Power quality ensured by dynamic voltage correction

Growing demands made by industry on power quality as well as the quality diversification that deregulation has brought, point to a need for additional devices that, by ensuring high-quality system voltages, prevent critical loads from failing and causing production downtime. Options include the Dynamic Voltage Restorer, which has its own energy storage unit, and the Unified Voltage Controller. Both system concepts allow economically and technically optimized corrective action, designed to counter voltage reductions or rises occurring in power transmission networks.

Changing boundary conditions in the electrical supply industry, due as much to market deregulation as to more sensitive loads, continue to influence the demands made on the power transmission equipment and on the quality of the electrical supply. Whereas utilities are concentrating on utilizing the existing transmission systems more efficiently, users are focusing on high reliability and power quality. Power quality efforts, besides targeting high frequency stability, increasingly aim at ensuring a constant voltage and an uninterrupted supply of energy.

Power quality is quantified technically on the basis of the following criteria [1]:

- Constant sine-wave shape; no harmonics
- Constant frequency; unchanged nominal value
- Symmetrical three-phase AC power system; three voltages with phases shifted by 120°
- Constant rms value; nominal power system voltage value unchanged over time
- Fixed voltage; power system voltage unaffected by load changes
- Reliability; energy in the required amounts available at all times

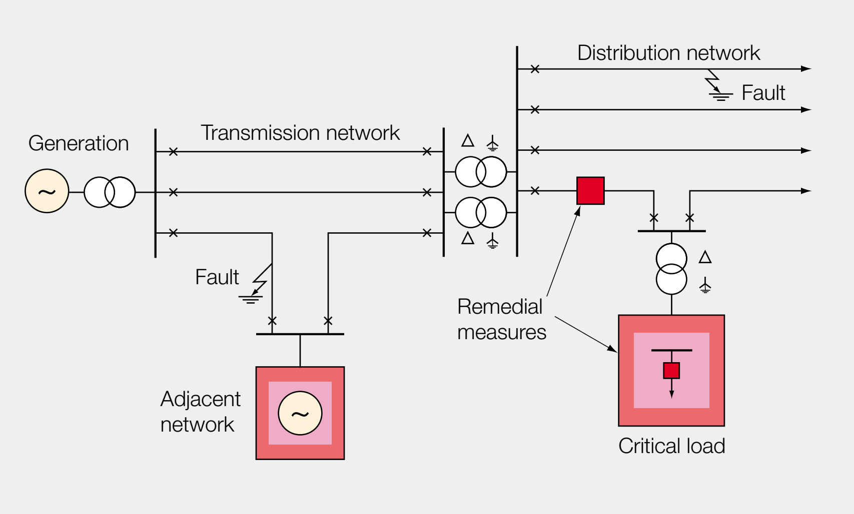
IEC (1000-2-2/4) and CENELEC (EN 50160) define power quality as a physical characteristic of the electrical supply provided under normal operating conditions which do not disturb or disrupt the customer's process. A precise definition of the physically measurable disturbances and of limits specified on the basis of them is currently the subject of intensive work being carried out by standardization committees [2, 3].

Thomas Jauch
Alexander Kara
Mohamed Rahmani
Dr. Dirk Westermann
ABB High Voltage Technologies Ltd

Among the most severe disturbances endangering power quality are voltage dips and transient power supply interruptions [4]. Highly automated production processes are particularly susceptible to temporary changes in the magnitude and phase of the power supply voltage. Even voltage depressions lasting only a few milliseconds are enough to bring entire production lines to a standstill, causing considerable economic damage as well as endangering the production equipment itself. Sectors typically affected are the papermaking, semiconductor and chemical industries.

Even when the power supply has been designed for maximum reliability, such disturbances cannot be completely ignored, since the widely distributed energy supply process is subjected to both atmospheric influences and non-predictable component failure. Only additional measures, taken in the power system or at the users' end, can protect critical loads from disturbances of this kind **1**.

Preventive measures at the users' end involve interposing power conditioning devices between the supply and the load, and offer only local corrective solutions tailored to specific disturbances. Eliminating the actual cause of the problem in a way that guarantees power quality is possible by installing equipment for improving the power quality in the power system itself. The installation of such equipment guarantees a high-quality supply of electrical energy to critical loads even in cases of power system disturbance.



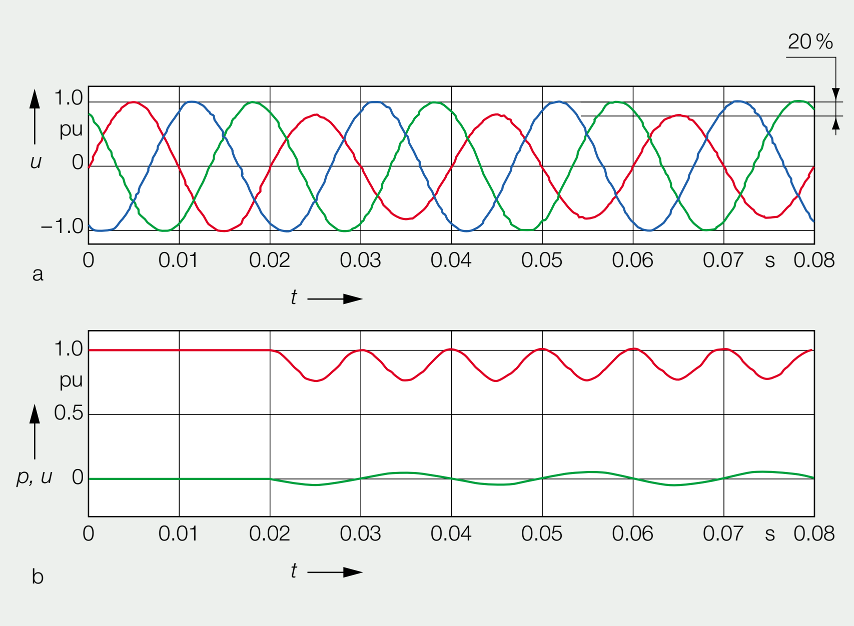
Typical situation in a power network **1**

Power system disturbances and their effect at the load end

The faults involved – single-phase-to-earth, two-phase-to-earth, phase-to-phase and three-phase faults – influence the amplitude and phase angle of the supply voltage on the load side. In about 80 percent of all cases the fault is of the phase-to-earth type. Switching operations, such as the connection and disconnection of large loads are another cause of sudden changes in the total load and therefore in the voltage.

Influence of a single-phase voltage reduction of 20 % (from t = 0.02 s) on the load-side quantities, without transients **2**

a *Phase voltages u at connecting point*
b *Momentary power p (red curve)*
and negative-sequence voltage u (green curve)



The influence of such disturbances at the terminal of a load depends on the distance to the origin of the disturbance and on the power capacity, as well as the level of interconnection and design of the interposed transmission links. This applies especially to single-phase and multiphase disconnection following a fault, either of which can lead to all the power supply phases being interrupted if the network has been designed with insufficient redundancy.

Symmetrical voltage sags can cause a sudden reduction in the output torque of drive systems. When the drives are used in industrial processes, the result is a deterioration in product quality, leading in the worst case to production coming to a complete standstill. The power consumption of torque-controlled drives increases when the voltage decreases, possibly causing the power supply to be interrupted due to thermal overloading or tripping of the overcurrent protection. The risk of spurious tripping is especially high where electromechanical protection equipment is installed.

Influence of asymmetry

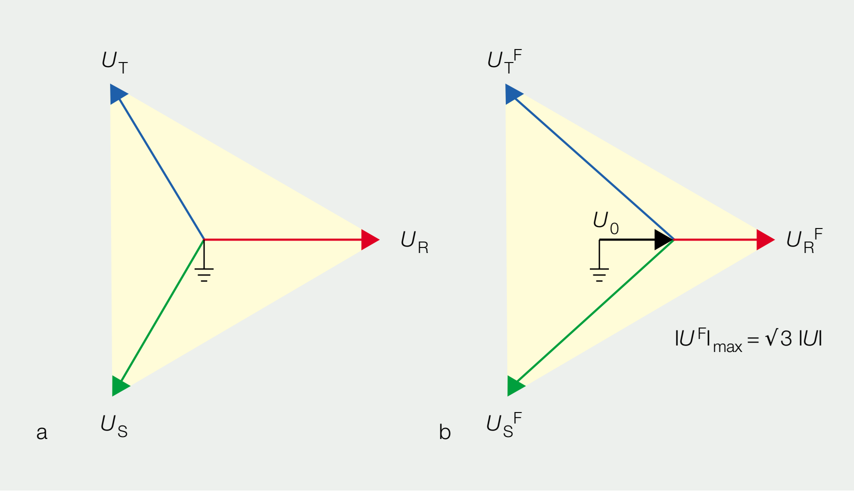
Asymmetry exists in three-phase AC networks when the rms values of the voltage between a phase and the neutral or the angles between successive phases are not identical. Since the voltage sources in the power system are balanced, asymmetry is caused primarily by phase-to-earth faults or phase-to-phase faults as well as by asymmetrical load currents or asymmetrically built transmission equipment.

Single-phase voltage drops cause a negative phase-sequence system (u_(t)), ie a voltage system rotating in the direction opposite to that of the symmetrical three-phase AC system, given by:

$$u_-(t)=\frac{1}{3}\left(u_{\mathrm{R}}(t)+u_{\mathrm{S}}(t)e^{-j\frac{2}{3}\pi}+u_{\mathrm{T}}(t)e^{j\frac{2}{3}\pi}\right) \quad (1)$$

The negative phase-sequence system periodically weakens the rotating field that is generated to produce the driving torque for polyphase machines. In the case of asynchronous machines, which are used for most drives, the output torque depends on the square of the terminal voltage, with the result that asymmetry leads to a reduction in the drive output **2**.

The resulting increase in mechanical load reduces the service life of the machines, and a fluctuating output torque reduces the production quality in a connected manufacturing process. Inadmissible temperature rises in the stator and rotor windings – the result of additional losses – lower the total efficiency and endanger the machines. Thermal protection equipment may instigate disconnection of the plant. Even a single-phase voltage reduction of 20 % leads to a sharp rise in the power consumption of a connected machine in a 50-Hz system. The superimposed 100-Hz oscillation with a peak-to-peak displacement equal to 25 % of the nominal power corresponds to the additional reactive power that is absorbed.



Vector diagram of the phase voltages **3**

a *Symmetrical system, voltages* U_R, U_S, U_T
b *Asymmetrical system, phase-to-earth fault, voltages* U_R^F, U_S^F, U_T^F

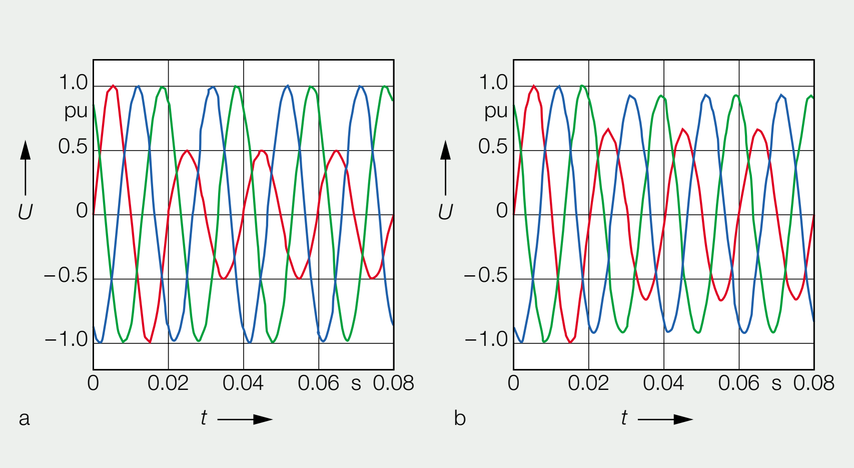
In the event of a phase-to-earth fault with single-phase voltage reduction in a symmetrical three-phase system, the influence of this disturbance on the phases not affected by the fault depends on the vector group of the loads and transformers. In the case of a star connection with earthed neutral the reference potential is fixed. The single-phase disturbance has a limited effect with regard to the voltage change on the faulted phase. A disadvantage is the increased flow of current through the neutral, since the latter can form a circuit in the case of phase-to-earth faults. Such a circuit cannot be formed when the equipment operating within a galvanically coupled network is connected either in delta or in star, without earthing of the neutral. In the case of a phase-to-earth fault, part of the phase voltage acts in parallel with the neutral of a star-connected transformer, resulting in a cophasal voltage system. This zero phase-sequence system $u_0(t)$ can be calculated according to eqn 2.

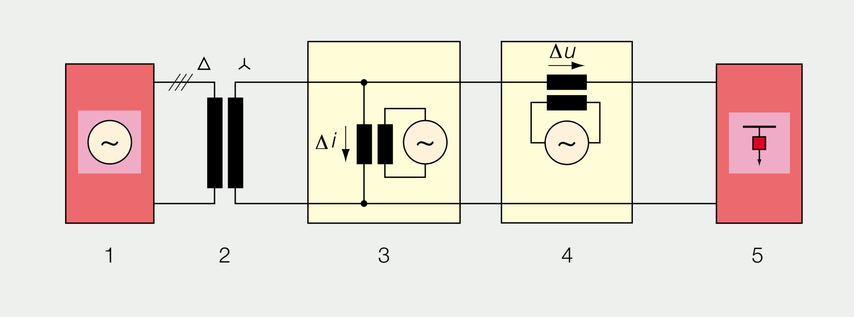
$$u_0(t)=\frac{1}{3}\left(u_{\mathrm{R}}(t)+u_{\mathrm{S}}(t)+u_{\mathrm{T}}(t)\right) \quad (2)$$

In addition to the voltage at the neutral increasing to the maximum phase-to-earth voltage, the phase-to-earth voltages of the phases unaffected by the fault

Phase voltages U_R, U_S, U_T ***in the case of a phase-to-earth fault*** **4**

a *With zero phase-sequence system (primary)*
b *Without zero phase-sequence system (secondary)*





Basic options for power quality improvement **5**

1 *Transmission system*
2 *Step-down transformer*
3 *Current injection*
4 *Voltage injection*
5 *User*

also increase in the worst case by the factor √3 **3**.

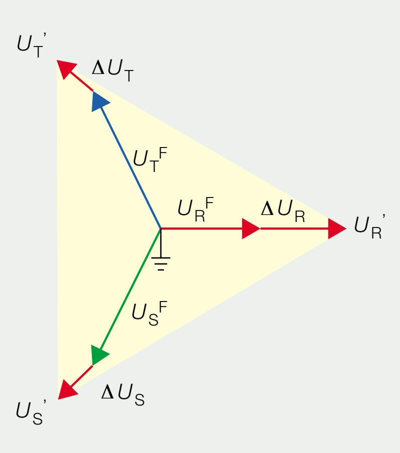
Due to the phase coincidence, the zero phase-sequence system is unable to supply power to a three-phase AC load. A disadvantage of the zero phase-sequence system at the load end is, besides the higher insulation costs, the asymmetry of the phases and magnitudes of the terminal voltages. Zero-sequence currents in three-phase lines cause large voltage drops because the voltages induced by the coupling inductances of the lines do not weaken each other mutually as they do in a three-phase AC system. The result of this is a further reduction in voltage on the load side.

Influence on the load

Whereas the negative phase-sequence system is transmitted via transformers, irrespective of their vector group, from the HV power line to the distribution system and beyond to the load network, star connections which are operated as isolated systems or transformers with delta-connected windings act as a filter for the zero sequence system. Due to the zero sequence system being in phase it can only be transmitted from one galvanically coupled network area to another provided that the neutrals of the primary and secondary windings of a transformer are electrically coupled.

Step-down transformers with typical vector groups (eg, YyO or Yd5) filter the zero sequence components. The filtering has the effect of inducing symmetry and reducing the consequences of a fault. On the secondary of such a transformer the magnitude of the faulted phase voltage is raised. The phase voltage values of the non-faulted phases decrease slightly, so that the degree of asymmetry also decreases in comparison with the voltage system on the primary. For example, in the case of a single-phase voltage reduction in phase R by 50 %, filtering of the zero phase-sequence system on the secondary leads to a phase voltage of approximately 66 %. The voltage in the phases not affected by the fault decrease in value by about 8 %; the phase is displaced by approximately 8° **4**.

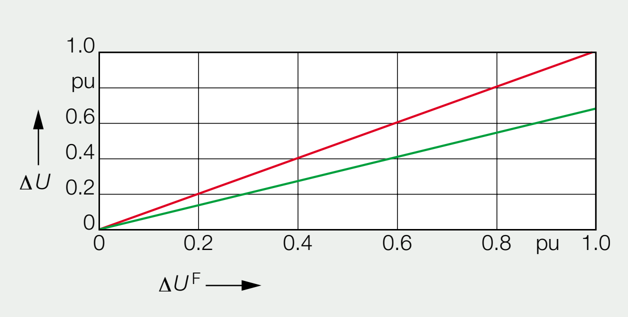
Vector diagram of the phase voltages U_R, U_S, U_T with voltage correction by means of series voltage injection **6**



Transformers, which suppress the zero sequence system in the way described, are installed in most sections of transmission and distribution networks. Moreover, the physical expanse of the galvanically coupled network areas decreases with the nominal voltage. Corrective measures in the network of a critical load area concentrate primarily on fast suppression of the negative sequence. For the high-speed correction of voltage asymmetry by means of active components there are two basic options: current injection or voltage injection **5**.

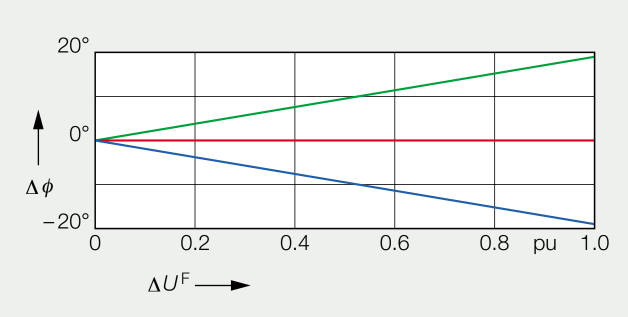
In the case of current injection a boosting current (Δ*i*) is superimposed upon the operating current by a source in parallel with a transmission line. The goal is to balance the line currents and indirectly achieve symmetry between the terminal voltages at the load end. As the short-circuit level at the connection point of such a source increases, the influence on the phase voltages which is possible with current injection decreases. Additionally, it is more difficult to optimize the control algorithm when this method is used.

In terms of improving the voltage quality at the load end, a voltage source connected in series with the transmission line operates more effectively **6**. The injection of an extra voltage (Δ*u*) into each of the network phases in order to correct the magnitude and phase, is



Value of maximum additional voltage ΔU for single-phase voltage reductions ΔU^F **7**

Red	With zero-sequence components
Green	Without zero-sequence components



Change $\Delta\phi$ in the phase angles in the non-faulted phases as a function of the single-phase voltage reduction ΔU^F in phase R **8**

Red	*Phase R*
Green	*Phase S*
Blue	*Phase T*

an effective way of achieving symmetry for the three-phase AC system. Faults in adjacent galvanically coupled network areas no longer have any influence when this method is used at the load end.

The magnitude and phase of the additional voltage depends on the voltage reduction in the phases affected by the fault and on the influence of the zero sequence components. In the case of phase-to-earth faults, filtering of the zero sequence system results in the maximum additional voltage necessary for symmetry being considerably lower than in systems with a zero-sequence voltage **7**. The per-phase power output from the series-connected voltage source behaves similarly. The zero sequence system filtering has no influence on the total power.

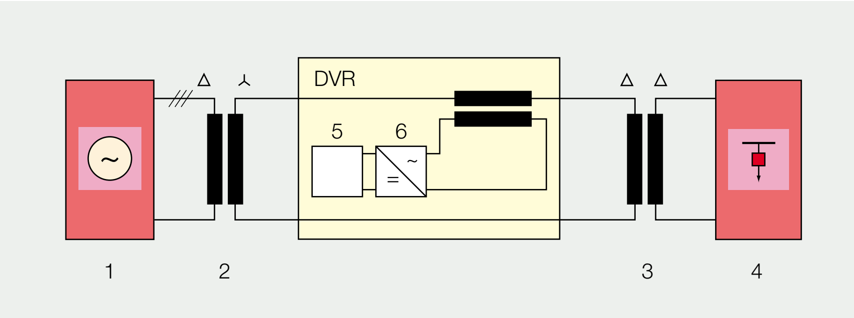
When determining the additional voltage to be injected it is important to consider the change in magnitude and phase angle in the non-faulted phases. Even with a single-phase voltage reduction of 50 %, phase displacements of approximately 10° take place in the phases in a three-phase AC system which are not affected by the fault. The voltages shift in the direction of phase opposition **8**. Equalizing currents in the transmission network strengthen this tendency.

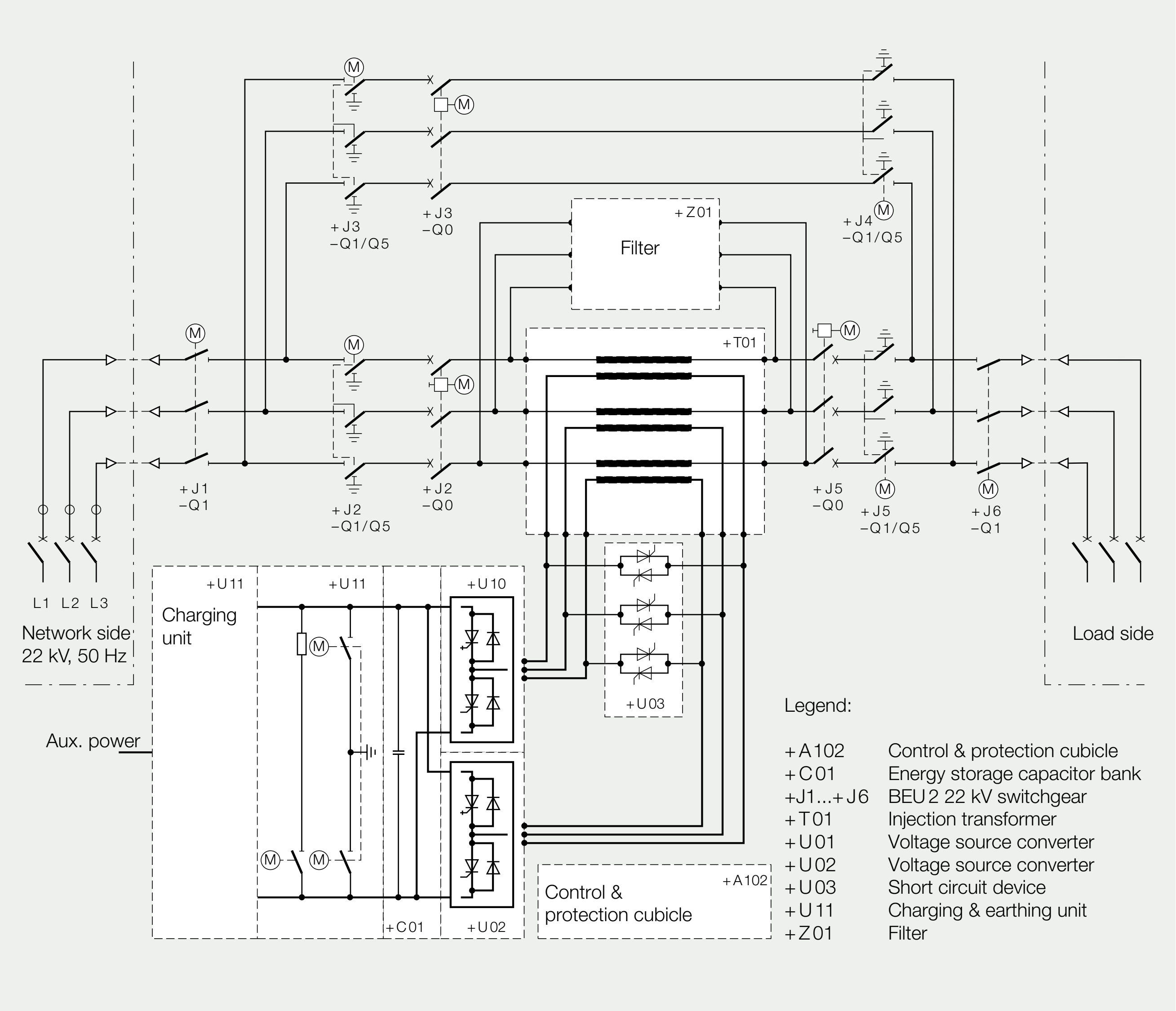
Voltage correction

Load-end voltage correction by means of voltage injection requires both active and reactive power to be injected via the source providing the additional voltage. The value of the active and reactive power is equal to the product of the phase current and the series-injected voltage. For typical load angles, ϕ_L, in the range cos $\phi_L > 0.9$, the output is primarily active power. This can be provided either by energy storage units or from adjacent sections of the network using additional equipment (eg, transformers). Power quality (PQ) equipment employing this method of voltage correction is offered by ABB High Voltage Technologies, which continues to develop the technology for a wide range of network configurations and user-specific requirements. Two basic system concepts are implemented in the Dynamic Voltage Restorer (DVR) and the Unified Voltage Controller (UVC). Both systems are able to avoid load-end disturbances resulting from reductions or rises in voltage.

Section of power system with Dynamic Voltage Restorer (DVR) for correcting voltage depressions **9**

1	*Transmission system*	4	*Load*
2	*Step-down transformer*	5	*Storage unit*
3	*Step-down transformer*	6	*Voltage source converter*





Simplified three-phase circuit diagram of an installed Dynamic Voltage Restorer **10**

Dynamic Voltage Restorer

The Dynamic Voltage Restorer, by injecting an additional voltage in series with a transmission line, ensures a symmetrical three-phase AC system with constant rms value at the load end. The required energy is provided by an energy storage unit **9**.

A typical case in which the DVR concept is employed to improve the power quality is a semiconductor production plant with an installed 4-MVA load which is affected by voltage reductions. Even single-phase voltage depressions of a few 10 % in the millisecond range lead in this case to the loss of a full day's production due to interruption of the manufacturing process. The installed DVR corrects single-phase voltage depressions of up to 50 % and three-phase voltage depressions of up to 38 % for a duration of up to 150 ms.

The required output voltage is supplied by voltage source converters, the output waveform of which is generated using a pulse-width modulation (PWM) switching scheme. Since a symmetrical three-phase AC system has to be restored on the load side within a few milliseconds after detection of the fault, the storage system is built with DC capacitors. These satisfy all of the requirements made on the dynamic response of the energy storage unit. The maximum load angle (cos ϕ_{Lmax}), maximum injected voltage (ΔU_{max}), maximum line current (I_{max}) and maximum duration of the disturbance (T_{cor}) in the case of a three-phase voltage reduction together determine the storage capacity E_{DC} of the DC circuit:

$$E_{DC} = \frac{1}{T_{cor}} \int_{T_0}^{T_0+T_{cor}} \underbrace{\left(\int_{T_0}^{T_0+T_{cor}} \Delta u_R(t) i_R(t) + \Delta u_S(t) i_S(t) + \Delta u_T(t) i_T(t) \mathrm{d}t \right)}_{\le 3 \Delta U_{max} I_{max} \cos\phi_{L\,max} T_{cor}} \mathrm{d}t \qquad (3)$$

If the required maximum duration of correction T_{cor} is 150 ms and the load is 4 MVA, an energy E_{DC} of approximately 194 kJ has to be taken from the DC storage unit in order to correct a three-phase voltage dip of 38 % on the high-voltage side, assuming cos $\phi_{L,max} = 0.85$:

$$E_{DC} = \underbrace{3 \Delta U_{max} I_{max}}_{0.38 \quad 4MVA} \underbrace{\cos\phi_{L\,max}}_{0.85} \underbrace{T_{cor}}_{0.15s} \approx 194\,\mathrm{kJ} \qquad (4)$$

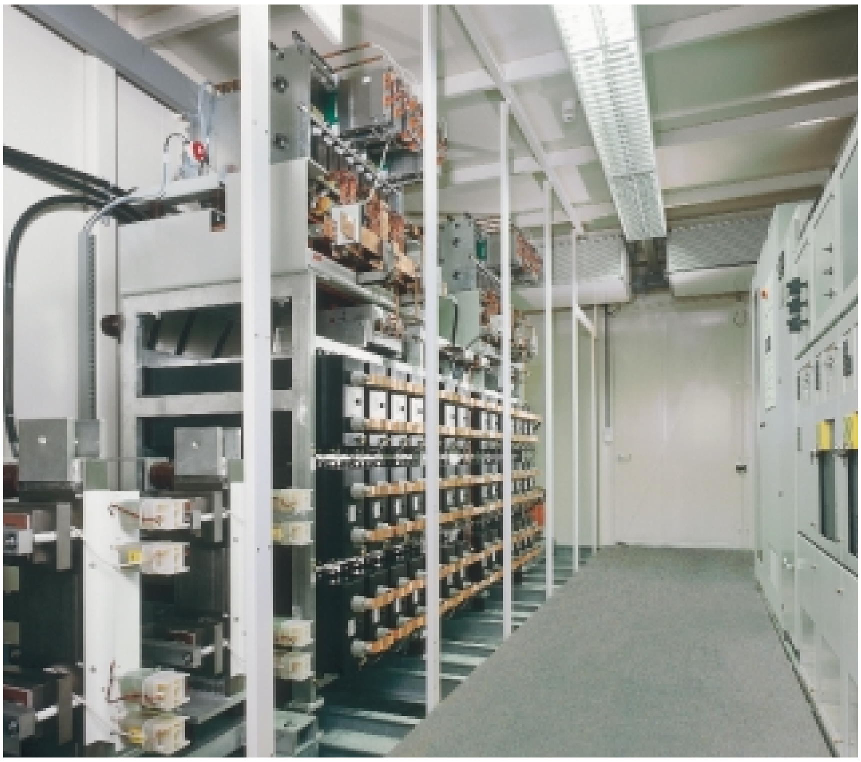
The equipment comprises, besides the storage unit and the converter, the booster transformer for the voltage injection, the harmonic filter, the short-circuit device, the charging equipment for the storage unit, and the equipment for control and protection **10**. If a 4-MVA DVR is installed, the short-circuit device, DC capacitors, converter modules and charging equipment can be arranged on one side of a container. The gas-insulated MV switchgear for the connection to the power system and all of the control and protection equipment can be placed on the other side **11**.

All three output voltages can be controlled in terms of their magnitude and phase. No additional inductive or capacitive components are needed for the reactive power output on account of the voltage source converters incorporated in the system.

During normal, undisturbed power system operation the DVR remains in a loss-optimal standby mode. The low-voltage side of the booster transformer is short-circuited, so that only the leakage inductances, which have been minimized due to special design measures, are active on the high-voltage side.

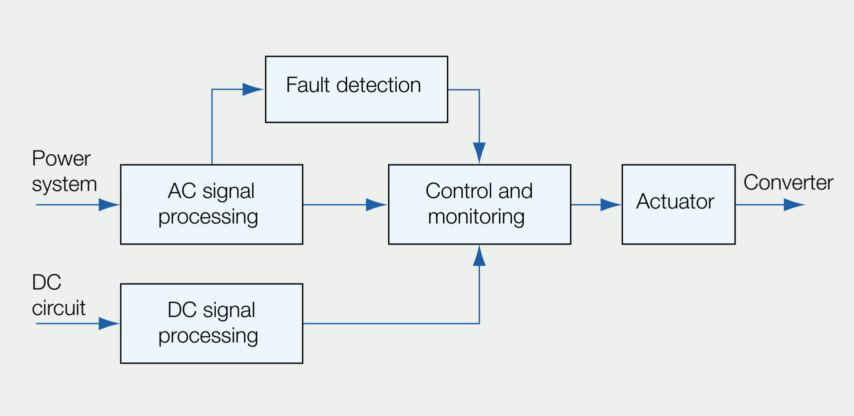
The converter, consisting of a 2-point bridge connection with gate turn-off thyristors for each phase, allows the booster transformer to be operated with a short-circuited secondary winding. The semiconductor components are controlled such that the terminals of the booster transformer secondary are connected to one potential of the DC circuit. Only the semiconductors in the conducting state produce losses. Since modules with integrated gate-commutated thyristors (IGCT) [5, 6] are used, these losses are lower than the losses of the booster transformer short-circuited on the low-voltage side.

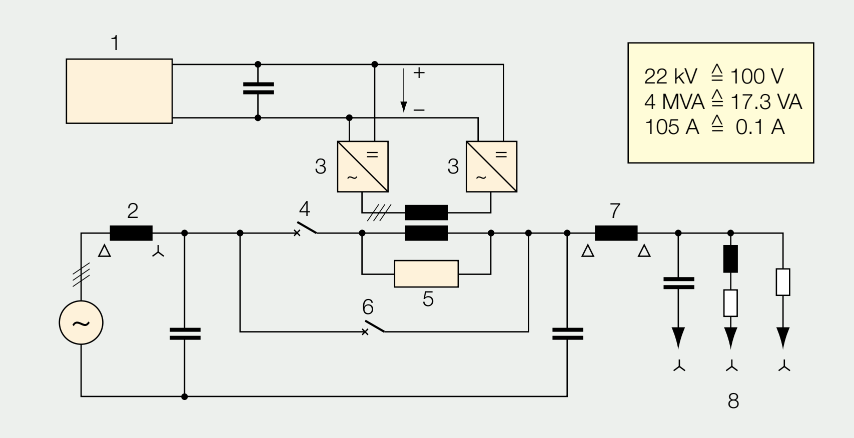
If a fault occurs on the load side of the DVR, a very high current flows through the conducting IGCT modules on account of the current transformation of the



DC capacitors, IGCT converter module and electronic short-circuit device of the Dynamic Voltage Restorer **11**

Block diagram of the DVR controller (correction control) **12**





DVR model set up on an analogue simulator in the laboratory **13**

1 DC circuit
2 Step-down transformer
3 Voltage source converter
4 Breaker
5 Filter
6 Bypass breaker
7 Step-down transformer
8 Load model

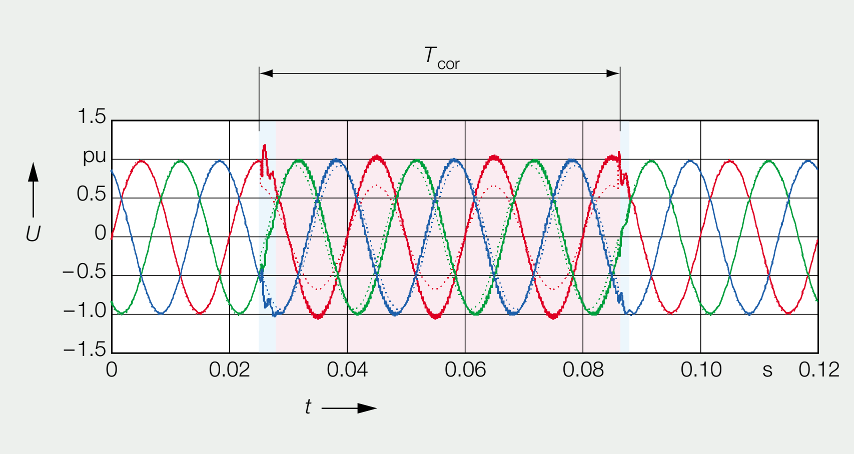
booster transformer. To prevent these modules from being thermally destroyed the thyristors of the short-circuit device are triggered and subsequently conduct. This effectively commutates the fault current from the converter to the now parallel-connected circuit. The mechanical bypass breaker is tripped simultaneously. This short-circuits the overall arrangement, causing the fault current to commutate from the shorting circuit to the bypass circuit and allowing the converter to be disconnected without risk.

Injection of a pulse-width modulated voltage begins as soon as a power system disturbance is detected. The emission of harmonics that accompanies this can be considerably reduced by means of a high pulse frequency and staggered switching of the two converters. The suppression of the harmonics occurring at a pulse frequency f_T of 1,500 Hz around the 60th harmonic requires an additional filter since the level of the pulse frequency is limited in order to achieve an optimum economic balance between the converter losses and the size and cost of the filter. The excitation of resonant frequencies can be avoided by adapting the pulse pattern to the system conditions. These tasks are carried out by control loops subordinated to the control system for the voltage correction. The main components of this control system are a fault detection unit and a powerful signal processing unit for the DC and AC quantities **12**.

Voltage correction with a Dynamic Voltage Restorer (DVR) in the case of a single-phase-to-earth fault. The pulse frequency is 1,500 Hz. **14**

T_{cor} *Correction time*

┈ *Phase voltages in front of DVR*
═ *Phase voltages behind DVR*



The three-phase voltage system on the network side of the DVR is transformed via signal processing into a rotating two-phase reference system. Due to the delta connection of the transformers used, the zero sequence components do not appear on the load side. No account has to be taken of the zero-sequence components by the signal processing. A signal processing system with phase locked loop (PLL) generates from the rotating reference system a voltage reference system which forms the basis for the in-phase synchronization between the additional voltages to be injected into the system and the phase voltages. The fault detection is based on a comparison of the power system voltages with a synchronous reference system. The firing pulses for the IGCT module are generated according to the magnitude and phase of the required additional voltage.

The initial design of the controller for the PQ devices plays a major role in the design of the overall installation. Thorough analysis is necessary of both the power system conditions at the

DVR location and the structure of the load in the end-user's power network. Software simulators are available with which the controller structure and parameters can be optimized. Due to the complexity of the controlled object, not all of the dynamic properties of the real system are simulated in the software models. Validation of the performance of the hardware requires additional effort and time.

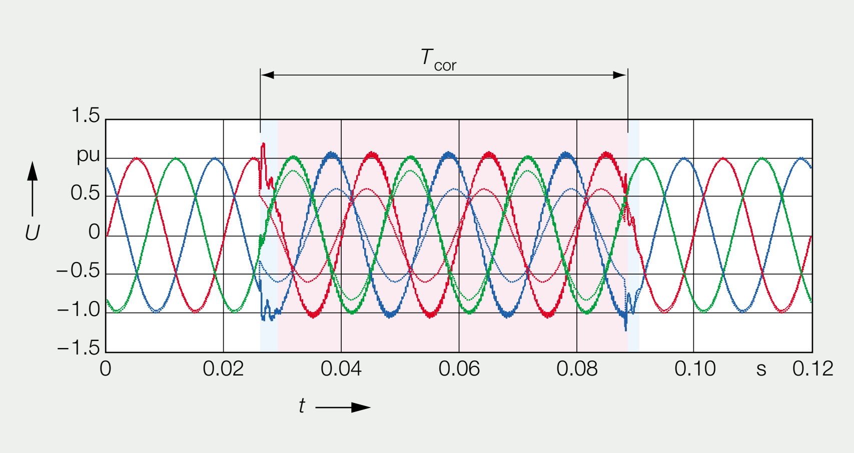
The hardware components of PQ devices can be validated with the help of hardware simulators. Even modelling just the immediately adjacent operating equipment, the power system infeed and the DVR, provides the high model accuracy needed for a detailed validation **13**.

The software simulation shows the effectiveness of the voltage correction. In the case of a single-phase voltage reduction in the transmission system **9** of 50 % in phase R over a time span of $T_{cor} \approx 60$ ms, an asymmetrical three-phase AC system appears on the secondary side of the step-down transformer T_1 with the amplitudes

$$\hat{u}_R \approx 0.66 \text{ pu}, \hat{u}_S \approx \approx 0.92, \text{ pu}, \hat{u}_T \approx 0.92 \text{ pu} \qquad (5)$$

as well as phase angles slightly displaced in comparison with the symmetrical system (**14**, dotted voltage curves). The phase displacement, besides being a result of the zero sequence system filtering, is also influenced by the asymmetrical line currents.

The DVR injects an additional voltage as soon as the disturbance appears in the region close to the voltage peak in phase R. A symmetrical three-phase system results on the load side. The transient phenomena due to the fault subside just 3 ms after the disturbance disappears. A voltage reduction at the voltage peak of a phase, as opposed to a disturbance at the voltage zero-crossing, represents the maximum system excitation. The transient phenomena last no longer than 2–3 ms after detection and clearing of the fault **14**, irrespective of the moment at which the disturbance appears.



Voltage correction with a Dynamic Voltage Restorer (DVR) in the case of a double-phase-to-earth fault. The pulse frequency is 1,500 Hz. **15**

T_{cor} *Correction time*

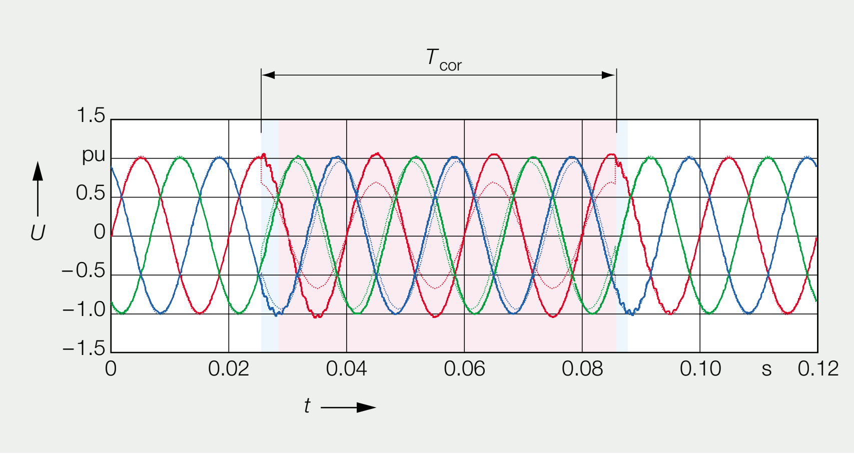
┈ *Phase voltages in front of DVR*
═ *Phase voltages behind DVR*

The injection of a pulse-width modulated additional voltage injects in this case a DVR output voltage with a low harmonics content. On the one hand, the filter installed on the booster side prevents the emission of harmonics from the booster circuit. On the other, the value of the injected voltage is smaller for

DVR voltage correction without filter in the case of a single-phase-to-earth fault. The pulse frequency is 5,000 Hz. **16**

T_{cor} *Correction time*

┈ *Phase voltages in front of DVR*
═ *Phase voltages behind DVR*



a single-phase voltage reduction than for a two-phase disturbance **15**.

The larger phase displacement in the non-faulted phases due to the zero-sequence system filtering necessitates a higher-value additional voltage in the case of two-phase voltage reductions; this is also true for filtered zero-sequence systems:

$$\begin{bmatrix} \overline{U}_\mathrm{R}^\mathrm{F} \\ \overline{U}_\mathrm{S}^\mathrm{F} \\ \overline{U}_\mathrm{T}^\mathrm{F} \end{bmatrix} \approx \begin{bmatrix} 0.6\ \cdot e^{j6^\circ} \\ 0.6\ \cdot e^{-j6^\circ} \\ 0.84 \cdot e^{j3^\circ} \end{bmatrix} \left[\overline{U}_\mathrm{R}, \overline{U}_\mathrm{S}, \overline{U}_\mathrm{T}\right] \wedge \qquad (6)$$

$$\wedge \left|\Delta U_\mathrm{R}\right| = \left|\Delta U_\mathrm{S}\right| = 0.5\,\mathrm{pu}$$

As in the case of the single-phase disturbance, the excellent control performance of the DVR ensures the restoration of a symmetrical three-phase system on the load side within 2 to 3 ms even in the case of a two-phase voltage reduction of 50 % in the HV network.

The economic design of the installation comes from optimum matching of the IGCT switching losses and the RC filter network; it also determines the switching frequency. The switching losses of the IGCTs increase with an increasing switching frequency.

The converter can be operated with a higher switching frequency when the critical load has a lower installed rating. Developments in the power electronics components sector allow switching frequencies in the kHz range with a practically unchanged high switching capability already today in prototype applications [6]. Operation of the DVR with a switching frequency of 5,000 Hz shows the positive effect on the voltage curves on the load side **16**.

An increase in the switching frequency by a factor of 5 allows a disproportionately large reduction in the transient phenomena. The harmonics content of the phase voltages on the load side is also clearly reduced. A filter for limiting the harmonics emission from the booster circuit is no longer necessary, enabling the economy of this system concept to be improved even further.

Unified Voltage Controller

For applications in power systems with a high short-circuit rating there is no need for the energy storage unit providing the active power. The Unified Voltage Controller (UVC) injects an additional voltage in series with a transmission line. Thus, a symmetrical three-phase system with constant amplitude is ensured on the load side without energy having to be taken from a storage unit during the voltage correction **17**.

The main system components of the UVC are the autotransformer, connected in star with an electrically isolated tertiary winding, and the converters U_1 and U_2. The voltage source converter U_1, acts as a series voltage source. The maximum possible voltage reduction on the secondary side of the step-down transformer T_1 at the injection point in the transmission network determines the transformation ratio of the autotransformer. It is equal to half of the voltage reduction. If, for example, the UVC has to correct a maximum voltage reduction of 40 % on the secondary side of T_1, a transformation ratio of $\ddot{u}$ = 1.25 will be necessary (eqn 7).

$$\ddot{u} \approx \frac{1}{1-0.5\Delta U} = \frac{1}{0.8} = 1.25\Big|_{\Delta U=0.4} \qquad (7)$$

When there is no voltage reduction converter U1 generates an additional voltage to counteract the step-up produced by the autotransformer, so that the overall transformation ratio of the UVC is equal to unity **18**.

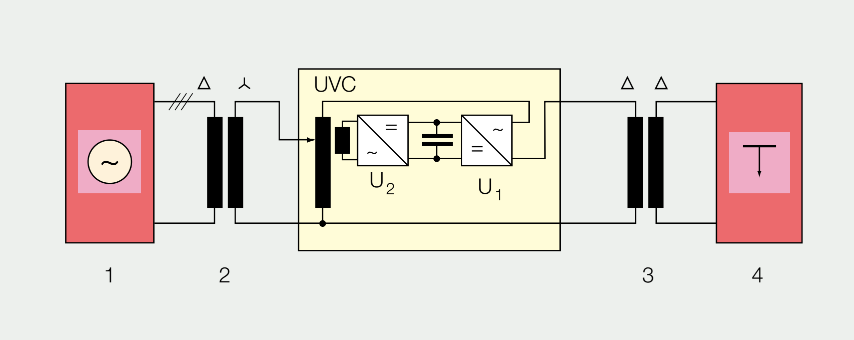
Converter U_2, which is connected to the autotransformer via the electrically isolated tertiary winding, provides the active power produced by converter U_1. If there is a voltage reduction in the transmission network, the voltage generated by converter U_1 changes in order to generate a symmetrical three-phase system on the load side. Resembling the functionality of the DVR, the voltage difference is determined by comparing the voltages on the input side with a reference system.

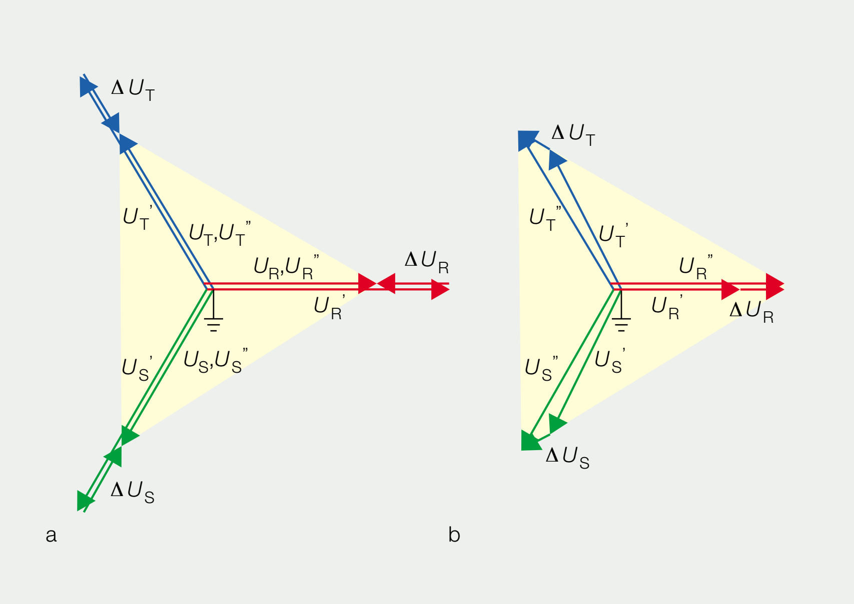
In this operating state the active power output of converter U_1 is also provided by

Section of power system with Unified Voltage Controller (UVC) for correcting voltage depressions **17**

1 *Transmission system*
2 *Step-down transformer* T_1
3 *Step-down transformer* T_2
4 *Industrial network*

U_1, U_2 *Voltage source converters*





Voltage vectors after step-down from transmission system (a) during normal operation of Unified Voltage Controller (UVC) and (b) in the case of a single-phase-to-earth fault in the transmission network **18**

U	*Phase voltage from transmission network*
U'	*Phase voltage without additional voltage*
U"	*Resultant load voltage behind UVC*
Δ*U*	*Additional voltage*

converter U_2, which takes the extra power from the tertiary winding. The active power is taken by converter U_2 from the phases which are unaffected by the fault, or in the case of a three-phase voltage reduction from all the phases. To allow active power to be taken the phase currents have to change. Since the direction of the current flow is given by the network configuration, taking active power from the tertiary winding causes the phase currents to increase, which can bring about a further reduction in the voltage. This will be negligibly small if the short-circuit power at the location where the voltage is injected into the transmission network is sufficiently high compared with the power absorption of the shunt-connected voltage source converter.

The voltage reduction caused by the tertiary winding of the autotransformer is proportional to the power injected or absorbed. Power taken from a network node or injected into a node with the short-circuit rating S_k leads to a voltage reduction ΔU which is proportional to the value obtained by dividing the power injected into the node by the short-circuit power (eqn 8) [7].

$$\frac{\Delta U}{U_n} = \frac{\Delta S}{S_k} \qquad (8)$$

Production processes which are sensitive to voltage reductions are found throughout the highly industrialized countries. Due to the power networks in these countries having been expanded over several decades, their topological configurations today feature a high level of interconnection and therefore a high short-circuit power rating at the ties to the distribution network. These systems are therefore well able to meet the UVC-related requirements with respect to the short-circuit rating.

In a sample project, a 4-MVA load is protected from voltage reductions with a duration of up to 150 ms. As regards the UVC, this means that during this time it is necessary for converter U_1 to supply 1.3 MVA. Even when 1.3 MW of active power is taken from the tertiary winding the voltage on the input side of the UVC is reduced by only 0.01 pu per phase when the short-circuit power in the non-faulted phases has the comparatively low value of 130 MVA. This voltage reduction lies within the normal operational voltage fluctuations during daily operation of the transmission network. With a single-phase voltage reduction of 50% in the distribution network, the total active power required for voltage correction can be taken from the phases not affected by the faults. When the nominal voltage is 22 kV, the additional current is about 51 A. Due to the additional voltage drop in these phases, it has a positive influence on the voltage symmetry.

Besides correcting the voltage when power system faults occur, the UVC has numerous advantages for normal, undisturbed power system operation. Due to the continuous voltage injection it is possible, in combination with a suitably structured controller, to actively control the power factor of the connected loads. In interconnected distribution network topologies the additional voltage, with its controllable magnitude and phase angle, can be used to systematically influence the power flows. In cable networks, in particular, these often lead to local bottlenecks in the transmission capacity, mainly on account of thermal problems. Consequently, there is a risk of unnecessary protection tripping causing a loss of power quality. By systematically regulating the reactive power output, the UVC helps to meet the capacitive reactive power demand of cable networks, which is higher than that of overhead lines and which occurs primarily during low-load periods, when it often causes inadmissible voltage increases. In addition, the UVC reduces the harmonics at the distribution network level which are caused by the increased use of decentralized power generation plant. It does this by means of active filtering via voltage injection with converter U_1.

Summary

Ongoing demand for PQ measures to be taken within the power system itself makes the installation of appropriate equipment a priority for the utilities. With regard to the quality criterion 'load voltage', the PQ equipment has to reduce the asymmetry causing load disturbances as well as suppress transient power supply interruptions. The main cause of a drop in power quality is the voltage unbalance that results from asymmetrical faults in the transmission system.

The PQ devices allow a fundamental improvement by injecting series voltages into the network areas close to the critical loads. Based on the power system configuration and the short-circuit level at the location of the equipment, a fundamental decision has to be made: whether to install PQ devices with or without an energy storage unit.

The Dynamic Voltage Restorer, which features energy storage, has proven performance capability, particularly in applications where the short-circuit level is low. The power quality can be ensured wherever the DVR is installed, irrespective of the network configuration. A large proportion of the physical size of these installations is taken up by the energy storage unit, particularly in the higher power ranges.

The Unified Voltage Controller is an economic alternative to the DVR. It ensures a symmetrical three-phase system on the load side at all times, regardless of the disturbances occurring in the transmission network. Locations with a high short-circuit level even during disturbed power system operation are particularly suitable for the UVC, as they do not require a storage facility for the provision of active power. Continuous operation of the UVC facilitates additional measures that improve the quality of the supply, among them power factor correction and load flow balancing in interconnected distribution networks, plus active filtering.

Both system concepts allow economically and technically optimized corrective action, designed to counter voltage reductions occurring in power transmission networks. When located on the distribution network side, they ensure a continuous, high-quality supply of power to the connected machines, guaranteeing the highest economy for industrial processes.

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Authors' address

Thomas Jauch
Alexander Kara
Mohamed Rahmani
Dr. Dirk Westermann
ABB High Voltage Technologies Ltd
CH-8050 Zurich
Telefax: +41 1 318 1724
E-mail:
thomas.jauch@chhos.mail.abb.com
alexander.kara@chhos.mail.abb.com
mohamed.rahmani@chhos.mail.abb.com
dirk.westermann@chhos.mail.abb.com