and lagging VAR compensation, respectively



- For leading and lagging VAR, the active and reactive powers can be expressed as

$$P = \frac{V_s V_{vR}}{X_l} \cdot \sin \delta_{vR} \quad Q = \frac{V_s^2}{X_l} - \frac{V_s V_{vR}}{X_l} \cdot \cos \delta_{vR}$$

Principle of VSC Operation

With reference to the previous figures and equations, the following observations are derived:

- The VSC output voltage V_{vR} leads the AC voltage source V_s by an angle δ_{vR} , and the input current either leads or lags the voltage drop across the reactor ΔV_x by 90°
- The active power flow between the AC source and the VSC is controlled by the phase angle δ_{vR} . Active power flows into the VSC from the AC source at lagging δ_{vR} ($\delta_{vR} > 0$), and vice versa for leading δ_{vR} ($\delta_{vR} < 0$)
- The reactive power flow is determined mainly by the magnitude of the voltage source, V_s , and the VSC output fundamental voltage, V_{vR} . For $V_{vR} > V_s$, the VSC generates reactive power and consumes reactive power when $V_{vR} < V_s$
- The DC capacitor voltage V_{DC} is controlled by adjusting the active power flow that goes into the VSC. During normal operation, a small amount of active power must flow into the VSC to compensate for the power losses inside the VSC, and δ_{vR} is kept slightly larger than 0° (lagging)

Principle of VSC Operation

- For leading and lagging VAR, the active and reactive powers can be expressed as

$$P = \frac{V_s V_{vR}}{X_l} \cdot \sin \delta_{vR} \quad Q = \frac{V_s^2}{X_l} - \frac{V_s V_{vR}}{X_l} \cdot \cos \delta_{vR}$$

Voltage relations	Power Exchange
	VSC ↔ AC
$V_{vR} > V_s$	Q →
$V_{vR} < V_s$	Q ←
$\delta_{vR} > \delta_s$	P →
$\delta_{vR} < \delta_s$	P ←

FACTS Equipment - STATCOM

Duke Power

ESKOM

Florida Power Corp.

Powercor Australia Ltd.

Salt River Project

Scottish Power

American Electric Power

British Columbia Hydro and Power Authority

Central Japan Railway

Chubu Electric Corp.

Kansai Electric Power Corp.

Mitsubishi Steel Co.

Oglethorpe Power

Gas Sumitomo Steel Co.

Public Service Electric

National Grid Co.

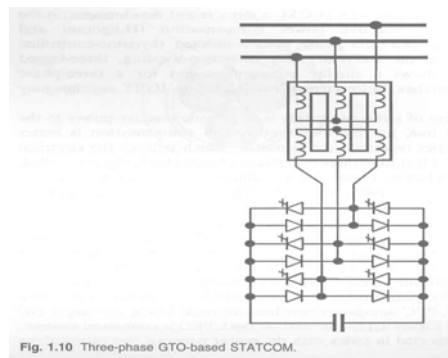
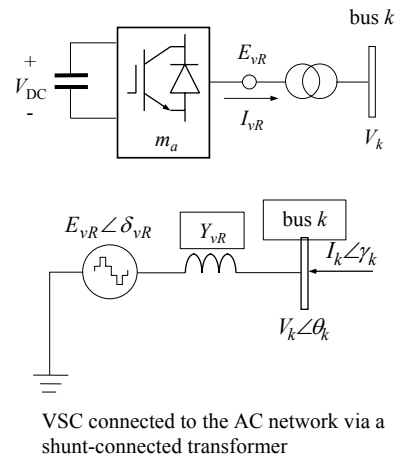


Fig. 1.10 Three-phase GTO-based STATCOM.

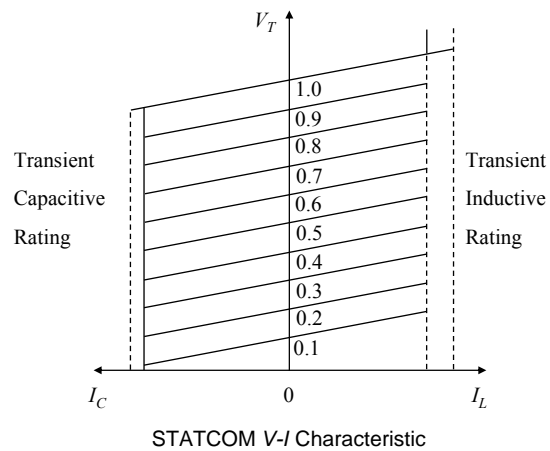
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FACTS Equipment - STATCOM

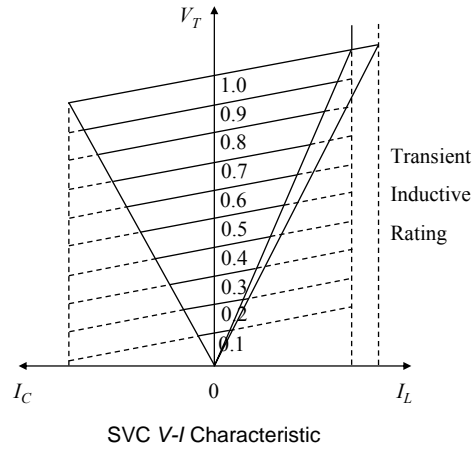
- The Static Compensator (STATCOM) consists of one VSC and its associated shunt-connected transformer, as illustrated in the figure opposite. The figure also shows the equivalent circuit, which is a shunt-connected voltage source
- It is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate because no moving parts are involved
- In principle, it performs the same voltage regulation function as the SVC but in a more robust manner because unlike the SVC, its operation is not impaired by the presence of low voltages



FACTS Equipment - STATCOM



FACTS Equipment - STATCOM



FACTS Equipment - STATCOM

With reference to the equivalent circuit shown above, and assuming three-phase parameters (a, b, c), the following transfer admittance equation can be written:

$$[\mathbf{I}_k] = [\mathbf{Y}_{vR} \quad -\mathbf{Y}_{vR}] \begin{bmatrix} \mathbf{V}_k \\ \mathbf{E}_{vR} \end{bmatrix}$$

where $\mathbf{I}_k = [I_k^a \angle \gamma_k^a \quad I_k^b \angle \gamma_k^b \quad I_k^c \angle \gamma_k^c]^t$ $\mathbf{V}_k = [V_k^a \angle \theta_k^a \quad V_k^b \angle \theta_k^b \quad V_k^c \angle \theta_k^c]^t$

$$\mathbf{E}_{vR} = [V_{vRk}^a \angle \delta_{vRk}^a \quad V_{vRk}^b \angle \delta_{vRk}^b \quad V_{vRk}^c \angle \delta_{vRk}^c]^t$$

$$\mathbf{Y}_{vR} = \begin{bmatrix} Y_{vRk}^a & 0 & 0 \\ 0 & Y_{vRk}^b & 0 \\ 0 & 0 & Y_{vRk}^c \end{bmatrix}$$

FACTS Equipment - STATCOM

- *In steady-state, fundamental frequency studies the STATCOM may be represented in the same way as a synchronous condenser, which in most cases is the model of a synchronous generator with zero active power generation*
- *A more flexible model may be realised by representing the STATCOM as a variable voltage source E_{vR} , whose magnitude and phase angle may be adjusted, using a suitable iterative algorithm, to satisfy a specified voltage magnitude at the point of connection with the AC network*

The shunt voltage source of the three-phase STATCOM and its operating limits may be represented by:

$$E_{vR}^{\rho} = V_{vR}^{\rho} (\cos \delta_{vR}^{\rho} + j \sin \delta_{vR}^{\rho})$$

$$V_{vR,\min}^{\rho} \leq V_{vR}^{\rho} \leq V_{vR,\max}^{\rho} \quad \text{and} \quad 0 \leq \delta_{vR}^{\rho} \leq 2\pi$$

where ρ indicates phase quantities, a , b and c

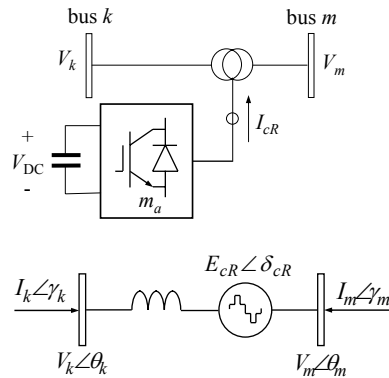
FACTS Equipment - STATCOM

Installations:

- Orange and Rockland	STATCOM	±1 MVA	1986
- WAPA	UPFC Model		1993
- TVA, Sullivan	STATCOM	±100 MVA	1995
- AEP, St Inez	STATCOM	±160 MVA	1997
	(UPFC)		
- SMI Arc Furnace	STATCOM	±80 MVA	1998
- Pacific Gas & Electric	STATCOM	-20/+60MVA	1998
- AEP, St Inez	UPFC	±320 MVA	1998
		(2 × ±160)	

FACTS Equipment - SSSC

- For the purpose of steady-state operation, the Solid State Series Compensator (SSSC) performs a similar function to the static phase shifter; it injects voltage in quadrature with one of the line end voltages in order to regulate active power flow
- However, the SSSC is a far more versatile controller than the phase shifter because it does not draw reactive power from the AC system; it has its own reactive power provisions in the form of a DC capacitor
- This characteristic makes the SSSC capable of regulating not only active but also reactive power flow or nodal voltage magnitude
- The schematic representation of the SSSC and its equivalent circuit are shown in figure opposite



VSC connected to the AC network via a series-connected transformer; (b) series solid-state voltage source

FACTS Equipment - SSSC

SSSC is a VSC connected to the AC network via a series-connected transformer

In transmission level applications the SSSC is not used on its own but forms an important part of more advanced controllers

In distribution level applications this controller is termed Dynamic Voltage Restorer (DVR). It is said to be able to complete the "missing voltage cycles"

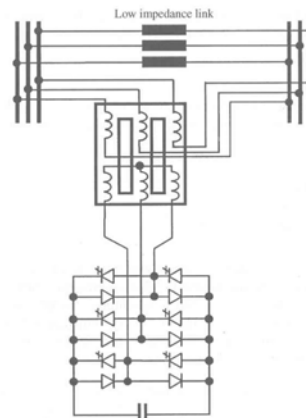


Fig. 1.14 Three-phase dynamic voltage restorer.

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FACTS Equipment - SSSC

The series voltage source of the three-phase SSSC may be represented by

$$E_{cR}^{\rho} = V_{cR}^{\rho} \left(\cos \delta_{cR}^{\rho} + j \sin \delta_{cR}^{\rho} \right)$$

where ρ indicates phase quantities, a , b and c

- The magnitude and phase angle of the SSSC model are adjusted using any suitable iterative algorithm to satisfy a specified active and reactive power flow across the SSSC
- Maximum and minimum limits exist for the voltage magnitude V_{cR} , which are a function of the SSSC capacitor rating. The voltage phase angle δ_{cR} can take any value between 0 and 2π radians

FACTS Equipment - SSSC

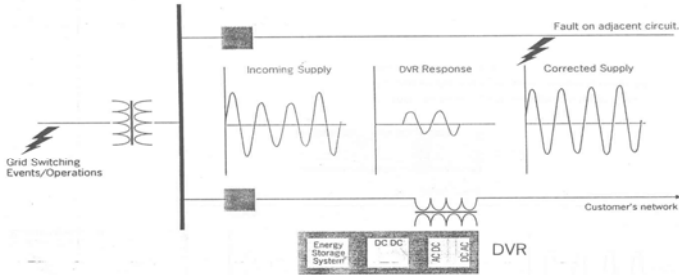
Based on the equivalent circuit shown above, and assuming three-phase parameters, the following transfer admittance equation can be written:

$$\begin{bmatrix} \mathbf{I}_k \\ \mathbf{I}_m \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{cR} & -\mathbf{Y}_{cR} & -\mathbf{Y}_{cR} \\ -\mathbf{Y}_{cR} & \mathbf{Y}_{cR} & \mathbf{Y}_{cR} \end{bmatrix} \begin{bmatrix} \mathbf{V}_k \\ \mathbf{V}_m \\ \mathbf{E}_{cR} \end{bmatrix}$$

In addition to parameters used in the STATCOM model the following quantities are defined,

$$\begin{aligned} \mathbf{E}_{cR} &= \left[V_{cR}^a \angle \delta_{cR}^a \quad V_{cR}^b \angle \delta_{cR}^b \quad V_{cR}^c \angle \delta_{cR}^c \right]^t \\ \mathbf{V}_m &= \left[V_m^a \angle \theta_m^a \quad V_m^b \angle \theta_m^b \quad V_m^c \angle \theta_m^c \right]^t \\ \mathbf{I}_m &= \left[I_m^a \angle \gamma_m^a \quad I_m^b \angle \gamma_m^b \quad I_m^c \angle \gamma_m^c \right]^t \end{aligned} \quad \mathbf{Y}_{cR} = \begin{bmatrix} Y_{cRk}^a & 0 & 0 \\ 0 & Y_{cRk}^b & 0 \\ 0 & 0 & Y_{cRk}^c \end{bmatrix}$$

FACTS Equipment - DVR

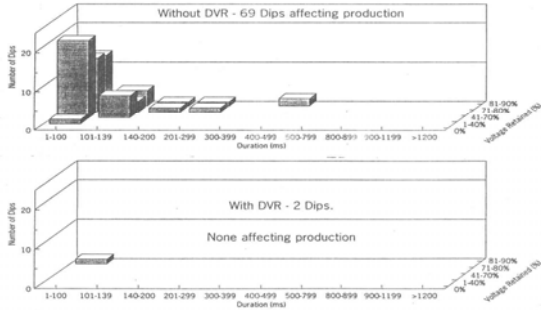


The DVR injects energy to compensate for the effect of a voltage dip. The customers network is protected from these disturbances.

DVR contribution to incoming supply with a voltage sag due to an upstream switching event or a short-circuit fault in a neighbouring feeder

FACTS Equipment - DVR

The top chart shows the recorded voltage dips at the mill before the DVR was fitted. The lower chart shows the effect that the DVR has in eliminating voltage dips which could cause the plant to stop operation.



Statistics relating to voltage sags in an actual installation: with no DVR and with a DVR in operation

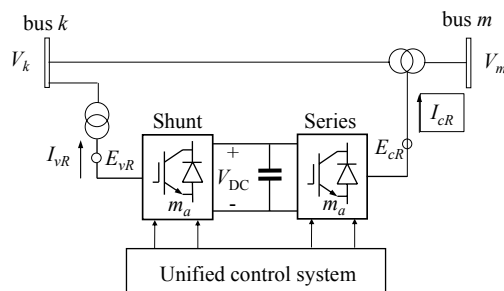
FACTS Equipment - DVR

Installations:

- Duke Power	DVR	2 MVA	1996
- Powercor (Australia)	DVR	2 MVA	1996
- Florida Power Corp	DVR	2 MVA	1997
- Scottish Power	DVR	4 MVA	1997
- Asian Electronics	DVR	2 MVA	1998
Manufacturer			
- Salt River Project	DVR	2×6MVA	1998
- BC Hydro	D-STATCOM	±2 MVA	1997
- AEP	D-STATCOM	±2 MVA	1997
- Hyosung Industries KEPRI	D-STATCOM	±1 MVA	1998

FACTS Equipment - UPFC

- *The UPFC may be seen to consist of two VSCs sharing a common capacitor on their DC side and a unified control system. A simplified schematic representation of the UPFC is given in the figure opposite*
- *The UPFC allows simultaneous control of active power flow, reactive power flow and voltage magnitude at the UPFC terminals. Alternatively, the controller may be set to control one or more of these parameters in any combination or to control none of them*



UPFC system - Two back-to-back VSCs with one VSC connected to the AC network using a shunt transformer and the second VSC connected to the AC network using a series transformer, with a unified control system

FACTS Equipment - UPFC

The UPFC system at St. Inez comprises two identical GTO-based inverters, each rated at ± 160 MVA

The anticipated maximum active power exchange between the inverters is 80 MW

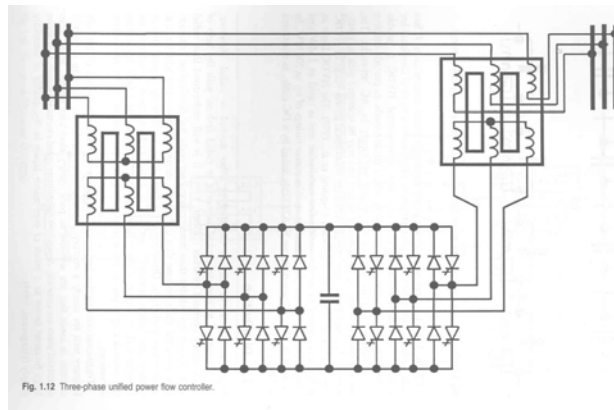


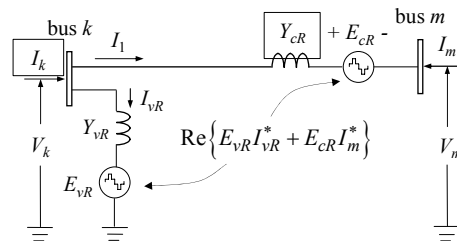
Fig. 1.12 Three-phase unified power flow controller.

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UPFC system – a more expanded view

FACTS Equipment - UPFC

- The active power demanded by the series converter is drawn by the shunt converter from the AC network and supplied to bus m through the DC link
- The figure opposite shows the UPFC equivalent circuit. It consists of a shunt connected voltage source, a series connected voltage source and an active power constraint equation which links the two voltage sources
- The two voltage sources are connected to the AC system through inductive reactances representing the VSC transformers



UPFC equivalent circuit

FACTS Equipment - UPFC

- *The output voltage of the series converter is added to the nodal voltage, at say bus k, to boost the nodal voltage at bus m*
- *The voltage magnitude of the output voltage V_{cR} provides voltage regulation and the phase angle determines the mode of power flow control*
- *In addition to providing a supporting role in the active power exchange that takes place between the series converter and the AC system, the shunt converter may also generate or absorb reactive power in order to provide independent voltage magnitude regulation at its point of connection with the AC system*
- *In a three-phase UPFC, suitable expressions for the two voltage sources and constraint equation would be*

$$E_{vR}^{\rho} = V_{vR}^{\rho} (\cos \delta_{vR}^{\rho} + j \sin \delta_{vR}^{\rho}) \quad E_{cR}^{\rho} = V_{cR}^{\rho} (\cos \delta_{cR}^{\rho} + j \sin \delta_{cR}^{\rho})$$

$$\text{Re} \left\{ -E_{vR}^{\rho} I_{vR}^{*\rho} + E_{vR}^{\rho} I_m^{*\rho} \right\} = 0$$

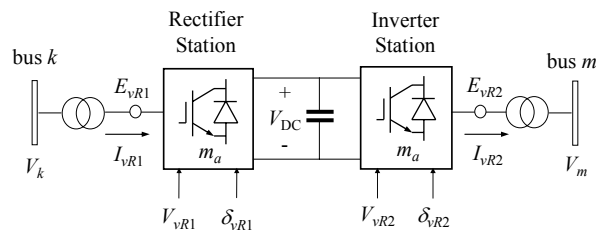
FACTS Equipment - UPFC

- *Similarly to the shunt and series voltage sources used to represent the STATCOM and the SSSC, respectively, the voltage sources used in the UPFC application would also have limits*
- *Based on the equivalent circuit shown above, and assuming three-phase parameters, the following transfer admittance equation can be written as:*

$$\begin{bmatrix} \mathbf{I}_k \\ \mathbf{I}_m \end{bmatrix} = \begin{bmatrix} (\mathbf{Y}_{cR} + \mathbf{Y}_{vR}) & -\mathbf{Y}_{cR} & -\mathbf{Y}_{cR} & -\mathbf{Y}_{vR} \\ -\mathbf{Y}_{cR} & \mathbf{Y}_{cR} & \mathbf{Y}_{cR} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{V}_k \\ \mathbf{V}_m \\ \mathbf{E}_{cR} \\ \mathbf{E}_{vR} \end{bmatrix}$$

FACTS Equipment – HVDC-VSC

- The HVDC-VSC comprises two VSCs, one operating as a rectifier and the other as an inverter. The two converters are connected either back-to-back or joined together by a DC cable, depending on the application
- Its main function is to transmit constant DC power from the rectifier to the inverter station, with high controllability
- The schematic representation of the HVDC-VSC is shown in the figure below



HVDC-VSC system - The VSC at the sending end performs the role of rectifier and the VSC at the receiving end performs the role of inverter

FACTS Equipment – HVDC-VSC

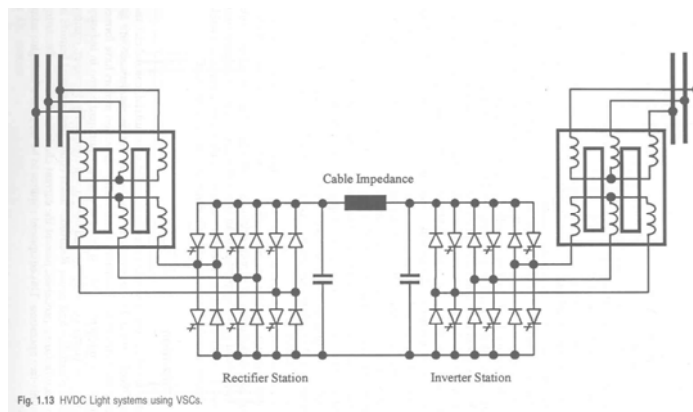


Fig. 1.13 HVDC Light systems using VSCs.

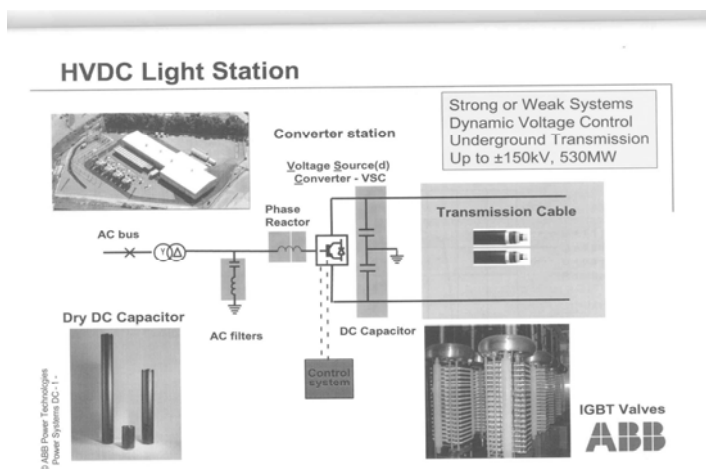
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HVDC-VSC system - The VSC at the sending end performs the role of rectifier and the VSC at the receiving end performs the role of inverter

FACTS Equipment - HVDC-VSC

- Continuous developments in power electronics devices with turn-on and turn-off capabilities makes Voltage Source Converter (VSC) technology more and more attractive for HVDC transmission applications
- This innovative technology provides substantial technical and economical advantages for a range of applications compared to conventional HVDC transmission systems based on conventional thyristor technology
- HVDC links based on the use of VSC, termed HVDC-VSC for the purpose of this talk, are found in the technical-commercial literature under the names of HVDC Light (ABB product) and HVDC Plus (power link universal systems, Siemens product)
- With current electronic valve technology, HVDC-VSC has a power rating in the range 7-530 MW and DC voltage in the range 10-150 kV
- In contrast, conventional HVDC systems are available in the power range 100-3000 MW and DC voltages up to 600 kV

FACTS Equipment - HVDC-VSC



HVDC-VSC Installations

- The HVDC-VSC stations use PWM control and operate at switching frequencies considerably higher than the fundamental frequency in order to have fast control of both active and reactive powers
- The HVDC-VSC is a very recent HVDC technology. It is reported that on 10th March 1977 power was transmitted on the world's first HVDC transmission system between Hellsjön and Grängerg in central Sweden. The HVDC-VSC is rated at 3 MW and ± 10 kV
- This was followed by the Gotland HVDC-VSC, rated at 50 MW, and linking a wind power farm on the southern tip of the Swedish island of Gotland to the City of Visby some 70 km away. The station transmits at ± 80 kV using underground cables and commissioning took place in mid-2000
- An HVDC-VSC transmission system, known as the Directlink, was also commissioned in mid-2000. It is rated at 180 MW, ± 80 kV and 65 km underground cable, and used to connect the Queensland and New South Wales grids between Terranora and Mullumbimby in Australia

HVDC-VSC Installations

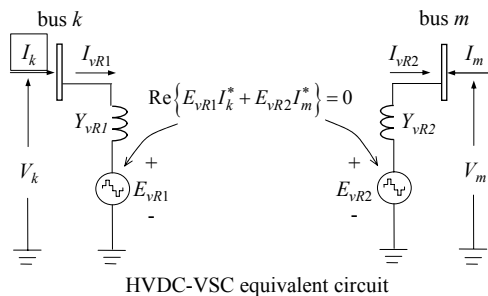
- Here-to-fore, the Cross Sound link in NY is the largest HVDC-VSC link, rated at 330 MW and operating at ± 150 kV. It was commissioned in September 2002
- This is followed in capacity by the Murraylink at 200 MW and ± 150 kV, which was commissioned in October 2002
- In mid-2000 an HVDC-VSC back-to-back was installed at the Eagle Pass substation in Texas. It features two 36 MW converter stations connecting to a 138 kV AC overhead line linking the interconnected Mexican system at the Piedras Negras substation
- All in all, thirteen Light installations (HVDC-VSC and STATCOM) are known to be in operation or in the construction stage

HVDC-VSC Applications

- The vendors of the technology argue that HVDC-VSC stations make it economically feasible to connect small-scale, renewable power generation plants to the main AC grid
- Similarly, that remote locations such as islands, mining districts, and drilling platforms can be supplied with power from the main grid via HVDC-VSC stations, hence, eliminating the need for inefficient, polluting local generation such as diesel units
- The voltage, frequency, and active and reactive powers can be controlled precisely and independently from each other, hence, finding application in the interconnection of weak and strong systems. Full power reversals may be achieved in a matter of a few hundred milliseconds, e.g. 400 ms
- Contrary to HVDC links using conventional thyristors, the HVDC-VSC, does not require commutation sources on the AC side of each converter station
- Similarly, large capacitor banks to meet reactive power requirements by the two conventional converter stations are not needed by the HVDC-VSC

FACTS Equipment – HVDC-VSC

- One VSC controls DC voltage and the other the transmission of active power through the DC link
- Assuming loss-less converters, the active power flow entering the DC system must equal the active power reaching the AC system at the inverter end minus the transmission losses in the DC cable
- During normal operation, both converters have independent reactive power control



FACTS Equipment – HVDC-VSC

- The HVDC-VSC system is suitably represented by two shunt-connected voltage sources linked together by an active power constraint equation
- Similarly to the STATCOM model, suitable expressions for the two three-phase voltage sources and the linking power equation are:

$$E_{vR1}^{\rho} = V_{vR1}^{\rho} (\cos \delta_{vR1}^{\rho} + j \sin \delta_{vR1}^{\rho})$$

$$E_{vR2}^{\rho} = V_{vR2}^{\rho} (\cos \delta_{vR2}^{\rho} + j \sin \delta_{vR2}^{\rho})$$

$$\operatorname{Re} \{ E_{vR1}^{\rho} I_{vR1}^{*\rho} - E_{vR2}^{\rho} I_{vR2}^{*\rho} \} = 0$$

where ρ indicates phase quantities a , b and c . Also, the following limits exist for the voltage sources representing the rectifier and inverter stations:

$$V_{vR1\min}^{\rho} \leq V_{vR1}^{\rho} \leq V_{vR1\max}^{\rho} \quad 0 \leq \delta_{vR1}^{\rho} \leq 2\pi$$

$$V_{vR2\min}^{\rho} \leq V_{vR2}^{\rho} \leq V_{vR2\max}^{\rho} \quad 0 \leq \delta_{vR2}^{\rho} \leq 2\pi$$

FACTS Equipment - HVDC-VSC

- Based on the equivalent circuit shown above, and assuming three-phase parameters, the following transfer admittance equation can be written

$$\begin{bmatrix} \mathbf{I}_k \\ \mathbf{I}_m \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{vR1} & -\mathbf{Y}_{vR1} & 0 & 0 \\ 0 & 0 & \mathbf{Y}_{vR2} & -\mathbf{Y}_{vR2} \end{bmatrix} \begin{bmatrix} \mathbf{V}_k \\ \mathbf{E}_{vR1} \\ \mathbf{V}_m \\ \mathbf{E}_{vR2} \end{bmatrix}$$

FACTS Equipment - HVDC-VSC

- *The HVDC-VSC at Piedras Negras – Eagle Pass uses IGBT-based converters, which switch at 1260 Hz ($m_f = 1260/60 = 21$)*
- *It connects the 138 kV grids of CFE and AEP-TCC. It consists of two 36 MVA VSCs*
- *PWM harmonics are generated at:: $f_h = (\beta m_f \pm \kappa) f_1$*

β	Harmonic order
1	19, 21, 23
2	39, 41, 43, 45
3	59, 61, 63, 65, 67
4	81, 83, 85, 87
...	...
10	207, 209, 211, 213
...	...

The 3rd harmonic is also significant

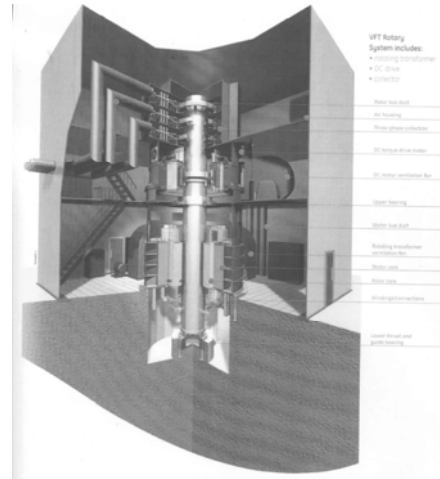
The 207th harmonic varied between 13% and 40% of the power frequency voltage, depending on the operation of the BtB and phase angle between the two inverters

Variable Frequency Transformer

- *The VFT is based on a combination of hydro-generator, transformer and drives technologies*
- *The VFT provides a means for controlling active power ex-changes between two grids*
- *The VFT may be seen as a three-phase, two-winding transformer with a rotary secondary, for continuously controllable phase shift. A drive system and control adjust precisely the phase angle and speed of the rotor to regulate the power flow through the VFT*
- *The VFT vendors argue that low complexity and low maintenance are key attributes of the technology:*
 - *Use of common substation components, e.g. transformers, capacitors*
 - *Low speed operation resulting in low maintenance requirements*
 - *Redundancy in auxiliary services, e.g. cooling fans*
 - *All main components have low operational stress resulting in high reliability*

Variable Frequency Transformer

- The figure opposite shows a cut-away drawing of a 100 MW VFT installed at Langlois, Canada where the main components are:
 - The rotary transformer
 - The drive motor
 - The collector
- The collector system conducts current between the three-phase rotor winding and its stationary busbar
- One power grid is connected to the VFT's rotor and the other grid is connected to the VFT's stator



Principle of Operation of the VFT

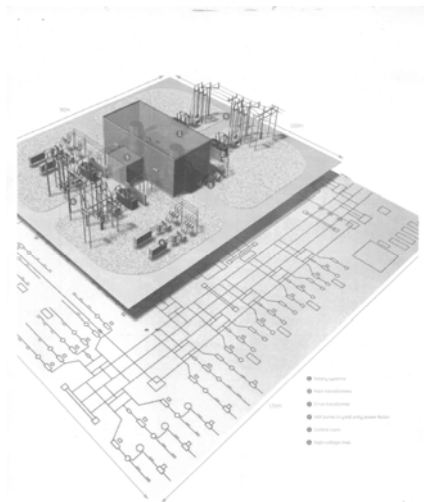
- Similarly to a phase-shifting transformer, power flow is a function of the angle of the rotary transformer
- Moreover, power flow through the VFT is proportional to the magnitude and direction of the torque applied to the rotor
 - (i) With torque applied in one direction, power flows from the stator winding to the rotor winding
 - (ii) With torque applied in the opposite direction, the power flow is from rotor to stator
 - (iii) With no torque applied, no power flows through the VFT
- If the VFT is used to interconnect two asynchronous grids then the rotor inherently orients itself to follow the phase angle difference imposed by the two asynchronous grids, rotating continuously. This is regardless of power flow

Principle of Operation of the VFT

- Torque is applied to the rotor by a drive motor, which is controlled by the variable speed drive system
- The VFT operates at zero speed when used to interconnect two power grids of the same frequency
- However, if the power grid on one side experiences a disturbance that causes a frequency excursion, the VFT will rotate at a speed proportional to the difference in frequency between the two power grids
- The scheduled power flow is maintained during the disturbance. In fact, the VFT is designed to continuously regulate power flow with drifting frequencies on both grids
- A closed loop power regulator maintains power transfer equal to an operator set point. The regulator compares measured power with the set point, and adjusts motor torque as a function of power error

Layout of a VFT Substation

- The figure opposite shows the layout of a 200 MW VFT substation, where the following items are highlighted:
 - (1) Rotary system
 - (2) Main transformers
 - (3) Drive transformer
 - (4) VARs banks to yield unity pf
 - (5) Control room
 - (6) High-voltage lines
- For comparison purposes, the layout of the VFT substation is superimposed on top of the layout of an 200 MW HVDC substation

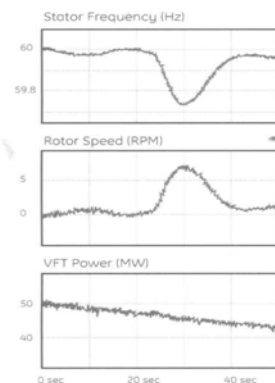


Reactive Power Requirements

- The VFT is essentially an induction machine and, as such, it will consume reactive power even when operated at no-load
- Capacitor banks are provided to enable VFT operation at unity power factor
- However, phase angle opening is also achieved at the expense of consuming reactive power, which is normally carried out in a dynamic fashion
- Provisions do not seem to be available for dynamic reactive power requirements let alone for enabling VARs support at the connecting busbars
- One open questions is, what is the amount of reactive power required by the VFT when transmitting 100 MW and how does this affect the voltage profile in neighbouring busbars

Operation and Control Quasi-Steady-State Response

- Steady state power control is smooth, with the operator setting the VFT's power command similar to dispatching generation on the system
- The figure opposite shows the response of the VFT at Langlois to a generator trip, while the VFT was ramping down
- The vendors of the VFT technology argue that its inertia improves the grid response to faults and transients
- They also argue that field tests and studies show that the VFT improves stability in neighbouring networks



Nov. 1, 2003 – Langlois VFT response to a Hydro-Quebec generator trip, while VFT was ramping.

Operation and Control Dynamic Response

- The figure opposite illustrates the VFT's response to steps in power order
- The red line is the torque command stepping from 0 to 1 pu, to -1, and back to 0
- The blue line in the same plot shows the actual VFT power transfer. The corresponding phase angle is shown in the lower plot
- These results were obtained using a real-time VFT simulator

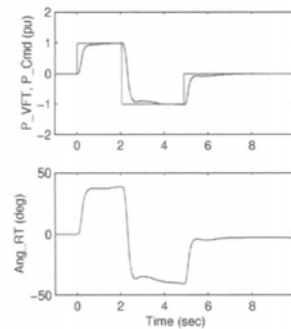


Figure 7. VFT step response

Operation and Control Dynamic Response

- The figure opposite illustrates the VFT's response to a fault in the AC network
- The voltages on the machine terminals remain above zero, due to contribution from the unfaulted side
- The VFT's inertia helps to keep the rotor relatively stationary during the fault
- After recovery, the control readjusts the position to meet the desired power flow

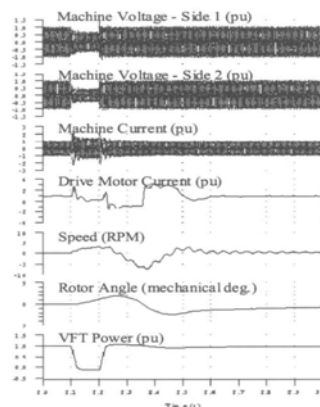


Figure 8. VFT response to fault in AC network

Comparison between HVDC-VSC and VFT Technologies

Comparisons

Function	HVDC Light	VFT
Core technology	IGBT valves	Induction machine plus variable speed drive
Network connection	Transformers plus series inductors	Transformers
Filtering and reactive compensation	Quite considerable filter requirements	Switched capacitors
Power control	0 to ± 150 MW	0 to ± 100 MW
Speed of response	Very fast	Quite slow
Modulation/control	Active and reactive powers	Active power
Voltage control	Continuous, fast and independent	Not possible
Black start	Yes	Yes
Maturity	Rapidly maturing – several sites	One installation
Full load losses	3.46%	1.78%

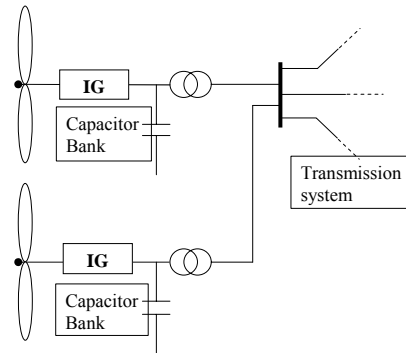
Comparisons
Further comments

- The VFT has a very slow response due to its rotor's inertia, compared to the HVDC-VSC. Hence, the VFT can only provide damping for low frequency power oscillations
- The risk that the VFT could decrease damping at high frequency oscillations should be fully assessed
- The ability of the drive motor to provide damping torque over a wide range of operation should be fully assessed
- A fault in one of the power grids will impact the other grid because reactive power will be exported to the point in fault through the VFT
- Unlike the HVDC-VSC, it is highly unlikely that the VFT will cause any harmonic distortion in the power network

Basic Concepts on Wind Generation

Wind Generation

- *The interest in wind energy has been growing steadily for the past twenty years in many countries around the world*
- *Most wind farms installed in the UK use induction generators with fixed-speed wind turbines*
- *Banks of capacitors are provided on site to provide the reactive power demanded by the induction generator*
- *It is envisaged that future large capacity wind farms will employ fast acting shunt capacitive compensation*



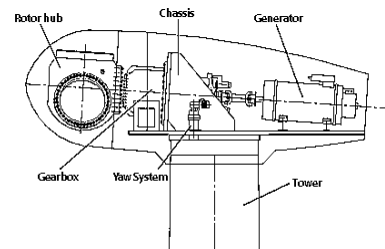
Wind-driven Induction generators with capacitor banks for power factor correction

Wind Generation

- From the viewpoint of hydrogen generation (fuel cells) for utility-level applications, the technology is still in its infancy
- Current wind turbines are very reliable and can be bought from a number of manufacturers but there is still considerable development of the technology, particularly as the size and rating of turbines increase
- In relation to wind turbines, major differences in design philosophy include:
 - (i) Fixed- or variable-speed operation
 - (ii) Direct drive generators or the use of a gear box
 - (iii) Stall or pitch regulation
- Fixed-speed wind turbines using induction generators are simpler and more robust
- It is not usual to use synchronous generators on network-connected fixed-speed wind turbines as it is difficult to include adequate damping in the rotor to control the periodic torque fluctuations of the aerodynamic rotor

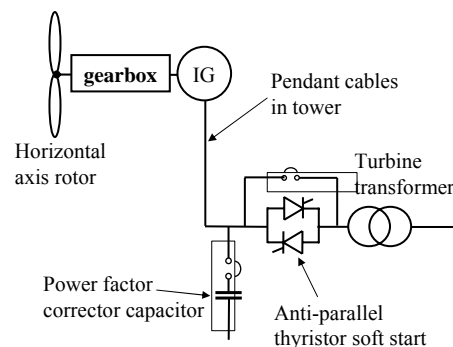
Wind Generation

- As shown in the figure opposite, the aerodynamic rotor is coupled to the induction generator via a speed increasing gear
- The induction generator is typically wound for 690 V, 1000 or 1500 rpm operation
- Pendant cables within the tower connect the generator to switched power factor corrector capacitors and an anti-parallel soft start unit located in the tower base
- It is common to bypass the soft-start thyristors once the generator has been fully fluxed
- A 1.5 MW wind turbine has a rotor diameter of some 60 m mounted on a 60-90 m high tower



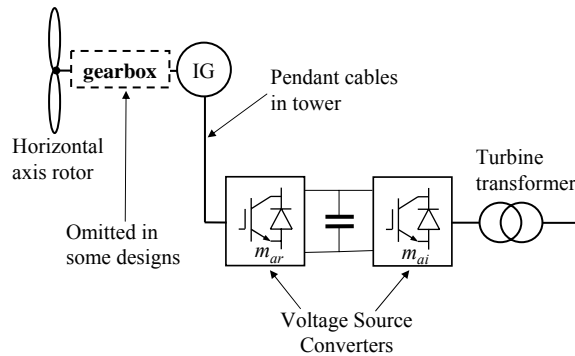
Wind Generation

- The figure opposite provides a more explicit picture of the various components
- The power factor correction capacitors are either all applied as soon as the generator is connected or they are switched in progressively as the average output power of the wind turbine increases
- It is not common to control these capacitors based on network voltage
- A local transformer, typically 690V/33 kV in UK wind farms, is located either inside the tower or adjacent to it



Wind Generation

- With variable-speed operation it is possible, in principle to increase the energy captured by the aerodynamics rotor by maintaining the optimum power coefficient over a wide range of wind speeds
- This requires an ancillary mechanism that decouples the speed of the rotor from the frequency of the network, such as a power electronic system of the kind illustrated in the figure opposite



Wind Generation

- The generator side bridge is commonly used to maintain the voltage of the DC link, whereas the network side converter is used to control the output power and hence the torque on the rotor
- The generator may be either synchronous or induction, and some form of PWM control is used to drive the electronic valves
- The gearbox is beginning to be dispensed with, since large-diameter direct-drive generators are beginning to be available. These generators rotate at the same speed as the aerodynamic rotor
- It is not practical to use large-diameter induction generators in this application and instead permanent magnet synchronous generators are being used. These are multi-pole generators which are then interfaced to the network as shown in the previous figure
- At the rated speed is necessary to limit the power into the wind turbine rotor, and some form of rotor regulation is required. Stall regulation operates on the rotor blades entering aerodynamic stall once the wind speed exceeds the rated value. In pitch regulated rotors the blades are rotated about their axis to limit the angle of attack seen by the airfoil

Wind Generation - Offshore

- Offshore wind farms are now being developed. They are in the range 50-100 MW and located many kilometres offshore
- The advantages of offshore installations include:
 - reduced visual impact
 - higher mean wind speed
 - reduced wind turbulence
 - low wind shear leading to lower towers
- The disadvantages include:
 - higher capital costs
 - access restrictions in poor weather
 - submarine cables required

Wind Power Plants

- A wind turbine operates by extracting kinetic energy from the wind passing through the rotor. The power developed by the wind turbine is

$$P = \frac{1}{2} C_p \rho V^3 A$$

where P is the power (W)

C_p is the power coefficient

V is the wind velocity (m/s)

A is the swept area of rotor disc (m²)

ρ is the density of air (1.225 kg/m³)

- As the power developed is proportional to the cube of the wind speed it is quite important to locate the wind turbines in areas high mean annual wind speed

Wind Power Plants

- Often the areas of high wind speed will be away from habitation and associated well-developed electrical distribution networks, leading to a requirement for careful consideration of the integration of wind turbines to relatively weak electrical distribution networks
- The wind turbines must be designed to withstand large forces during storms. Most modern designs use a three-bladed horizontal-axis rotor, which gives a good value of peak C_p
- *The power coefficient C_p is a measure of how much of the energy in the wind is extracted by the rotor turbine. It varies with rotor design and the relative speed of the rotor and wind, termed tip speed ratio, to give a maximum practical value of approximately 0.4*

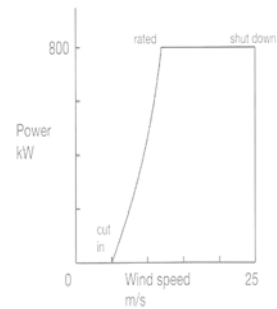


Figure 2.7 Wind turbine power curve

N Jenkins, R Alan, P Crossley, D. Kirschen and G Strbac

Power curve of a wind turbine, which indicates its output at various wind speeds

Wind Power Plants

- The figure opposite shows a typical annual distribution of hourly mean wind speeds from a UK lowland site
- In a typical installation from a UK lowland site the turbine will only be operating at the rated output for some 10-15% of the year
- *Depending on the site wind distribution, the turbine may be shut down due to low winds for up to 25% of the year*

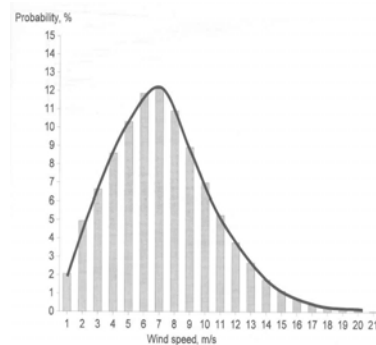


Figure 2.8 Distribution of hourly mean wind speeds of a typical lowland site

N Jenkins, R Alan, P Crossley, D. Kirschen and G Strbac

Distribution of hourly mean wind speeds of a typical lowland site

Wind Power Plants

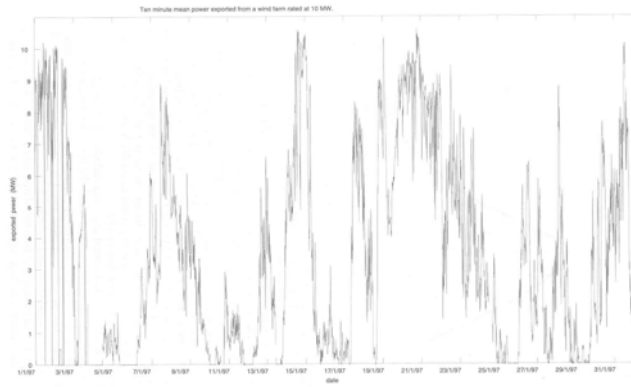


Figure 2.9a Time series output of a UK wind farm (Real Power)
Data courtesy of National Wind Power

N Jenkins, R Alan, P Crossley, D. Kirschen and G Strbac

Time series of the power outputs of a wind farm in the UK – active power

Wind Power Plants

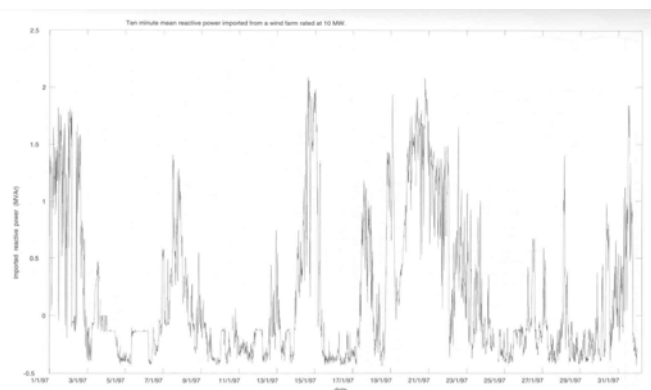


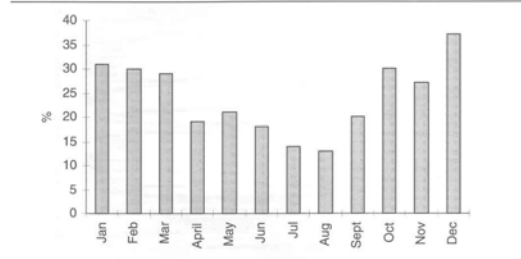
Figure 2.9b Time series output of a UK wind farm (Reactive Power)
Data courtesy of National Wind Power

N Jenkins, R Alan, P Crossley, D. Kirschen and G Strbac

Time series of the power outputs of a wind farm in the UK – reactive power

Wind Power Plants

Table 2.6 Monthly capacity factors of typical UK wind farms



N Jenkins, R Alan, P Crossley, D. Kirschen and G Strbac

Capacity factors of a number of wind farms in the UK

Wind Generation – Impact on the Distribution System

- Traditionally, the role of distribution networks has been confined to the interconnection between generation and transmission systems on one side and load centre on the other side
- Such networks are described as “passive” networks. However the integration of generation into the distribution networks will transform them from being passive to active networks
- The introduction of new or increased generation could have the following significant effects on the electrical system to which dispersed generation is connected to:
 - Increase in fault levels, which may necessitate switchgear replacement/enhancement
 - Alter power flows and voltage profile (usually an improvement)
 - Require adaptation of new protection practices in order to provide adequate protection for dispersed generators
 - Transient stability and motor starting performance of the system
 - May cause voltage fluctuations
 - Interfere with the control mechanism of voltage magnitude of distribution networks

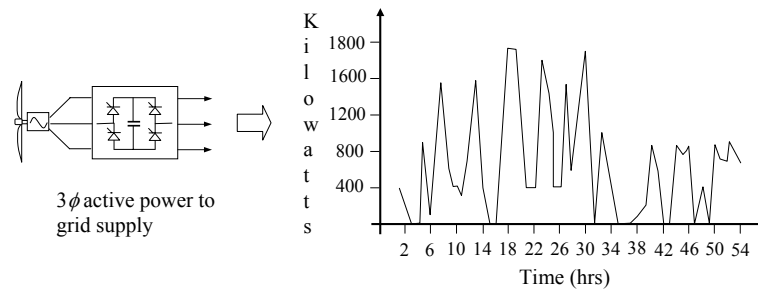
Wind Generation – Impact on the Distribution System

- Furthermore, dispersed generators of induction type, for instance wind turbine generator systems, may affect the voltage control process in two ways:
 - They may cause voltage fluctuation due to the fact that their power output is a function of wind speed, which is a variable quantity
 - Due to the inherent characteristic of induction generator, that usually draws almost fixed reactive power from the associated network
 - Consequently this may lead to further reduction of voltage magnitude due to the deterioration of system power factor condition.

A Wind Generator Model

- Wind generators slaved to the power network are mostly of the induction type. During high winds, when the rotor speed supersedes the synchronous speed, active power is injected into the grid
- In the presence of low winds, there is an automatic cut-out to prevent motoring from happening. During normal conditions, the turbine operates at nearly constant frequency
- The induction wind generator achieves its operation at the expense of consuming reactive power. From the power flow point of view, it makes engineering sense to treat the generator bus as a PQ bus with a positive active power injection and a negative reactive power injection
- However, these power injections must be time-dependent to reflect the stochastic nature of the prime mover, i.e. the wind
- For cases of wind farms of low capacity, their reactive power requirements can be met locally. Moreover, if suitable power electronics equipment is used in tandem with the wind generator set then the reactive power compensation can be met adaptively

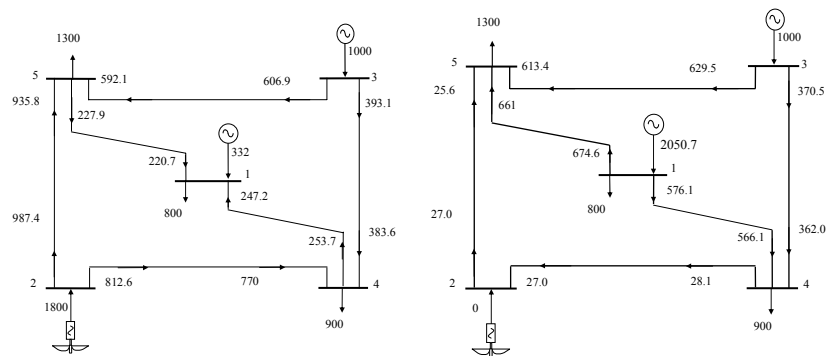
A Wind Generator Model



Wind generator model for power flow studies, which caters for time dependency

The figure above shows the active power output of a typical wind farm for a period of 54 hours, where very large variations between measurements are observed, e.g. the generator goes from zero power output at 16 hrs to 1.8 MW at 18 hrs

A Wind Generator Model



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