Power Quality
The new paradigm for MV power distribution

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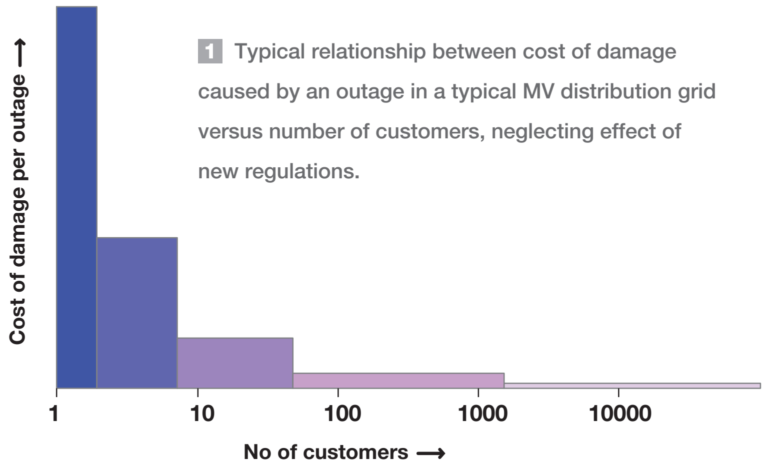
Classical grid disturbances due to lightning, utility switching and short circuits, the growing share of power based on renewable energy, and reduced redundancy in lines and substations, all have a negative impact on power quality in medium- and low-voltage distribution networks. To improve the quality of the power at these two voltage levels, at least for consumers operating sensitive processes, the market currently offers a wide range of products, based either on improved traditional technology or on power electronics conversion techniques. However, more economically attractive solutions are required in the future to meet the escalating demands of a competitive and deregulated electric energy market. Besides power electronics conversion systems, information technology will also play an important role in this new scenario.

The liberalization of the world's energy markets is forcing the electric supply industry to reorganize itself from the ground up. On the one hand, it is expanding to include energy services, power marketing and information technology based services; and on the other, it is increasing asset utilization, reducing maintenance costs, and saving on investments by optimizing operation of the existing grid and reducing staff, etc, in order to reach its profit goals.



1 Typical relationship between cost of damage caused by an outage in a typical MV distribution grid versus number of customers, neglecting effect of new regulations.

In addition, economic and environmental trends point to distributed power generation units with a power output of less than 10 MW being a genuine commercial alternative to centralized power generation in the very near future. It is expected that already in the year 2010 some 25% of all new power generation facilities will be of the distributed type.

Deregulation and the increase in power produced by distributed generation units will both have an impact on the power quality (PQ) in the distribution grids. In such a fast-changing and competitive market environment, an even higher value will be put on power quality than we already do today [1]. The investment required to reach a certain PQ level can vary considerably as it depends on the structure of the distribution system. On the other hand, the value of power quality is decided by the economic consequences of a PQ deficiency. For example, the cost of damage caused by an outage can range from millions of dollars for a small number of consumers (those with highly automated production plant, eg microchip manufacturers and the chemical industry) to nearly nothing for the vast majority. The diagram shown in 1 depicts a typical 'PQ sensitivity dependency', related to the number of customers in an MV distribution system.

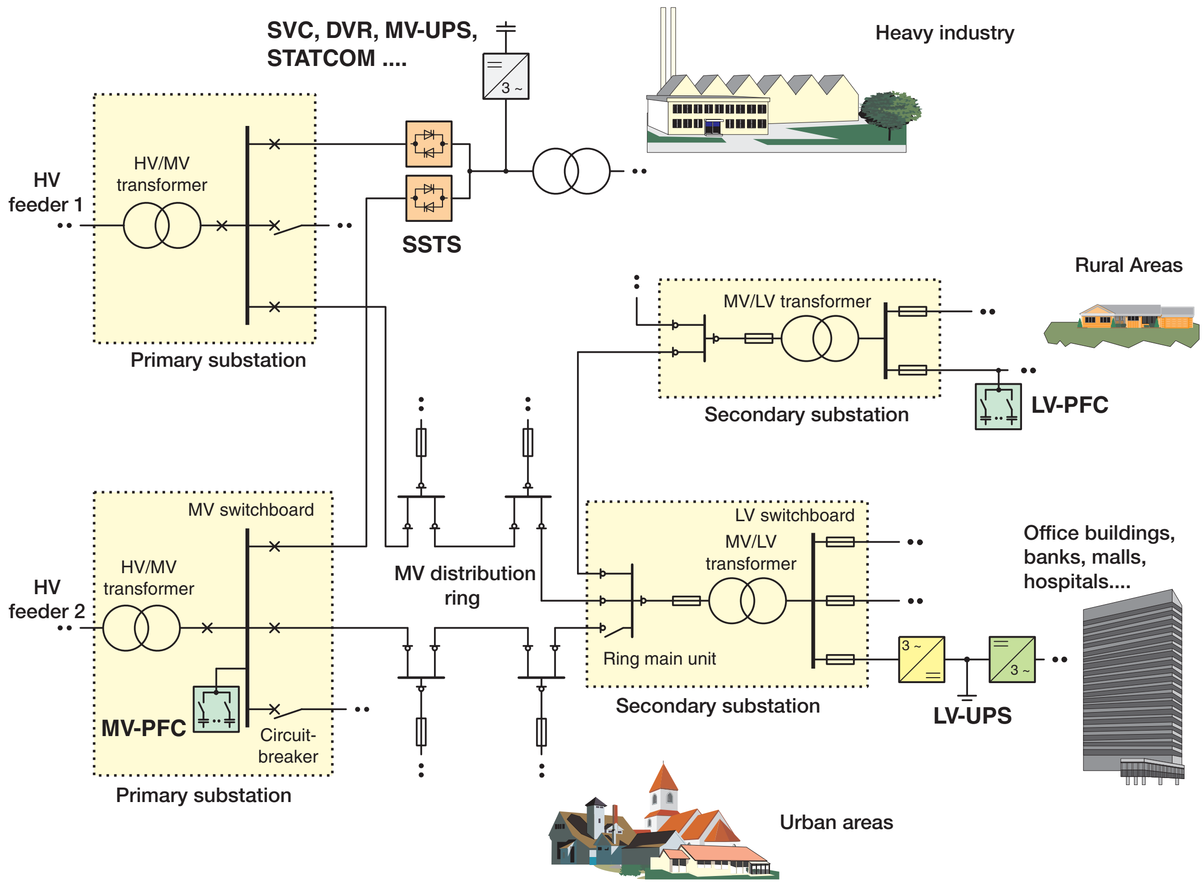
To meet the demand for high power quality there are, in principle, two possible solutions:

- The PQ of the complete MV distribution grid can be increased by installing grid-level PQ systems close to the primary substations.
- Decentralized PQ systems can be installed close to the sensitive consumer or in the direct vicinity of the critical load.

The power level of a decentralized PQ system ranges from small ride-through systems with a low power level of less than 1 kW to facility-wide protection systems for heavy industry with power levels that can reach several tens of MW. Small PQ systems are always installed on the LV side, whereas for systems with a high power level the MV side has advantages.

2 Typical MV distribution grid with devices for improving the power quality (focus on primary technology)

DVR	*Dynamic voltage restorer*	MV-UPS	*Medium-voltage uninterruptible power supply*
LV-PFC	*Low-voltage power factor compensator*	STATCOM	*Static synchronous compensator*
MV-PFC	*Medium-voltage power factor compensator*	SSTS	*Solid state transfer switch*
LV-UPS	*Low-voltage uninterruptible power supply*	SVC	*Static var compensator*



PQ systems are based either on improved traditional technology or on a power electronics conversion technique. A key role will also be played in the future by information technology. This will provide added, and sometimes new, services as well as reduce the outage times in grids caused, for example, by automatically operated MV switches.

Today, power electronics based solutions are usual for the LV grid, and a huge worldwide market for these systems has firmly established itself.

In MV grids, power electronics based solutions represent only a small fraction of the PQ equipment installed today. However, with costs falling rapidly and highly reliable, low-loss semiconductors with high frequency switching capability now available, such solutions can be expected to increase their share of the MV distribution grid market in the next few years. Moreover, power electronics conversion systems will penetrate MV power distribution market segments which are dominated today by mature electromechanical and electromagnetic technology.

Market needs will drive investment

The decision to invest in a PQ system is always based on an economic evaluation. The value of the system has to be considerably higher than the life cycle costs. Hence, utilities and product manufacturers have to find optimum solutions that yield the best possible cost-performance ratio. In the future, standardized modular building blocks with smart integrated primary and secondary technology, embedded value-added features and economy-of-scale manufacturing, will be required. The results will be a direct cost saving and reduced life cycle costs for the overall power delivery system.

Since the number of consumers operating highly automated processes is on the increase, a new market is developing for PQ systems in the medium-power range (100 kW to 1 MW).

A survey of power quality systems

A wide range of products is currently available for improving the PQ of HV transmission and MV and LV distribution grids [2–13].

In MV distribution grids, power quality solutions consist mainly of primary components that provide appropriate control of the system itself. For automated grids, an interface to the superordinate information and control system can be provided. 2 shows typical solutions which focus on primary technology.

Systems based on power electronics conversion

The best-known systems for MV grids are the static var compensator (SVC) for compensating reactive power, the dynamic voltage restorer (DVR), the MV uninterruptible power supply (MV-UPS) and the static synchronous compensator (STATCOM) [2–5]. Another one is the solid state transfer switch (SSTS), which allows the customer to switch to another feeder if a fault occurs in the connecting MV distribution grid. Modern power electronics based PQ systems are equipped with enhanced, low-loss, high-power semiconductors for switching frequencies of more than 1 kHz. This results in a very short response time and in low volume filter effort.

Power electronics based solutions for LV grids are different versions of the LV UPS system (offline, online and line interactive) for protecting sensitive loads against both voltage fluctuations and complete outages, as well as active filters to compensate current harmonics.

Systems based on improved traditional technology

Synchronous switched MV circuit-breakers and power factor compensation modules (PFC modules) with switched capacitor banks and resonance protection, form the other group of devices for improving power quality [6–8]. All of these are based on traditional switching technology. Compared with the PE-based solutions, they are very compact, reliable and cost-effective. They enable operating losses to be kept very low and are usually integrated in the standard MV switchgear system. Hence, such systems can use existing current and voltage measurement equipment. However, since their operating mechanisms limit the number of switching cycles they can handle, they are not suitable for all too frequent switching.

Connection of the MV PFC modules can be either centralized (ie, in primary substations for high kVAr ratings), decentralized in the MV distribution grid,

3 High-speed transfer system (HSTS) comprising two fast-acting circuit-breakers (total transfer time <30 ms). Rated voltage up to 24 kV; load current up to 2500 A; short-circuit current up to 40 kA. The HSTS is accommodated in two normal sized MV switchbays.

1 *Circuit-breaker with magnetic actuator*
2 *HSTS control unit*
3 *Switchbay control unit*

or, alternatively, on the LV side, which has advantages for the lower kVAr range. A PFC module on the MV side of the secondary substation, installed at any point in the ring, compensates the power factor not only for the loads of that particular substation, but also for the loads of the neighboring stations. This allows a smaller number of PFC modules to be installed. Good control of the power factor and the voltage drop on the MV side is also guaranteed.

An attractive alternative to the SSTS in terms of cost and losses is the high-speed transfer system (HSTS), which consists of fast-switching circuit breakers with magnetic actuators. This solution offers high reliability for a limited investment. The HSTS switches over to another supply in a very short time (typically less than one period). **3** shows an HSTS made up of two fast, magnetically driven circuit-breakers controlled by a sophisticated control system which guarantees fast and safe transfer.

Distribution Automation

PQ control has traditionally been one of the main objectives of Distribution Automation (DA) [9–11]. Minimizing the consequences of faults and keeping the voltage within tolerable limits are the most common PQ-related features provided by DA. These tasks are performed by intelligent electronic devices that receive their input from a range of different sensors, usually primary control equipment, such as switches and reclosing devices, capacitor banks, active filters, transformer taps, etc. Control schemes based on local autonomous intelligence, as well as schemes utilizing coordinated network-wide control can be found. The former is most widespread today as reclosing devices and circuit-breakers belong to this category.

In principle, substation and feeder automation systems include the same functionality. However, as there are relatively few substations, primary equipment is more costly, and the consequences of faults are more severe than for equivalent equipment further downstream, automation is far more common in substations than, for example, in MV feeder equipment. The *Table* gives an overview of how DA contributes to improved power quality.

Table

Contribution made by Distribution Automation (DA) to power quality improvement

MV Substation Automation
- Control & monitoring of breakers
- Primary substation condition monitoring
- Fault location, isolation & restoration
- Control of reactive power & voltage

MV Feeder Automation
- Control & monitoring of feeders
- Secondary substation condition monitoring
- Fault location, isolation & restoration
- Control of reactive power & voltage
- Wide area communication

LV Customer Automation
- Automated meter reading
- Remote service connection/disconnection
- Load control

The remarkable developments currently taking place in web technology and wireless communication are preparing the way for a new approach to remote monitoring and control in distribution networks. Secondary substations containing integrated web-servers and wireless GSM communication allow utilities to monitor and control critical nodes in their network at a reasonable price, since no investments need to be made in either the communications or the network control center.

As communication is based on the existing infrastructure, costs are limited to actual use, eliminating the need for substantial up-front investment. A web-browser, with which most people are now familiar, is all that is needed at the operator's end to monitor and control a secondary substation 4.

This represents a major milestone for customers, mainly because the investment required for small-scale systems is dramatically reduced. In addition, the new technology allows access from virtually anywhere, for example from a service vehicle, a control center, even from home. Finally, since the technology is intended for the consumer market, there are substantial benefits when it comes to interfacing with other systems, hardware and software development, support, etc.

An obvious, and crucial, concern when using web technology and public communication networks is security. No compromises are allowed. It is worth considering that web-based bank services have been around for a long time, while virtually every company is looking at new web-based business-to-business solutions as a means of simplifying trading with other companies. Neither of these businesses would tolerate any compromises where security is concerned, and the mere fact that they exist proves that web-based solutions can be made absolutely secure.

The required security can be achieved using any one of several techniques, for example: passwords, encryption, or 'call-back' schemes, in which remote operation is only allowed when the communication link is established by the controlled device itself.

Distributed resources, premium power

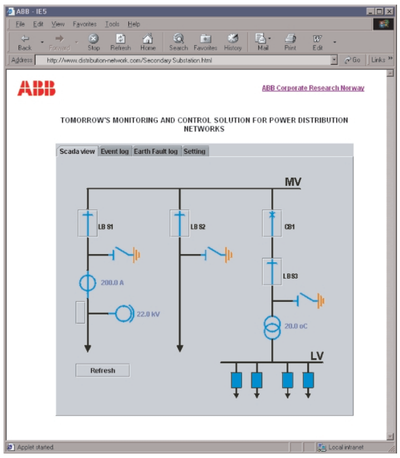
Distributed resources

Distributed resources are grouped into two different categories: uncontrollable and controllable.

Examples of uncontrollable distributed resources are wind turbine generators and photovoltaic systems. Most of them are promoted by governments and environmental organizations worldwide to help develop an environmentally friendly electric energy market. Because of the uncontrollability of the power level, they are a source of PQ problems.

Controllable distributed resources are of two types: generating units with full power controllability, such as conventional diesel generator sets or environmentally friendly generators (eg, small gas turbines and fuel cells), and energy storage devices with short-time storage capability, for instance batteries, flywheels and high-density capacitors. Within an existing grid, this kind of distributed resource can be used for peak power shaving, for tariff reductions or to avoid having to upgrade a grid, also to increase the efficiency of primary energy utilization through cogeneration. All controlled distributed resources can contribute to improved PQ, especially storage equipment for bridging short-time dips or outages, which are the most frequent PQ problems.

4 Web-based monitoring solution for a secondary substation



Premium power systems

These systems are designed for operation in MV distribution grids close to the customer. Premium power systems provide real-time network control, protect sensitive customer equipment from network disturbances, and protect the MV distribution grid from power disturbances originating on the load side.

A modular building block approach makes different configurations possible to take account of customers' different needs.

For example, the configuration shown in 5 is a premium power system connected to the MV ring. Normal and protected AC loads as well as DC loads can be supplied with power on the LV side. The premium power system consists of a secondary substation and local power generation units.

The secondary substation includes an integrated system for mitigating voltage dips or short-time outages. The LV fast switch between the unprotected and protected loads isolates the two parts of the busbar in the event of a fault.

Both short-time energy storage devices and local power generation is interconnected via a DC bus. Use of a common DC bus leads to a smaller number of components and allows connection to the grid via one common inverter. The DC link can be configured to enable different complementary units to be easily linked together.

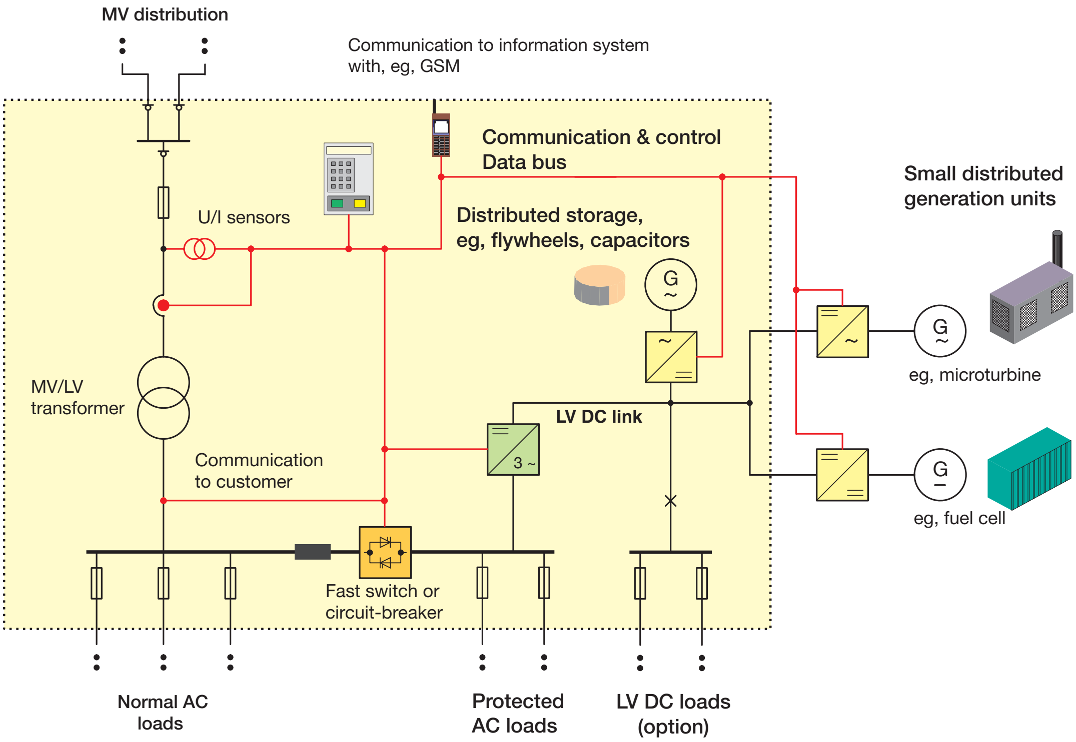
As modern distributed generation units, such as microturbines and fuel cells, have limited load-following capability, additional short-time energy storage units are necessary to guarantee stable system operation. The combination of a microturbine and flywheel, for instance, guarantees good load-following performance.

The integrated solution results in considerably lower life cycle costs than with traditional, non-integrated versions.

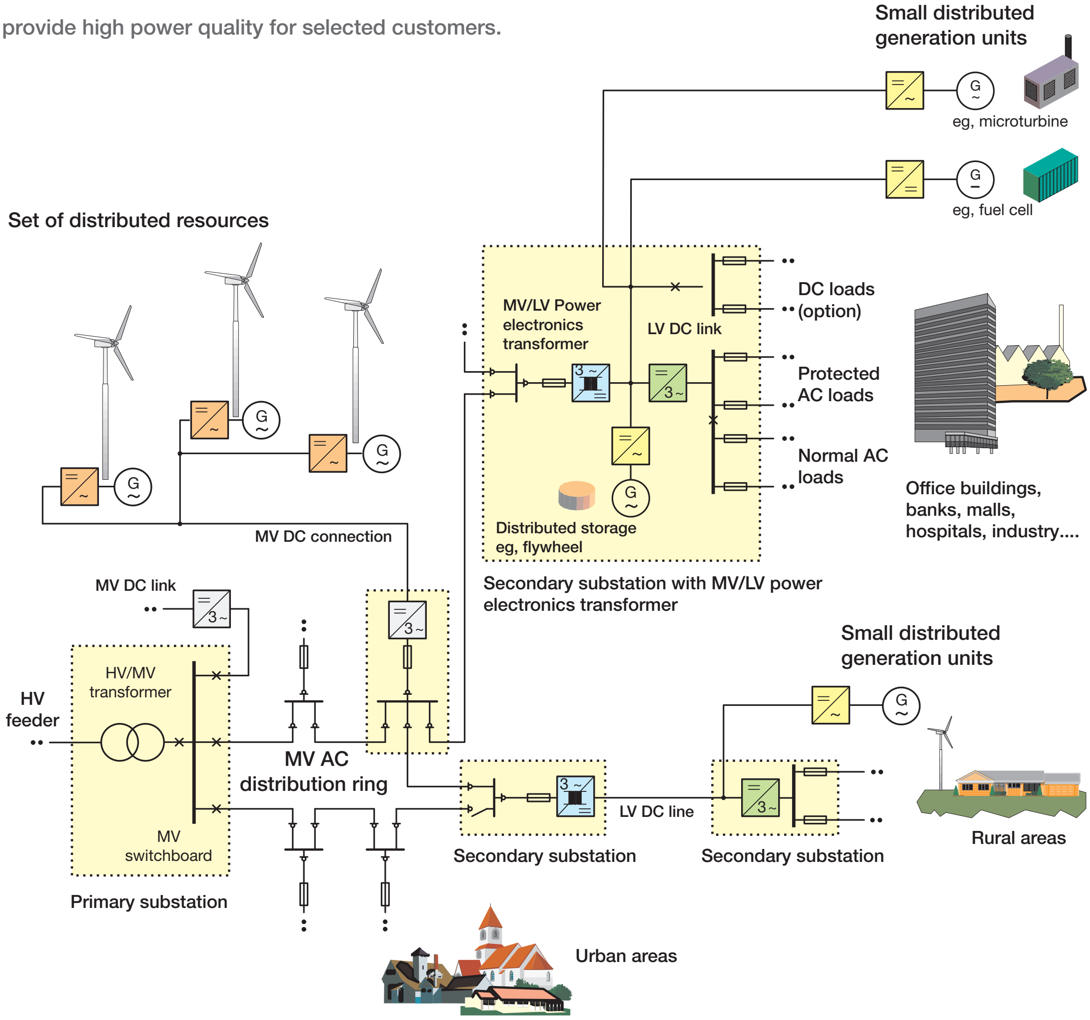
Future trends

HVDC technology will play an important role in the coming decades due to the availability of new high-power semiconductors with fast switching capabilities that allow extremely compact installations. Important breakthroughs in HVDC technology and in DC cable technology are resulting in the HVDC system approach beginning to be applied to the distribution grid level [15]. Hence, within the next few years the economical power range of HVDC systems is

5 Example of a pre-engineered premium power system installed in the secondary substation, with embedded UPS system to protect critical loads, integrated interface for distributed resources and advanced distribution automation products



6 MV distribution grid with DC subsystems (LV and MV grid) and a high-level of distributed resources. High frequency switched converters with a DC link provide high power quality for selected customers.



expected to fall to just a few MW, and to voltage levels typical of the MV distribution grid [12–14].

Until now, AC/DC converter technology has been too expensive for routine use in utility MV distribution systems. Technical innovations are changing this situation and making the replacement of even a typical 50-Hz MV/LV distribution transformer in the lower power range (100 kW to 2 MW per unit) by a high-frequency switched 'electronic transformer' economically feasible. The power electronics based transformer can operate either off an AC MV input (three-phase or single-phase) or a DC MV input. The system enables load balancing and guarantees low harmonic current distortion. Voltage dips or even complete short-time outages on the MV side can be bridged without any problems using available DC-link capacitors. For longer outages, local controllable resources can be connected directly to the DC link. 6 shows such a future MV distribution grid.

Moreover, MV and LV distribution networks benefit in several ways from greater use of DC links superimposed on the traditional AC MV distribution grid [15]:

- Local LV DC distribution networks can supply power direct to DC processes or power electronics systems with a DC link (eg, AC-motor drives) on the customer's site.
- The transfer of disturbances between MV distribution grids is drastically reduced when an MV DC link is used.
- Superimposed MV DC links allow efficient integration and high levels of power for large and widely spread distributed generation schemes (eg, offshore windfarms).
- Superimposed MV DC links in conjunction with appropriate power flow control provide high power quality for large regions and better utilization of the MV distribution grid

■ The cost of cables used for MV DC links are considerably lower than for AC.

Power electronics based, high frequency switched MV/LV transformers will begin as a niche product, where the higher functionality described above is of greater value.

The market share of such power electronics based solutions will grow at the same rate at which the cost and power losses of power electronics equipment falls. This will assure them of their place in the existing AC MV distribution grids.

Conclusions

As highly reliable, low-loss power semiconductors with highfrequency switching capability become widely available and their price falls rapidly, it can be expected that power electronics products and solutions will play an increasingly important role in the future of MV distribution. Power electronics solutions will serve to improve power quality and as very efficient interfaces between distributed power resources and the grid.

In addition, new solutions combining highly integrated apparatus based on conventional technology and controlled by state-of-the-art digital electronics with information technology will allow considerable improvements in the power quality of MV and LV distribution networks.

The coming regulatory and economic valuation of power quality in the electricity tariff structure in more and more markets will also support the economic attractiveness of investment in systems designed to improve power quality.

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