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Transformerless Reactive Series Compensators with Voltage Source Inverters

Herbert Stemmler and Andreas Beer, Non-members
The Swiss Federal Institute of Technology (ETH)
Power Electronics and Electrometrology Laboratory
ETH Zentrum/ETL H23,
CH-8092 Zurich, Switzerland

Hideo Okayama, Member
Mitsubishi Electric Corporation
Industrial Electronics & Systems Laboratory
8-1-1, Tsukaguchi-Honmachi, Amagasaki,
Hyogo 661, Japan

Abstract

This paper proposes a configuration for transformerless connected compensators consisting of voltage source inverters with parallel and series connected capacitors. The behavior of transmission lines and power flow control with reactive series compensators are described. After presentation of the circuits and configurations their mode of operation is shown in more details using an example which is representative for practical applications.

Keywords: FACTS (Flexible AC Transmission Systems), Power Flow Control, Transmission Line, Series Compensation, Transformerless VSI (Voltage Source Inverters), Hybrid Configuration

1. Introduction

In electric power systems large converters using conventional turn-on thyristors are state of the art for more than twenty years. Driven by the semiconductor technology, which allows to build improved turn-off power devices and driven by new market demands caused by the emerging deregulation in power systems, new activities in this field are coming up. With turn-off-thyristors or transistors the characteristics of modern converters can be improved to such an extent that new applications for FACTS (Flexible AC Transmission Systems) will be opened. They allow to control the active and reactive power flow in ac systems in a much more refined way and, therefore, they allow to make much better use of existing generators and power lines.

In this paper a configuration for reactive series compensators consisting of voltage source inverters with parallel and series connected capacitors is proposed and investigated. In chapter 2 the behavior of transmission lines and in chapter 3 power flow control with reactive series compensators are described. Chapter 4 presents circuits and configurations and in chapter 5 their mode of operation is shown in more details. Chapter 7 gives a summary.

2. Behavior of transmission lines

Transmission lines can be described with phasor equations and illustrated with phasor diagrams. Focussing at the receiving end (index 2) it is suitable to use (1) and (2) which are represented in fig.1. For reasons of simplification the losses are neglected in (1), (2), (5) and (6).

$$\underline{U}_1 = \underline{U}_2\cos\beta l + j\underline{I}_2 Z_0 \sin\beta l \qquad (1)$$

$$P = \frac{U_1 \cdot U_2}{Z_0 \sin\beta l}\sin(\varphi_{u1} - \varphi_{u2}) \qquad \text{where:} \qquad (2)$$

$\underline{U}_{1/2} = U_{1/2}e^{j\varphi_{u1/2}}$	: Input/Output voltage phasor	(3)
$\underline{I}_2 = I_2 e^{j\varphi_{i2}}$	: Output current phasor	(4)
P	: transfer power	
$Z_0 = \sqrt{L'/C'}$	: wave impedance	(5)
$\beta = \omega\sqrt{L'C'}$	: phase constant	(6)
l	: length of the line	
L', C'	: inductance/km, capacitance/km	

The phasor diagram in fig.1 illustrates the eqs. (1) and (2) for a 500km 400kV transmission line. The real axis is fixed in the direction of the phasor $\underline{U}_2=U_2$, the amplitude of which is kept at its rated value U_2=1*p.u.*. When the current phasor $\underline{I}_2$ - multiplied with Z_0 - at the receiving end is moving in the $\underline{I}_2Z_0$-sector, then the voltage phasor $\underline{U}_1$ at the sending end moves correspondingly in the $\underline{U}_1$-sector - which is a linear conformal mapping of the $\underline{I}_2Z_0$-sector, according to (1).

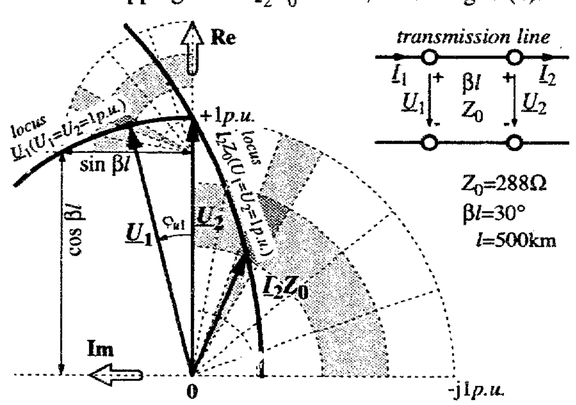

Fig.1. Transmission line, phasor diagram

Fig.1 shows: Increasing the consumption of active current $Re(\underline{I}_2)$ at the receiving end rises the angle $\varphi_{u1} = \angle(\underline{U}_1, \underline{U}_2)$ between the voltage phasors $\underline{U}_1$ and $\underline{U}_2=U_2$ at the terminals of the line. See also eq. (2).

The amplitude U_1 of the phasor $\underline{U}_1$ can only be kept at its rated value U_1=1*p.u.* if the current phasor $\underline{I}_2$ follows the characteristic $\underline{I}_2Z_0(U_1=U_2=1p.u.)$ in the $\underline{I}_2Z_0$-sector. This characteristic is a linear conformal mapping of the phasor $\underline{U}_1$ in the $\underline{U}_1$-sector, following a circle with radius U_1=1*p.u.*. That means: In order to keep the voltage at both ends of the line at the rated values $U_1=U_2$=1*p.u.* the generators - or reactive power compensators - in the ac system at the receiving end of the line have to compensate the reactive current consumption of the load in such a way that the current $\underline{I}_2$, taken out of the line, follows the above mentioned characteristic $\underline{I}_2Z_0(U_1=U_2=1p.u.)$.

3. Power flow control by reactive series compensators

3.1 Reactive series compensators

Reactive series compensators are voltage sources through which the line current is flowing. They, however, need no power supply because they only deliver reactive power. Their voltage phasor $\underline{U}_{comp}$, therefore, must be kept in a 90° leading or lagging position relative to the line current phasor $\underline{I}_2$.

$$\underline{U}_{comp} = jU_{comp}e^{j\varphi_{i2}} \quad \text{if} \quad \underline{I}_2 = I_2 e^{j\varphi_{i2}} \qquad (7)$$

U_{comp} pos./neg.: ind./cap. power consumption

In the leading position the compensator behaves like a controllable inductance and in the lagging position like a controllable capacitance. The amplitude U_{comp} of the compensator voltage phasor $\underline{U}_{comp}$ can be freely controlled between a positive and a negative maximum value by means of a PWM inverter. In chapter 4 and 5 circuits, configurations and operation modes of reactive series compensators are shown in more details.

3.2 Benchmark system

To demonstrate the power flow control with series compensators the configuration in fig.2 is used as a benchmark system: Two ac systems, 1 and 2, each consisting of distributed generators G and loads L are linked together via two transmission lines A and B. Line B is equipped with a series reactive power compensator. This configuration allows bidirectional power transfer. The ac system 2, however, shall be regarded as the system which normally receives energy. Therefore the main focus is on the receiving end of the transmission lines. It is assumed that both lines are coupled to the ac system 2 via transformers which reduce the high transmission voltage to an adequate level. These line transformers are represented in fig.2 by their leakage inductances L_σ. For reasons of simplification the transformers at the sending end are neglected.

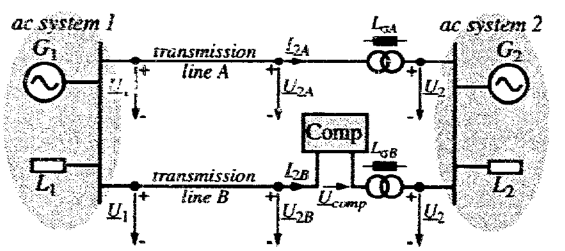

Fig.2. Benchmark system

The assumed energy deficit in the ac system 2 has to be covered by an energy surplus in the ac system 1. The power transfer $P=P_A+P_B$ of both lines compensates for the difference between generated and consumed power $P_{L_2}-P_{G_2}$ in the ac system 2.

$$P = P_A + P_B = P_{L_2} - P_{G_2} \qquad (8)$$

The series compensator fulfils the task to control the shares P_A and P_B of the total transfer power P.

3.3 Controlled and uncontrolled transmission lines

In the following equations it is assumed that both ac system voltages $\underline{U}_1$ and $\underline{U}_2$ are related to the high transmission voltage level.

a) *The characteristics of controlled transmission lines* - see fig.2 line B - can be derived from the equations of the line (1), the compensator (7) and the voltage (9) of the receiving end of the line.

$$\underline{U}_1 = \underline{U}_{2B}\cos\beta l_B + j\underline{I}_{2B}Z_0\sin\beta l_B \qquad (1)$$

$$\underline{U}_{2B} = \underline{U}_{comp} + j\omega L_{\sigma B}\underline{I}_{2B} + \underline{U}_2 \qquad (9)$$

$$\underline{U}_{comp} = jU_{comp}e^{j\varphi_{i2B}} \qquad (7)$$

Introducing (3) and (4) for the phasors

$$\underline{U}_1 = U_1 e^{j\varphi_{u1}}; \qquad \underline{I}_{2B} = I_{2B}e^{j\varphi_{i2B}} \qquad (3);(4)$$

and eliminating $\underline{U}_{2B}$ leads, after short, purely algebraic calculations, to (10). In equation (10) the real axis is fixed in the direction of the voltage phasor $\underline{U}_2 = U_2$.

$$U_1 e^{j\varphi_{u1}} = U_2\cos\beta l_B + je^{j\varphi_{i2B}}(U_{comp}\cos\beta l_B + I_{2B}X_{L_B}) \qquad (10)$$

$$\text{where:} \quad \underline{U}_2 = U_2; \qquad X_{L_B} = Z_0\sin\beta l_B + \omega L_{\sigma B}\cos\beta l_B \qquad (11)$$

b) *The characteristics of uncontrolled transmission lines* follows from (10) for $U_{comp}=0$:

$$U_1 e^{j\varphi_{u1}} = U_2\cos\beta l_A + je^{j\varphi_{i2A}}I_{2A}X_{L_A} \qquad (12)$$

$$\text{where:} \quad \underline{U}_2 = U_2; \qquad X_{L_A} = Z_0\sin\beta l_A + \omega L_{\sigma A}\cos\beta l_A \qquad (13)$$

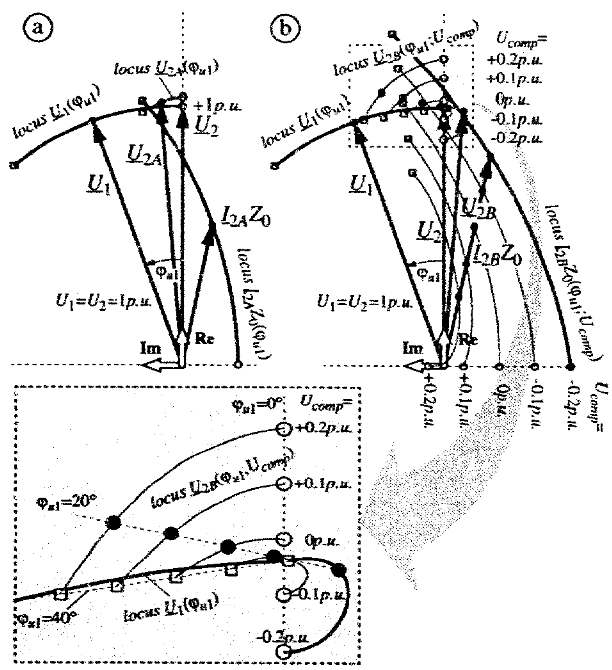

Fig.3. Uncontrolled and controlled transmission lines

The characteristics of controlled and uncontrolled transmission lines - according to fig.2 - are illustrated in fig.3 for 500km 400kV ($\beta l_{A,B}$=30°) transmission lines with a transformer ($\omega L_{\sigma A,B}/Z_0$=15%) at the receiving end. In both cases the real axis is fixed in the direction of the voltage phasor $\underline{U}_2=U_2$ in the ac system 2. It is assumed that the voltage control of both ac systems keeps the amplitudes U_1 and U_2 at their rated value 1*p.u.*. Fig.3a contains the characteristics for the *uncontrolled* line A. It shows the locus of the phasors $\underline{U}_1(\varphi_{u1})$, $\underline{I}_{2A}Z_0(\varphi_{u1})$ and $\underline{U}_{2A}(\varphi_{u1})$ as a function of the phase angle φ_{u1} between the phasors $\underline{U}_1=U_1\cdot e^{j\varphi_{u1}}$ and $\underline{U}_2=U_2$ of both ac systems.

Fig.3b contains the same phasors $\underline{U}_1(\varphi_{u1};U_{comp})$, $\underline{I}_{2B}Z_0(\varphi_{u1};U_{comp})$ and $\underline{U}_{2B}(\varphi_{u1};U_{comp})$ for the *controlled* line B with the amplitude U_{comp} of the series compensator voltage as a parameter: U_{comp} = $-0.1p.u.$; $-0.2p.u.$; $+0.1p.u.$ and $+0.2p.u.$.

In the *uncontrolled* line A the phase angle φ_{u1} between the phasors $\underline{U}_1$ and $\underline{U}_2=U_2$ of both ac systems determines the active current $Re(\underline{I}_{2A})$ and the transfer power $3/2 \cdot U_2 Re(\underline{I}_{2A})$.

In the *controlled* line B the transfer power at a given phase angle φ_{u1} can be controlled with the amplitude U_{comp} of the compensator voltage (the phasor $\underline{U}_{comp}$ of which has a 90° phase shift to the current phasor $\underline{I}_{2B}$ - as explained in chapter 3.3.1 (7)). Fig.3b shows how the control works: The amplitude I_{2B} of the current $\underline{I}_{2B}$ is amplified or reduced when the amplitude U_{comp} of the compensator voltage phasor $\underline{U}_{comp}=jU_{comp}e^{j\varphi_{i2B}}$ is rising in the negative or positive direction. That means: *Reactive series compensators act on the amplitude I_{2B}, not on the phase angle φ_{i2B}, of the current phasor $\underline{I}_{2B}=I_{2B}e^{j\varphi_{i2B}}$ at the receiving end of the line B.*

The control characteristics are represented in fig.4. It shows the current amplitude I_2 at the receiving end of the line and the transmission power $P=3/2 \cdot U_2 Re(\underline{I}_2)$ as a function of the angle φ_{u1} between the voltage phasors $\underline{U}_1$ and $\underline{U}_2=U_2$ of the ac systems 1 and 2, with the amplitude U_{comp} of the compensator voltage phasor $\underline{U}_{comp}=jU_{comp}e^{j\varphi_{i2}}$ as a parameter. In fig.4 currents, voltages and active power are related to their nominal values I_N, U_N and S_N, defined in chapter 5.5.1.

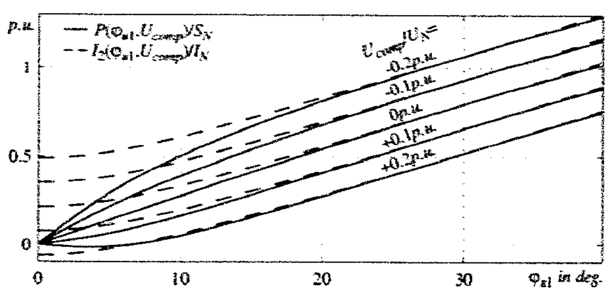

Fig.4. Transmission line. Control characteristic.

Reactive series compensators shorten or lengthen the transmission line electrically: At a given phase angle φ_{u1} between the voltage phasors $\underline{U}_1$ and $\underline{U}_2$ of both ac systems, the compensator increases the power transfer when absorbing capacitive reactive power (U_{comp} neg.). At the same phase angle φ_{u1} the power transfer is reduced when the compensator absorbs inductive reactive power (U_{comp} pos.).

3.4 Power flow control in networks

Electrical power utilities are under pressure to deregulate, allow access to network by independent power producers and lend their network to big customers for wheeling power from chosen suppliers. This change in operation presents new challenges.

Reactive series compensators are means to control the power flow in highly interconnected electrical power transmission networks with distributed generation and loads. Shortening or lengthening the transmission lines electrically they allow to choose the optimal routes for power transfer.

4. Circuits and configurations

In commercial FACTS applications, up to now, only line commutated high voltage converters with series connected turn-on thyristors could be used. GTOs with their high individual differences in turn-off time did not allow series connection on a commercial basis.

Recent developments, however, with hard driven, low inductance ring-gate GTOs shortened and equalized the individual turn-off times to such an extend that series connection becomes a problem that can be solved easily. In addition solutions to supply the gate unit directly out of the power circuit - instead of energy transfer from ground potential - are on the way to be developed [2]. This opens the way for real high voltage high capacity voltage source inverters in fault tolerant N+1 configuration, which are suited for FACTS applications.

4.1 Basic circuits

Future reactive series compensators basically consist of transformerless connected voltage source inverter bridges in each of the three phases in the transmission line. These bridges consist of two 2- or 3-level halve bridges. They need no dc power supply because they generate only reactive power.

The focus in this paper is on 3-level halve bridges. In fig.5 top each 3-level halve bridge is represented by a change over switch, the output of which can be connected to the positive, negative or zero potential of the dc voltage. Fig.5 left also shows the circuit of a 3-level halve bridge with four reverse conducting GTOs and two clamping diodes.

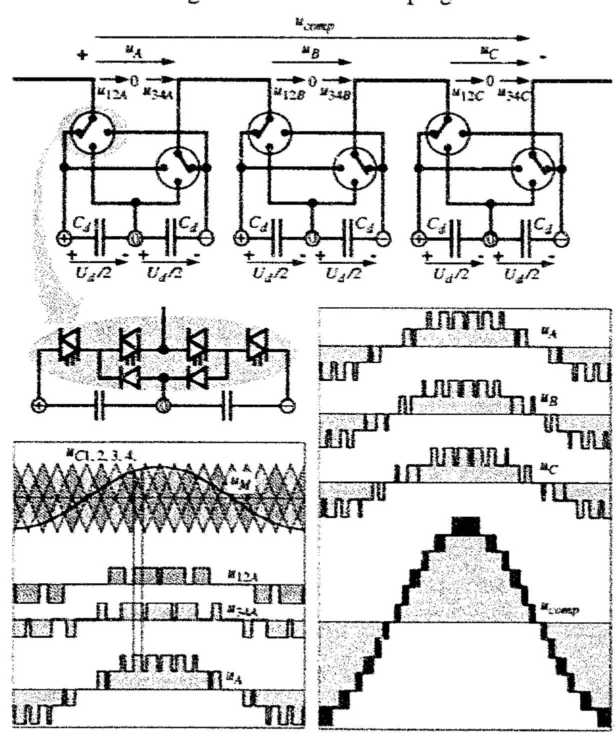

Fig.5. Basic circuits. Pulse pattern generation.

Each 3-level halve bridge can be controlled with *two* independent 2-level pulse patterns. The full bridge, therefore, can generate an output voltage, which is composed of *four* pulse patterns. As illustrated in fig.5 left each of the four pulse patterns is generated by the intersections of the same sinusoidal modulation signal u_M with one of the four triangular carrier signals $u_{C1,2,3,4}$ which are 90° phase shifted against each other.

The sinusoidal modulation signal u_M determines amplitude U_{inv} and frequency f of the fundamental component of the inverter output voltage u_{inv}. The frequency F of the carrier signals $u_{C1,2,3,4}$ determines the switching frequency F per GTO. The 90° phase shift between the carrier signals leads to a staggered switching sequence of the individual GTOs and to a four times higher pulse frequency $4F$ in the resultant output voltage of the inverter bridge - thus reducing the harmonics drastically.

4.2 Series connection

Single inverter bridges consisting of 3-level halve bridges without direct series connection of GTOs can be built with today's GTOs for about the following ratings:

rated dc voltage:	U_d	≈5kV
max. output voltage ampl.:	$U_{comp} \approx U_d$	≈5kV
rated power per phase:	$S \approx 1/2 \cdot U_d \cdot 2\text{kA}$	≈5MVA

In most cases this are too low ratings for FACTS applications. Therefore series connection is a must. Two kinds of series connection have to be taken into account: series connection of semiconductors and of inverter circuits.

a) *Series connection of N semiconductors* has two main advantages: It allows to build high voltage inverter bridges with higher capacity per single unit and with fault tolerant design using one semiconductor more (N+1) than needed. The above mentioned ratings per single unit increase with the number N of series connected GTOs. With N=4, for example, the ratings are:

rated dc voltage:	U_d	≈20kV
max. output voltage ampl.:	$U_{comp} \approx U_d$	≈20kV
rated power per phase:	$S \approx 1/2 \cdot U_d \cdot 2\text{kA}$	≈20MVA

b) *Series connection of inverter bridges* - shown in fig.5 top - has the main advantage, that the resultant pulse frequency increases with the number of series connected bridges. With three series connected bridges the resultant pulse frequency is 4·3=12 times higher than the switching frequency per GTO. This reduces the harmonics drastically while keeping the GTO switching frequency low and the inverter efficiency high. See fig.5 right. With three bridges in series, for example, the ratings are:

rated dc voltage times 3:	$3 \cdot U_d$	≈15kV
max. resultant voltage ampl.:	$U_{comp} \approx U_d$	≈15kV
res. rated power per phase:	$S \approx 3/2 \cdot U_d \cdot 2\text{kA}$	≈15MVA

c) The *combination of series connected semiconductors and series connected inverter bridges* combines the advantages of both methods. With N+1=4+1 GTOs in direct series connection and with three inverter bridges in series, for example, the resultant ratings are:

rated dc voltage times 3:	$3 \cdot U_d$	≈60kV
max. resultant voltage ampl.:	$U_{comp} \approx U_d$	≈60kV
res. rated power per phase:	$S \approx 3/2 \cdot U_d \cdot 2\text{kA}$	≈60MVA

That means: The resultant voltage amplitude U_{comp}=60kV of the series compensator is U_{comp}/U_N=18.3% of the phase voltage $U_N=400\text{kV} \cdot \sqrt{2}/\sqrt{3}=327\text{kV}$ in a 400kV transmission line. As shown in chapter 3 fig.3, this is the order of magnitude to control the power flow in a 500km 400kV line.

4.3 Hybrid configurations

The power flow control range of inverters is basically symmetrical: The power flow can be increased or decreased when the inverter absorbs capacitive (U_{comp} negative) respectively inductive (U_{comp} positive) reactive power. This was shown in chapter 3.3.3, figs. 3 and 4.

Reactive series compensators, however, can also be composed as a combination of inverters with series connected capacitors C_s or reactors as shown in fig.6b. The purpose of these hybrid configurations is to fulfil the control task with reduced inverter capacity. This is, however, only possible with an unsymmetrical control range: Inverters combined with *series connected capacitors* C_s extend the control range for power flow increase (U_{comp} neg.) and reduce the control range for power flow reduction (U_{comp} pos.). Inverters combined with *series connected reactors* do exactly the contrary. In the following the focus is on inverters in combination with series connected capacitors.

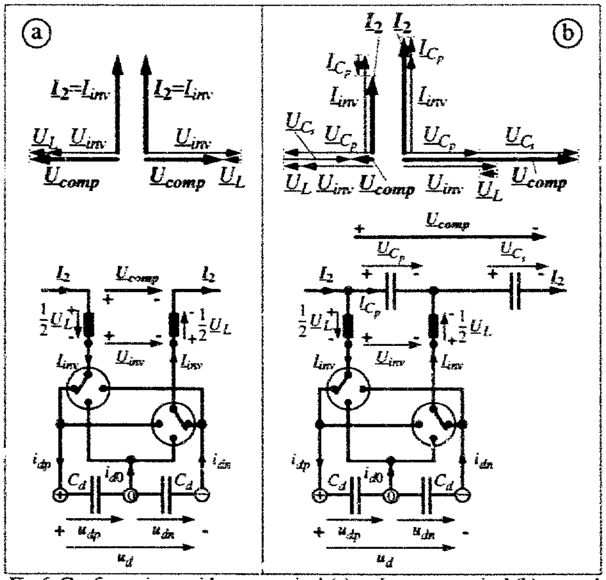

Fig.6. Configurations with symmetrical (a) and unsymmetrical (b) control range. AC quantities are represented as phasors, DC quantities as instantaneous values.

In addition it is useful to install parallel connected capacitors C_p which serve as filters. Dimensioned only for a small fundamental component of the current they, however, are able to absorb the current harmonics of the inverter. Fig.6b shows the hybrid circuit for one phase and the corresponding phasor diagram. Fig.6a shows the inverter alone for comparison. The mode of operation will be illustrated and explained in more details in the following chapter 5.

5. Mode of operation

5.1 Phasor diagrams and control range

The hybrid configuration in fig.6b with a capacitor C_s in series to the inverter and a filter capacitor C_p in parallel can be described by the following phasor equations and illustrated by the phasor diagram in fig.6b top.

$$\underline{U}_{comp} = \underline{U}_{C_p} + \underline{U}_{C_s}; \qquad \underline{I}_2 = \underline{I}_{C_p} + \underline{I}_{inv} \qquad (14)$$

$$j\omega L \underline{I}_{inv} = \underline{U}_{C_p} - \underline{U}_{inv}; \qquad j\omega C_p \underline{U}_{C_p} = \underline{I}_{C_p} \qquad (15)$$

$$j\omega C_s \underline{U}_{C_s} = \underline{I}_2 \qquad (16)$$

If the inverter works in the capacitive mode (fig.6b top right) the inverter voltage $\underline{U}_{inv}$ (minus $\underline{U}_L$, which is small) and the series capacitor voltage $\underline{U}_C$ sum up to an increased resultant voltage $\underline{U}_{comp}$ of the compensator. With the inverter working in the inductive mode (fig.6b top left) the inverter voltage $\underline{U}_{inv}$ is in opposite direction to the series capacitor voltage $\underline{U}_C$ and the resultant compensator voltage $\underline{U}_{comp}$ becomes small. In this way the control range of the compensator becomes unsymmetrical: an increased range for power flow increase and a reduced range for power flow reduction.

This is shown in fig.7 which contains the compensator voltage amplitude U_{comp} as a function of the inverter voltage amplitude U_{inv} with the line current amplitude I_2 as parameter. (U_{comp} pos./neg. in the ind./cap. mode for power flow reduction/increase). Fig.7 shows: The higher the line current I_2 the more unsymmetrical is the power flow control range.

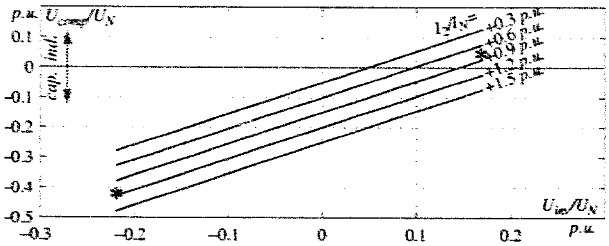

Fig.7. Unsymmetrical control range

The characteristics in fig.7 are valid for 500km 400kV transmission lines for the following figures, which could be representative in future applications.

Transmission line:

Z_0 =288Ω; βl =30°; l =500km (17)

$\omega L_{\sigma A,B}/Z_0$ =15% (18)

U_N =400kV$\cdot\sqrt{2}/\sqrt{3}$ =326.60 kV (19)

I_N =U_N/Z_0 = 1.13 kA (20)

S_N = 1/2 $U_N I_N$ =185.19 MVA (21)

Z_0: Wave impedance; β: phase constant; l: length

$\omega L_{\sigma A,B}$: Transformer leakage reactance

U_N, I_N : Rated phase voltage and current amplitude

S_N : Rated apparent power per phase

Inverter (series connection of three inverters):

U_d =$U_{inv}(m_0{=}1)$ =20%U_N=3·21.8kV= 65.4 kV (22)

Q_{inv} = 1/2$U_{inv}I_N$ =20%S_N = 37 MVA (23)

X_{inv} =$U_{inv}(m_0{=}1)/I_N$ = 57.6 Ω (24)

F =225 Hz (25)

U_d : Rated dc voltage

U_{inv} : Rated ac voltage amplitude (m_0=1)

m_0 : Modulation degree (m_0=0...1)

Q_{inv} : Rated reactive power per phase

X_{inv} : Rated equivalent reactance

F : Switching frequency per GTO

Capacitances and inductance:

X_{C_d} =$(\omega C_d/2)^{-1}$ = 50% X_{inv} = 28.8Ω (26)

X_L =ωL = 20% X_{inv} = 11.5Ω (27)

X_{C_p} =$(\omega C_p)^{-1}$ =500% X_{inv} =288 Ω (28)

X_{C_s} =$(\omega C_s)^{-1}$ =100% X_{inv} = 57.6Ω (29)

X_{C_d} : Reactance of the inverters dc capacitance $C_d/2$

X_L : Reactance of the decoupling inductance L

X_{C_p} : Reactance of the parallel filter capacitance C_p

X_{C_s} : Reactance of the series capacitance C_s

It is interesting to note that the rated reactive power $3Q_{inv}$=111.1MVA of the inverter is only Q_{inv}/S_N=20% of the rated transmission power $3S_N$=555.5MVA of the line.

5.2 Line diagrams

The line diagrams in fig.8 illustrate two operation modes - marked with "*" in fig.7 - in more details for the figures given in chapter 5.5.1.

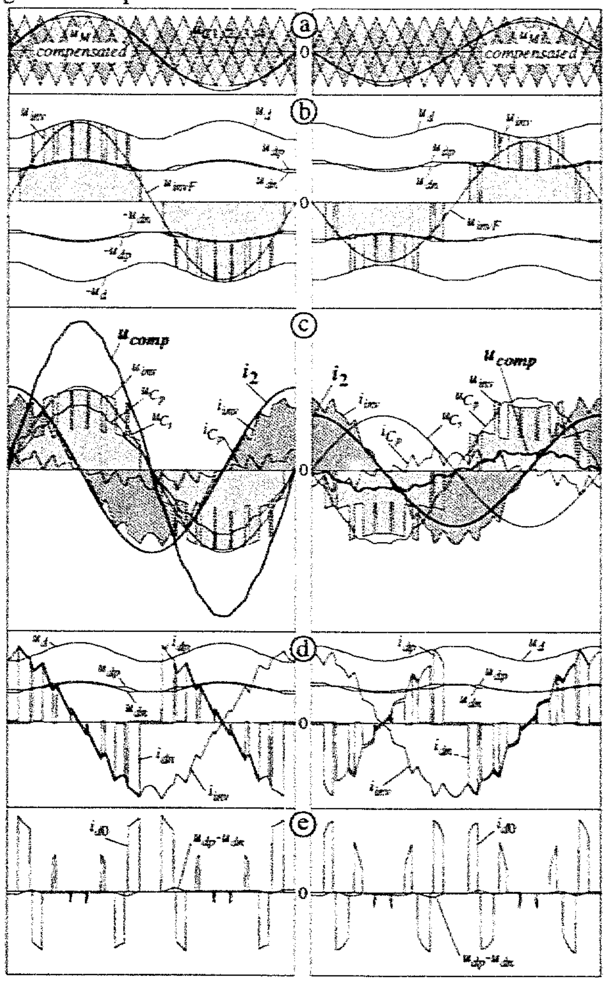

Fig.8. Maximum capacitive (left) and maximum inductive (right) mode of operation.

a) capacitive compensator voltage

The mode with maximum capacitive compensator voltage u_{comp} for power flow increase is shown in fig.8 left for a line current i_2, which is assumed to be 118% of the rated current I_N. The modulation signal u_M and four carrier signals $u_{C1,2,3,4}$ in fig.8a generate the resultant inverter output voltage u_{inv} in fig.8b with a staggered switching sequence of the individual GTOs.

This picture also contains the dc voltages u_d, u_{dp} and u_{dn} of the inverter. They oscillate around the rated values U_d resp. $U_d/2$ for reasons, which are explained below. The modulation signal u_M in fig.8a, therefore, has to be compensated in such a way, that the short term mean value u_{invF} of the inverter output voltage remains purely sinusoidal - despite of the deviations in the dc voltages.

The inverter current i_{inv} in fig.8c generated in the decoupling inductance L by the difference of the inverter voltage u_{inv} and the smoothing capacitor voltage u_{C_p}

$$i_{inv} = \frac{1}{L} \cdot \int (u_{C_p} - u_{inv})dt \tag{30}$$

contains harmonics, the pulse frequency of which is four times higher than the GTO switching frequency: $4F$=4·225Hz=900Hz. The lower the switching frequency F per GTO, the better is the efficiency of the inverter - but the higher are the harmonics. F=225Hz is a suitable switching frequency for todays GTOs.

Fig.8c shows that the harmonics i_{invH} in the inverter current i_{inv} are absorbed by the smoothing capacitor C_p.

$$i_{invH} = -i_{C_pH} \qquad \textit{(index H: Harmonics)} \tag{31}$$

The capacitor C_p - dimensioned according to (28) - is large enough to keep its voltage u_{C_p} in a good sinusoidal shape and small enough to draw only a small fundamental current component. The resonance frequency f_{res} of the filter is above the fundamental frequency f and below the resultant pulse frequency $4F$.

$$f_{res} = \frac{1}{2\pi\sqrt{LC_p}} = 250\text{Hz} \tag{32}$$

$$f\text{=50Hz} < f_{res}\text{=250Hz} < 4F\text{=900Hz} \tag{33}$$

The harmonics in the line current i_2 are nearly negligibly for reasons explained below. The series capacitor voltage u_{C_s}, therefore, is sinusoidal.

$$u_{C_s} = \frac{1}{C_s}\int i_2 dt \tag{34}$$

Fig.8c also contains the resultant compensator voltage u_{comp} which is the sum of the capacitor voltages u_{C_p} and u_{C_s}.

$$u_{comp} = u_{C_p} + u_{C_s} \tag{35}$$

The resultant compensator voltage u_{comp} is about two times higher than the inverter voltage u_{inv} - according to the objective of this hybrid configuration.

Fig.8d shows the reasons for the dc voltage deviations of the inverter: In reactive single phase inverters the short term mean values of the dc currents i_{dp} and i_{dn} follow a $2f$=100Hz sinus-line and cause a 100Hz ripple in the dc voltages u_{dp}, u_{dn} and u_d.

$$u_{dp} = \frac{1}{C_d}\int i_{dp}dt\,; \qquad u_{dn} = \frac{1}{C_d}\int i_{dn}dt\,; \qquad u_d = u_{dp} + u_{dn} \tag{36}$$

The higher the dc capacitance C_d - dimensioned according to (26) - the lower is the 100Hz ripple in the dc voltage - but the higher are cost and volume of the inverter. The 100Hz ripple in the dc voltage could also be eliminated with a 100Hz LC filter at the inverters dc side. This is state of the art in inverter locomotives with single phase ac supply. Inductances, however, are rather bulky components which should be avoided, if possible, in voltage source inverters.

Fig.8e finally shows the zero point current $i_{d0}=i_{dp}-i_{dn}$. Its mean value must be kept at zero in order to avoid an unbalance of the dc voltages u_{dp} and u_{dn} [3]. See $u_{dp}-u_{dn}$ and i_{d0} in fig.8e.

The harmonic content of the resultant compensator voltage u_{comp}, which is already low, can be further reduced to a negligible level with, for example, three series connected compensators each with a dc voltage of U_d=21.8kV (and N=4 series connected GTOs). In this case the groups of four carrier signals allocated to the modulator of each of these three compensators have to be phase shifted against each other in such a way, that all harmonics up to the resultant pulse frequency $4F$·3, which is 12 times higher than the individual GTO switching frequency F, are eliminated: The harmonics generated in the line current i_2 by the compensator become negligibly low.

$$4F \cdot 3 = 12F = 12 \cdot 225\text{Hz} = 2.7\text{kHz} \tag{37}$$

b) Inductive compensator voltage

Figs.8a..e right show - in exactly the same sequence of line diagrams as in fig.8 left - the operation mode with maximum inductive inverter voltage for a line current i_2 which is assumed to be 79% of the rated current.

Since inverter voltage u_{inv} and series capacitor voltage u_{C_s} now are in opposite direction the resultant inductive compensator voltage u_{comp} is very small. See also "*" in fig.7.

Comparing the inverter output voltages u_{inv} in fig.8b left and fig.8b right it is interesting to note that the inverter voltage in fig.8b left is at its maximum, when the dc voltage u_d is also at its maximum. In fig.8b right, however, the inverter voltage maximum is at the dc voltage minimum. That means: the maximum amplitude of the fundamental component u_{invF} in the inverter output voltage has to be kept lower in case of inductive inverter voltage and can be increased in case of capacitive inverter voltage.

6. Alternative configuration

The series compensator needs a considerably lower insulation level, when it is possible to shift it to the grounded neutral point of an existing line transformer. In addition, in a three phase ac system, this allows to build the converter of the compensator as a three phase inverter with a common dc bus - such avoiding a $2f$=100Hz power pulsation which would generate a 100Hz dc voltage fluctuation. Fig. 9 left shows this configuration for a three phase ac system. Fig. 9 right represents the corresponding single phase configuration as it is used for ac supply of railway systems.

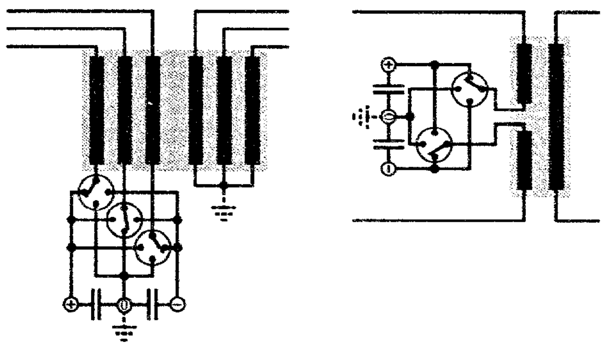

Fig.9. Three phase and single phase connection of the series compensator in the grounded neutral point of an existing line transformer.

7. Conclusion

Based on improved GTOs with hard driven, low inductance ring-gate and with gate unit power supply out of the main power circuit, high-voltage inverters with series connected GTOs can be built, the ratings of which are sufficiently high for high power FACTS applications. This paper proposes and describes a transformerless connected reactive series compensator consisting of voltage source inverters and parallel and series connected capacitors for power flow control in interconnected electrical power transmission system networks.

Transformerless connection means the elimination of a bulky and expensive system component.

The compensator needs a considerably lower insulation level, when it is shifted to the side of the grounded neutral point of an existing line transformer.

Power flow control can - of course - also be used to damp low frequency power system oscillations.

It has been shown that power flow can be controlled with inverters, the rated power of which is very small compared to the controlled power flow. By means of staggered switching sequences and filter capacitors the harmonics which the compensator introduces into the ac system can be kept at a negligibly low level - despite of a low GTO switching frequency, which is necessary to keep the inverter efficiency at a high level. Circuits, configurations and mode of operation have been illustrated.

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Herbert Stemmler (non-member) was born in Speyer (Germany) in 1935. Electrotechnical studies in the field of automation at the Technical University in Darmstadt (Germany). From 1961 up to 1991 he continuously worked with Brown, Boveri & Co., respectively ASEA Brown Bovery, in Baden (Switzerland), at first as development engineer, after 1971 as head of the Department for development, engineering, test, commissioning and trouble-shooting of power electronic systems. In 1987 he was appointed vice-president of this Departement. Working-fields: converter and inverter locomotives, all kinds of a.c.-drives, reactive power compensators, HVDC-transmissions, low power electronics, standardized and tailor-made electronic control units. Parallel to that, he graduated in 1971 with a doctoral thesis at the Technical University of Aachen (Germany). Since 1991 he is Professor for power electronics at the Swiss Federal Institute of Technology (ETH) in Zurich (Switzerland) and head of the Power Electronics and Electrometrology Laboratory.

Andreas Beer (non-member) was born in Tavanasa (Switzerland) in 1970. He studied at the Swiss Federal Institute of Technology (ETH) in Zurich (Switzerland), and received the diploma in electrical engineering in 1996. Since then he works as a research assistant at the Power Electronics and Electrometrology Laboratory at the ETH.

Presently he is working towards his doctoral degree with a thesis on Transformerless Reactive Series Compensators with Voltage Source Inverters.

Hideo Okayama (member) was born in Hyogo (Japan) in 1965. He graduated from Kansai University in 1989. Since 1989, he has been a researcher with Industrial Electronics & Systems Lab., Mitsubishi Electric Co. He belongs to the Power Electronics Dept., where he has engaged in the developments of such large capacity power converter systems as HVDC systems using 6-inch LTTs and drive systems using 6-inch GTOs. He has been collaborating on FACTS at the ETH in Zurich (Switzerland) since October in 1996.