ECONOMICAL POWER QUALITY ENHANCEMENT IN MV DISTRIBUTION NETWORKS BY POWER ELECTRONICS SOLUTIONS

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SUMMARY

Besides the classical reasons for power quality problems a growing share of power generated by renewable energy sources, together with a reduction of redundancies in lines and substations, have a negative impact on the Power Quality (PQ) in the medium voltage (MV) and the low voltage (LV) power distribution network. Some PQ deficiencies, like short term outages have an extremely high impact on a small percentage of consumers (e.g. for those with PQ-sensitive processes). Other PQ deficiencies, like flicker, have an impact on nearly all consumers. Therefore, the level of economically justified investment for mitigation of PQ deficiencies varies in a wide range. New PQ regulations have a superimposing influence.

As a consequence, utilities, system operators and device manufacturers have to find optimal “cost-performance ratio” solutions, which are fully compatible with existing installations of the distribution network.

Today, PQ-systems in the MV/LV-distribution grid are based either on improved traditional technology (e.g. switched capacitor banks) or on Power Electronics (PE) conversion technique (e.g. the Dynamic Voltage Restorer to mitigate voltage fluctuations). Those PQ-systems are normally installations dedicated to one particular PQ problem resulting in high investment costs.

However, due to the unique properties of PE-modules several PQ functions can be realised within the same device. Therefore, the next generation of PE based PQ-systems will not only be designed to mitigate voltage dips or to bridge short term outages or to compensate current harmonics generated by the loads. Modern PQ-systems will provide all these “classical” functions and will allow also the simple connection of local power generation units to bridge long-term outages (e.g. fuel cells or a small gas turbine). The figure shows such a system in the form of a prefabricated compact secondary substation.

Technologies derived from modern HVDC-systems will play an important role in the architecture of modern future distribution systems, because this allows extremely compact installations with extended functionality integration. Such a future oriented PQ-system will comprise a high frequency switched “electronic transformers”, integrated short term bridging devices and simple interfaces to local power generation units to bridge long-term outages and to serve for co-generation.

In this case the higher costs of such an electronic switched transformer (compared to a standard power frequency one) can be compensated easily by counting the integrated “Free of charge” functions together.

Increased use of PE causes new challenges on the system level. Novel system design approaches and new methods to analyse such complex distribution systems will be requested. Applied to a specific network these methods are used for deriving the functions needed for improving the quality of the entire system and e.g. to find a critical path in the distribution grid with poor PQ. Technology integration and combining functions is the base for an economic attractiveness, low investment costs, low life cycle costs, low operational losses, high reliability and long life time. This results in an excellent return on investment for the network operator.

![Future oriented PQ-system installed in a secondary substation](image-url)
1. INTRODUCTION

Besides the classical reasons for power quality problems a growing share of power generated by renewable energy sources, together with a reduction of redundancies in lines and substations, have a negative impact on the power quality in the Medium Voltage (MV) and the Low Voltage (LV) power distribution network. At the same time the number of consumers with Power Quality (PQ) sensitive processes is increasing. Since the economic consequences of power disturbances for at least those consumers can be extremely high, a wide range of products for the improvement of PQ for both, the MV- and the LV grid are available. These products are based either on improved traditional technology or on power electronics conversion technique.

Within this paper the economic drivers and possibilities of how electrical power distribution systems can be designed to ensure a suitable level of PQ will be presented. A brief description of the economical consequences and technological trends, an overall architecture is derived and discussed. After shortly highlighting the consequences for system analysis and synthesis the second emphasis is given on application examples.

2. ECONOMIC DRIVERS

To meet the escalating demands of the competitive and open deregulated electrical energy market in future only economically attractive and technically demanding solutions on the system and on the device level will be requested to improve the PQ and to allow to interface Distributed Resources (DR), like distributed generators, storage etc., in an efficient way. On the system level a wide area power flow control with special attention of DR are of importance to facilitate the increasingly complex utilisation of the MV- and the LV distribution network. On the device level standardised modular building blocks with smart integrated primary & secondary technology, embedded value adding features and economy-of-scale manufacturing will be requested, see [1], [2]. Information Technology and Power Electronics (PE) conversion technique will play an important role, see [3]-[8].

The decision to invest in a PQ-system is always based on an economic evaluation because the total life cycle costs of a PQ system have to be considerable lower compared to the economic consequences or compared with a non technical attempt (e.g. by an insurance to cover the costs caused by damages), see [9].

Costs of damages caused by an outage can range from millions of Dollars for a small number of consumers (those with a highly automated production like microchip manufacturers and chemical industry) to nearly nothing for the majority of them. Other PQ- problems like flicker will affect more consumers because human beings, working or living in the neighbourhood of a flicker generating device are often stressed by the consequences of the flicker phenomenon (e.g. changing light density of lamps). Flicker still has negative impact on sensitive production processes, too.

As an example in diagram 1a and diagram 1b typical “PQ Sensitivity Dependencies” related to the number of consumers in a MV distribution grid are illustrated. Diagram 1a shows the tendency of related costs in case of a short outage. Diagram 1b depicts an another case. Here the costs for the mitigation of flicker in dependence of the number of consumers are illustrated schematically.

![Figure 1: Costs of different PQ events in a typical electrical power distribution grid versus number of consumer applications](image-url)
3. PRESENT STATUS AND MARKET NEED

Today PE-based solutions to improve the PQ are usually installed on the LV-side and a huge worldwide market for those systems exists, see [10]-[12]. PE based solutions on the LV-side are the different versions of LV UPS-systems (passive-standby, double conversion and line interactive) to protect sensitive loads against voltage fluctuations and complete outages as well as Active Filters to compensate current harmonics, see [13]-[14]. The most known systems on the MV-side are the Static Var Compensator (SVC) to compensate reactive power, the Dynamic Voltage Restorer (DVR), the MV Uninterruptible Power Supply (MV-UPS) and the Static Synchronous Compensator (STATCOM). The Solid State Transfer Switch (SSTS) enables the consumer to switch to another feeder in case of a fault in the connecting MV distribution grid, see [6] and [7].

The power level of a PQ-system in MV/LV distribution systems is ranging from small ride through systems with a low power level of less than one kW up to facility wide protection systems in the MW-range. For systems with a higher power level the MV-side is more favourable.

Today, most PQ-systems have local control. Only in case of an automated distribution network an interface to a network control system is provided.

According to [10] the total PQ-market can be differentiated by load size and consumer (industrial, commercial, residential). PQ-equipment with a power level of less than 30 kVA represent 71% of the revenues of the total PQ-market (mainly computer protection systems). Only 4% are related to equipment with a power level of more than 500kVA (mainly MV-side) and the remaining 25% are related to equipment in the mid power range (30-500 kVA). Figure 2 gives an overview.

![Figure 2: PQ market segmentation by load size, according to [10]](image)

Besides the classical PQ-problems which can be mitigated with the standard PQ-systems as described above, the growing share of DR (uncontrollable and controllable one’s) and new network control strategies (e.g. the Virtual Utility approach) with wide area communication requirements have to be considered.

Uncontrollable DR are e.g. wind turbine generators and photovoltaics systems. The power level of such uncontrollable DR is in the range of less than 10 kW (e.g. photovoltaics systems) and of more than 1 MW for large scale wind turbines. Because of the uncontrollability of the power level and of short term fluctuations of the power generation they are a source of PQ problems.

Controllable DR are on the one hand generating units with full power controllability, like conventional diesel generator sets, environmentally friendly generators like small gas-turbines or fuel cells and on the other hand energy storage devices with short term energy storage capability, like batteries, flywheels and high density capacitors. Within an existing grid this kind of DR can serve for peak power shaving, for tariff reductions or to avoid upgrading of the grid and for co-generation to increase efficiency of primary energy utilisation. Today a new market for such controllable environmentally friendly DR in the power range of 50kW-1MW is developing very fast. It is expected, that already in the year 2010 approximately 25% of all new installation will be DR kind. All controlled DR can contribute to PQ improvements, in particular storage equipment for bridging short term dips or outages which are the most frequent PQ problems.

Hence, in future classical PQ-problems cannot be considered alone any longer and the integration of different functions for different applications will lead to economically attractive solutions.

Besides the classical functions like transformation and protection, in table 1 an overview of typical functions in modern power distribution systems and the market related to these functions (DPG = Distributed Power Generation Market, DA = Distribution Automation Market) is given.

<table>
<thead>
<tr>
<th>Function</th>
<th>Market</th>
</tr>
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<tbody>
<tr>
<td>Mitigation of voltage dips</td>
<td>PQ</td>
</tr>
<tr>
<td>Bridging of complete outages</td>
<td>PQ</td>
</tr>
<tr>
<td>Flicker compensation</td>
<td>PQ</td>
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<tr>
<td>Compensation of harmonics</td>
<td>PQ</td>
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<tr>
<td>Load balancing</td>
<td>PQ</td>
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<tr>
<td>Power conditioning</td>
<td>PQ</td>
</tr>
<tr>
<td>Peak load shaving</td>
<td>DPG</td>
</tr>
<tr>
<td>Distributed power generation</td>
<td>DPG</td>
</tr>
<tr>
<td>Remote control &amp; monitoring</td>
<td>DA</td>
</tr>
<tr>
<td>PQ-monitoring</td>
<td>DA</td>
</tr>
</tbody>
</table>

Table 1: Typical functions of a future oriented PQ-system

Today, each function can be realised by one discrete solution, see [6] and [7]. But due to the unique properties of PE modules several functions can be realized within the same devices. The integrated solutions result in considerably lower life cycle costs compared to the traditional non-integrated versions.

4. NEXT GENERATION OF PQ-SYSTEMS
Figure 3 shows a future oriented PQ-system, able to fulfil the functions listed in table 1.

The novel PQ-system consists of a secondary substation with a connection to the MV-grid via a typical distribution transformer. On the LV-side normal and protected AC loads as well as DC loads can be supplied. A LV fast switch between the normal and the protected AC-loads isolates the two parts of the LV-switchboard in case of a fault.

The integrated conditioning system consists mainly of a LV DC-to-AC converter connected to a common DC-bus on one side and to the protected AC loads on the other side. The system allows to mitigate voltage dips or short term outages with an integrated energy storage device (e.g. flywheel, battery or capacitor). In addition, the system enables the simple connection of local power generation units to bridge long-term outages and to serve for co-generation (e.g. fuel cells or small gas turbines). Both, short-term energy storage devices as well as local power generation units are physically interconnected via the DC bus.

In the natural operation mode (no grid disturbances) the DC-to-AC converter acts as an active filter to compensate current harmonics generated by the loads. Simultaneously electrical energy generated by a local generation unit can be fed into the grid and the LV DC-link can be loaded with some other loads (e.g. a drive). In case of an outage of the AC-supply the system serves as a line interactive UPS.

Figure 4 shows measurements during the natural operation mode. To show the improvement achieved and to visualise the power flow, the active power \( P \), the total apparent power \( S \), the fundamental reactive power \( Q \) and the distortion reactive power \( D \) caused by the current harmonics were determined using a suitable application software.

5. FUTURE SYSTEM ARCHITECTURE

Important breakthroughs in DC-cable technology and in technologies derived from modern HVDC-systems will play an important role in the future, see [15] as example, because new high power semiconductors with fast switching capability allow extremely compact installations with extended functionality integration. Within the next years the economical range of a PE-based MV power distribution system is expected to go down to

\[ \text{approximately 1 kW converter losses have to be considered to equalise the complete power budget.} \]
typical power and voltage levels of the MV-distribution grid.

Driven by these technical innovations also the economical replacement of a MV/LV distribution transformer with a high frequency switched “electronic transformer” seems to be feasible. The PE based transformer can operate either on an AC MV input (3 phases or 1 phase) or a DC MV input. The electronic transformer can be considered as a fully integrated PQ-system which enables load balancing, mitigates flicker and guarantees low harmonic current distortion. Voltage dips or outages on the MV-side can be bridged.

Figure 5 shows such a future oriented PQ-system. The system consists of a high frequency switched “electronic transformer” with MV and LV DC-bus, an integrated short term bridging device (e.g. a flywheel connected directly to the common LV DC-bus) and an interface for local power generation units to bridge long-term outages and to serve for co-generation.

Moreover, as mentioned in [3]-[5], greater use of DC links superimposed on the traditional AC MV distribution grid has several advantages for MV- and LV distribution networks:

- Local LV DC distribution networks, can directly supply power to DC-processes or power electronics systems with DC-link (e.g. AC motor drives) on the consumer's site.
- Transfer of disturbances between MV-distribution grid sections will be drastically reduced by using a MV DC-link.
- Superimposed MV DC links allow an efficient integration and a high level of power generated by big and widespread DR (e.g. offshore wind parks).
- Superimposed MV DC-links in conjunction with an appropriate power flow control will provide a high power quality for large regions and a better utilisation of the MV distribution grid.
- Transmission network access for distribution system with symmetrization and power flow control without increase in short circuit power.
- The costs of cables used for MV DC-links are considerably lower than for AC.

Consequently new challenges on the system level will arise. Novel system design approaches and new methods to analyse such complex distribution systems will be requested.

Today, a system analysis is mainly covering planning and operation issues. For the expansion planning the solution set has to comprise the whole range of PE applications in terms of possible functions. For distribution system operation the analysis results can additionally be used for topology optimisation. However, the needed analysis functionality is beyond the traditional planning tools, see [16] as example.

The functional system specification creates a certain need for special design and analysis tools. Beyond the already existing system analysis tools where all dynamic and transient phenomena can be studied to a very detailed extend, functional analysis is enabled in the first stage by certain quality performance indices. Applied to a specific network these performance criteria are used for deriving the functions needed for improving the quality of the entire system, e.g. to find a critical path in the distribution grid with poor PQ.

The system models used for this type of analysis are the same as used for well known network calculation processes. Only performance measurement algorithms have to be added to a already existing simulation software. In conclusion this specific way of system analysis helps to optimally

- visualise paths of different supply quality
- calculate quality performance indices
- locate and size DR
- scale the reliability of supply according to the distribution network owners and operators need.
6. THE VALUE OF INTEGRATION

The power electronics based high frequency switched MV/LV transformer will start as a niche product, where a high functionality is of value. In this case the higher costs of such an electronic switched transformer (compared to a standard power frequency one) can be compensated easily by counting the integrated “Free of charge” functions together. This is illustrated schematically in figure 6 (curve no. 3), where the costs of the such a future oriented PQ-system in dependence of the number of functions is shown. In addition, a comparison with a traditional approach (curve no.1 with step by step integration by adding modules for each new function) and the PQ-system according to figure 3 (curve no. 2) is given.

![Figure 6: Cost comparison (in per unit) of different PQ-systems depending on the No. of functions needed](image)

7. CONCLUSION

Driven by the open, competitive and deregulated electrical energy market, cost effective and value generating solutions providing a high Power Quality for at least sensitive processes are requested. In this paper the systemic impact of PQ solutions within the distribution grid has been discussed. It has been shown that the majority of critical loads (i.e. those who are affected by poor power quality) is below 500 kVA. In this case the economy is more difficult to reach with classical solutions than with new approaches based on power electronics as key technology. These solutions are fully compatible with the existing installations of the distribution network and designed according to economic attractiveness, low investment costs, low life cycle costs, low operational losses, high reliability and long life time – resulting in an excellent return on investment for the network operator. Besides the application of power electronics it has been shown, that the function oriented system analysis yield a more detailed insight into the real design requirements. By combining functions within one component a distinctive cost reduction for the entire system costs can be achieved, so that both, power electronic applications and technology integration on a function base represents the basis for most economic distribution system expansion.

8. REFERENCES