2. Shunt and Series Compensation

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2.1 Uniformly distributed fixed series and shunt compensation-1

- The line performance is determined by the characteristic impedance Z_C and the electrical length (also referred to as line angle) θ;
- *Without compensation*:

$$Z_C = \sqrt{\frac{L}{C}} = \sqrt{\frac{x_L}{b_C}} = \sqrt{\frac{X_L}{B_C}} \tag{11.38}$$

$$\theta = \beta l \tag{11.39}$$

$$\beta = \omega\sqrt{LC} = \sqrt{x_L b_C} = \frac{\sqrt{X_L B_C}}{l} \tag{11.40}$$

2.2 Uniformly distributed fixed series and shunt compensation-2

With **shunt** compensation:

$$b'_C = b_C - b_{sh} = b_C(1-k_{sh}) \tag{11.41}$$

Degree of shunt compensation:

$$k_{sh} = \frac{b_{sh}}{b_C} \tag{11.42}$$

Characteristic impedance and phase constant with shunt compensation:

$$Z'_C = \sqrt{\frac{x_L}{b'_C}} = \frac{Z_C}{\sqrt{1-k_{sh}}} \tag{11.43}$$

$$\beta' = \beta\sqrt{1-k_{sh}} \tag{11.44}$$

2.3 Uniformly distributed fixed series and shunt compensation-3

*With **series** compensation:*

$$x_L' = x_L - \frac{1}{\omega C_{se}} = x_L - x_{Cse} \qquad (11.45)$$

$$= x_L(1 - k_{se})$$

Degree of series compensation:

$$k_{se} = \frac{x_{Cse}}{x_L} \qquad (11.46)$$

Characteristic impedance and phase constant with series compensation:

$$Z_C' = \sqrt{\frac{x_L'}{b_C}} = Z_C\sqrt{1 - k_{se}}$$

$$\beta' = \beta\sqrt{1 - K_{Se}}$$

2.4 Uniformly distributed fixed series and shunt compensation-4

With both **series and shunt** compensation:

$$Z_C' = Z_C\sqrt{\frac{1-k_{se}}{1-k_{sh}}} \qquad (11.49)$$

$$\beta' = \beta\sqrt{(1-k_{sh})(1-k_{se})} \qquad (11.50)$$

Line angle and natural load:

$$\theta' = \theta\sqrt{(1-k_{sh})(1-k_{se})} \qquad (11.51)$$

$$P_0' = P_0\sqrt{\frac{1-k_{sh}}{1-k_{se}}} \qquad (11.52)$$

2.5 The effect of compensation on voltage-1

Light load

- inductive shunt compensation;
- with $k_{sh} = 1$ (100% inductive compensation), θ' and P_0' are zero and Z_C'- is infinite →V is flat at zero load.

Heavy load

- ***shunt*** capacitive compensation;
- to transmit $1.4P_0$ with a flat voltage profile, the required shunt capacitive compensation is k_{sh}= ??? (please, calculate)

What about series compensation?

2.6 The effect of compensation on voltage-1

Light load

- inductive shunt compensation;
- with $k_{sh} = 1$ (100% inductive compensation), θ' and P_0' are zero and Z_C'- is infinite →V is flat at zero load.

Heavy load

- ***shunt*** capacitive compensation;
- to transmit $1.4P_0$ with a flat voltage profile, the required shunt capacitive compensation is $k_{sh}= -0.96$.

What about series compensation?

2.7 The effect of compensation on voltage-2

- series capacitive compensation may be used instead of shunt compensation to give a flat voltage profile, under heavy loading;
- flat voltage profile can be achieved at a load of $1.4P_0$ with a distributed series compensation of $k_{Se}=$???;
- in practice, lumped series capacitors are not suitable for obtaining a smooth voltage profile along the line.

2.8 The effect of compensation on voltage-2

- series capacitive compensation may be used instead of shunt compensation to give a flat voltage profile, under heavy loading;
- flat voltage profile can be achieved at a load of $1.4P_0$ with a distributed series compensation of $k_{Se} = 0.49$;
- in practice, lumped series capacitors are not suitable for obtaining a smooth voltage profile along the line.

2.9 The effect on maximum power

$$P_R = \frac{E_S E_R}{Z_C' \sin\theta'} \sin\delta \tag{11.53}$$

How to increase maximum power?

1. Decrease Zc';
2. Decrease θ';
3. Decrease both Zc' and θ'.

But with shunt compensation:

↓Zc' ⇒ ↑θ' (capacitive shunt)
↓θ' ⇒ ↑ Zc' (inductive shunt)

Series compensation contributes to both.

Set priorities!

2.10 Uniformly distributed regulated shunt compensation

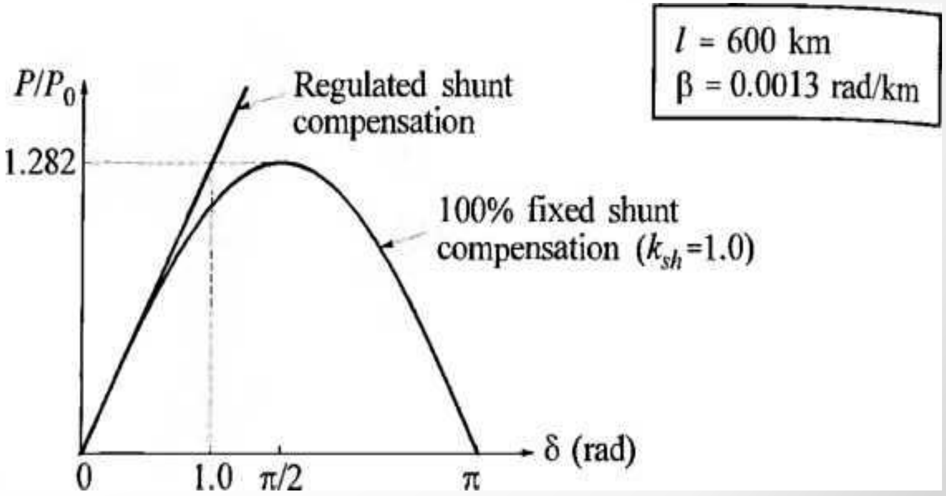
$$P = \frac{P_0'}{\sin\theta'}\sin\delta$$

$$\frac{P}{\delta} = \frac{P_0'}{\theta'} = \frac{P_0\sqrt{1-k_{sh}}}{\theta\sqrt{1-k_{sh}}} = \frac{P_0}{\theta} = \text{constant}$$

$$\begin{aligned} Q_V &= (V^2\omega C - I^2\omega L)l \\ &= P_0\theta\left[1-(P/P_0)^2\right] \end{aligned}$$

For the 600 km, 500 kV line:

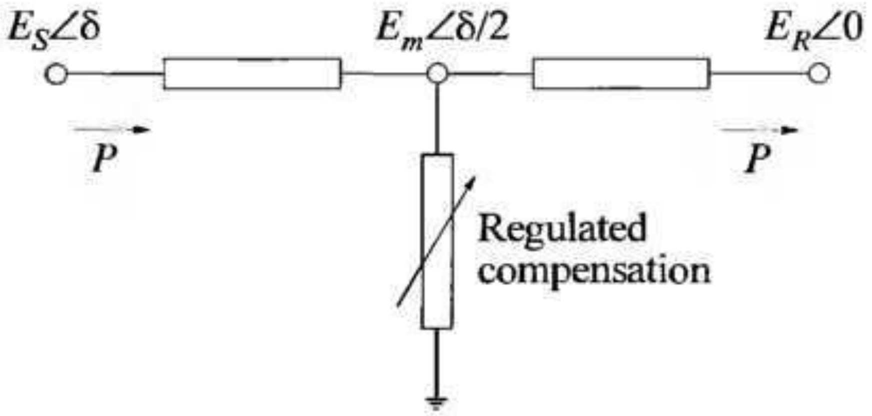
$$\frac{P/P_0}{\delta} = \frac{1}{\theta} = \frac{1}{0.78} = 1.282 \quad \text{pu/rad}$$



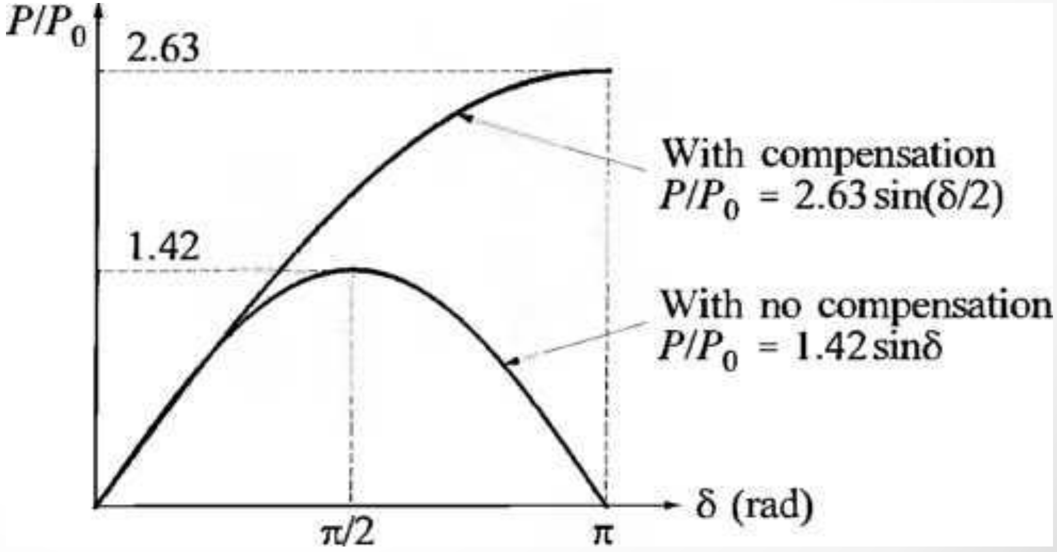
2.11 Regulated compensation at discrete intervals

$$P = \frac{E^2}{Z_C \sin(\theta/2)} \sin(\delta/2)$$

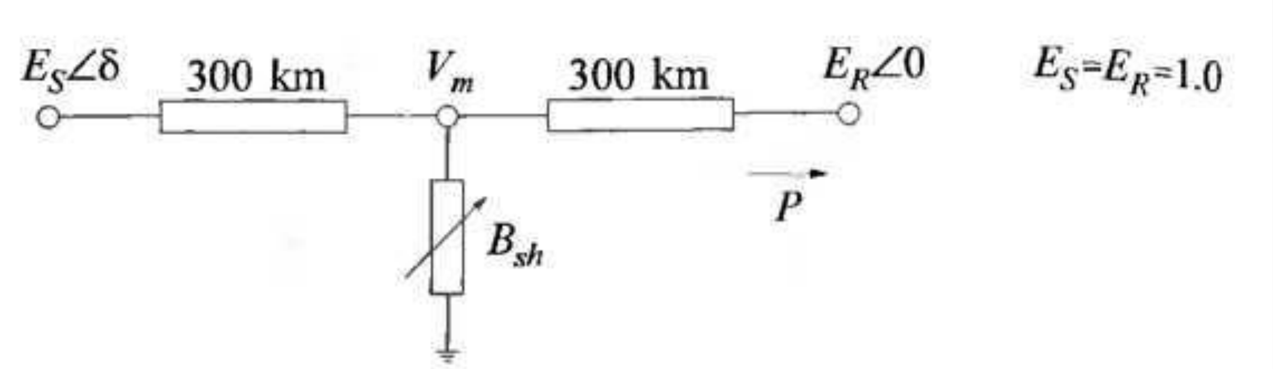
$$P = \frac{P_0}{\sin(\theta/2)} \sin(\delta/2)$$

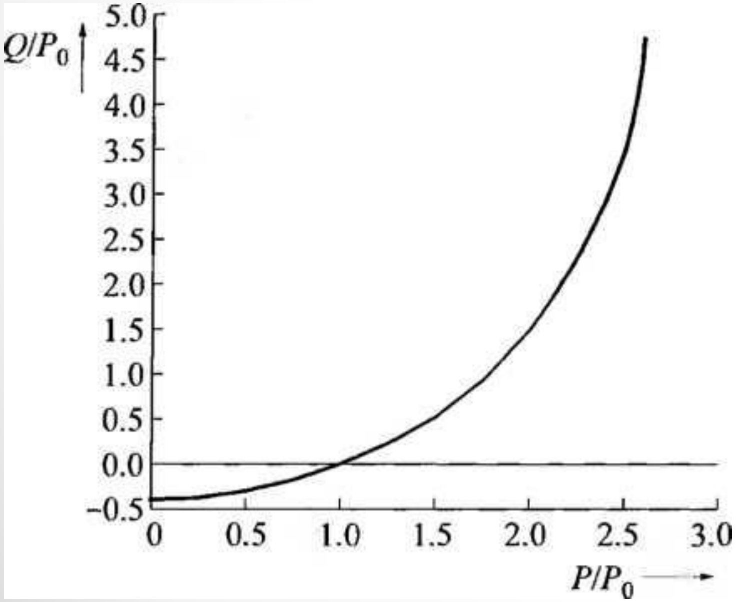


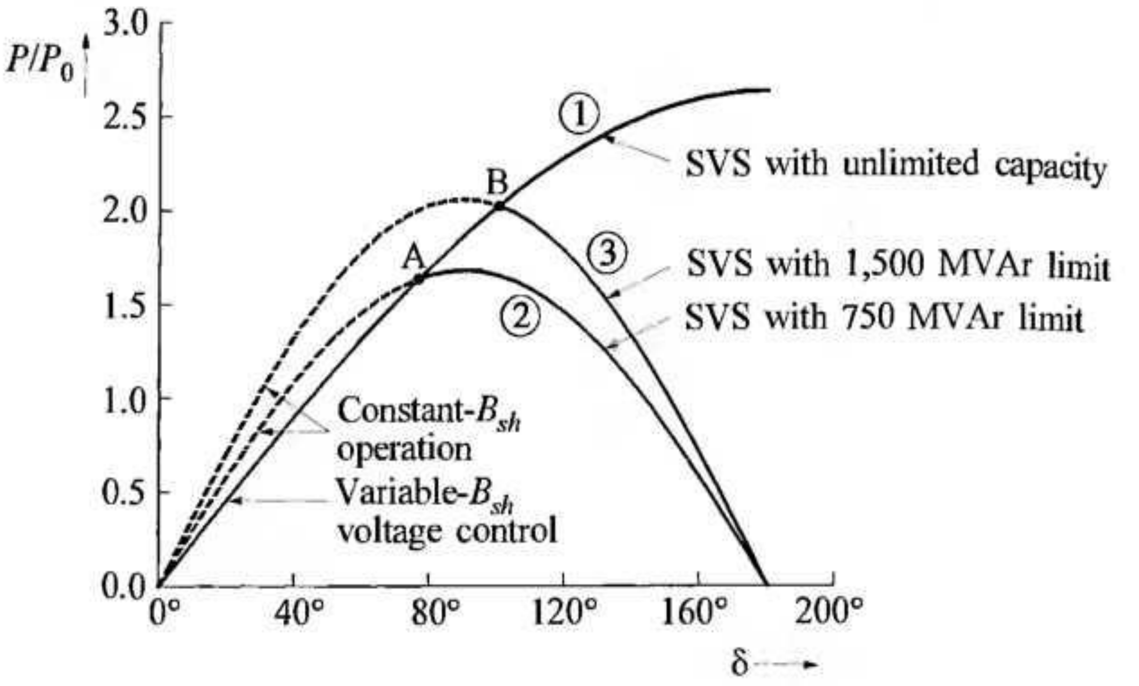
$$\frac{P'_{max}}{P_{max}} = \frac{\sin\theta}{\sin(\theta/2)}$$



2.12 Performance of a 600 km line with an SVS regulating midpoint voltage

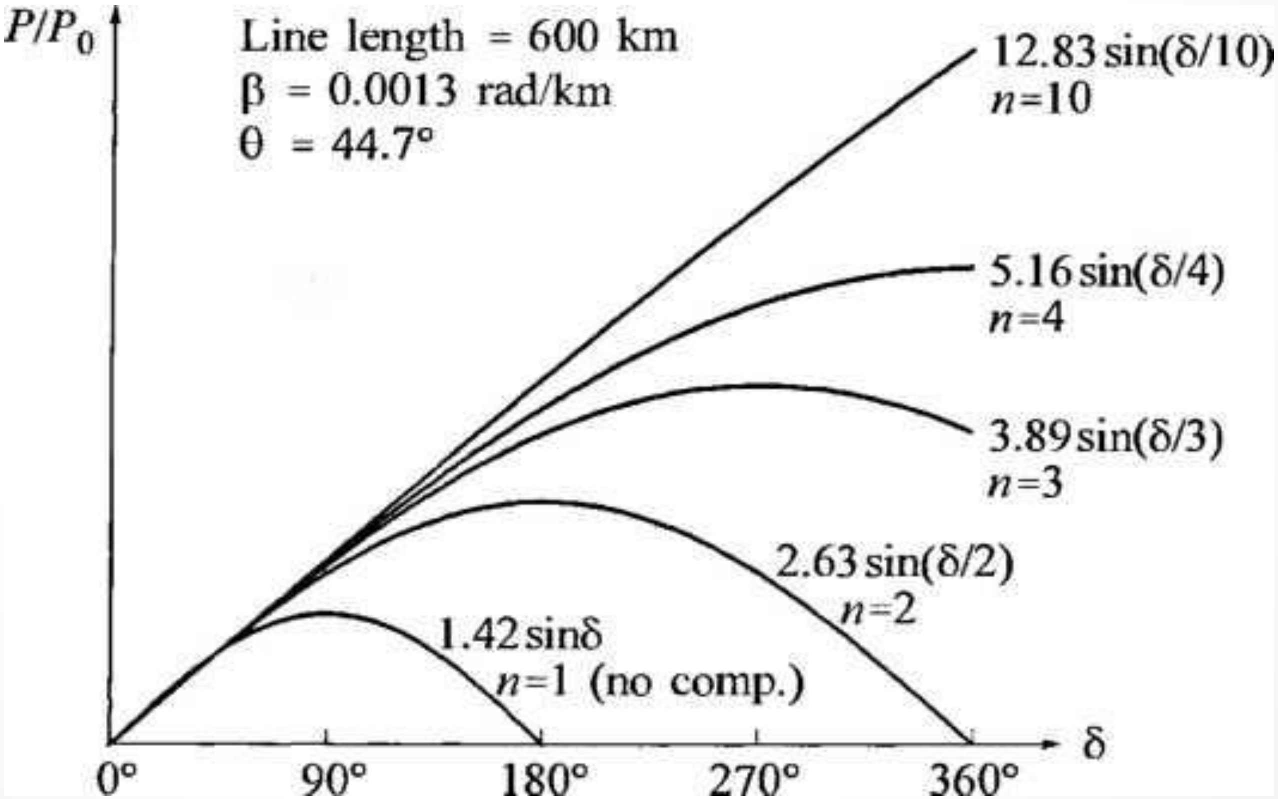






2.13 Arbitrary number of regulated compensators

$$P = \frac{P_0}{\sin(\theta/n)}\sin(\delta/n) \Rightarrow \frac{P'_{max}}{P_{max}} = \frac{\sin\theta}{\sin(\theta/n)}$$



2.14 Intermediate Summary

- switched shunt capacitor compensation generally provides the most economical reactive power source for voltage control;
- heavy use of shunt capacitor compensation could lead to reduction of small-signal (steady-state) stability margin and poor voltage regulation;
- series capacitor compensation is self-regulating, i.e., its reactive power output increases with line loading;
- series capacitor compensation could cause subsynchronous resonance problems requiring special solution measures;
- a combination of series and shunt capacitors may provide the ideal form of compensation in some cases;
- a static var system is ideally suited for applications requiring direct and rapid control of voltage.

Series Capacitors

Application to distribution feeders

- Self-excitation of large induction and synchronous motors during starting. The motor may lock in at a fraction of synchronous (subsynchronous) speed due to resonance conditions. The most common remedy is to connect, during starting, a suitable resistance in parallel with the series capacitor.
- Hunting of synchronous motors (in some cases induction motors) at light load, due to the high *R*/*X* ratio of the feeder.
- Ferroresonance between transformers and series capacitors resulting in harmonic overvoltages. This may occur when energizing an unloaded transformer or when suddenly removing a load.

Application to EHV systems

- Series capacitors have been primarily used to improve system stability and to obtain the desired load division among parallel lines.
- Complete compensation of the line is never considered. At 100% compensation, the effective line reactance would be zero, and the line current and power flow would be extremely sensitive to changes in the relative angles of terminal voltages. A practical upper limit to the degree of series compensation is about 80%.
- It is not practical to distribute the capacitance in small units along the line. Therefore, lumped capacitors are installed at a few locations along the line. The use of lumped series capacitors results in an uneven voltage profile.
- Series capacitors operate at line potential; hence, they must be insulated from ground.

Voltage rise due to reactive current

Voltage rise on one side of the capacitor may be excessive when the line reactive current flow is high, as might occur during power swings or heavy power transfers. This may impose unacceptable stress on equipment on the side of the bank experiencing high voltage. The system design must limit the voltage to acceptable levels, or the equipment must be rated to withstand the highest voltage that might occur.

Bypassing and reinsertion

The series capacitors are normally subjected to a voltage which is on the order of the regulation of the line, i.e., only a few percent of the rated line voltage. If, however, the line is short-circuited by a fault beyond the capacitor, a voltage on the order of the line voltage will appear across the capacitor.

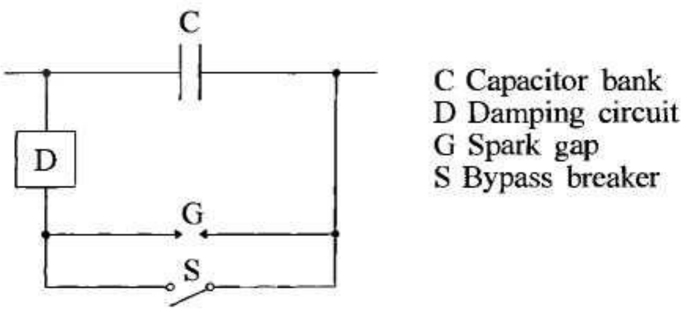
It would not be economical to design the capacitor for this voltage, since both size and cost of the capacitor increase with the square of the voltage. Therefore, provision is made for bypassing the capacitor during faults and reinsertion after fault clearing. Speed of reinsertion may be an important factor in maintaining transient stability.

Bypassing and reinsertion (2)

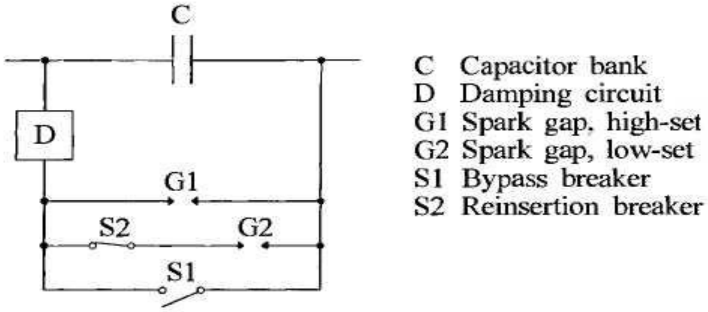
(a) bypassing was provided by a spark gap. Reinsertion time of 200 to 400 ms.

(b) dual-gap scheme. Reinsertion time on the order of 80 ms.

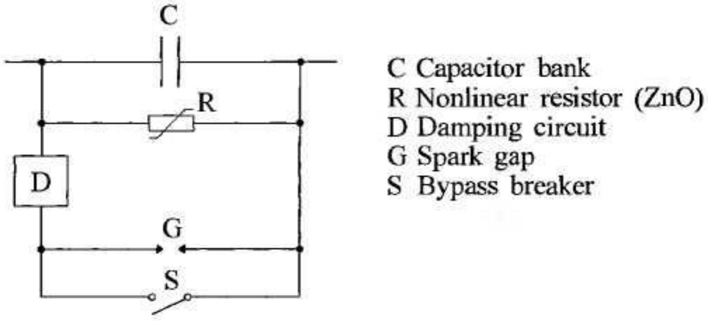
(c) nonlinear resistor of zinc oxide (ZnO) limits the voltage across the capacitor bank during a fault and reinserts the bank immediately on termination of the fault current.



(a) Single-gap protective scheme



(b) Dual-gap protective scheme



(c) Zinc-oxide protective scheme

Location of SC

A series-capacitor bank can theoretically be located anywhere along the line. Factors influencing choice of location include cost, accessibility, fault level, protective relaying considerations, voltage profile and effectiveness in improving power transfer capability.

- The following are the usual locations considered:
- Midpoint of the line
- Line terminals
- 1/3 or 1/4 points of the line

The midpoint location has the advantage that the relaying requirements are less complicated if compensation is less than 50%. In addition, short-circuit current is lower. However, it is not very convenient in terms of access for maintenance, monitoring, security, etc.

Splitting of the compensation into two parts, with one at each end of the line, provides more accessibility and availability of station service and other auxiliaries. The disadvantages are higher fault current, complicated relaying, and higher rating of the compensation.

GTO Thyristor-Controlled Series Capacitor (GCSC)

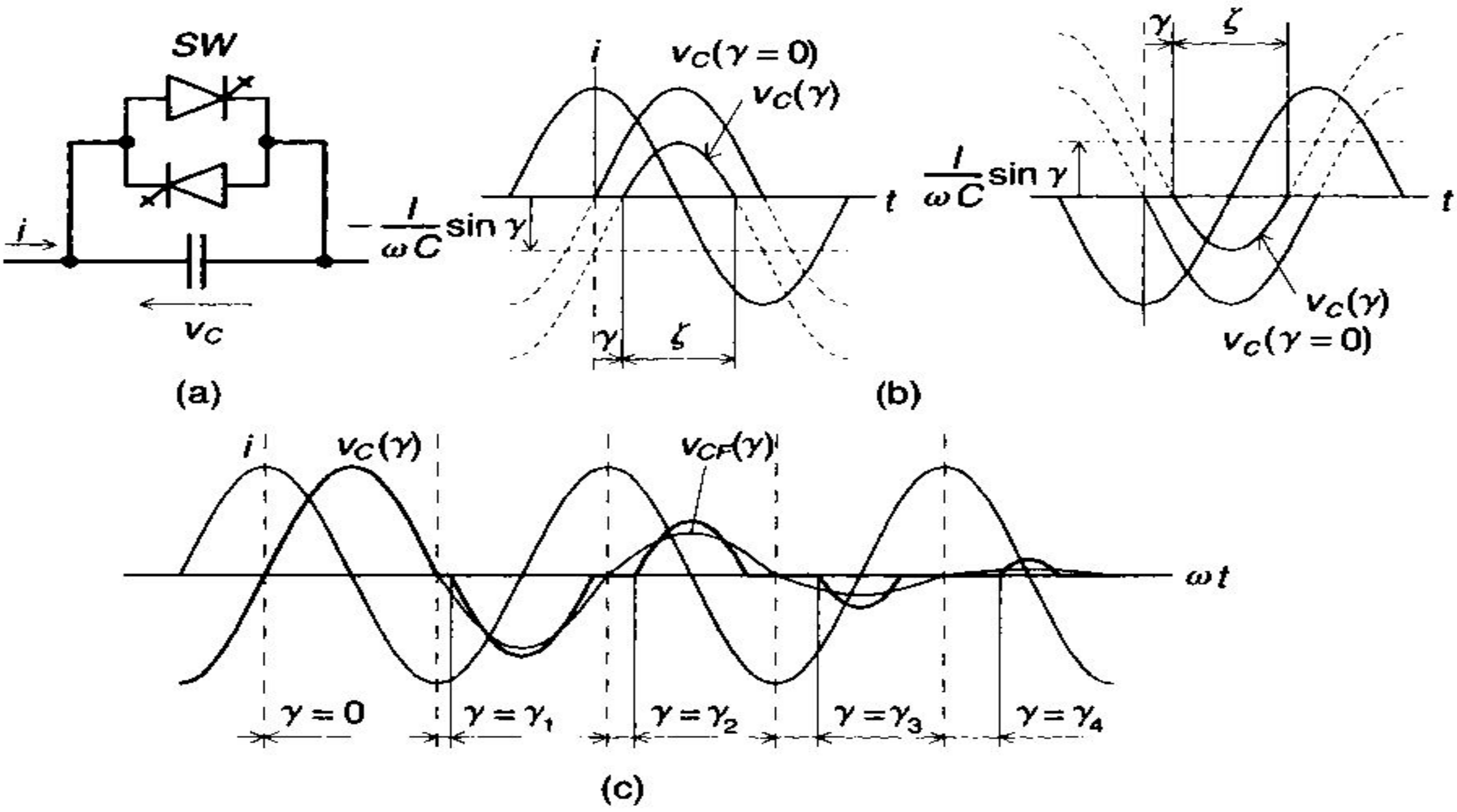


Figure 6.5 Basic GTO-Controlled Series Capacitor (a), principle of turn-off delay angle control (b), and attainable compensating voltage waveform (c).

GTO Thyristor-Controlled Series Capacitor (2)

varying the fundamental capacitor voltage at a fixed line current, could be considered as a variable capacitive impedance

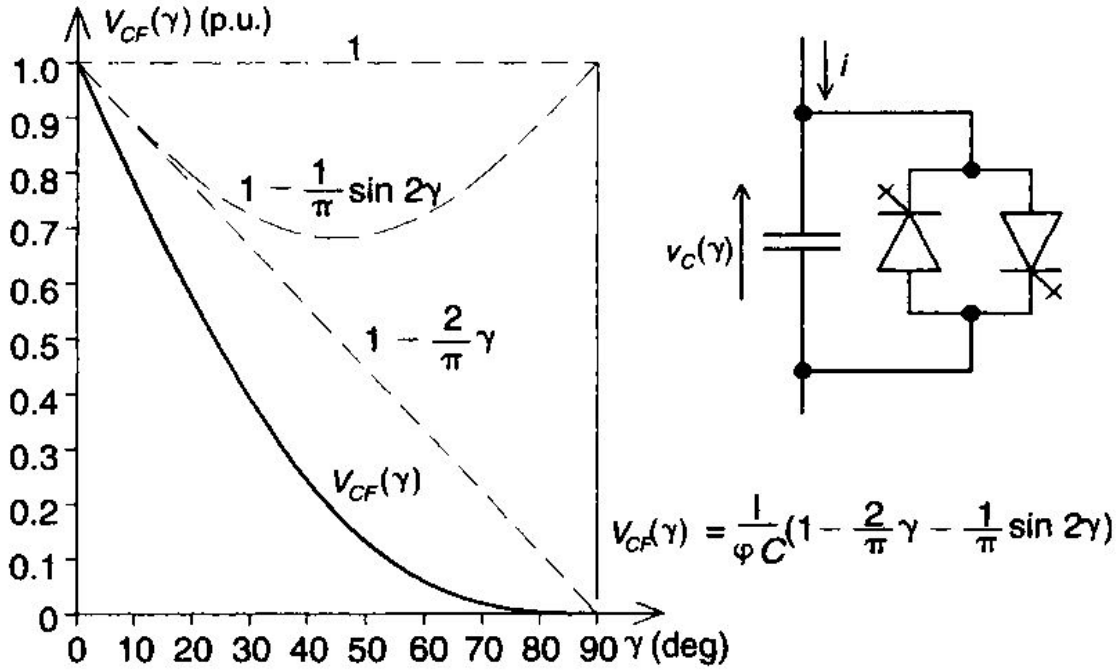


Figure 6.6 Fundamental component of the series capacitor voltage vs. the turn-off delay angle γ.

Thyristor-Switched Series Capacitor (TSSC)

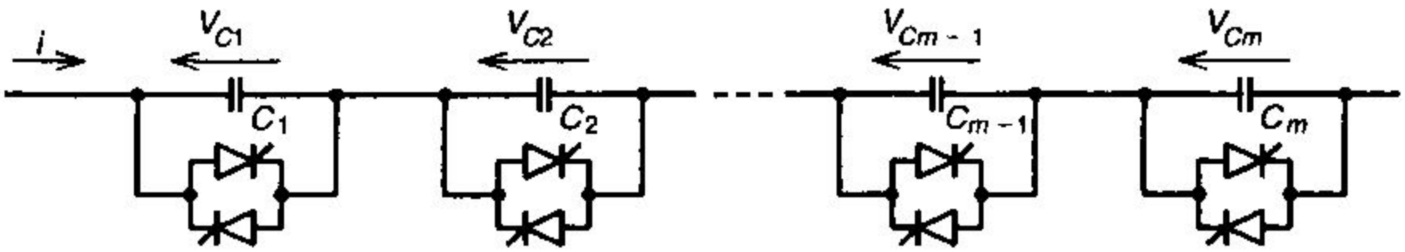


Figure 6.10 Basic Thyristor-Switched Series Capacitor scheme.

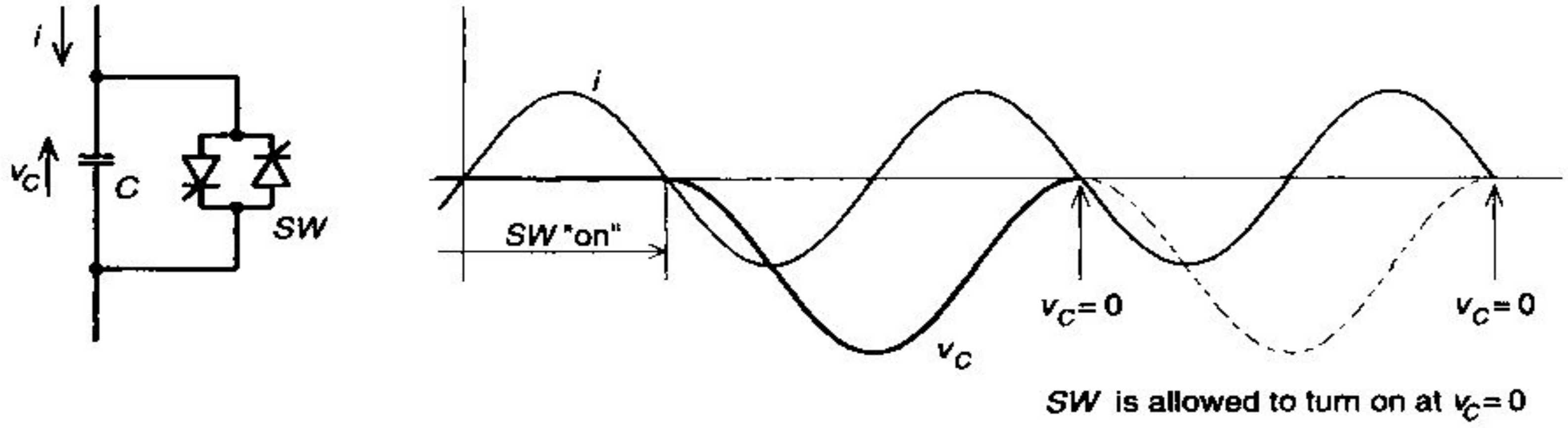


Figure 6.11 Illustration of capacitor offset voltage resulting from the restriction of inserting at zero line current.

Thyristor-Controlled Series Capacitor (TCSC)

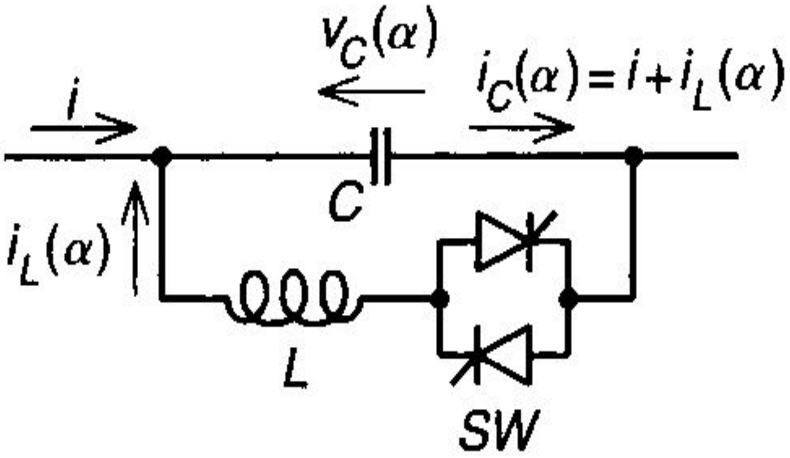


Figure 6.13 Basic Thyristor-Controlled Series Capacitor scheme.

the basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR

Impedance-delay angle characteristic of TCSC

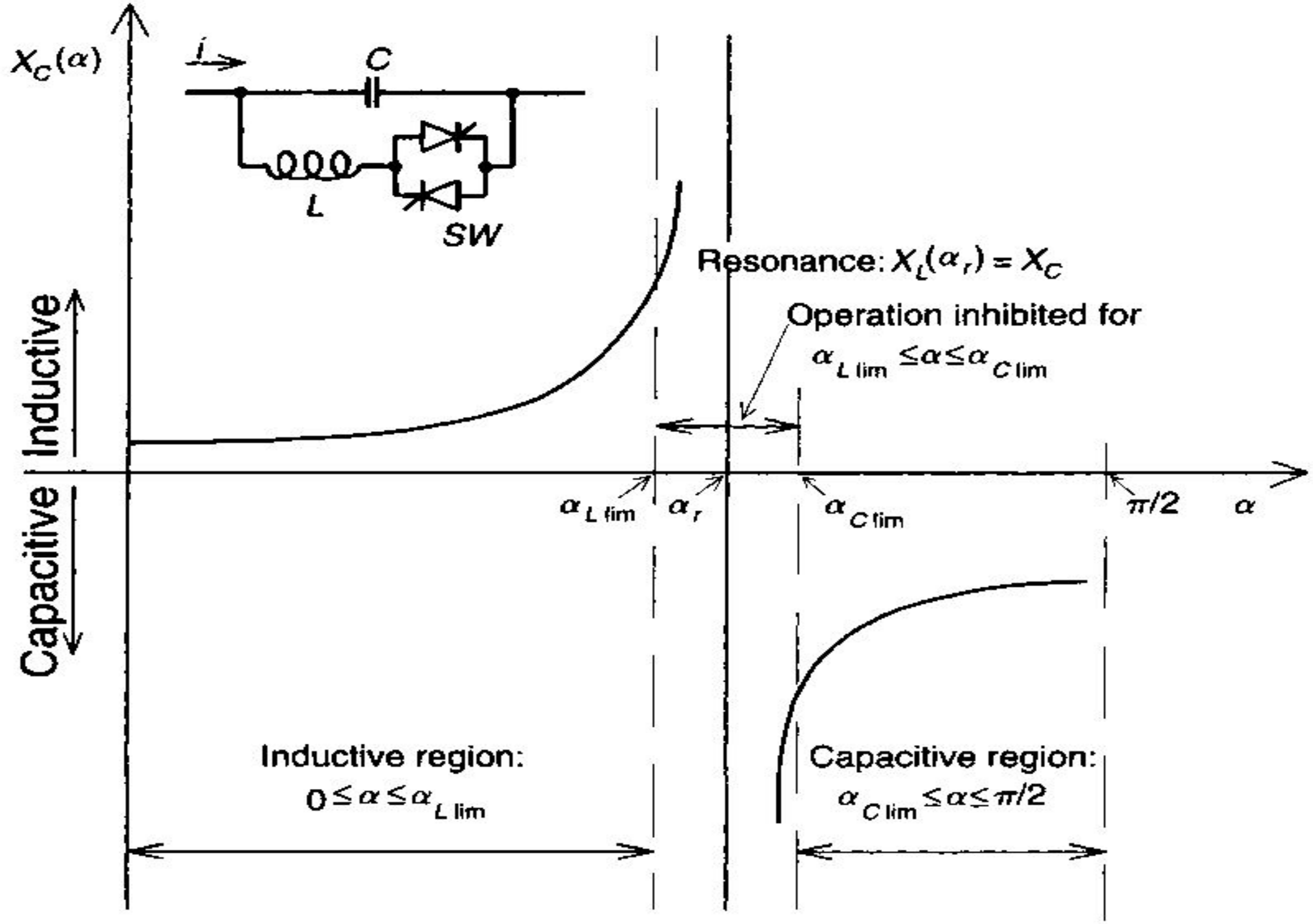


Figure 6.14 The impedance vs. delay angle α characteristic of the TCSC.

Shunt compensation. Static VAR systems

Types of SVS

Basic types of reactive power control elements which make up all or part of any static VAR system:

- Saturated reactor (SR)
- Thyristor-controlled reactor (TCR)
- Magnetically controlled reactor (CSR)
- Thyristor-switched capacitor (TSC)
- Thyristor-switched reactor (TSR)
- Thyristor-controlled transformer (TCT)
- Self- or line-commutated converter (SCC/LCC)

Characteristic of an ideal SVS

Ideally, an SVS should:

1) hold constant voltage

2) possess unlimited var generation/absorption capability

3) have zero active and reactive power losses

4) provide instantaneous response

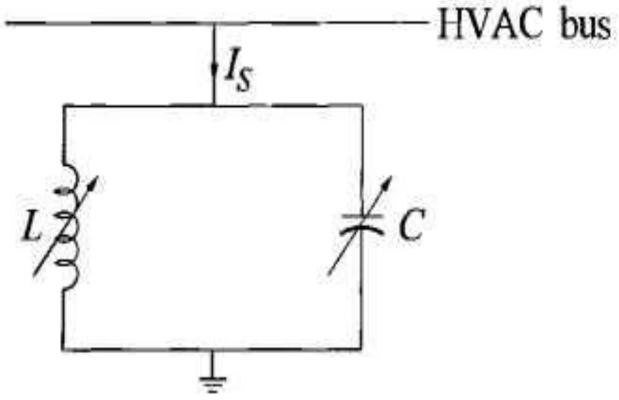


Figure 11.39 Idealized static var system

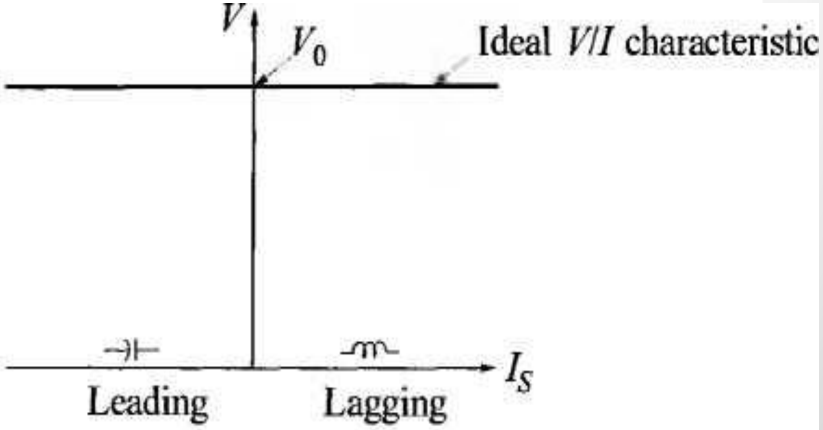
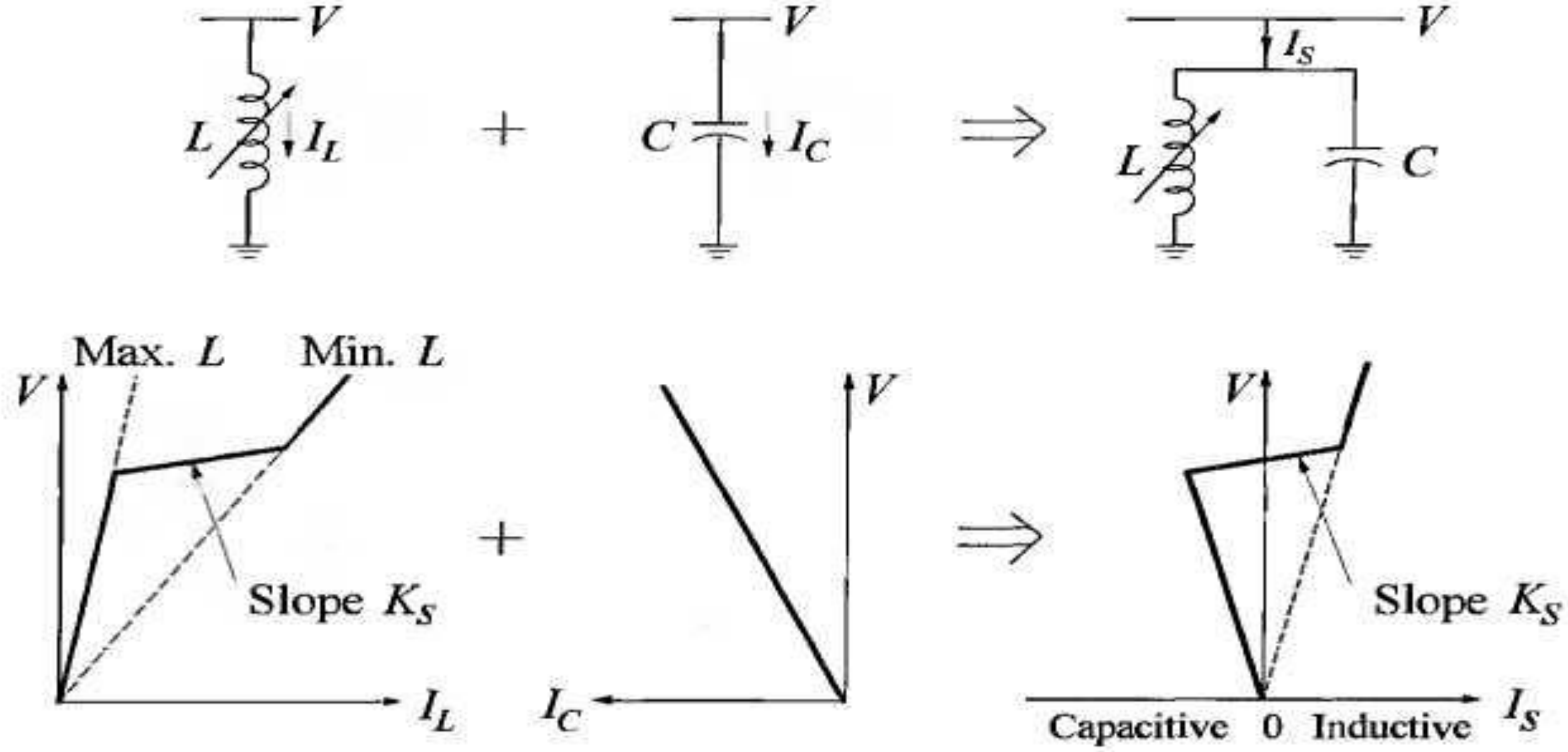


Figure 11.40 *V/I* characteristic of ideal compensator

Composite characteristics of SVS



(a) Controllable reactor

(b) Fixed capacitor

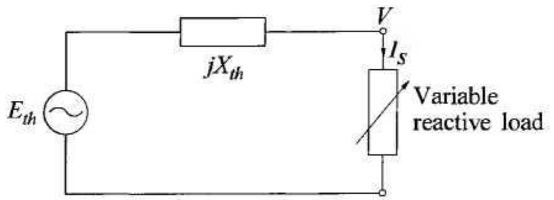
(c) SVS

Figure 11.41 Composite characteristics of an SVS

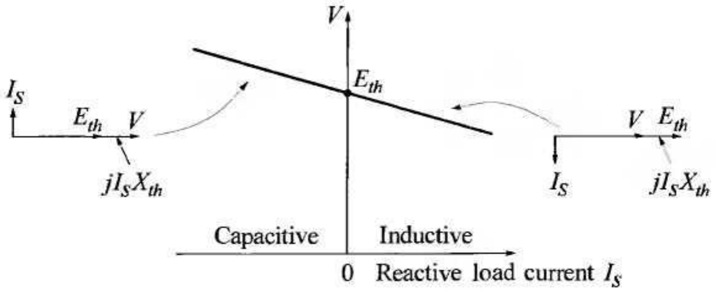
Power system characteristic

The Thevenin impedance is predominantly an inductive reactance.

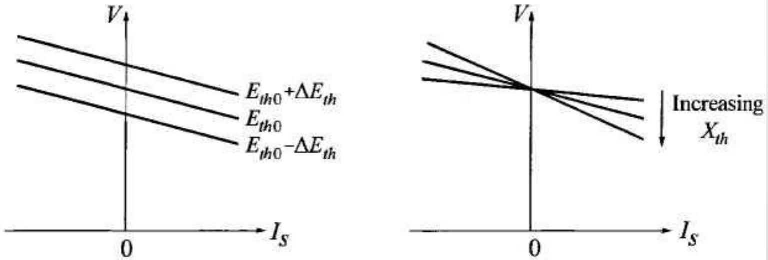
The voltage V increases linearly with capacitive load current and decreases linearly with inductive load current.



(a) Thevenin equivalent circuit of HVAC network



(b) Voltage-reactive current characteristic



(c) Effect of varying source voltage E_{th}

(d) Effect of varying system reactance X_{th}

Figure 11.42 Power system voltage versus reactive current characteristic [38]

Composite SVS - power system characteristic

Graphically illustrated solution of SVS and power system characteristic equations.

The middle characteristic represents nominal system conditions

point A:

$V=V_0$ and $I_s=0$

$$V = E_{th} - X_{th} I_S$$

$$V = V_0 + X_{SL} I_S$$

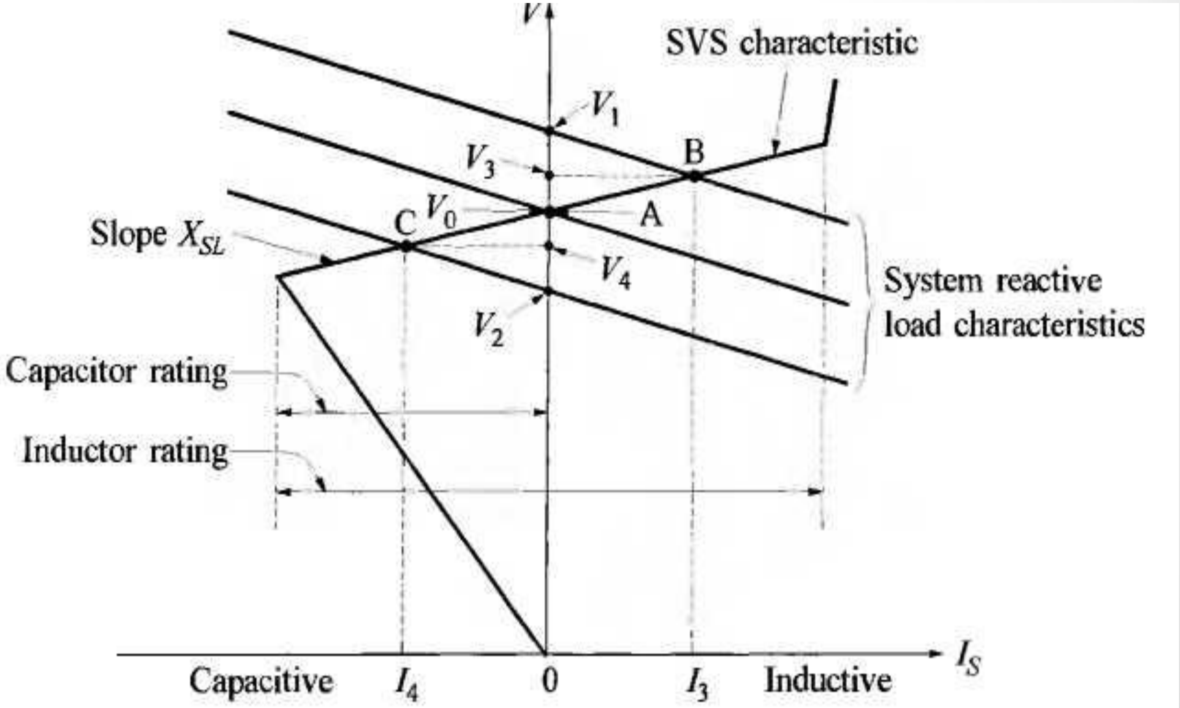


Figure 11.43 Graphical solution of SVS operating point for given system conditions

The effect of switched capacitors

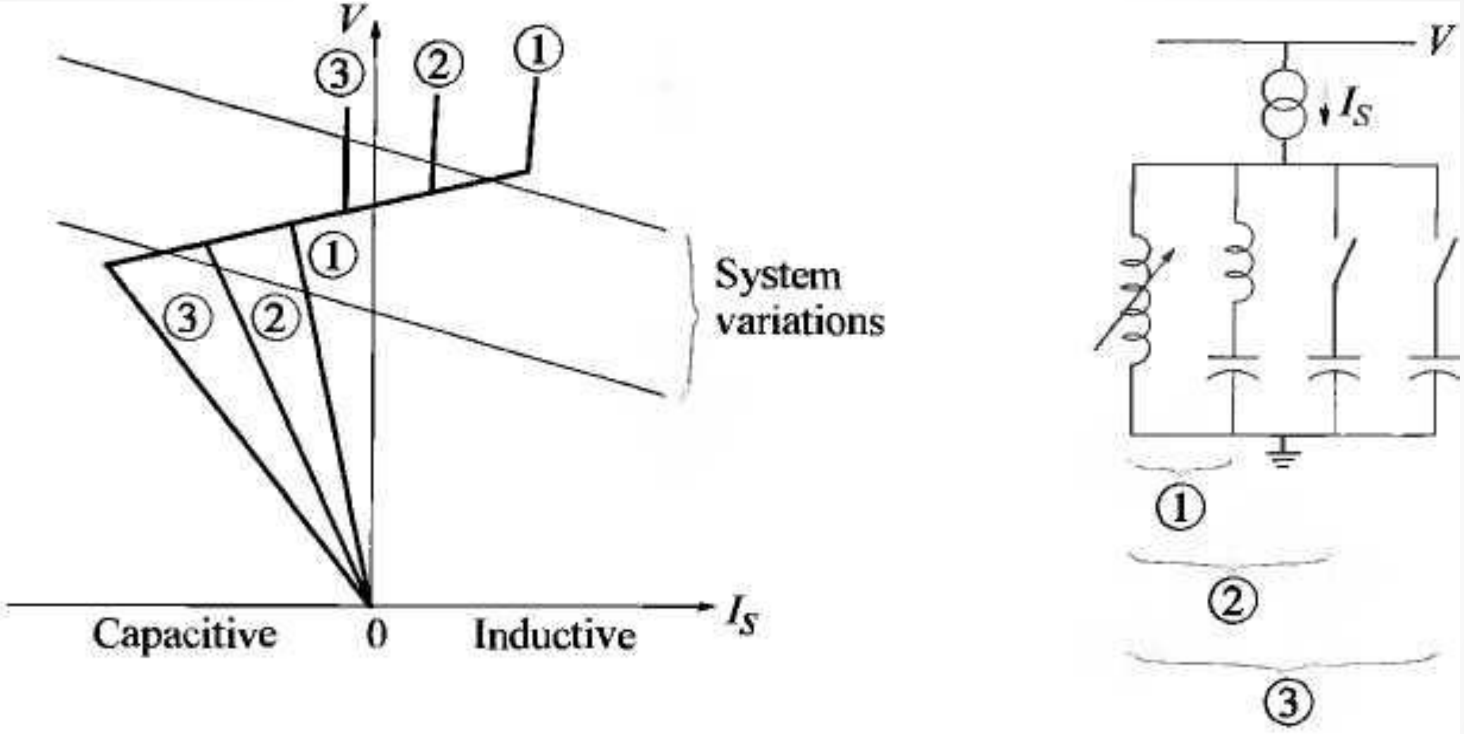


Figure 11.44 Use of switched capacitors to extend continuous control range

Thyristor-controlled reactor (TCR)

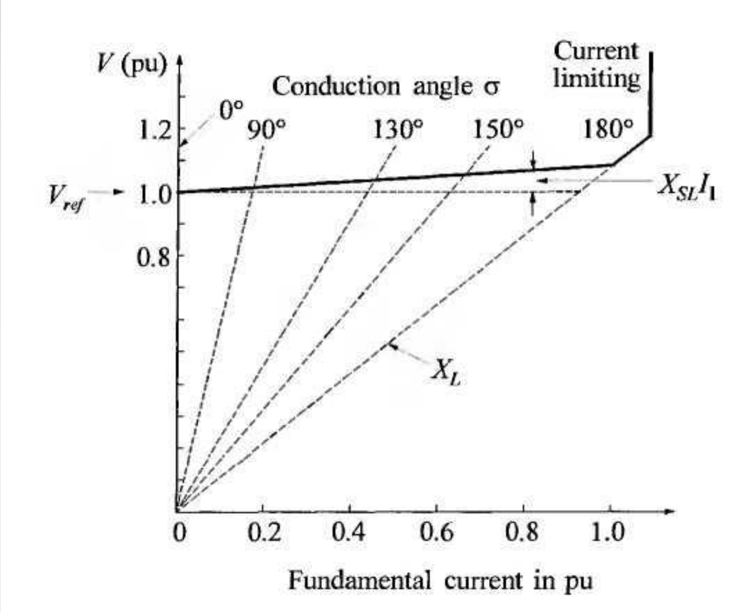
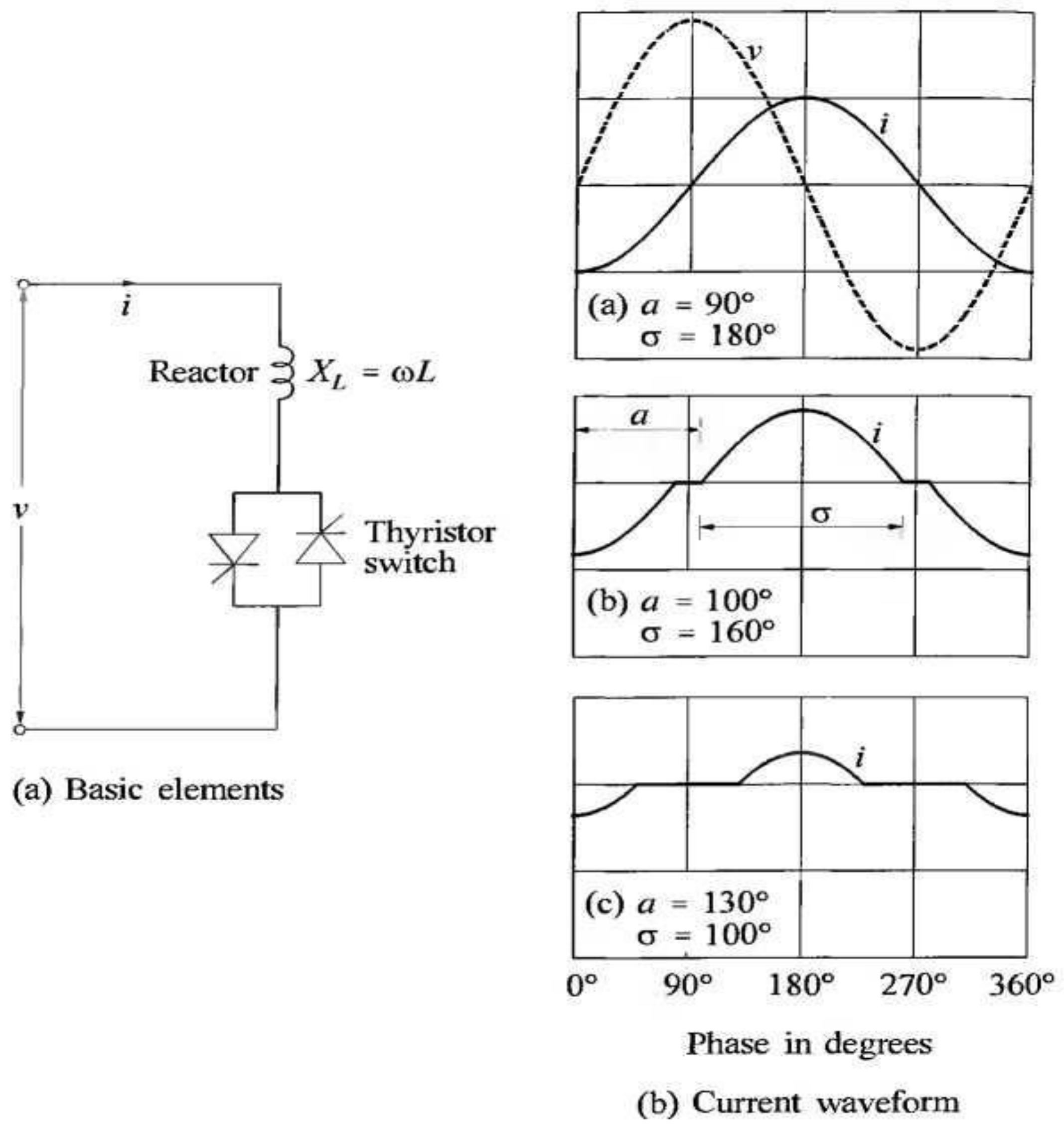


Figure 11.46 Fundamental voltage-current characteristic of TCR



(a) Basic elements

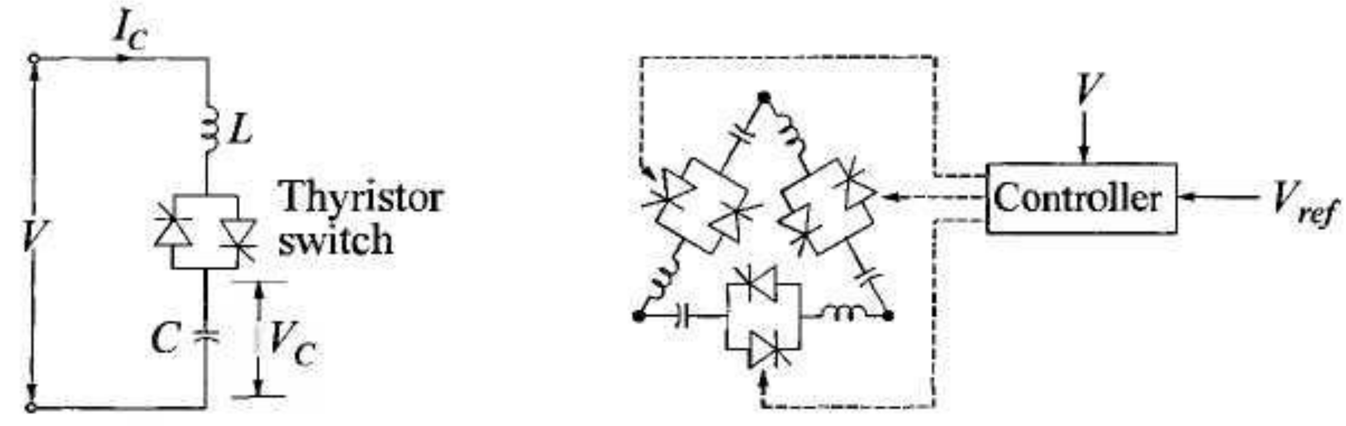
(b) Current waveform

Figure 11.45 Thyristor-controlled reactor

Generates harmonics

-

Thyristor-switched capacitor (TSC)



(a) Single-phase unit

(b) Three-phase unit

Figure 11.48 Thyristor-switched capacitor (TSC)

The thyristor firing controls are designed to minimize the switching transients

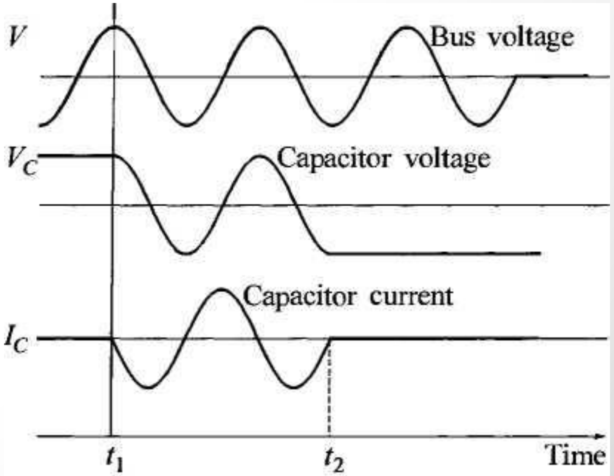


Figure 11.49 Switch operation of a TSC

Practical SVC

Applications :

- Control of temporary overvoltages
- Prevention of voltage collapse
- Enhancement of transient stability
- Enhancement of damping of system oscillations

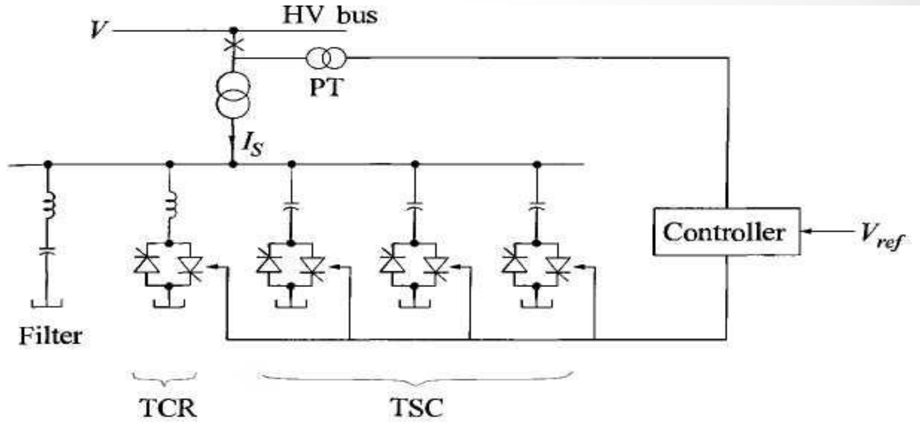
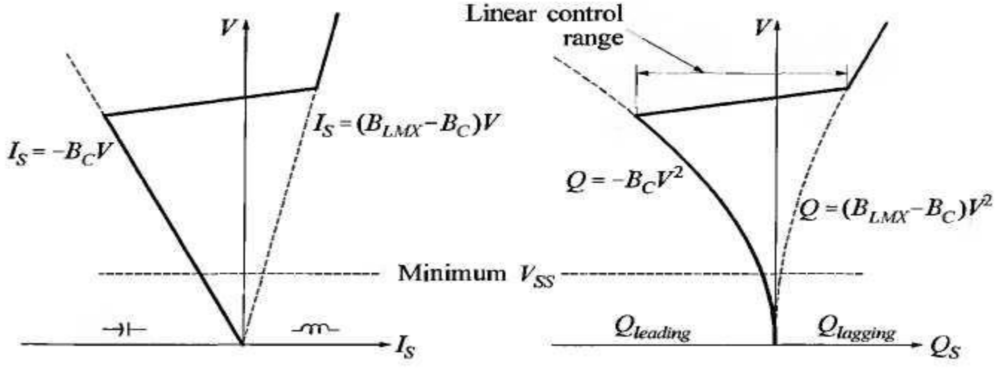


Figure 11.52 A typical static var system



(a) Voltage-current characteristic

(b) Voltage-reactive power characteristic

Figure 11.53 SVS steady-state characteristics

VSC-based compensators

VSC-based compensators construction

Insulated Gate Bipolar Transistors (IGBT) vs Power Thyristors

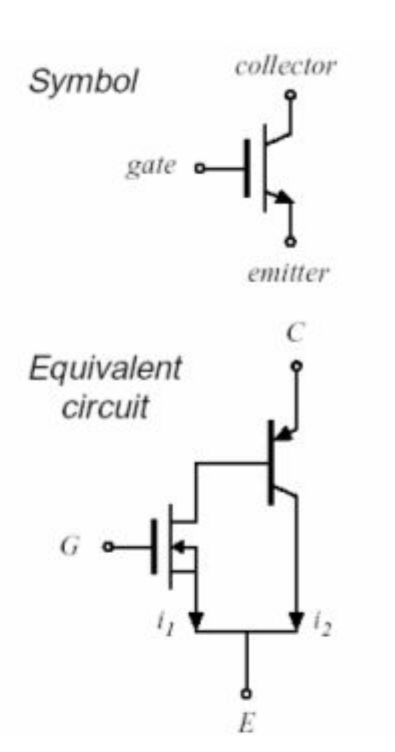
Thyristors can only be turned on
(not off) by control action, the control system only has one degree of freedom.

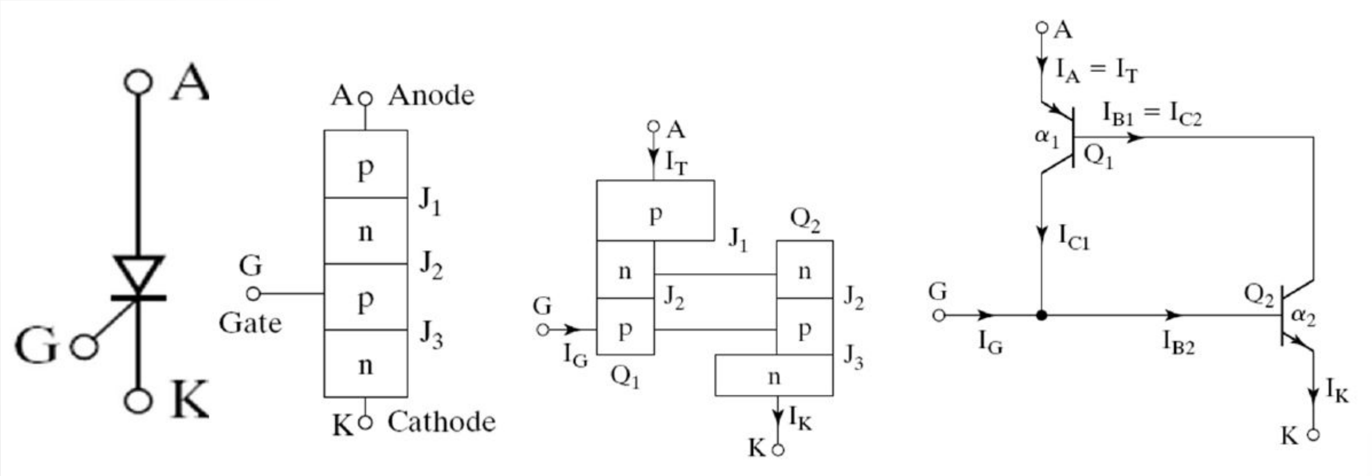
With the insulated-gate bipolar transistor (IGBT), both turn-on and turn-off can be controlled, giving a second degree of freedom.

There are GTO Thyristors (Gate Turn-Off), but they have quite poor performance characteristics, considering switching frequencies, and require very large currents in the gate terminal to change the mode into conducting mode.

IGBTs can be used to make self-commutated converters:

- the polarity of DC voltage is usually fixed;
- DC voltage, being smoothed by a large capacitance, can be considered constant.





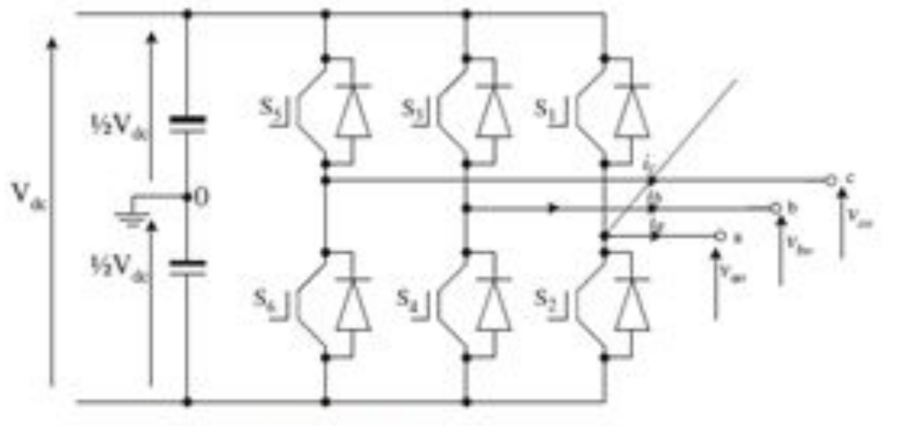
Voltage Source Converter

The additional controllability gives many advantages:

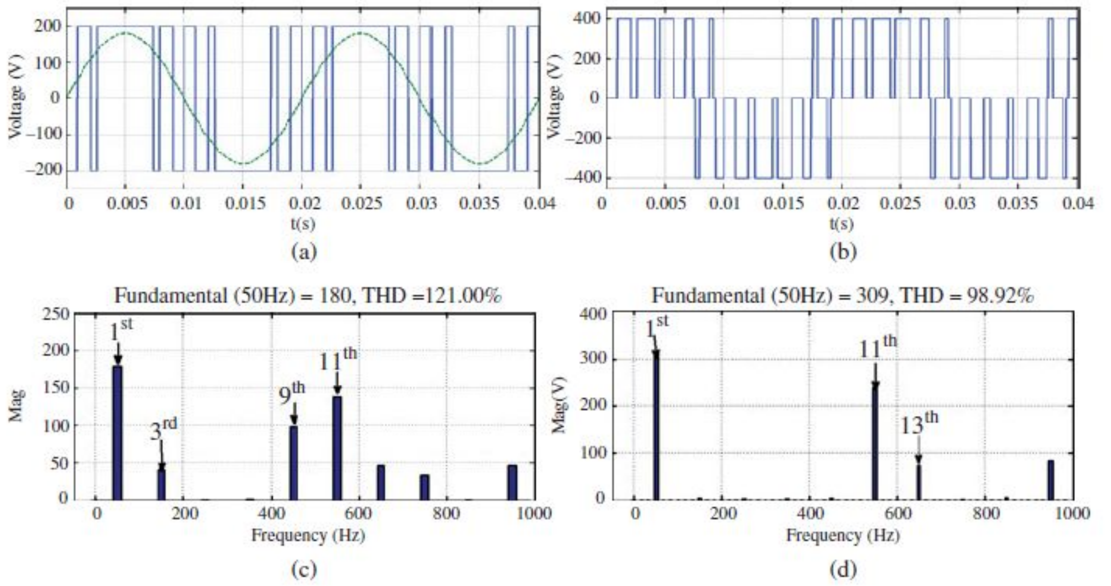
- the ability to switch the IGBTs on and off many times per cycle in order to improve the harmonic performance.

- being self-commutated, the converter no longer relies on synchronous machines in the AC system for its operation (independent control of active and reactive power!).

- a voltage sourced converter can feed power to an AC network consisting only of passive loads, something which is impossible with LCC HVDC.



Two-level voltage source converter.



(a) (b)

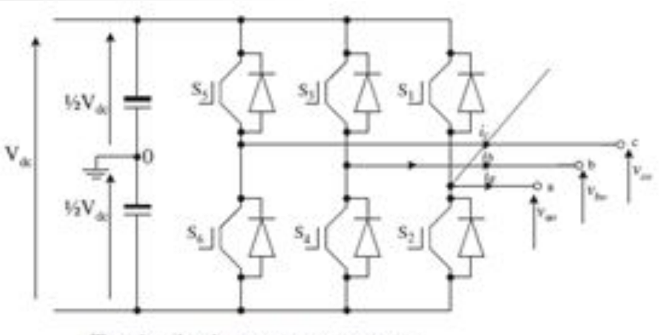
(c) (d)

Figure A.6 Phase and line voltage waveforms obtained when a three-phase two-level voltage source converter is controlled using selective harmonic elimination with a modulation index m = 0.9, and elimination of the 5th and 7th harmonics. (a) Phase voltage relative to the supply mid-point; (b) Line voltage; (c) Phase voltage spectrum; (d) Line voltage spectrum.

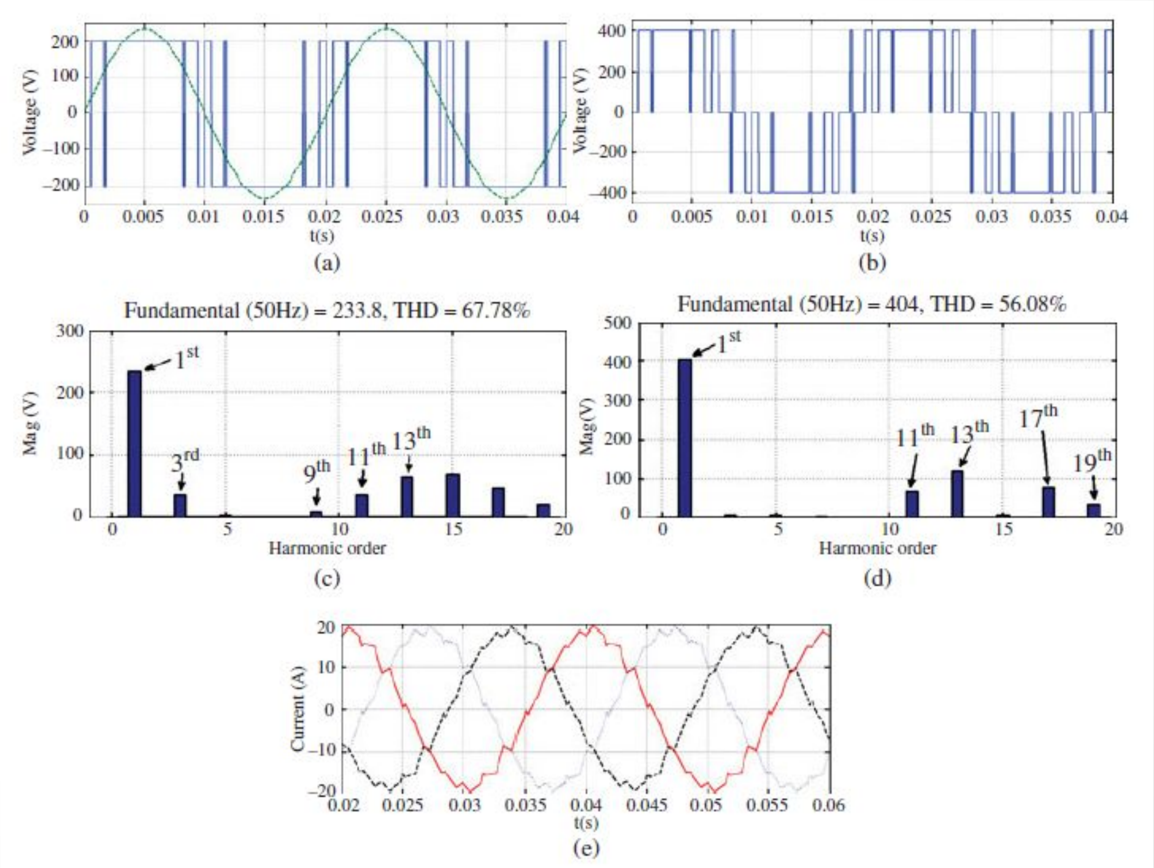
Selective Harmonic Elimination Control Strategy

Selective harmonic elimination explicitly defines the switching angles on the output phase voltage that are needed to set the magnitude of the fundamental component of the phase voltage and to eliminate specific harmonics.

Thus, one of the switches, opposite to currently conducting one, is used to create opposite signals, eliminating specific harmonics.



Two-level voltage source converter.



(a)

(b)

(c)

(d)

(e)

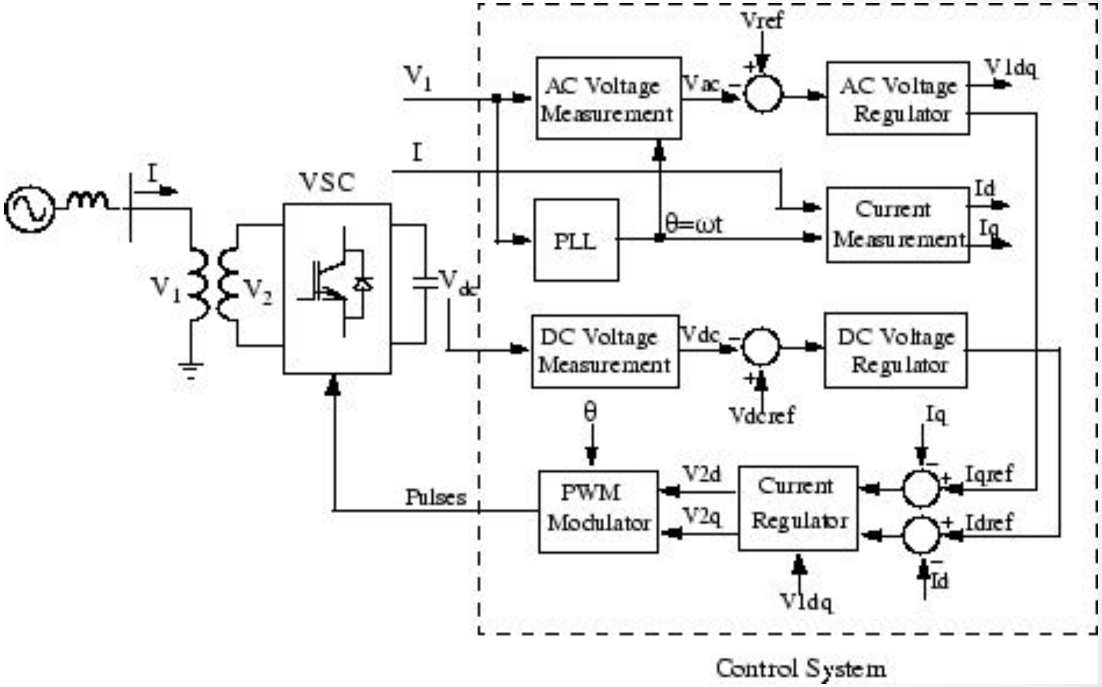
Static Compensator (STATCOM)

In steady state operation, the voltage V2 generated by the VSC is in phase with V1 (δ=0), so that only reactive power is flowing (P=0). If V2 is lower than V1 (taking into account transformation), Q is flowing from V1 to V2 (STATCOM is absorbing reactive power).

On the reverse, if V2 is higher than V1, Q is flowing from V2 to V1 (STATCOM is generating reactive power). The amount of reactive power is given by

$$Q = (V_1(V_1 - V_2)) / X$$

A capacitor connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage V2 has to be phase shifted slightly behind V1 in order to compensate for transformer and VSC losses and to keep the capacitor charged.



Static Compensator (STATCOM)

The control system consists of:

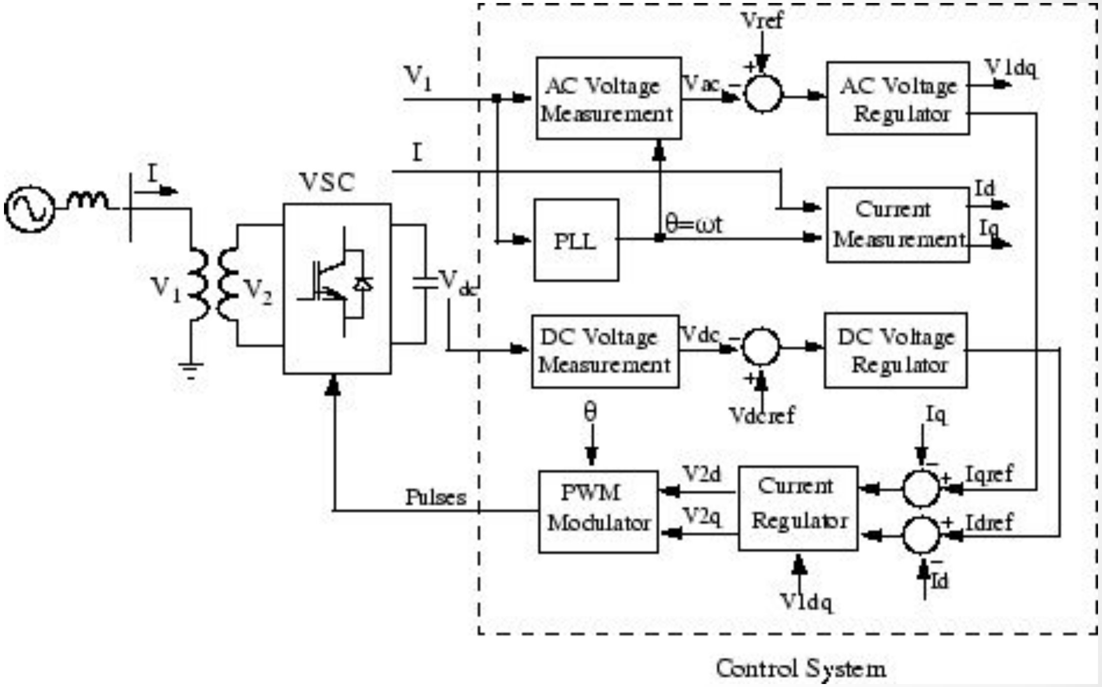
- A phase-locked loop (PLL) (computes angle $\Theta=\omega t$).

- Measurement systems measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage Vdc.

- An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. AC voltage controls reactive power flow (by setting Iq) and calculates V1d, V1q. DC voltage regulator controls active power flow (by setting Id).

- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by the converter (V2d V2q) in voltage control mode.

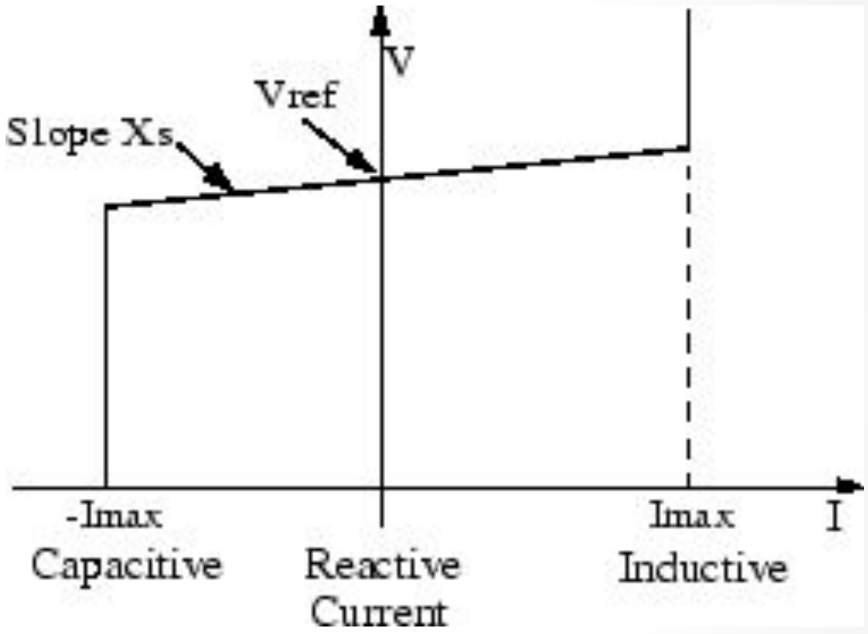
- The current regulator is assisted by a feed forward type regulator which predicts the V2 voltage output (V2d, V2q) from the V1 measurement (V1d, V1q) and the transformer leakage reactance.



STATCOM V-I characteristic

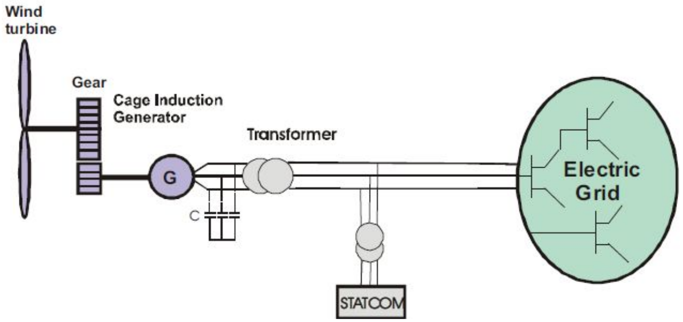
As long as the reactive current stays within the minimum and maximum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref.

However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. In the voltage regulation mode, the V-I characteristic is described by the following equation:



$$V = V_{ref} + Xs\, I$$

STATCOM Grid Operation



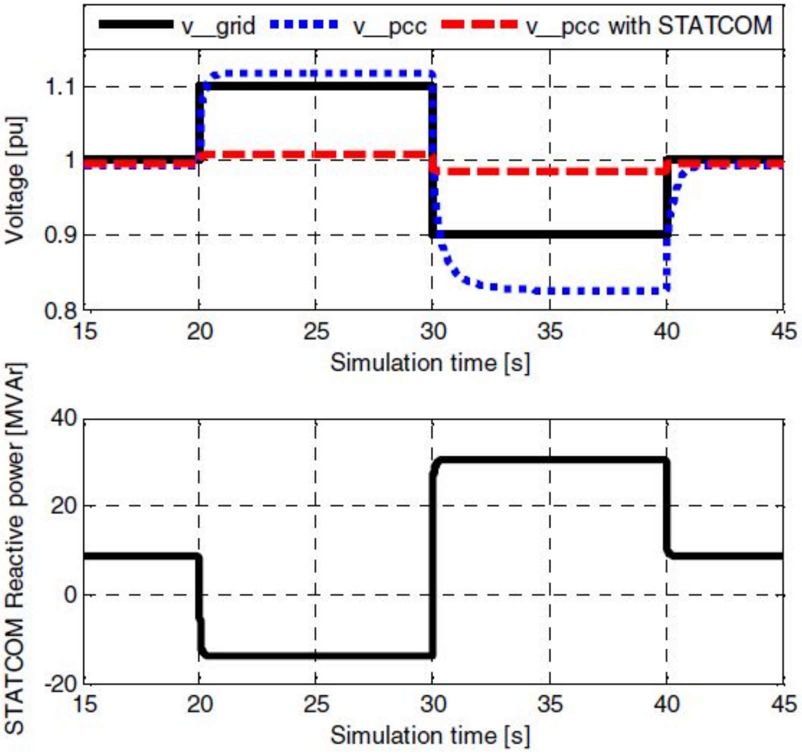


Fig. 3. Voltage at PCC during swell/sag sequence with constant capacitor compensation and with compensation by STATCOM

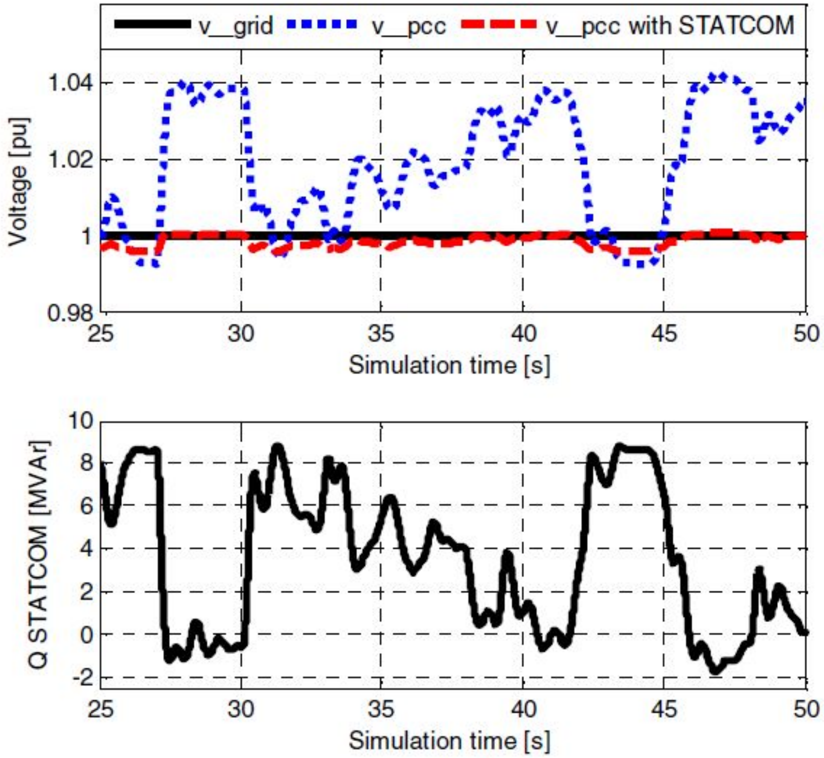
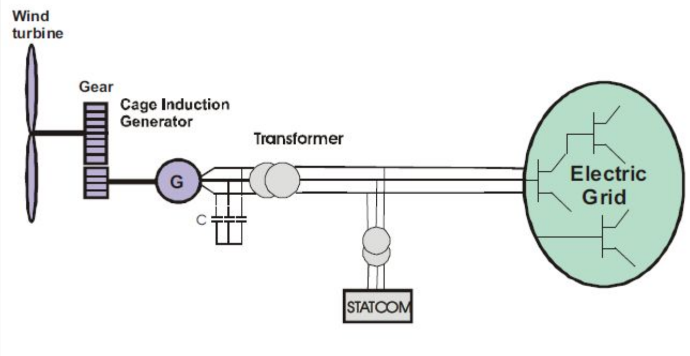


Fig. 4. Voltage at PCC with variable wind speed. Constant capacitor compensation compared to compensation by STATCOM, and corresponding output of reactive power from the STATCOM

STATCOM Grid Operation



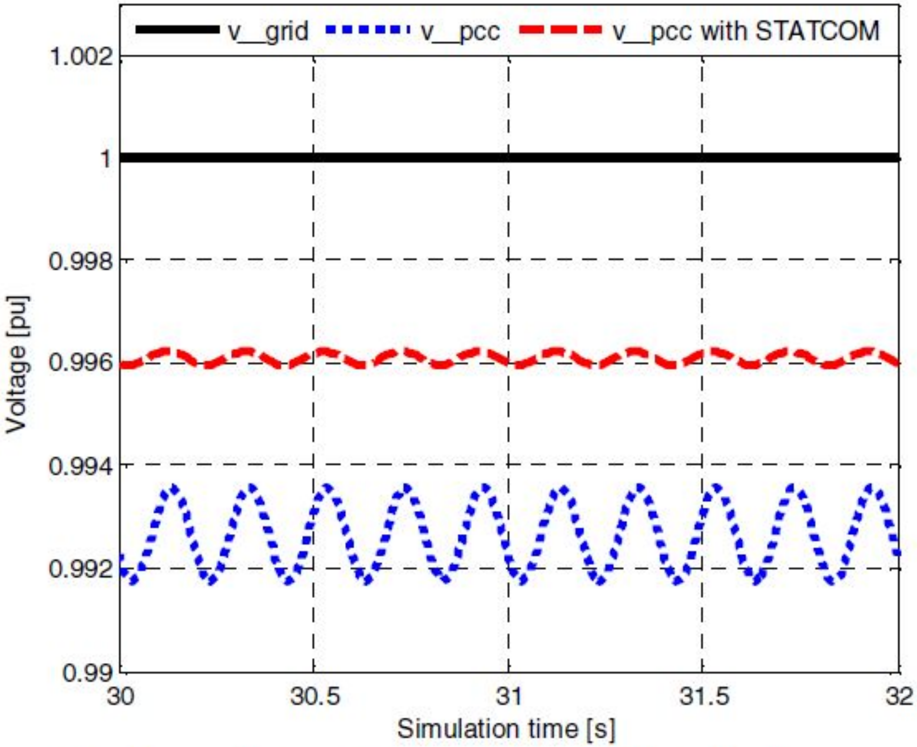


Fig. 5. Voltage at PCC with and without STATCOM when a stationary torque oscillation is imposed on the generator shaft

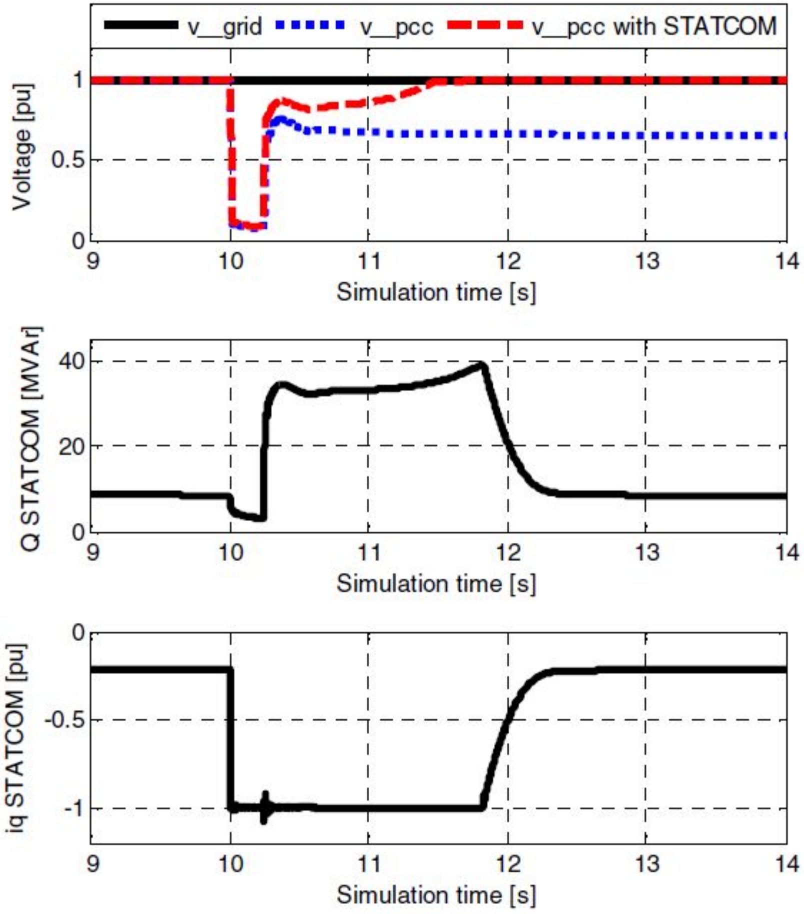
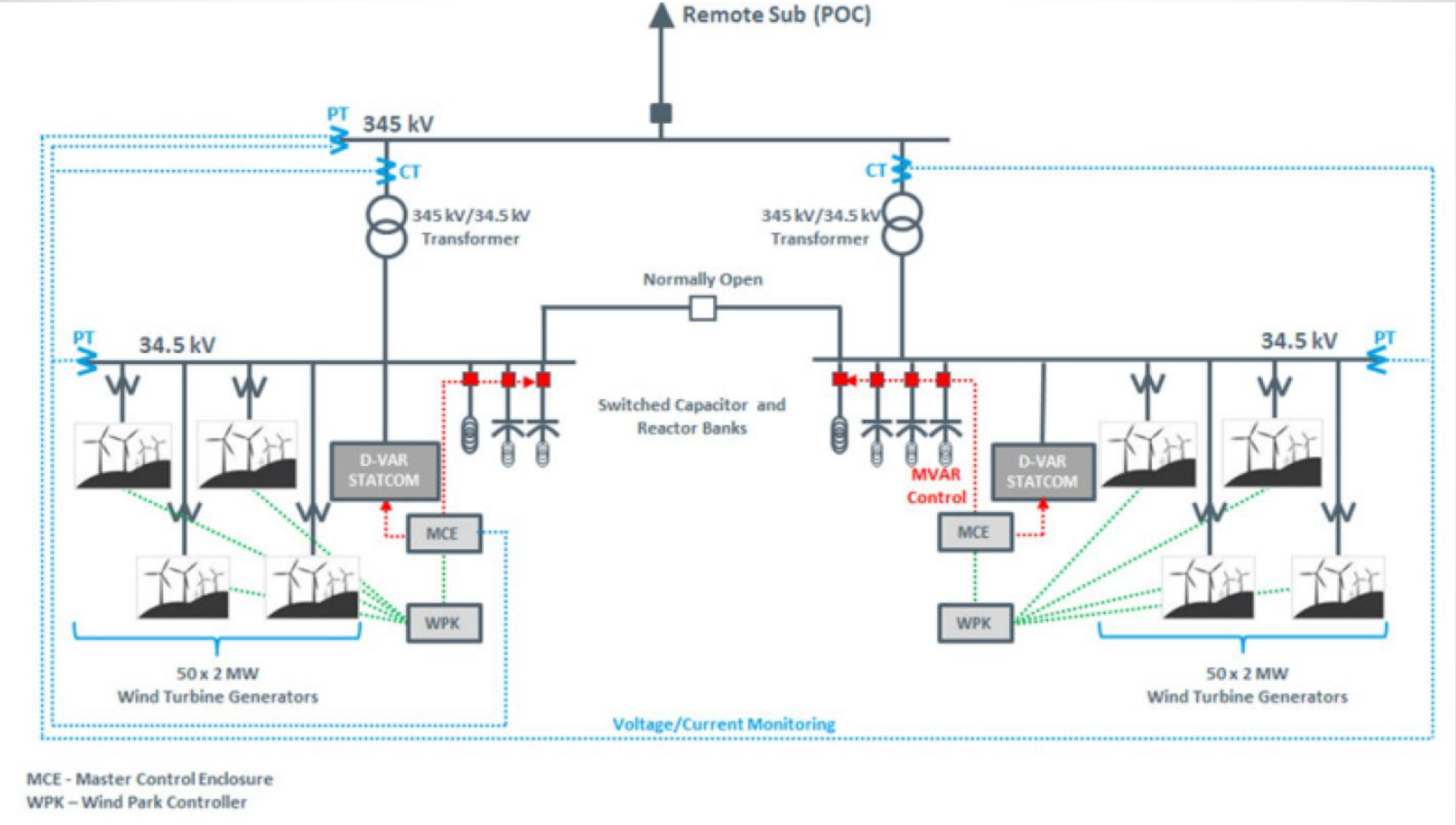


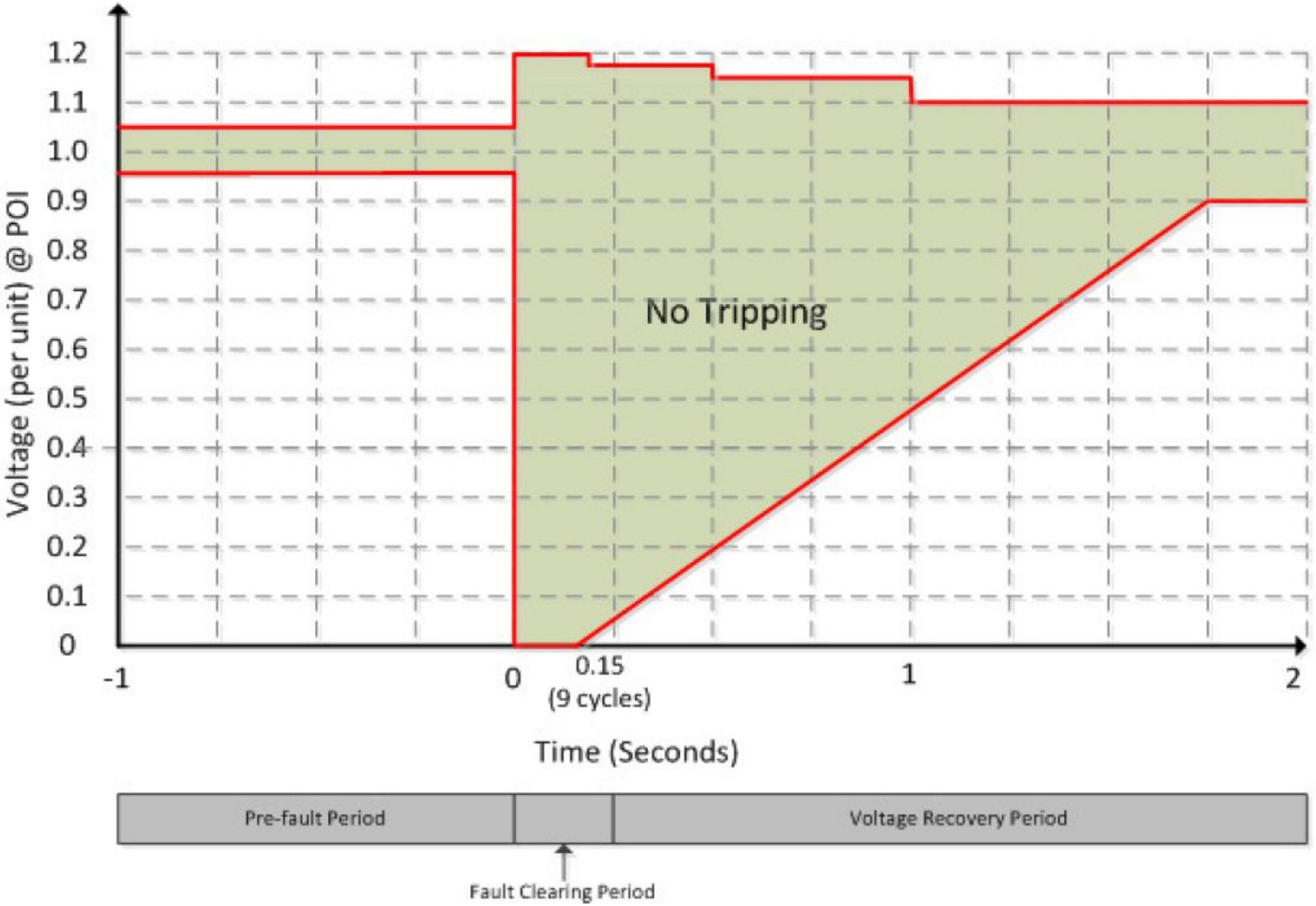
Fig. 6. Ride through for 240 ms three-phase short circuit

STATCOM Application for Wind Farms – Typical Installation

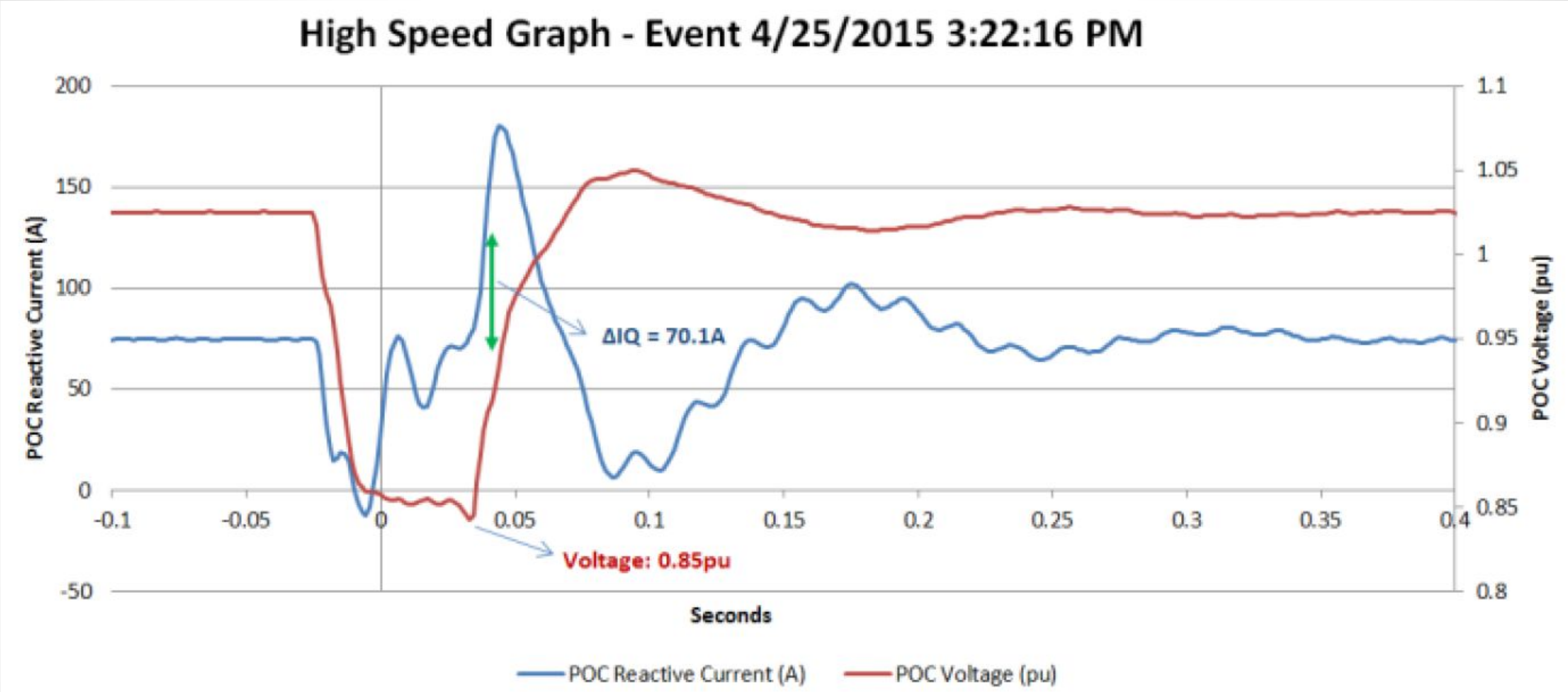


MCE - Master Control Enclosure
WPK – Wind Park Controller

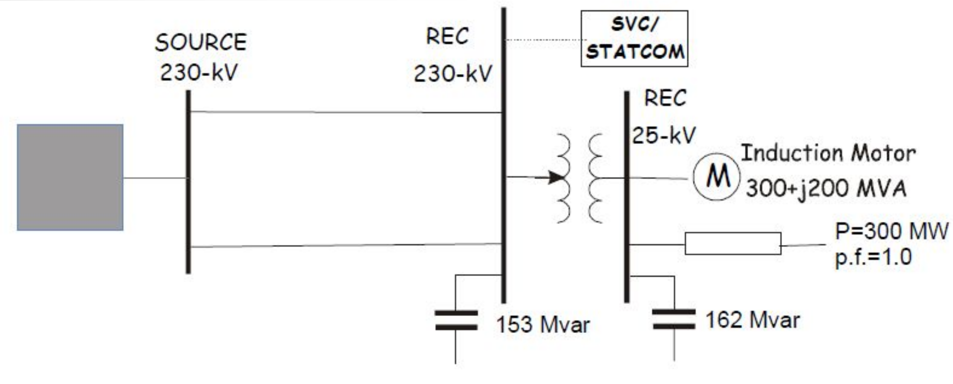
STATCOM Application for Wind Farms - LVRT

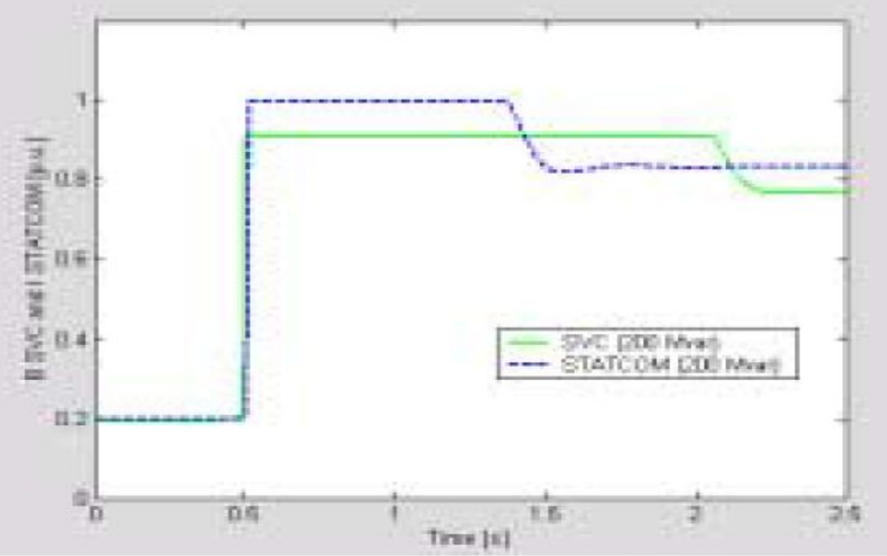


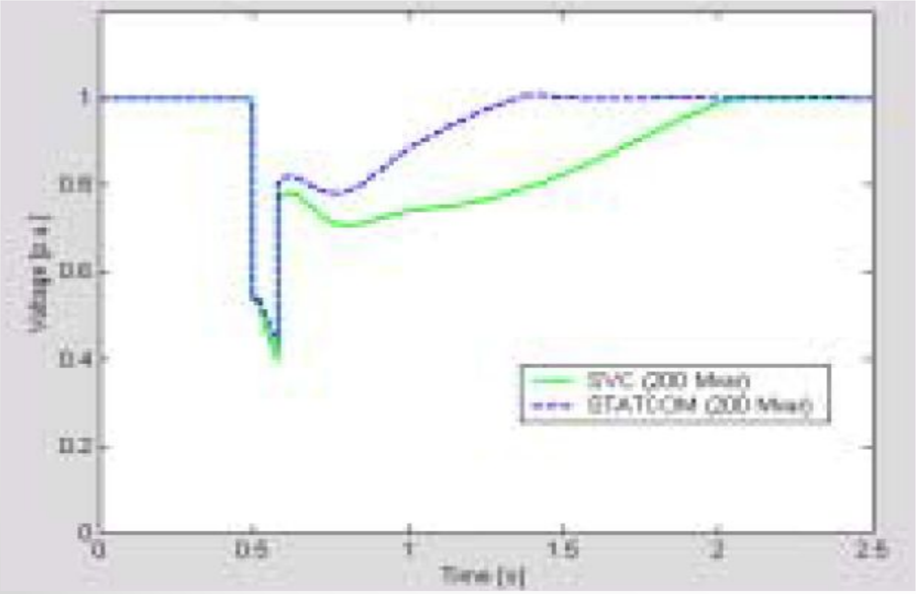
STATCOM Application for Wind Farms – Transient Response

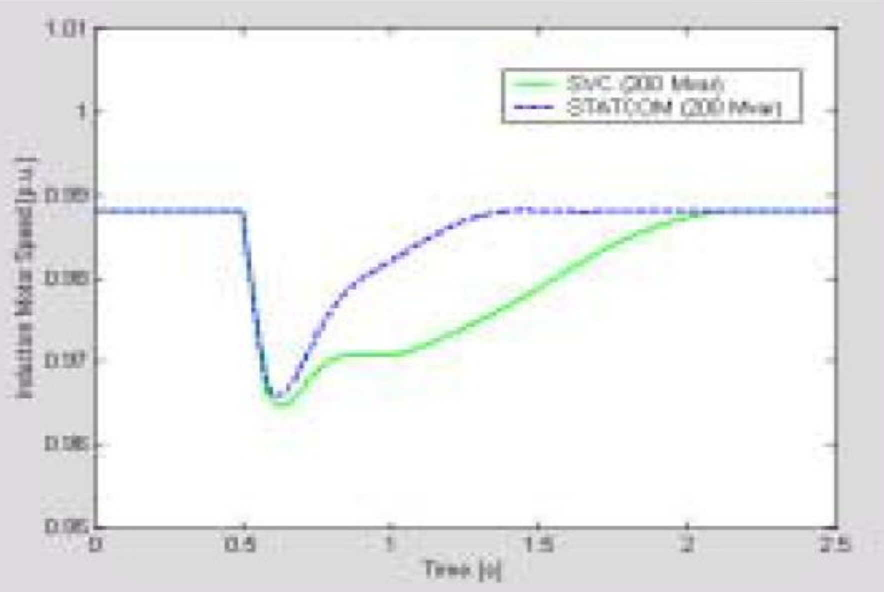


STATCOM vs SVC



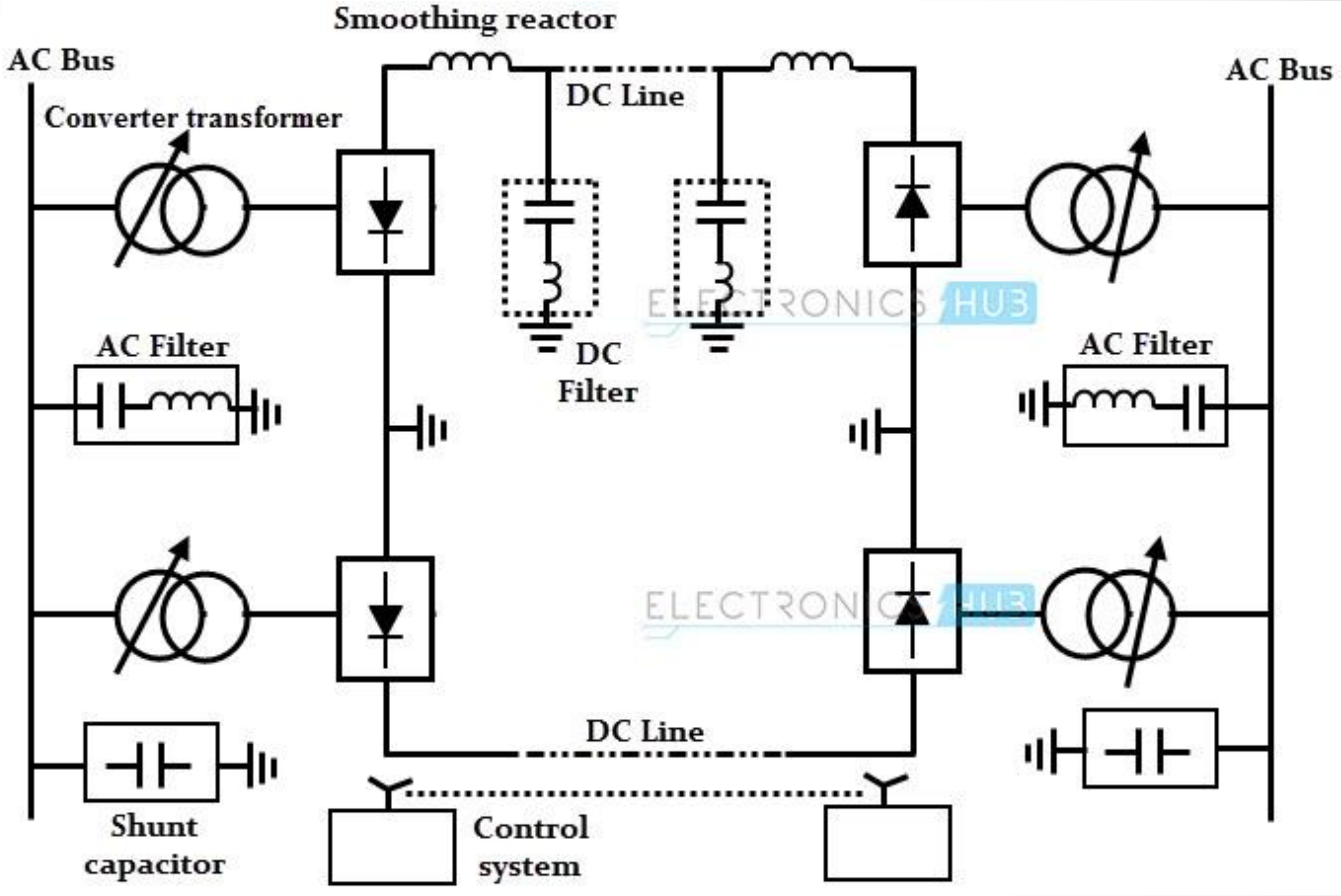






HVDC Link

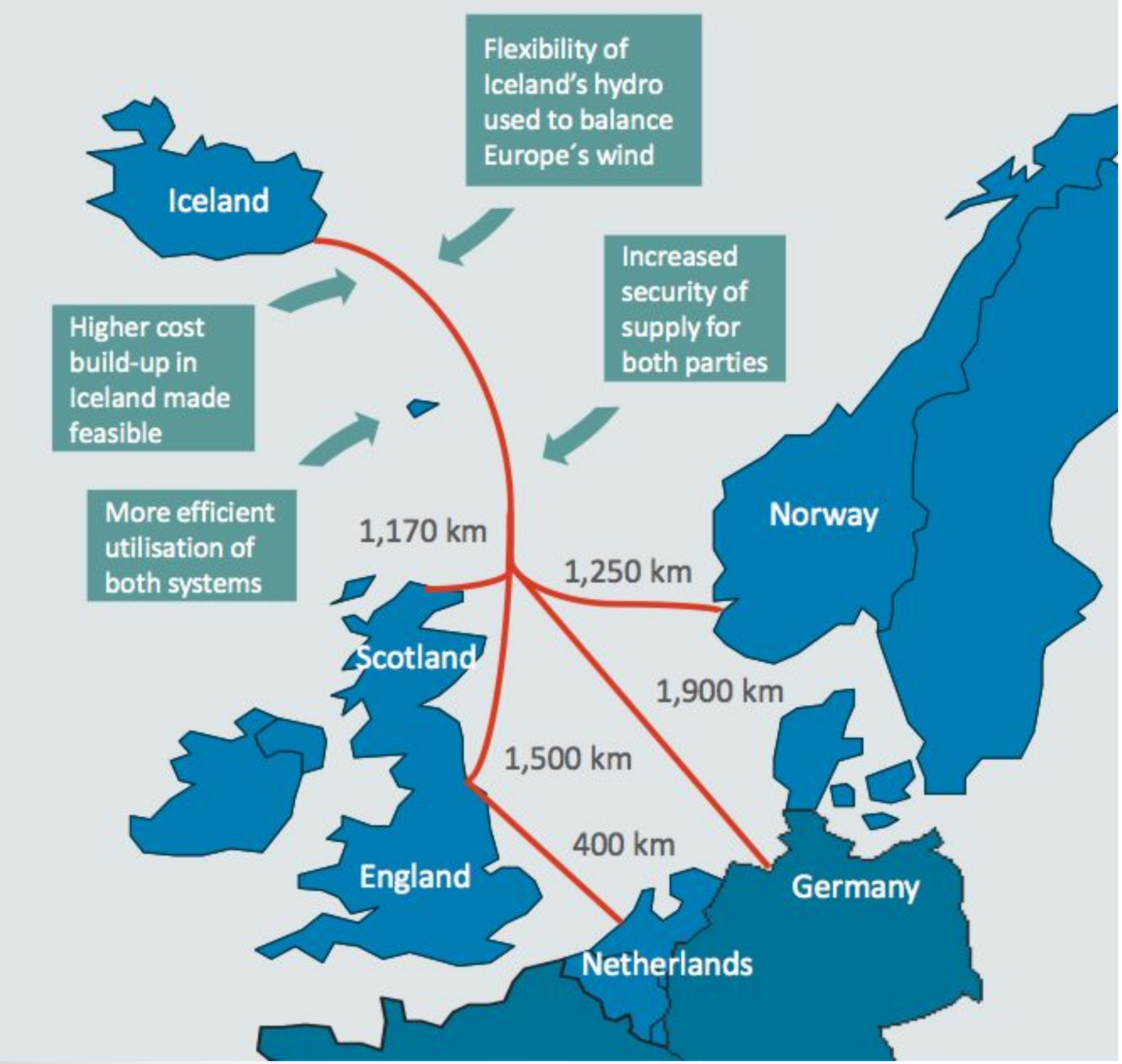
- Long distance bulk power transmission
- Bulk power transmission through underground or underwater cables
- Interconnection of individually controlled AC systems
- Stabilization of power flows in integrated power system
- Frequency conversion



HVDC Link Advantages

- In DC transmission, only two conductors are needed for a single line.
- It can transport power economically and efficiently over long distances with reduced transmission lines compared with losses in AC transmission.
- The DC link connected between two AC systems eliminates the need for maintaining the synchronization between them. The supply frequencies may or may not be equal on the two sides. HVDC systems always maintain the power flow as long as the voltage of the systems linked by HVDC is maintained at certain limits. But in case of HVAC system, synchronization of the supply frequency is a must.
- The power flow in HVDC system can easily be controlled at high speed. The automatic controllers in the converter station determine the power flow through the link.
- No stability problems due to the transmission line length because no reactive power is needed to be transmitted.
- Fault isolation between the sending end and receiving end can be dynamically achieved due to fast efficient control of the HVDC link.
- In case of HVAC transmission for voltages greater than 400KV, it is necessary to limit the possible switching transients due to economic reasons. With the use of HVDC, such problems do not occur.

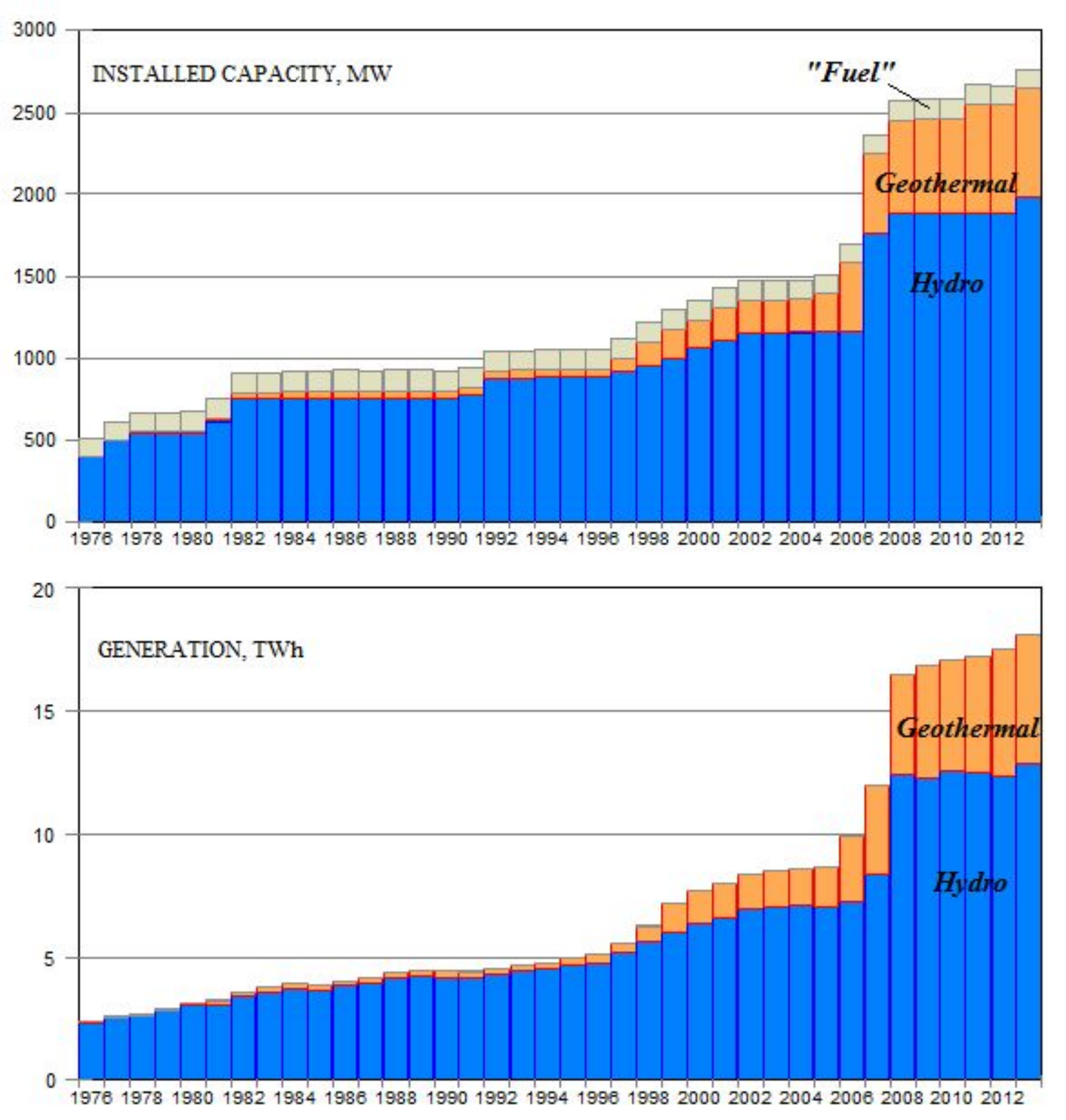
HVDC Link Examples - IceLink



IceLink details

- *The interconnector will be over 1000km long, 800 – 1200MW HVDC transmission link connecting Iceland to GB, and offering bi-directional flows;*
- *IceLink will deliver a volume of >5TWh flexible renewable electricity per annum;*
- *We anticipate that the total cost to the UK consumer will be competitive with other domestic low-carbon alternatives;*
- *IceLink delivers reliable and flexible energy into the GB system at times of thin supply margins;*
- *IceLink allows energy to flow to Iceland at times of low hydro generation potential, e.g. due to unusually low precipitation levels.*

HVDC Link Examples - IceLink



In 2013 Iceland generated 18.1TWh of electricity:
- 12.9TWh hydro;
- 5.2TWh geothermal;

from 2,768MW of installed capacity:
- 1,986MW hydro;
- 665MW geothermal;
- 115MW "fuel".

Over three-quarters of the 18.1TWh was consumed in Iceland's aluminum smelters and ferroalloy plants.

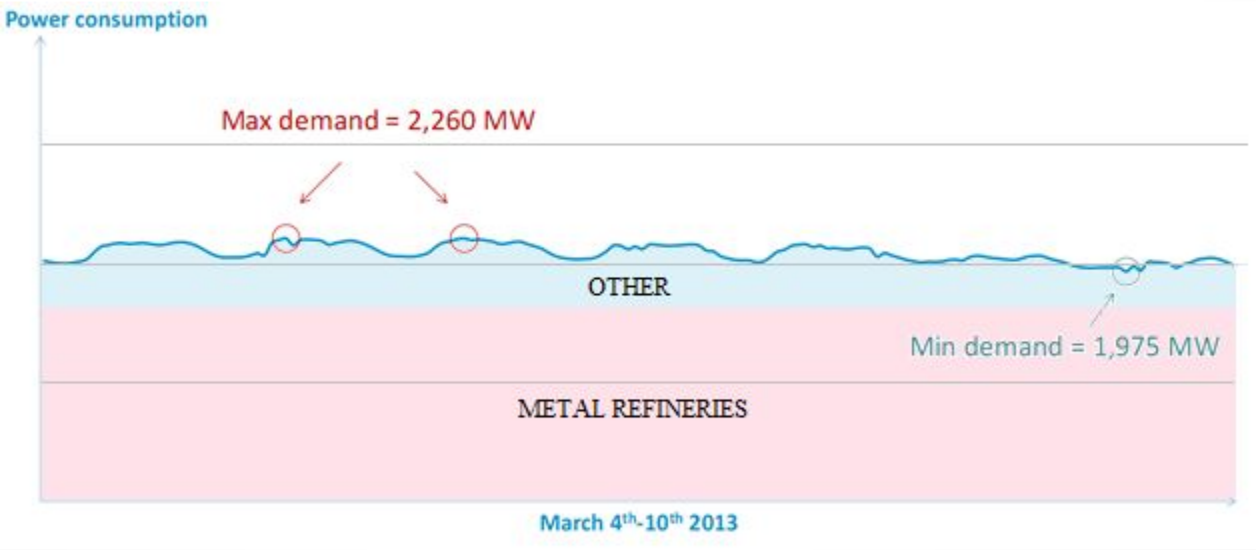
HVDC Link Examples - IceLink

Availability of power for export

Can Iceland deliver terawatt-hours a year of electricity to UK after Icelink goes into operation? It certainly could not have done so in 2013; it would have to generate a lot more electricity before it could. Where is it to come from?

- building more dams and hydro PP;
- expand geothermal
- build wind farms.

Advantage – flat demand curve.



HVDC Link Examples - IceLink

Power imports from Iceland

IceLink will have a capacity of only ~1GW – a small fraction of the UK's ~55GW peak winter demand – but it's a gigawatt of hydro (with maybe some geothermal in it) so it could be the difference between lights on and lights out during a cold, sunless, windless winter evening when no one else in Europe has any power to spare.

~5TWh of annual imports also represents a small fraction of the UK's ~320TWh annual consumption but could be useful in balancing intermittent renewables generation.

However, the question is whether the £4 billion installation cost wouldn't be better spent on a few gigawatts of new CCGTs or as a down-payment on a nuclear plant.

Finally comes the question of what the Icelanders think of becoming a power exporter. There's a certain amount of local opposition to the concept of turning Iceland into a power plant for Western Europe.

HVDC Link Examples – France-Spain

- It is a 320 kV direct current line. Due to its technical characteristics (underground line and length of 64.5 km) and in order to reduce power losses during the underground transmission, the interconnection will work with direct current.
- With a total length of 64.5 kilometres, the entire interconnection link is completely underground and has been housed in a concrete trench, except for the stretch that crosses the Pyrenees and that runs through an 8.5 kilometre tunnel.
- The tunnel, that runs parallel to the high-speed railway line, is 8.5 kilometres in length and 3.5 metres in diameter and houses the cables in the stretch of line that crosses through the Pyrenees.
- Two converter stations have been built, one at each end of the interconnection route: Santa Llogaia (Spain) and Baixas (France). These will be used to convert alternating current to direct current and vice versa. Each station has more than 5,400 power modules for the conversion process.
- This is the first time in Europe that Voltage Source Converter (VSC) technology has been used in an electrical interconnection link of this power capacity, a technology with the capability to quickly convert alternating current to direct current.

HVDC Link Examples – France-Spain

€700 million
Overall budget

€350 million
European Investment Bank loan

€225 million
European Union financial grant

2,800 MW
Exchange capacity doubled from 1,400 to 2,800 MW

2x1,000 MW
Power transported through the cables in direct current at

250 km
Kilometre of cable used

64.5 km
Length of the interconnection link

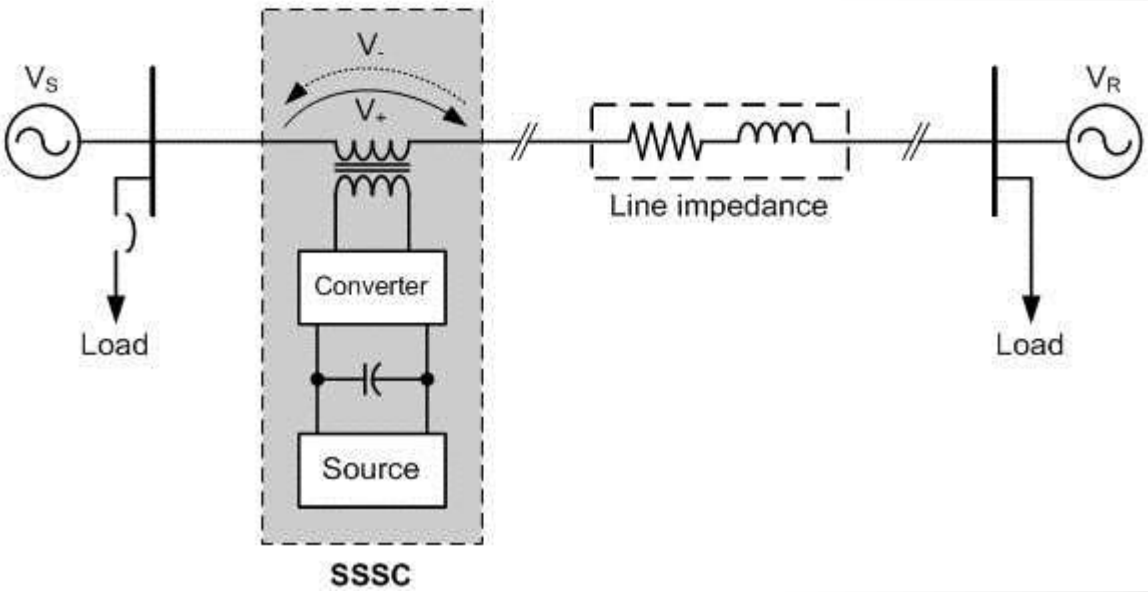
8.5 km / 3.5 m
Tunnel dimensions: 8.5 km in length and 3.5 m in diameter

5,400
Number of power modules

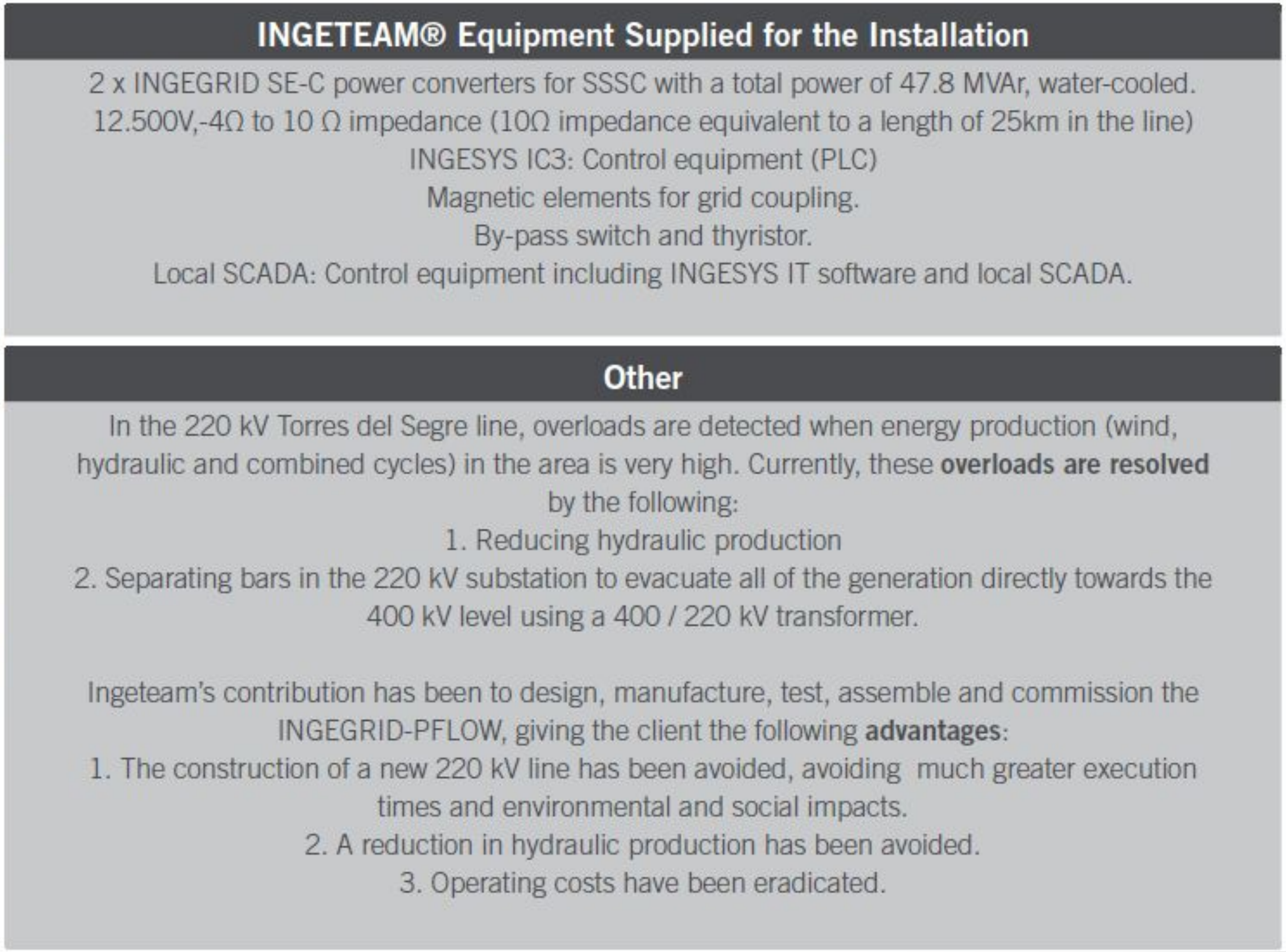
SSSC

- Serially connected STATCOM. It is able to transfer both active and reactive power to the system, permitting it to compensate for the resistive and reactive voltage drops – maintaining high effective X/R that is independent of the degree of series compensation. However, this is costly as a relatively large energy source is required.

- On the other hand, if control is limited to reactive compensation then a smaller supply should be enough. In this case only the voltage is controllable because the voltage vector forms 90º with the line intensity. Subsequently, the serial injected voltage can advance or delay the line current, meaning, the SSSC can be uniformly controlled in any value.



Application of SSSC



INGETEAM® Equipment Supplied for the Installation

2 x INGEGRID SE-C power converters for SSSC with a total power of 47.8 MVAr, water-cooled.
12.500V,-4Ω to 10 Ω impedance (10Ω impedance equivalent to a length of 25km in the line)
INGESYS IC3: Control equipment (PLC)
Magnetic elements for grid coupling.
By-pass switch and thyristor.
Local SCADA: Control equipment including INGESYS IT software and local SCADA.

Other

In the 220 kV Torres del Segre line, overloads are detected when energy production (wind, hydraulic and combined cycles) in the area is very high. Currently, these **overloads are resolved** by the following:

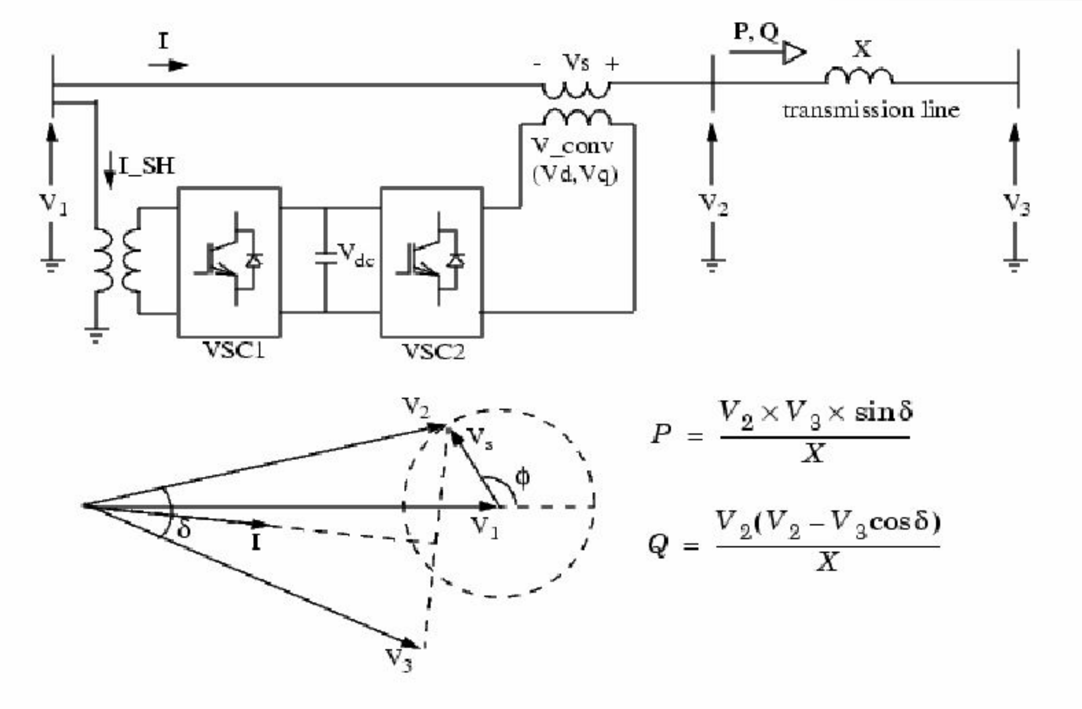
1. Reducing hydraulic production
2. Separating bars in the 220 kV substation to evacuate all of the generation directly towards the 400 kV level using a 400 / 220 kV transformer.

Ingeteam's contribution has been to design, manufacture, test, assemble and commission the INGEGRID-PFLOW, giving the client the following **advantages**:

1. The construction of a new 220 kV line has been avoided, avoiding much greater execution times and environmental and social impacts.
2. A reduction in hydraulic production has been avoided.
3. Operating costs have been eradicated.

Unified Power Flow Controller

- UPFC is the combination of STATCOM and SSSC which are coupled by via a common DC link.
- It has an ability to perform independent control of real and reactive power flow. Also, these can be controlled to provide concurrent reactive and real power series line compensation without use of an external energy source.
- It can also supply or absorb the controllable reactive power to the transmission line to provide independent shunt reactive compensation.



$$P = \frac{V_2 \times V_3 \times \sin\delta}{X}$$

$$Q = \frac{V_2(V_2 - V_3\cos\delta)}{X}$$

Unified Power Flow Controller Simulation Results

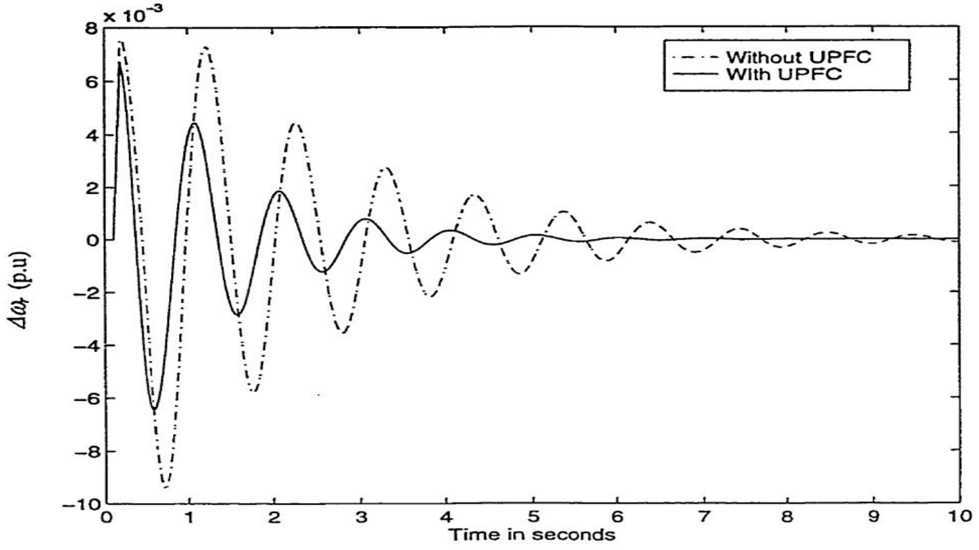


Fig.5.4 Generator rotor speed ($\Delta\omega$) oscillation damping with and without UPFC.

Small-signal and transient stability analysis has shown that the UPFC contributes positively to local mode and inter-area mode damping. In the case of SMIB, the local mode damping increased from 0.073 to 0.14. In the case of multi-machine power system, the inter-area mode damping increased from 0.09 to 0.144.

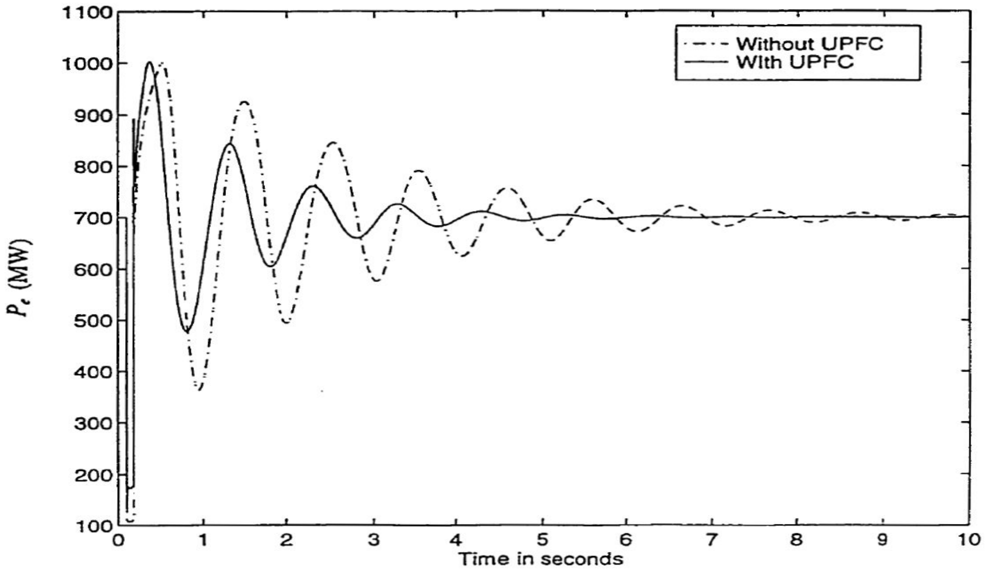


Fig.5.5 Generator electrical power (P_e) oscillations with and without UPFC.

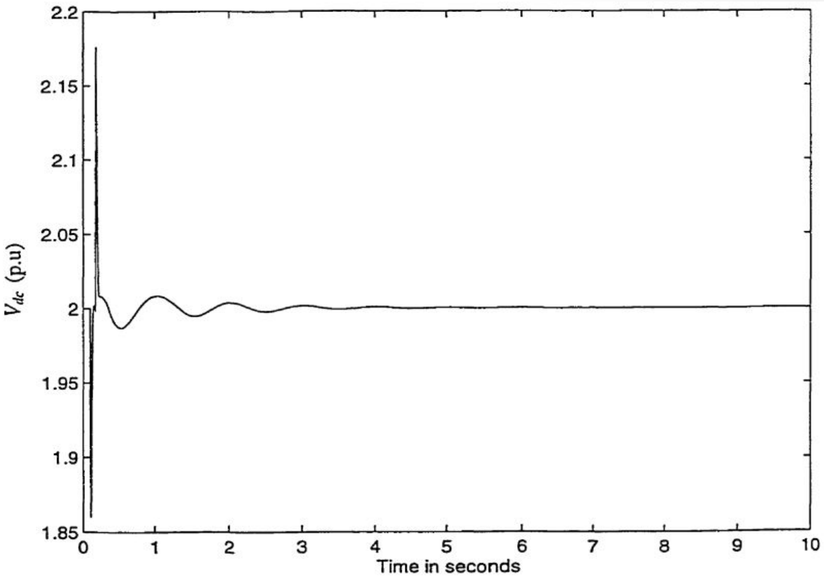


Fig.5.6 DC link capacitor voltage (V_{dc}) oscillations for three phase fault at the generator terminals.

Thank you for your attention!