Historical overview on dynamic reactive power compensation solutions from the begin of AC power transmission towards present applications

Heinz K. Tyll, *SM, IEEE*, and Dr. Frank Schettler[1]

Abstract— **The transmission of electrical energy using AC started at the end of the 19th century and replaced smaller existing local DC distribution systems. By extending local supply areas and providing energy transfer over longer distances various problems regarding mainly voltage control and stability were observed caused mainly by reactive power unbalances in the systems. Switched reactive power compensation (shunt capacitors, shunt reactors) were primarily used to control the steady state system voltages. Dynamic reactive compensation were based on rotating machines, eg synchronous condensors. In the mid 60's of the 20th century first static compensation devices, ie DC controlled reactors (mercury arc bulbs) and thyristor controlled devices (thyristor switched capacitors-TSC, thyristor controlled reactors-TCR) came up. Fast response times, lower losses and less maintenance requirements of thyristor controlled devices resolved the limitations of rotating machines and DC controlled devices. Evaluation of operating losses resulted more and more in the use of Static Var Compensators (SVC) which were built up by combinations of TCR and TSC branches. These shunt devices together with series connected devices TCSC (thyristor controlled series capacitors) provided a base for FACTS (Flexible AC transmission systems). FACTS allows transmission systems to be more efficiently used with regard to improved dynamic system voltage control on one side and higher power transfer capabilities on the other side. In AC transmission systems SVCs are installed presently with a total size of more than 100000 MVA.**

New power electronic devices (GTOs, IGCT, IGBT) were introduced to the FACTS market and allowed the use of current and voltage source converters (VSC) for providing fast reactive power compensation. With further improvement of controls, development of semiconductors and new arrangements of VSC technology to-days reactive power compensation is a key method to establish a reliable AC power transmission.

The paper gives an overview from the early days of reactive power compensation towards the present transmission system situation. It compares early solutions with to-days devices, provides decisive factors for the steps in development of arrangements and discusses advantages of the present devices.

Index Terms--**FACTS, SVC, TCR, TSC, TCSC, Thyristor, VSC, GTO; IGCT, IGBT.**

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I. Introduction

AC power transmission started in the late 19th century from low voltage levels and restricted supply areas towards larger distances, higher power transfers and using increasing transmission voltages [1]. Figure 1 gives an example for the increase of system voltages over the years.

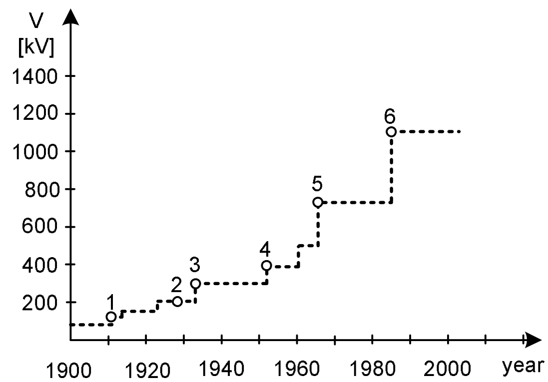

Fig. 1. Increase of transmission system voltages over the years
Milestones:

1	1911	110 kV	Lauchhammer-Riesa, Germany
2	1929	220 kV	Brauweiler-Hoheneck, Germany
3	1932	287 kV	Boulder Dam-Los Angeles, USA
4	1952	380 kV	Harspranget-Halsberg, Sweden
5	1965	735 kV	Manicougan-Montreal
6	1985	1200 kV	Ekibastuz-Kochetav, USSR

Consumers of electrical energy and its generation typically are not located in close vicinity. Large cities as well as large industrial areas are often supplied from distant located generation. The system components as well as the load itself include components of Var sources (capacitances, inductances) which influence system voltage profile and system stability. Transmission lines in HV systems (735 kV) may reach 200 MVars capacitive at a line length of 100 km. Cable connections have even higher Var contribution. Large load centers containing electric arc furnaces or large mill drives may reach up to 100 MVar inductive. Without proper reactive power compensation (RPC) critical system operating conditions may occur resulting in large voltage deviations and system stability problems in long transmission lines. These problems can be re-solved by proper shunt and series compensation schemes.

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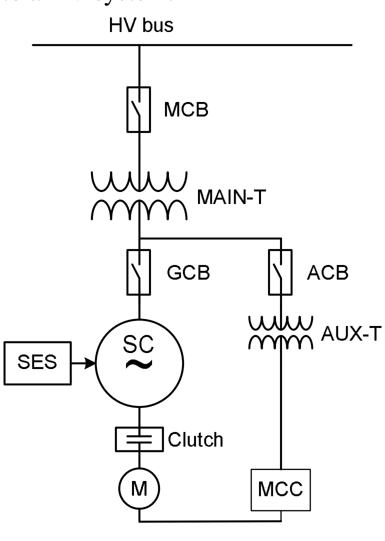
II. Shunt Compensation

Today's switched and continuously controllable RPC is used. The capacitive power of transmission lines or cable networks is partially compensated by parallel shunt connected line reactors, the inductive loads are compensated by shunt capacitors. Line reactors are permanently connected to the transmission lines to provide a continuous compensation over a large operating range. Shunt capacitors are typically split into more banks to compensate partially a specific load condition. Continuous control of reactive power in the early days was only available by the field control of generators or dedicated synchronous condensors. First static compensation devices were saturable reactor configurations [2,3] followed by thyristor type installations [3,7]. Latest compensation devices are based on VSC (Voltage Sourced Converters) [4-6,8,10] using first GTO (Gate turn-off Thyristors) now IGBT (Integrated bipolar Thyristors)

A. Synchronous Condensers

The behaviour of a synchronous condenser can be explained by the action of an electro-magnetic force behind a reactance. In some cases older generators were decoupled from their turbines and used for reactive power control avoiding new investment costs. Newly built synchronous condensors have been used at specific system locations to improve the voltage profile and/or to increase the short circuit level especially at connection points of HVdc stations. With the introduction of thyristor controlled excitation systems the response time of the machines were improved. Figure 2 shows a single line diagram of a synchronous condenser connection to a HV system.



Components
MCB
Main Circuit breaker
GCB
Generator CB
ACB
CB for Auxilliary supply
Main-T
Main transformer
Aux-T
Aux transformer
MCC
Motor Control Center with variable speed drive
SES
Static excitation system
M
Starting Motor
SC
Synchronous condenser

Fig. 2. Single line of a synchronous condenser connection

Figure 3 shows the V/I operating diagram. The slope of the operating curves depends on the reactances of the maschine and its main transformer. Adjustment of voltage reference setting in the control results in overexcitation or underexcitation operation (capacitive support or inductive absorption) of the synchronous condenser. It reacts inherently, i.e. without control action, and provides an additional voltage support outside its steady state operating characteristic in transient conditions.

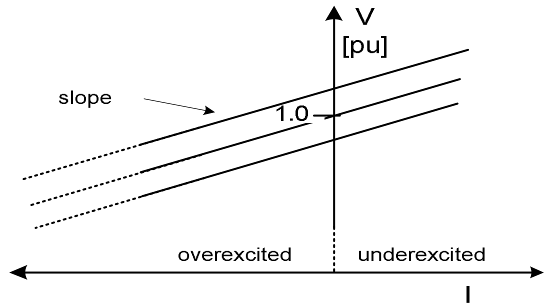


Fig. 3. Voltage-Current diagram of a synchronous condenser

B. Static Compensators based on saturable reactors

These first static compensators were built up by static (non-movable) components ie capacitors and reactors. The reactors operated in its saturation region thus limiting voltage changes. Figure 4 shows such an arrangement together with its operating characteristics.

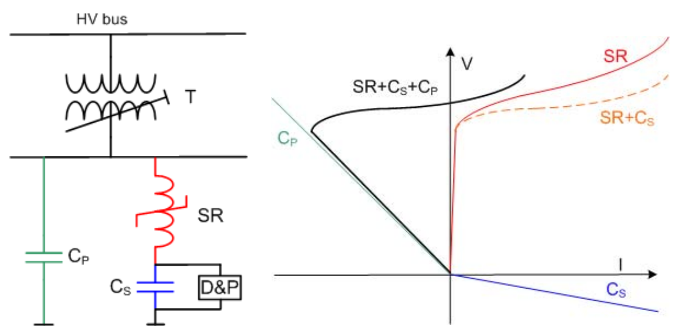


Fig. 4. Single line of a saturable static compensator and its characteristics

T	Transformer	SR	Saturable reactor
Cs	slope correcting capacitor	Cp	parallel shunt capacitor
D&P	Damping filters and capacitor protection		

The saturable reactor (SR) is typically designed as a nine-limb iron core reactor to neutralize the triple harmonic in the line current. The slope characteristic of the SR is reduced by a capacitor (Cs) connected in series. Both are paralleled by a shunt capacitor (Cp) which provides the capacitive voltage support of the whole arrangement. The right side of Fig. 4 shows the characteristic of each component (SR, Cs, and Cp). SR and Cs result in SR+Cs and finally after paralleling with Cp in the final characteristic SR+Cs+Cp. The saturable static compensator reacts inherently on system voltage changes. The reference voltage setting for its operating characteristic is made by the tap changer of the main transformer. Damping filters are connected parallel to the capacitor Cs to eliminate the risk of ferroresonance together with capacitor overvoltage protection. The total operating range can be adjusted by stepwise switched shunt capacitors. The static compensator works well under symmetric system voltage conditions.

C. Static Var Compensators (SVC)

An SVC [15] is built up by static components i.e. inductances and capacitances which may be fast controlled by semiconductors i.e. thyristors. The advantages of SVCs compared to synchronous condensors are lower maintenance (non-moving parts), fast three phase or single phase control, other optional control possibilities and lower costs compared at equal ratings. Figure 5 shows the typical components of an SVC.

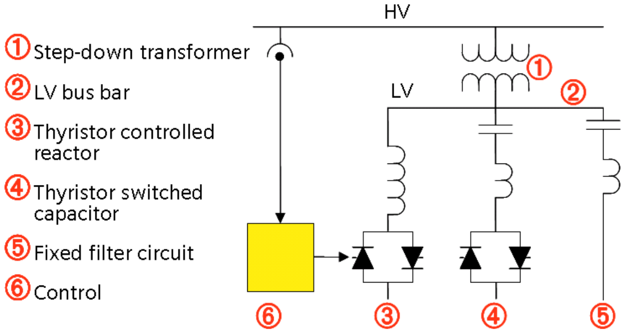


Fig. 5. Single line of an SVC

The required capacitive power for the system will be installed in capacitive branches which are fixed (FC) connected to the LV bus or switched by thyristor valves (thyristor switched capacitor - TSC). FC branches are typically tuned by series reactors for harmonic filtering purposes. The inductive power is installed in single phase or three phase reactor combinations which are smoothly controlled by thyristor valves (TCR). The branches are connected to the HV system via a dedicated SVC transformer. The transformer adjusts the system voltage to a level optimized for the thyristor operating capabilities.

TCR branches

A TCR branch contains reactors which are phase angle controlled by thyristor valves. Three single phase branches are connected in delta to reduce the generation of triplen harmonics in symmetrical operation.

TSC branches

A TSC branch contains capacitors and current limiting reactors which are switched on and off by thyristor valves. TSC branches can be delta or star connected. In star connection one valve becomes obsolete and can be left out in one of the three phases. Using the same thyristors in terms of current carrying capability as for a TCR the branch rating will be lower accordingly.

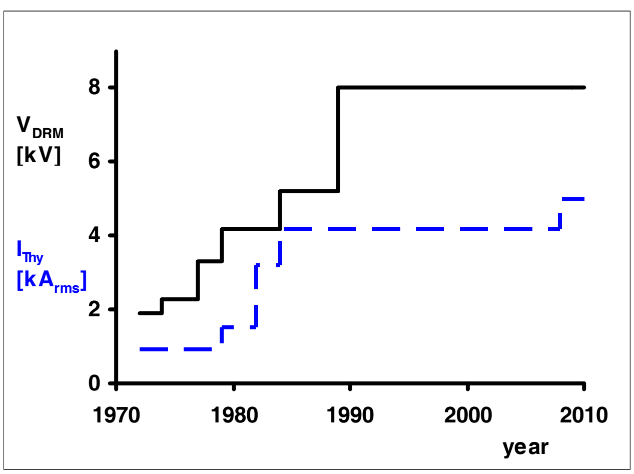


Fig. 6. Development of thyristors over the years

Thyristortechnology

The development of high power thyristors laid down the basis for the use of high power electronics application in the system.

The development of thyristors is shown in Figure 6 starting from the 70's. The current carrying capability was increased stepwise from around 800 Arms towards 4000 Arms using silicon wafers with a diameter from 40 to 125 mm. At the same time the blocking voltage was increased from 1.6 to 8 (10) kV. A further step in current capabilities is expected beginning of 2009.

SVC Configurations

In the beginning of SVC installations thyristors were paralleled to cope with the required output requirements of the different thyristor controlled branches. The series connection of thyristors were limited to LV bus voltages typically below 36 kV. 12pulse connections at that time were used to separate the thyristor controlled branches with the advantage of lower short circuit current on each valve bus and avoiding 6 pulse harmonic distortion of the system. Figure 7 below shows a typical SVC in 12pulse connection using only TCR and fixed capacitive (FC) branches.

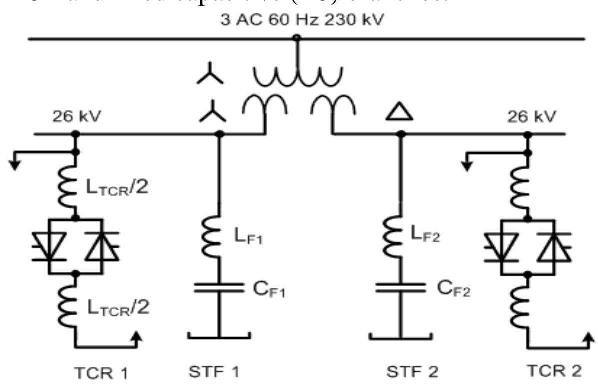


Fig. 7. SVC in 12 pulse configuration

TCR/TSC configurations

The SVC configurations changed by the time due to the thyristor development towards higher current ratings and upcoming discussions on losses, space requirements and relocatability.

Losses

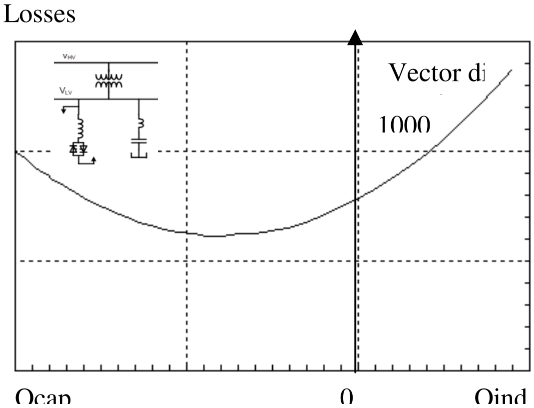


Fig. 8. SVC operating losses (TCR – FC arrangement)

An SVC configuration consisting of TCR and FC branches results in operating losses as shown in Figure 8.

The loss figure includes no load and load losses from the transformer, reactor losses in the TCR branch and from the filter reactor, dielectric losses from the capacitors, all valve related losses like on-state losses and switching losses (on/off), losses of the cooling equipment (transformer and valves) and auxiliary equipment. The averaged operating losses of a TCR/FC arrangement amounts approximately to 0.5 to 0.7% of the rated capacitive power. Figure 9 shows the operating losses of a TCR/TSC/FC arrangement.

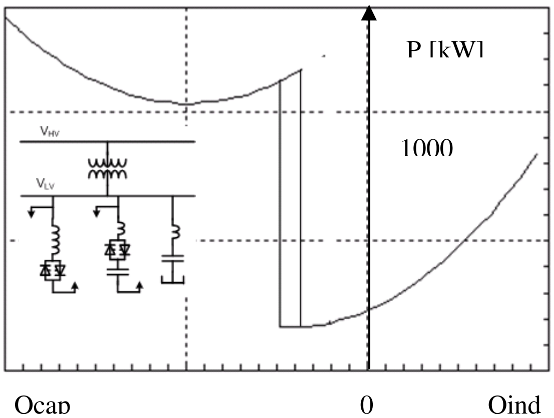


Fig. 9 SVC operating losses of a TCR – TSC - FC arrangement

The averaged operating losses of a TCR/TSC/FC arrangement amounts also to approximately 0.5 to 0.7% of the rated capacitive power of the SVC. The cost of an TCR/TSC/FC SVC configuration with additional TSC valves increase compared to the TCR/FC configuration due to the additional cost on TSC valves. Due to the intention that an SVC should operate most of its time around zero output to be prepared for fast voltage support in system contingencies the cost of losses are to be evaluated in the operating area.

The evaluation procedure could be at follows:

$$Pveval = Pv1 \times t1 + Pv2 \times t2 + Pv3 \times t3 + + Pvn \times tn$$

Pveval evaluated total operating losses
Pv1,2…n averaged losses in an operating range 1,2…n for
t1,2…n operating times 1,2…n.

The operating time sums up to 8760 h per year.

The cost of losses will be finally calculated by multiplying Pveval x specific cost for losses $/kW of the customer. Specific cost of losses vary from utility to utility. In specifications [15] they vary from 1500 to 8000 $/kW.

Such evaluated the total cost of an SVC is the sum of its investment cost (components, installation etc) and the loss costs. An SVC solution TCR/TSC/FC may then be more economical than the simpler TCR/FC configuration. Recent SVC installations were mostly TCR/TSC/FC configurations.

Space

Despite the fact that TCR/TSC/FC configurations need more space because of more branches the effective space requirement could be reduced by more than 50% for earlier installations down to 8 m2/MVar nowadays. Space requirement can also be used as an evaluation criteria.

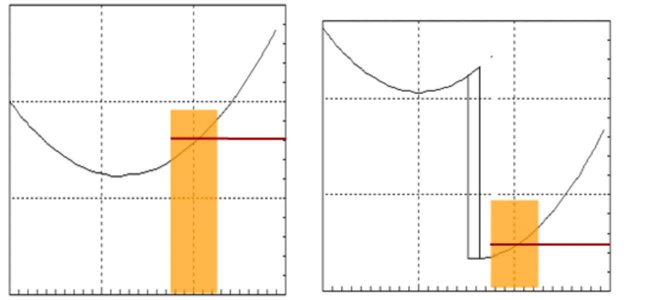


Fig. 9 Evaluation of SVC operating losses (Ref to Figures 8 and 9)
Based on 3000 $/kW the loss cost of the TCR/FC configuration would amount to 2.4 Mio$ versus to 0.75 Mio$ of the TCR/TSC/FC configuration

Relocatabilty

Due to liberalization and privatization the load flow can be changed in some HV systems within a few years [xy]. An SVC previously installed at a specific node may be no longer effective at this location and is required at another system point. Relocatability of an installation may also be used as a total cost evaluation criteria.

Development of control analog to digital.

Over the years the control and protection changed from pure analog control to digital controls. The advantage of digital controls is driftfree parameterization and signaling, software controlled functionality, graphically configurable, self diagnosing and modular structure. A modern SVC control can fulfill manifold control functions and allows the SVC to be perfectly integrated into the system. Figure 10 shows a control block diagram including various control functions in the closed loop control.

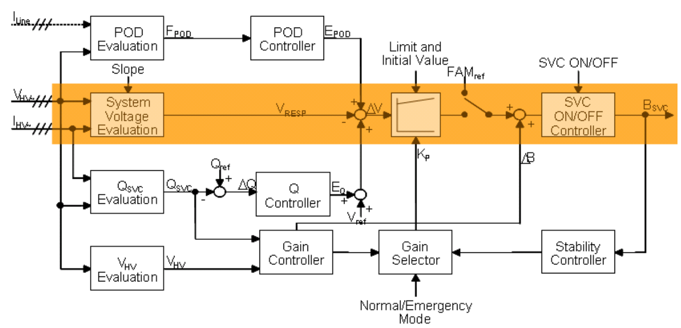


Fig. 10 Standard control function within an SVC control

The controls diagram above shows the typical voltage control path (highlighted). The voltage control signal can be modulated by a fast POD (power oscillation damping) control in case of severe system stability problems after system faults. A slower acting reactive power control path helps the SVC to operate from pre-determined optimum operating point, e.g. Zero MVar. From this optimum operating point the SVC shall be able to support or absorb very fast reactive power at critical system conditions.

D. Voltage Sourced Converters(VSC)

The idea to apply self commutated converters to static reactive power compensation was discussed a long time before first applications based on Thyristors with special forced commutation circuits were built in the 70's of the 20th century [9]. In principle converters with fixed dc voltage or dc current could be used. However, supported by the rapid development of other industries, e.g. electrical drive systems a broad variety for semiconductors with controlled turn–off and asymmetrical blocking capability became available. High power Gate Turn-Off Thyristors (GTO) were used in first prototypes of so called Voltage Sourced Converter (VSC) based static compensators (STATCOM) [10,12].

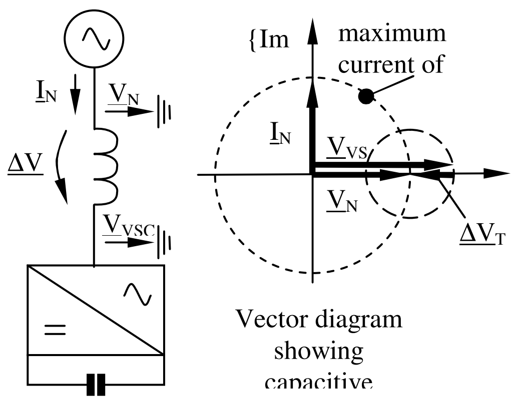


Fig.11: Operating principle of VSC

The operating principle of VSC is illustrated in Figure 11. The Vector diagram shows capacitive operation. Phase angle and magnitude of current can be controlled by changing $\underline{V}_{VSC}$. For a given system voltage $\underline{V}_N$ the converter voltage $\underline{V}_{VSC}$ is controlled to obtain a current $\underline{I}_N$ which can be anywhere within the circuit marked "maximum current of converter". Disregarding power losses, an STATCOM is operated with a current leading or lagging the system voltage by 90°. The maximum current is inherently symmetric with respect to leading or lagging operation. For a wide range of varying system voltages the current can be kept constant. This feature is visualized in Figure 12, where the VI characteristics of a STATCOM and a SVC are compared. Under low voltage conditions the STATCOM can provide more power than an SVC, under overvoltage conditions the maximum output of the STATCOM is less.

The development of VSC technology for RPC has been aiming at objectives like: increased system support in case of undervoltages, higher speed of response to compensate flicker, more compact design and easy relocatability, less harmonic interaction with the power system. Today, there are different technical solutions on the market which may be summarized as multi converter concepts, high voltage PWM converters or multilevel converters. History reveals the background for the current situation and points towards the future.

In first VSC applications the number of GTOs in direct series connection was restricted mainly because equal voltage sharing across the individual GTO levels could not be assured. This caused the power output of a single converter to be limited to a few Mvar. Moreover, high switching losses largely prevented the converters from being controlled by efficient Pulse Width Modulation (PWM) techniques to achieve close to sinusoidal current wave shapes. These limitations were first overcome combining several converters using harmonic cancellation by magnetic circuits [11].

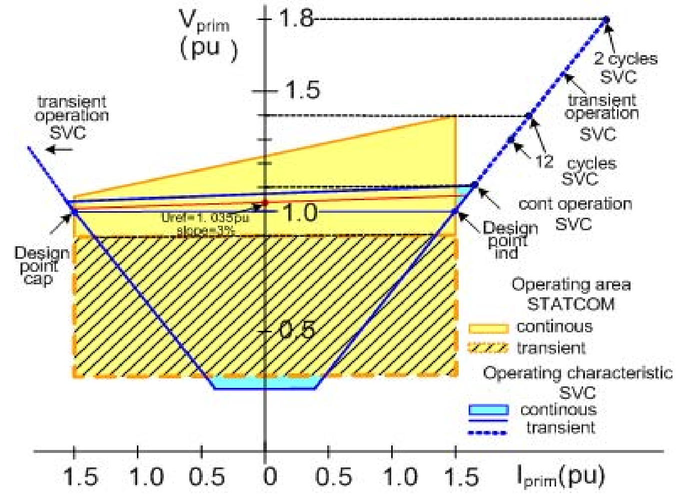


Fig. 12: VI characteristics of Thyristor based and VSC based SVC

Later on semiconductor devices with improved switching capabilities became available. With the introduction of Integrated Gate-Commutated Thyristors (IGCT) high power converters have been built reaching power ratings up to some 10 MVA. Focusing on dc transmission high voltage Insulated Gate Bipolar Transistors (IGBT) valves of 300 kV and more were realized giving a power rating of a single converter in the range of some 100 MVA.

For IGBT based converters a sinusoidal ac output current is achieved by high switching frequency PWM in the kHz-range. Besides the fact that the high switching frequency still leads to significant converter losses, the steep dv/dt associated with the high valve voltages require special equipment withstanding the high frequency stresses and measures limiting electromagnetic interference.

A further growing market of high power semiconductors and powerful control systems allow overcoming the disadvantages of high frequency switched high voltage valves today. Converter systems recently presented [15] are modularly structured and generate a close to sinusoidal ac output voltage from a big number of different output voltage levels (multilevel converter).

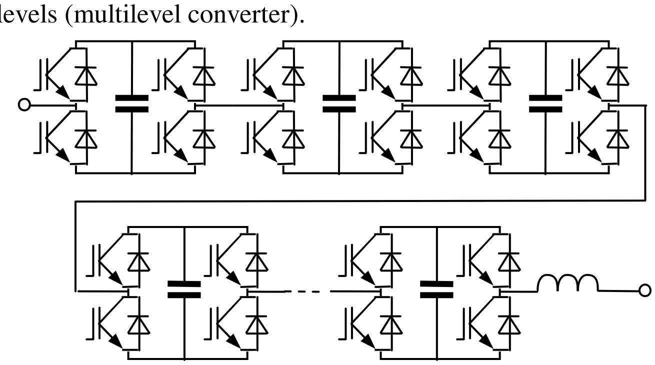


Fig 13: Single phase arrangement of a multilevel VSC used as SVC

Figure 13 shows a single phase converter configuration as used for SVCs. Three of such phase arrangements can be connected in delta. Considering the voltages and currents the behavior of multilevel converters gets very close to those of synchronous condensers but with much shorter response times. Due to reduced harmonic interaction with the surrounding system multilevel converter based SVCs need less components and are easier to integrate in power systems than all other types of static compensators. Power losses of a multilevel converter are considerably lower than those of other VSCs of the same power rating but still partially higher than those of Thyristor based SVCs.

Up to now the installed capacity of SVCs amount to approximately 110000 Mvars where VSC applications for transmission systems reach an installed power of approximately 4000 Mvars.

III. Series Compensation

Power plants are built at places which are not close to the load centers due to economical reasons. The generated energy has to be transported via long distances. Figure 14 shows the voltages at the end of a 345 kV line as a function of transmitted active power for three line length (100, 200 and 300 km). The surge impecance loading of this line is 410 MW.

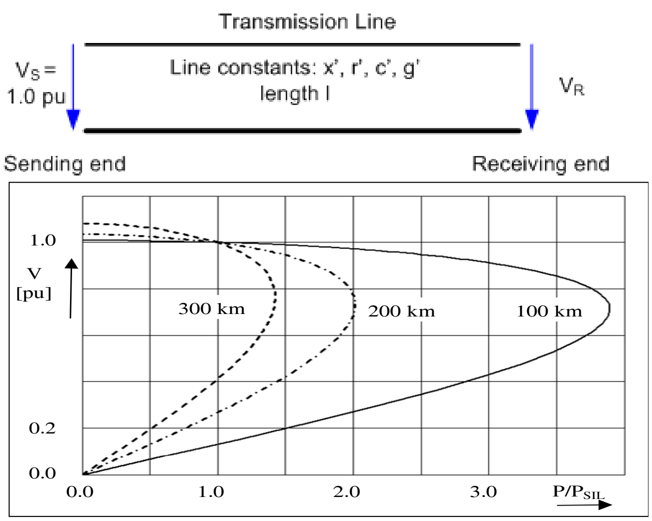


Fig. 14 Voltages at the receiving end

The longer the line the lower is the maximum transmittable active power. The electrical length of a line can be extended by inserting series capacitors. This principle was also used in the early times to compensate transformer impedances improving the voltage of larger variable loads connected to the LV side.

A. *Fixed Series Capacitors (FSC)*

Series capacitors can be inserted at both line ends or at the midpoint. The main consideration will be the voltage profile along the line during power transmission. The compensation degree typically should not exceed 70 % of the line impedance. The FSC can be inserted as one major block or in sub-blocks to allow a step-wise adaption of the compensation degree for various system operating conditions.

B. *Thyristor Controlled Series Capacitors (TCSC)*

In some applications part of the FSC has been equipped with a parallel TCR branch which allows continous control within a certain firing angle range [16]. Figure 15 shows the arrangement of such a TCSC together with the possible impedance control characteristic.

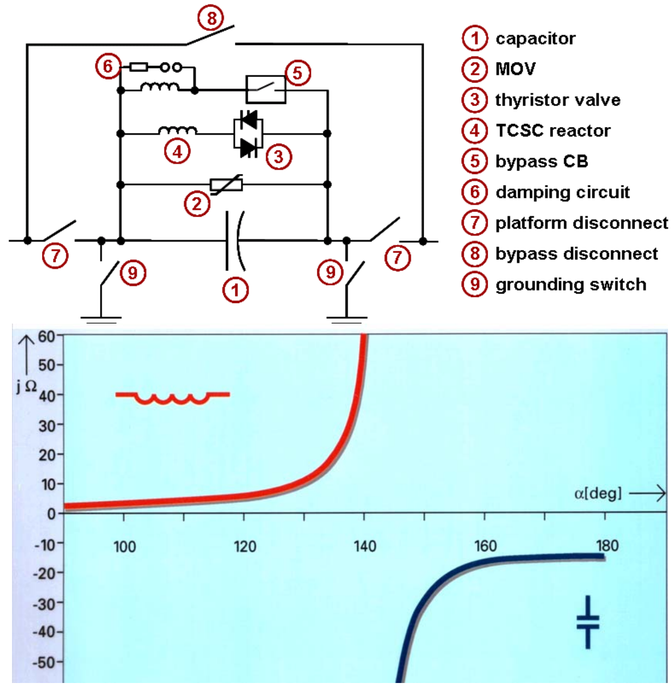
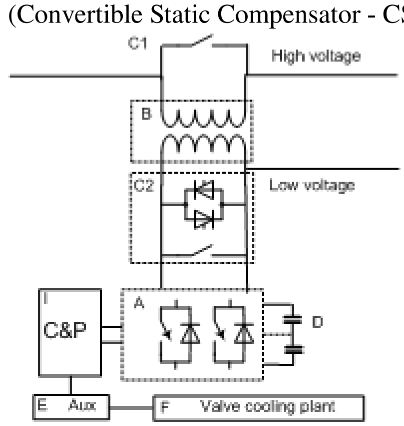


Fig. 15 Single line of a TCSC and its operating characteristic.

A TCSC has a limited firing angle operating range from around 150 to 180 deg. Continuous operation in the inductive range is not feasible because of very high currents flowing through the thyristors. Only operation at TCR full conduction is allowed.

C. *Voltage Sourced Converters (VSC)*

VSC configurations have been added to STATCOM installations series inserted to the line forming a UPFC (Unified Power Flow Controller). In other stations such series connected VSC configurations have been installed for power flow / load sharing purposes between parallel lines (Convertible Static Compensator - CSC).



A
VSC configuration
B
Series connected transformer
C1
By-pass CB
C2
by-pass by fast thyristor and CB
D
DC circuit
E
Auxilliary supply
F
Valve cooling

Fig. 16 Single line of a VSC in series connected line and components

The advantage of VSC based series installations is their capability to be controlled also in the inductive region.

IV. Conclusion

Dynamic reactive power compensation controlled by power electronics has improved system operation and is now an established means among other compensation devices.

The broad variety of FACTS technologies provides reliable solutions to most challenging requirements in power transmission.

The combination of dynamic and conventional switched RPC often results in cost effective solutions for steady state and transient system operation [13]. VSC based FACTS are expected to be more widely used especially in the lower and medium power range.

More RPC installations are probably required in the near future to overcome system limitations which is seen an important contribution to increase system stability and prevent blackouts.

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VI. Biographies

Heinz Karl Tyll (M'88, SM'93) graduated in 1968 in Electrical Engineering from Coburg Polytechnikum. In 1974 he received the Diplom degree from the Technical University of Berlin. After joining Siemens AG, he worked in their High Voltage Transmission Engineering Department since 1975 in the field of network and SVC system analysis with transient network analyzer and digital programs. In 1988 he transferred to the System Engineering Group of the HVDC and SVC Sales Department. Since 1996 he was responsible for Basic Design of SVC, SC and FACTS applications. He contributed to CIGRE WG 38 TFs and to relevant IEEE WG. He is member of IEEE and VDE. Presently he acts as chairman for the revision TF of IEEE STD 1031.

Frank Schettler received his Dipl.-Ing. and PhD in Electrical Engineering from the Technical University of Ilmenau, Germany in 1992 and 2003 respectively. He has been working with Siemens in the field of power transmission and distribution for about 16 years. As a systems engineer he gained experience in the fields of power system design, development, application engineering and sales for FACTS and HVDC. He is currently head of the System Engineering team for FACTS and Grid Access Solutions in Siemens.