Regulating transformers in power systems – new concepts and applications

Originally, regulating transformers were installed in power systems to compensate for voltage fluctuations. However, studies have shown that they also have several other important advantages for transmission systems. By carefully choosing the transformation ratios, it is possible to control the active and reactive power flow in the power system to allow for a more economic utilization of the transmission capacity. In addition, the power losses associated with energy distribution can be considerably reduced and circulating currents largely avoided. When these transformers are installed at strategic locations in the network, return on investment is achieved within a short time. New applications for phase-shifting transformers have evolved in connection with Interphase Power Control technology.

Economic as well as environmental pressures are behind the present efforts being made by electric supply companies to utilize their transmission lines more efficiently. This goal can be achieved in a very reliable way with the help of regulating transformers. The conventional way to construct these transformers is to connect separate booster transformers in series with the main transformer. ABB Sécheron has developed a concept in which the regulating windings are integrated in the main transformer, making additional booster transformers unnecessary. Transformer regulation is achieved with the help of separately adjustable tap-changers and corresponding winding connections.

Power transmission losses should be as low as possible. The natural load flow determined by the network impedances and load conditions can be altered and the power distribution set by means of phase-shifting transformers such that the circulating currents, and consequently the transmission losses, are substantially reduced.

Transmission systems can be operated more efficiently and economically by regulating and redistributing the power flows. Through the action of controllers, the power flows can be redistributed according to the available transmission capacity. For example, the transmitted power can be redistributed to higher voltage level corridors, which often are under-utilized. This reduces the loading of transmission systems at the lower voltage levels, which normally carry the bulk of the power; system losses are correspondingly reduced. Systematic power-flow control by means of regulating transformers also enables power system operators to exchange electrical energy for the most part along specified contract paths, without making any extra demands on third-party networks. The importance of this has to be seen against the background of planned extensions to the international grid systems and the deregulation of the power markets.

Power supervision also helps to prevent overloading of individual lines, which sooner or later would have to be disconnected from the system. In addition to these functions, regulating transformers can be used to set the interchange power specified in contractual agreements.

Ernst Wirth
ABB High Voltage Technology Ltd

Jean-François Ravot
ABB Sécheron SA

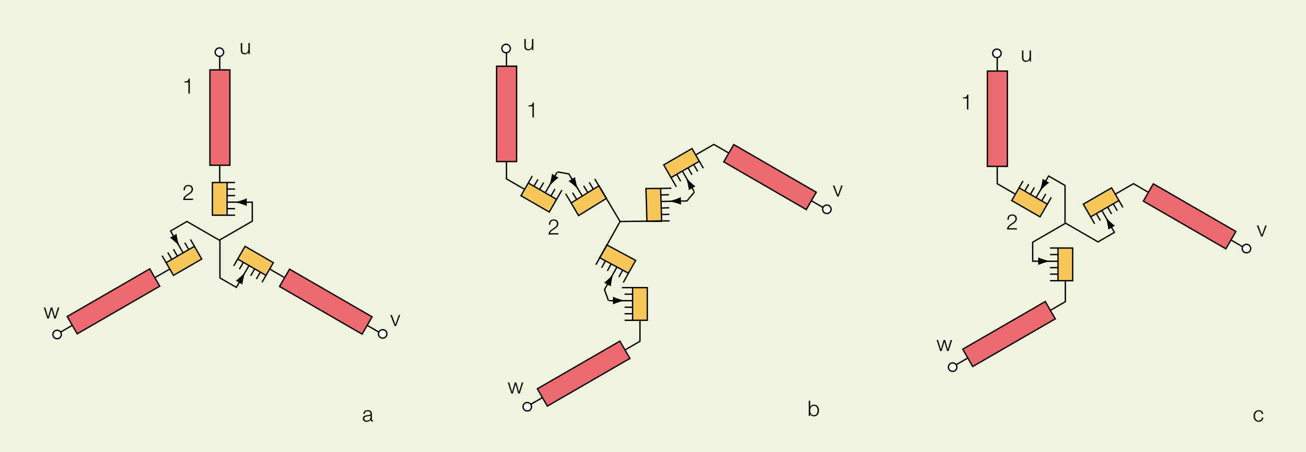
In-phase, quadrature and phase-shift control

The purpose of transformer regulation is to match the transformation ratio to the actual conditions in the power system [1, 2]. The principle of neutral point regulation that is usually adopted is shown in **1**.

In-phase control **1a** – the most common type of regulation in use – is characterized by the control voltage being in phase with the main-winding voltage. The transformation ratio is adjusted according to the load fluctuations that occur in operation, the goal being to provide the best possible voltage support. Influence is exerted mainly on the reactive power flowing via the transformer.

Quadrature control **1b**, with an additional voltage at an angle of 90° to the main-winding voltage, is used to regulate the active power flowing via the transformer. No support is given to the power system voltage.

Conventional phase-shift transformers working with a constant phase angle require just one tap-changer in order to be able to inject the additional voltage **1c**.



Typical regulation transformer configurations with the regulating windings at the neutral point of the main winding **1**

a *In-phase control: control voltage in phase with main winding voltage*
b *Quadrature control: control voltage perpendicular to main winding voltage*
c *Phase-shift control: control voltage out of phase with main winding voltage*

1 *Main winding* 2 *Regulating winding*

Unlike in-phase and quadrature control, phase-shift control regulates both the reactive and active power flow. Due to the impedance angles in high-voltage systems always being smaller than 90°, network interconnection transformers designed with 60° phase shift have also proved to be very useful for active power regulation.

If separate regulating windings are provided for the phase-shift control and separately adjustable tap-changers for the in-phase and quadrature directions, the magnitude and phase angle of the additional voltage can be set as required in all four quadrants.

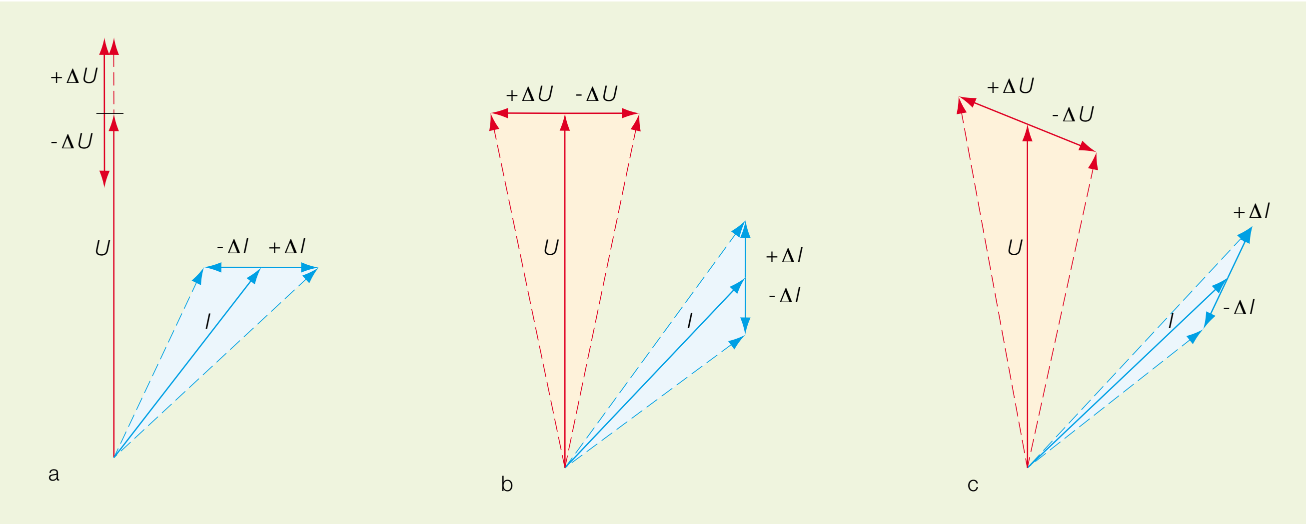
The method of operation and the control of the transformer for in-phase, quadrature and phase-shift regulation can be seen in the simplified vector diagram in **2**. **2a** shows the effects on the voltage and current of a transformer for in-phase control, **2b** for quadrature control and **2c** for phase-shift control.

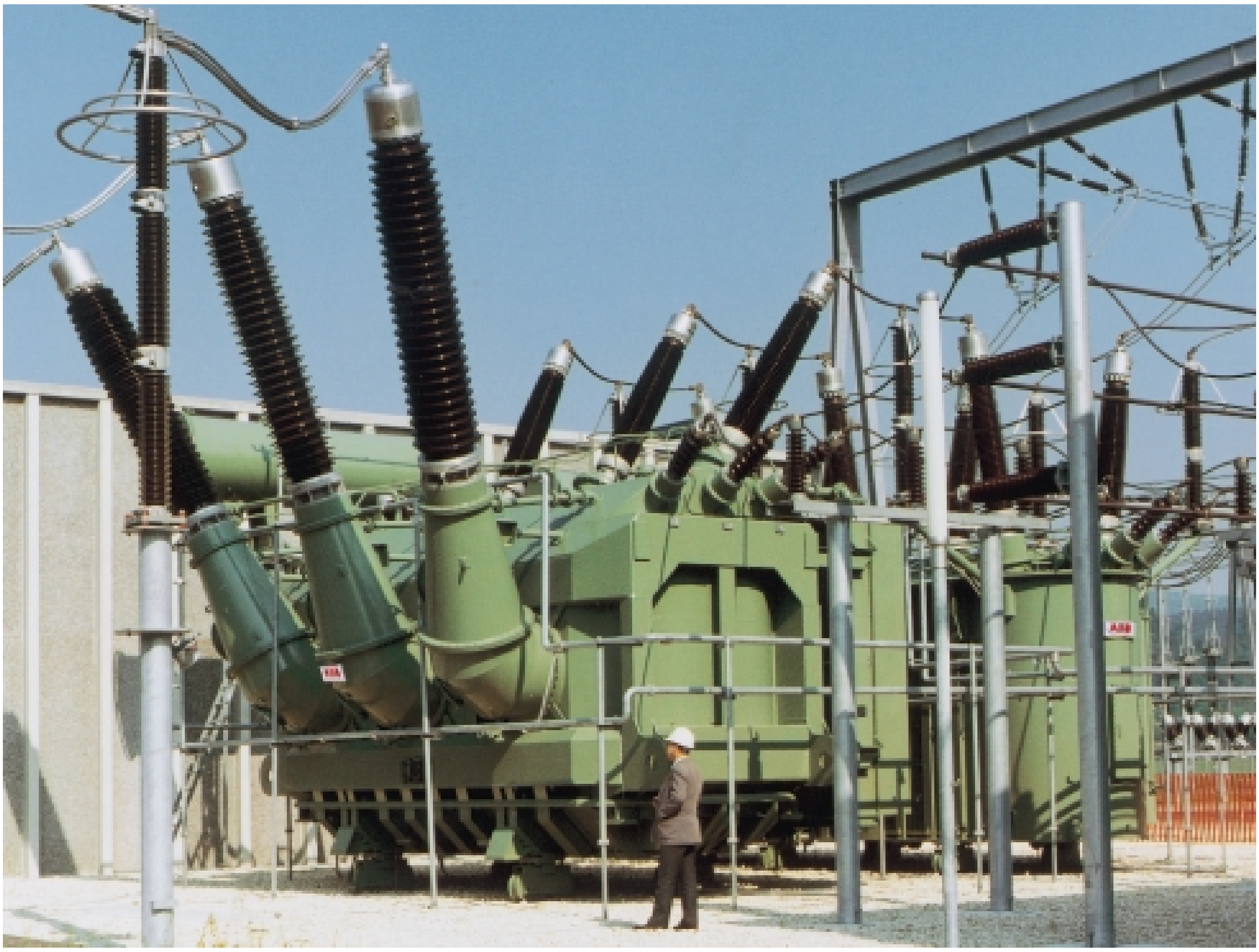
Many other connections apart from the star (neutral) point connection are possible. The optimum connection is project-specific, and is determined by:

- The necessary or maximum permitted short-circuit impedance of the transformer

Simplified vector diagrams showing the function of in-phase, quadrature and phase-shift control of transformers **2**

a *In-phase control* b *Quadrature control* c *Phase-shift control* *U* *Voltage* *I* *Current*

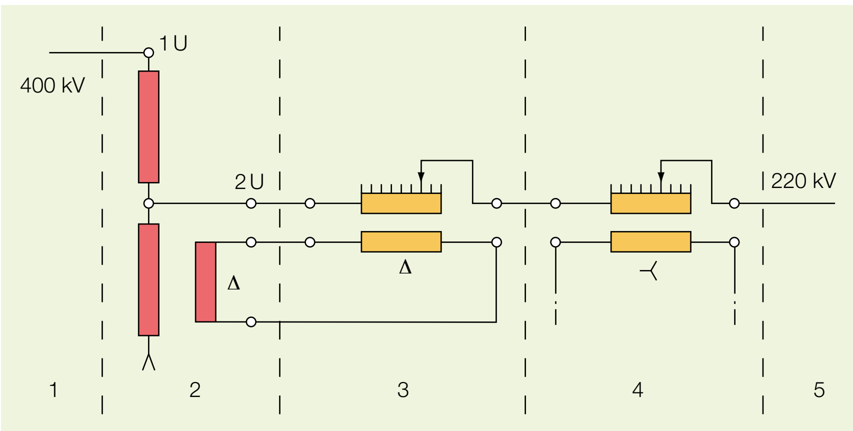




400-MVA autotransformer bank for 400/237 ± 17 × 2.06/49 kV, for separate in-phase and quadrature control **3**

Circuit diagram of the 400-MVA transformer bank in Fig. 3. Separate transformers were chosen for in-phase and quadrature control to be able to independently adjust the active and reactive powers. **4**

1 *400-kV network*
2 *Main transformer*
3 *Transformer for in-phase control, fed by tertiary winding U*
4 *Transformer for quadrature control, fed by tertiary winding V*
5 *220-kV network*



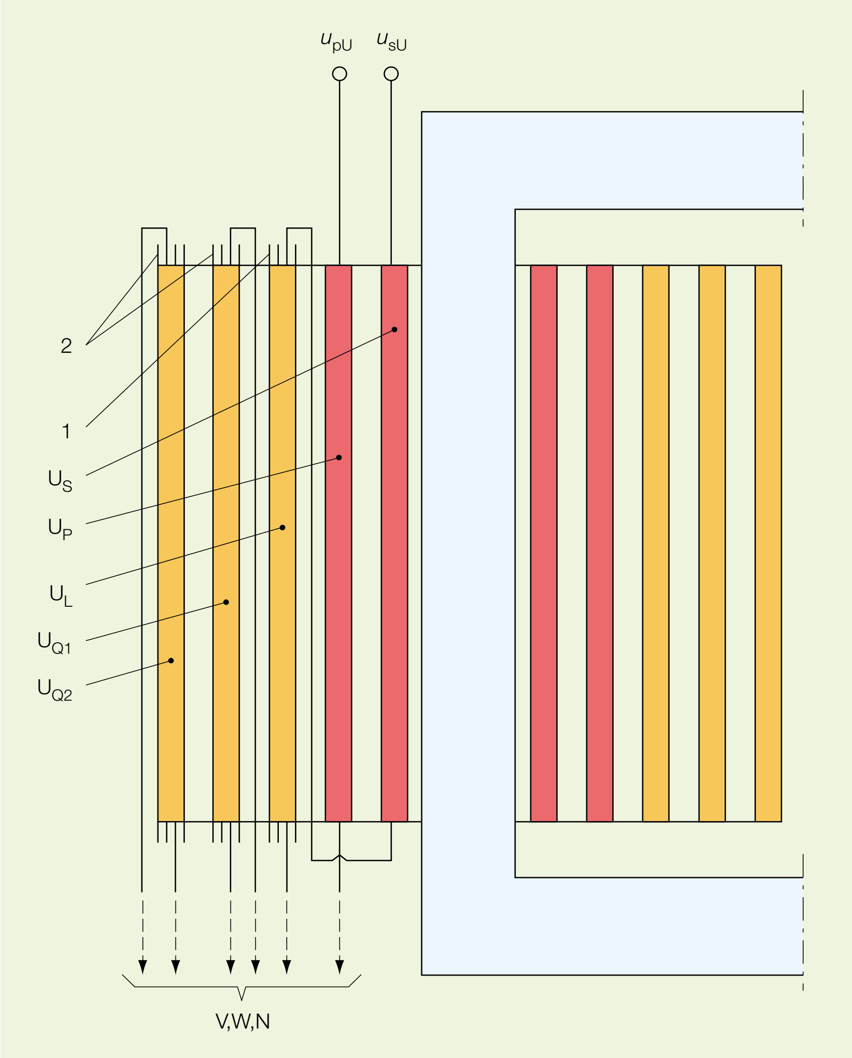
- Magnitude and setting range of the additional voltage
- Rating of the transformer
- System voltages

ABB's experience with regulating transformers goes back many years, and the company is well-positioned to offer optimized solutions for the given power system conditions that also take full account of customers' requirements. The vastly improved technologies in use today have brought about major benefits that include sharp reductions in operating losses as well as in the cost of manufacturing.

As an example, a 400-MVA three-phase transformer bank for 380/220 kV with two booster transformers and tap-changers for in-phase and quadrature control is shown in **3**.

Design of the new compact regulating transformer, which combines the main transformer and the regulating windings in a common tank. Independently adjustable tap-changers for the in-phase and quadrature control allow regulation of the voltage and the transmitted active power. **5**

1, 2 *Tap-changer terminals*
U_P *Primary winding*
U_S *Secondary winding*
U_L *In-phase control winding*
U_{Q1} *Quadrature control winding 1*
U_{Q2} *Quadrature control winding 2*
u_{pU} *Primary voltage*
u_{sU} *Secondary voltage*



Conventional and new concepts for regulating transformers

To achieve independent control of the active and reactive power, ie for phase-shift control with a variable angle, conventional technology requires regulating transformers to consist of a main transformer and two series-connected transformers with tap-changers. The circuit diagram of the above-mentioned 400-MVA regulating transformer in the described configuration is shown in **4**.

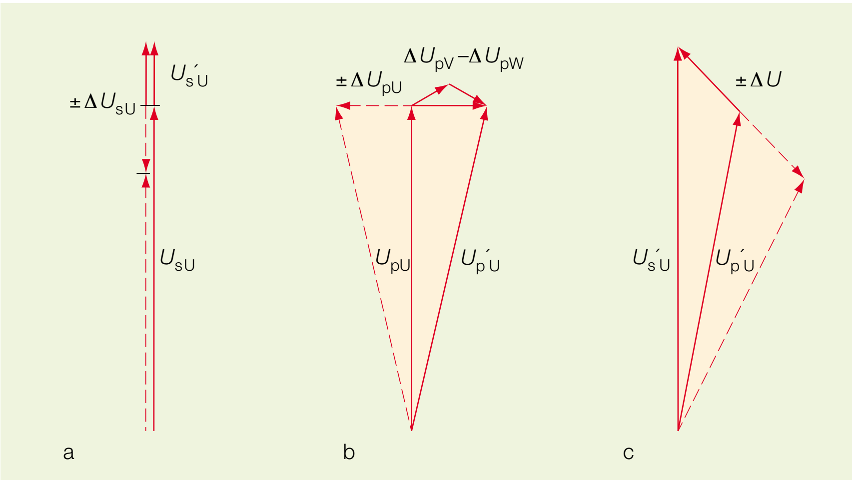
Although booster transformers for in-phase and quadrature control are highly flexible, they have the disadvantages of being costly and of requiring a relatively large space for their installation. Another factor which has to be considered is the cost of the iron and copper losses.

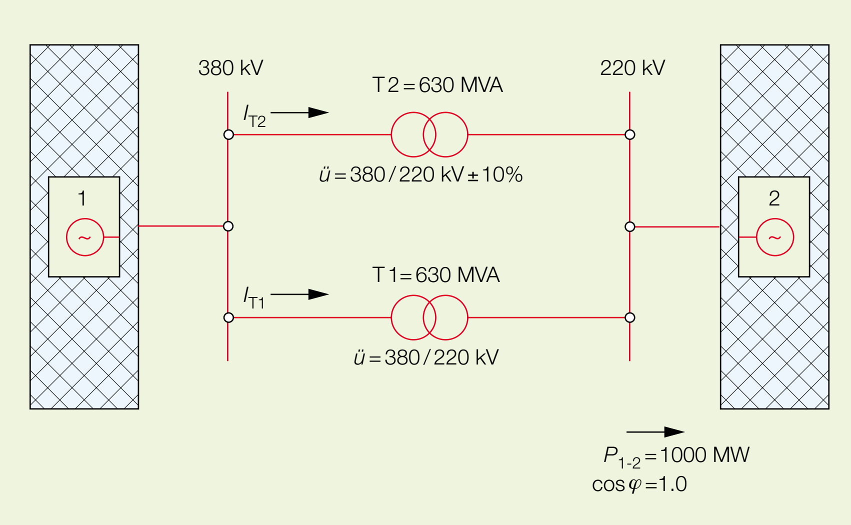
A new concept developed by ABB Sécheron allows the booster transformers connected in series with the main transformer to be replaced by just a few extra windings in the main transformer. This considerably reduces not only the first-time costs but also the operating costs. The main saving is in the transformer cores and the copper windings. Another key benefit is the significantly smaller space that is required [3]. **5** shows the design of the transformer with two tap-changers for the in-phase and quadrature control.

The in-phase control windings U_L, V_L and W_L are connected to the secondary

Possible regulation of the additional voltage ΔU in all four quadrants by means of independently adjustable tap-changers **6**

a *In-phase control of secondary winding*
b *Quadrature control of primary winding*
c *Superposition of in-phase and quadrature control effect*





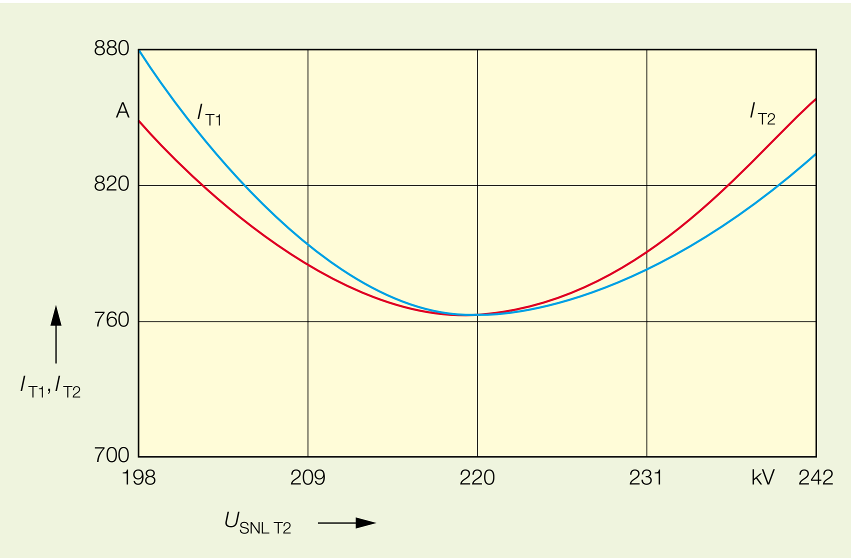
Addition of a 630-MVA in-phase regulating transformer T2 to an existing power system intertie. The transformation ratio of the existing transformer T1 is constant. **7**

1, 2	*Networks*
I	*Current*
ü	*Transformation ratio*

windings of the same phase, U_S, V_S and W_S, by means of tap-changer 1. This tap-changer is used to simultaneously vary the three secondary voltages u_{sU}, u_{sV} and u_{sW} by the in-phase voltages m^*u_{sU}, m^*u_{sV} and m^*u_{sW}.

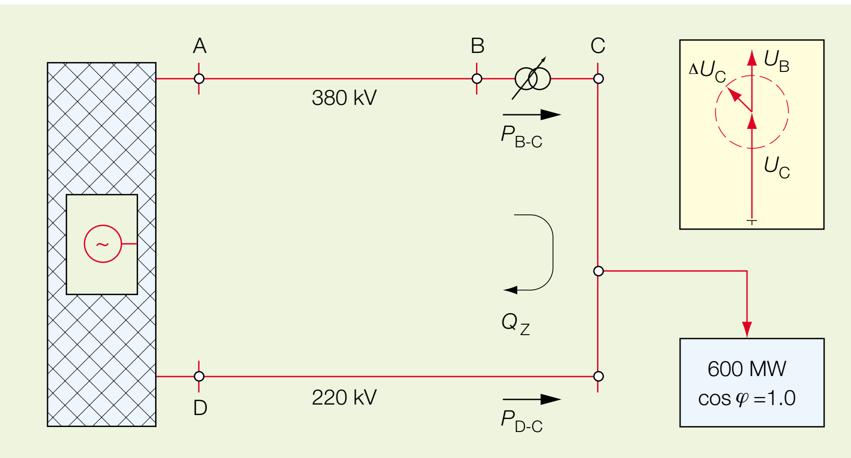
Quadrature control is achieved with the primary regulating windings U_{Q1}, U_{Q2}, V_{Q1}, V_{Q2}, W_{Q1} and W_{Q2}, which are connected by means of tap-changer 2 to the main windings U_p, V_p and W_p. The voltage magnitude $n^*(u_{pV} - u_{pW})$ generated by the quadrature control windings (phases V and W), which is added to the primary voltage u_{pU} (phase U), is always perpendicular to u_{pU} and therefore fulfils the condition for quadrature control. The same relationships apply to the other two phases V and W. Since both the in-phase and the quadrature control of the transformer can be adjusted, control is possible in all four quadrants **6**.

As an alternative, the in-phase control can be made to act on the primary and the quadrature control on the secondary of the transformer. In such a case, the primary windings U_p, V_p and W_p are connected by tap-changer 1 to the in-phase control windings U_L, V_L and W_L and the secondary windings U_S, V_S and W_S by tap-changer 2 to the corresponding quadrature control



Currents I_{T1} and I_{T2} in the 380-kV substation shown in Fig. 7 during variation of the transformation ratio of T2 from 380/198 kV to 380/242 kV, for a constant consumption of 1000 MW at the 220-kV end **8**

$U_{SNL\ T2}$ *No-load secondary voltage of T2*



Effect of installing a regulating transformer on the parallel operation of 100-km lines at different voltages. The vector diagram illustrates the resultant no-load voltage of the transformer on the regulated 220-kV side. **9**

A, B, C, D	*Network nodes*
P	*Transmitted power*
Q_Z	*Circulating reactive power*

windings in the adjacent phases. The result is, again, an additional quadrature control voltage leading or lagging the main winding by 90° – this time on the transformer secondary.

Other configurations are possible – as requested by the customer or due to design constraints – in which all of the regulating windings act either on the primary or the secondary.

Regulating transformers have multiple applications

As already mentioned, the original purpose of regulating transformers was to compensate for voltage fluctuations caused by a variable system load. If, in addition to the in-phase control that is necessary for this, quadrature control is also provided, both the reactive power necessary to support the voltage and the active power can be adjusted. A whole series of possible applications in the network results at both the high-voltage and the medium-voltage levels. The combination of such regulating transformers with other conventional equipment, such as capacitors and reactors, creates highly robust FACTS[1)] components. *Table 1* summarizes the key application areas and the advantages for power system operators.

Network interconnection transformers

It is often the case in coupled power systems that several transformers are operated in parallel. If the transformation ratios of the interconnection transformers are not identical, a voltage difference ΔU appears and causes a circulating current when they are under load.

In the example referred to **7**, the 630-MVA interconnection transformers T1 and T2 link two systems at nominal voltages of 380 kV and 220 kV, respectively. The transmitted power is 1000 MW. The transformation ratio of the first transformer is constant, being given by the nameplate voltages. The second unit T2 was constructed as an in-phase regulator during later expansion of the system to allow control of the voltage on the 220-kV side. T2 has otherwise the same basic specifications as T1.

Observation of the load flow shows the conditions arising during operation and also the drawbacks of such a solution. To illustrate this more clearly, the in-phase control on the 220-kV side was varied from a minimum of 198 kV to the maximum value of 242 kV.

The resulting current distribution in the 380-kV substation is shown by **8**. With the tap-changer set at mid-tap, the transformation ratio of the two transformers is the same, as are the currents. When the tap-changer of T2 is set to either of the end-tap positions, the currents in each of the transformer banks is considerably higher since a compensating current is now added. Unlike the current which flows when T1 and T2 have the same transformation ratio, the compensating current is mainly inductive and in the example under discussion has a magnitude of approximately 400 A on the 380-kV side. The higher currents in the transformers result in additional costs due to the higher losses.

To avoid circulating currents, which only cause additional losses and make extra demands on the transformers, parallel system interconnection transformers should therefore have the same transformation ratio and, of course, the same vector group.

Optimization of transmission losses on parallel-operated transmission corridors at different voltages

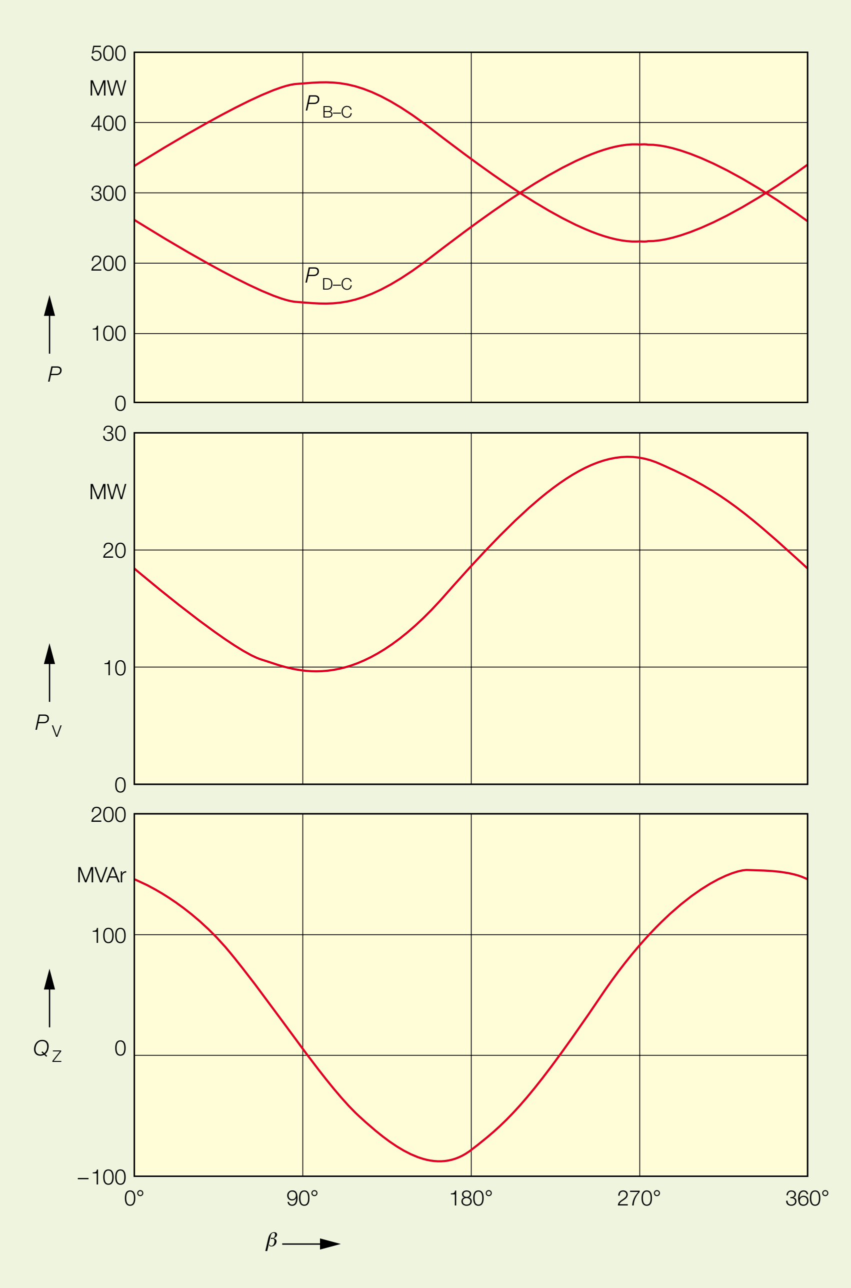
9 shows a section of a 380/220-kV power system. Two lines 100 km long feed power into a 220-kV substation. To interconnect the two voltage levels whilst minimizing the losses, a regulating transformer is installed with an additional voltage ΔU of 26.4 kV on the 220-kV side. The specified load consumption at the 220-kV substation is 600 MW. An investigation of a computer model of this system configuration was performed by varying the angle β of the control voltage in the range 0 to 360°.

The results presented in **10** show the

Table 1:
Regulating transformers – areas of application and benefits for power system utilities

- Avoidance/reduction of circulating currents
- Prevention of unwanted exchange of reactive power
- Regulation of interchange power
- Minimization of losses in parallel transmission corridors with different voltage levels and/or different lengths
- Energy transmission redistributed to higher voltage levels, which are often under-utilized
- Redistribution of power flows in heavily loaded networks
- Energy transfer over specified contract paths without/with minimal loading of third-party networks
- Higher reliability for power supply plus improved distribution of power flow
- Highly robust FACTS components achieved in combination with reactors and capacitors

[1)] FACTS = Flexible AC Transmission Systems



Transmitted powers (P), total losses (P_V) and circulating reactive power (Q_Z) for the network configuration in Fig. 9 as a result of variation of the phase angle (β) of the additional voltage ΔU from 0 to 360° **10**

powers transmitted, the total line and transformer losses, and the resulting circulating reactive power, which is most pronounced during in-phase control.

As expected, the power transmitted on the 220-kV line decreases first as the angle β is increased. This is due to the decreasing phase difference between the voltages at the line ends, which is caused by the leading additional voltage ΔU. At the same time, the power transmitted on the 380 kV line increases from 340 MW with in-phase control (β = 0°) to about 455 MW with quadrature control (β = 90°).

The result of this is that the losses in both lines and in the transformer decrease from approximately 18.7 MW with in-phase control to about 9.8 MW with quadrature control. Assuming a price per kilowatt-hour of Sfr 0.05 (approx US$ 0.034), the annual saving for the section of network considered and the given transmitted power of 600 MW is approximately Sfr 3.9 million (approx US$ 2.67 million).

As **10** shows, the effect is opposite when the additional voltage is lagging. The power transmission now shifts to the 220-kV line, since the phase angle between the voltages at the beginning and end of the 220-kV line is increased. The losses now increase to about 4.6 percent, corresponding to 27.7 MW; under these conditions, the costs due to losses would be about SFr 12.1 million (approx US$ 8.3 million) per year.

The above considerations underscore the advantages of power flow control. It should be noted that the choice of transformation ratios (for minimum losses) depends strongly upon the topology of the network and the actual load conditions. Only with a variable control voltage which can be freely adjusted between 0 and 360° can the different boundary conditions be effectively controlled.

Flexible AC transmission systems with phase-shifting transformers: Interphase Power Controller

With Interphase Power Control technology, either electronic or conventional switchable, phase-shifting transformers can be used for the power-flow control and for coupling transmission systems operating at the same or different voltages [4, 5].

11 shows the schematic of the Interphase Power Controller (IPC), which consists of a capacitor and a reactor in parallel. Connected in each branch in series are the phase-shifting components, for example regulating transformers. The two branches of the IPC can be tuned to exhibit the same impedance value for the fundamental frequency.

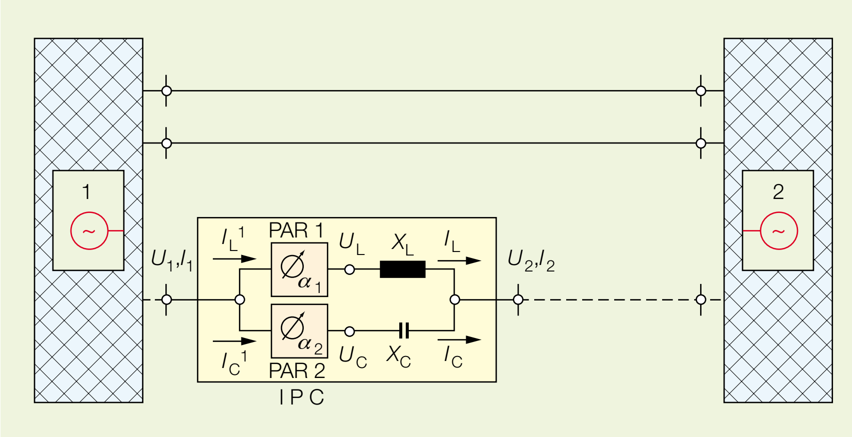
The setting of the phase angles α_1 and α_2 of the two transformers PAR1 and PAR2 determines both the active power transmitted by the IPC and the reactive-power characteristics. The reactive power input or output of the IPC is given – when the transformer losses are neglected – by the vector sum of the reactive powers of the reactor and capacitor. If the IPC is tuned and the difference $\alpha_1 - \alpha_2$ is zero, no power will flow.

The mode of operation of the IPC can be seen from the vector diagram in **12**. The voltage U_L between PAR1 and the reactor is shifted counter-clockwise by the angle α_1; the voltage U_C between PAR2 and the capacitor is shifted clockwise by the angle α_2. For currents I_L and I_C, the displacement angles α_1 and α_2 are the same, assuming similar conditions.

Different configurations are possible, eg with only one phase-shifting device in the inductive or the capacitive branch of the IPC, depending on the type of system and the existing power system conditions. However, some control properties are lost in such cases.

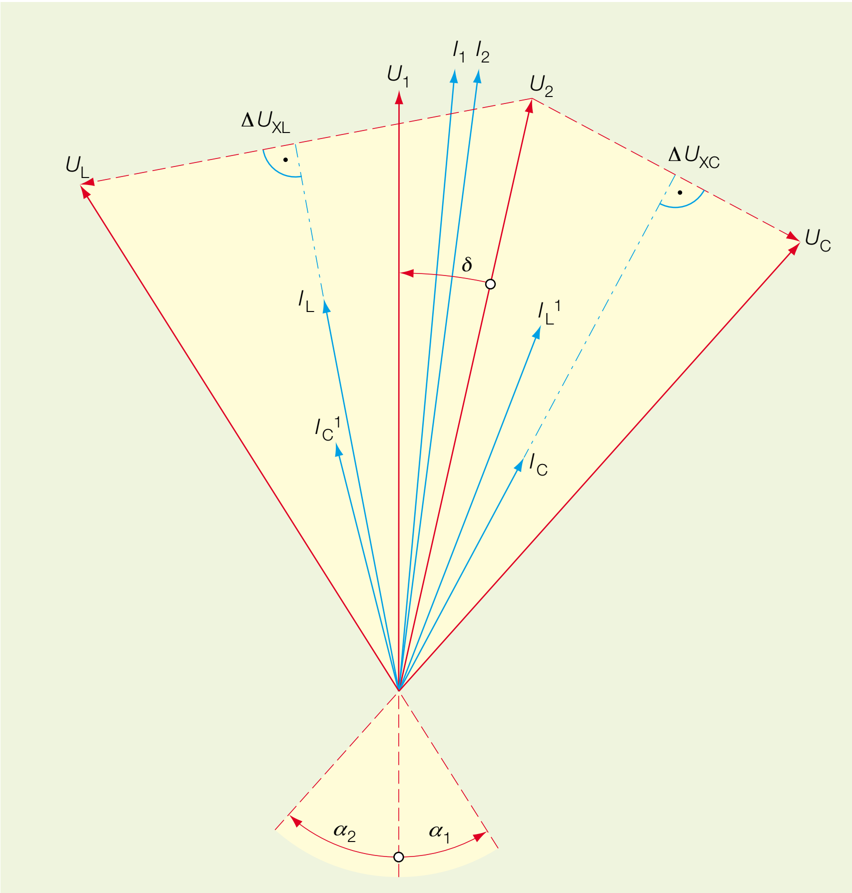
IPCs are highly robust Flexible AC Transmission Systems (FACTS), which contain passive elements. Together, these power system components offer a whole series of operational advantages:

- The direction and magnitude of the transmitted active power can be freely adjusted. With the right adjustment, the active power remains practically constant, irrespective of the angle between the voltages of the interconnected power systems **13**.
- The IPC can absorb or supply reactive power without actually transmitting it itself **13**.
- The tuned IPC has a decoupling effect. It is best applied in situations where no additional synchronizing power or damping is required. Disturbances and faults on one side of the power system are hardly observable on the other side.



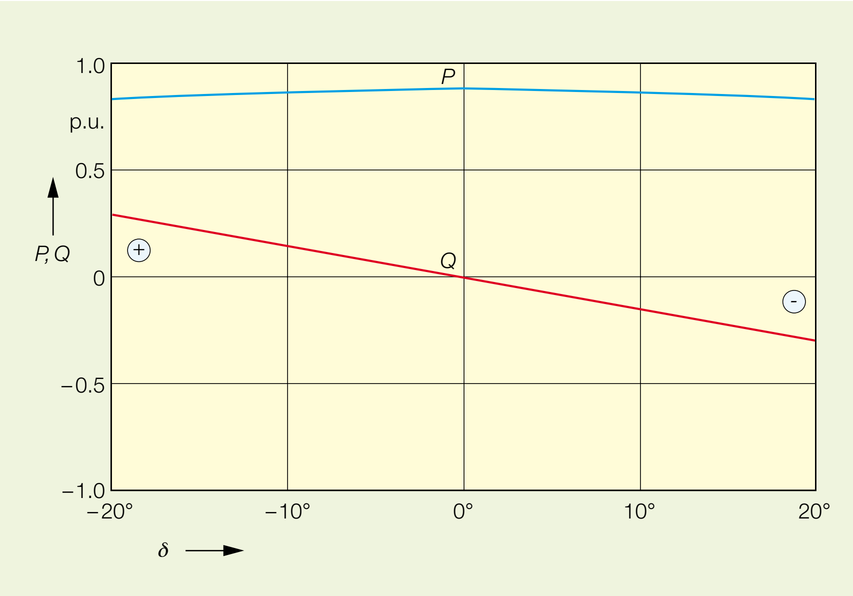
Schematic of an Interphase Power Controller. It has two independently adjustable regulating transformers – one each for the inductive and the capacitive branch. IPCs allow existing networks to be upgraded without increasing the short-circuit levels to unacceptable values. **11**

1, 2	*Networks*	U_1, U_2	*Voltages on network sides 1 and 2*
PAR1, 2	*Regulating transformers*	U_L	*Voltage between PAR1 and reactor*
α_1, α_2	*Phase-shift angle*	U_C	*Voltage between PAR2 and capacitor*
X_L	*Reactor*	I_1, I_2	*Currents on network sides 1 and 2*
X_C	*Capacitor*	I_L, I_C	*Currents in reactor and capacitor*
		I_L^1, I_C^1	*Currents in reactor and capacitor, referred to network side 1*



Currents and voltages of the Interphase Power Controller shown in Fig. 11, neglecting the transformer losses **12**

δ *Phase angle*



Typical active and reactive power characteristics of the Interphase Power Controller for different phase angles δ between network 1 (U_1) and network 2 (U_2). When the active power flows from network 1 to network 2, a lagging voltage U_1 (δ = −20°... 0°) will result in reactive power output on both sides; a leading voltage U_1 (δ = 0°... +20°) results in reactive power absorption. **13**

P Terminal active power, IPC

Q Terminal reactive power, IPC

Because of this, the grounding conditions on the two sides of the IPC can be different.

- The installation of IPCs allows closely intermeshed networks, which are found in most industrialized countries, to be further extended without exceeding the rated breaking capacities in the substations. If the short-circuit levels are already approaching a critical value, the situation can be improved by retrofitting IPCs.
- Existing installations with phase-shifting transformers can be converted to IPCs providing certain system conditions are fulfilled.

Partnerships between customers and the manufacturer yield the best results

The best results are obtained when the manufacturer and utility collaborate closely in projects, preferably beginning with planning and continuing right up to commissioning. Specialists are able to provide optimum solutions, custom-designed to meet the client's exact requirements.

ABB High Voltage Technology and ABB Sécheron can submit proposals and realize projects in partnership with customers based on the specified MVA rating, the requested control properties of the transformer, and the permitted maximum (or required minimum) short-circuit impedance.

High quality is ensured already at the fabrication stage by extensive type-testing and other special verifications that include thermal and impulse voltage tests. After commissioning of the transformer banks, routine maintenance and checks ensure trouble-free operation.

Power system studies are carried out from case to case to determine the advantages of redistributing the load flow and providing voltage support. Such studies generate reliable analyses of the current power system operating conditions as well as good predictions of the future situation.

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Authors' addresses

Ernst Wirth
ABB High Voltage Technology Ltd
P.O. box 8546
CH-8050 Zurich
Telefax: +41 1 311 2664
E-mail: ernst.wirth@chhos.mail.abb.com

Jean-François Ravot
ABB Sécheron SA
P.O. box 2095
CH-1211 Geneva 2
Telefax: +41 22 306 2026
E-mail:
jean-françois.ravot@chsec.mail.abb.com