An Output Regulation-Based Unified Power Quality Conditioner With Kalman Filter

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Abstract— Power Quality is characterized by parameters that express harmonic pollution, reactive power and load unbalance. The best possible solutions to these problems are reviewed and their control systems are elaborated on. Solutions present in the field are explained and field results are presented. It is shown that by using the right technology a variety of Power Quality problems can be solved rendering installations trouble free and more efficient, and can render them compliant with even the strictest requirements. Different applications of a Unified Power Quality (UPQC) for the improvement in power quality are presented. In addition to the power-factor correction, load balancing and mitigation of voltage and current harmonics, it can regulate the load voltage against voltage sag/swell and voltage dip in a three-phase three-wire distribution system for different combinations of linear and non-linear loads.

Keywords— Unified Power Quality, reactive power, harmonic pollution, power-factor correction, load balancing, voltage sag/swell.

I. INTRODUCTION

Ideally, the best electrical supply would be a constant magnitude and frequency sinusoidal voltage waveform. However, because of the non-zero impedance of the supply system, of the large variety of loads that may be encountered and of other phenomena such as transients and outages, the reality is often different. The Power Quality of a system expresses to which degree a practical supply system resembles the ideal supply system.

- If the Power Quality of the network is good, then any loads connected to it will run satisfactory and efficiently. Installation running costs and carbon footprint will be minimal.
- If the Power Quality of the network is bad, then loads connected to it will fail or will have a reduced lifetime, and the efficiency of the electrical installation will reduce. Installation running costs and carbon footprint will be high and/or operation may not be possible at all.

In order to characterize the Power Quality, different indices have been defined and will be reviewed later in this article.

II. POWER QUALITY PARAMETERS

Reactive power and power factor (cos)

In an AC supply, the current is often phase-shifted from the supply voltage. This leads to different power definitions (Fig. 2):
- The active power P [kW], which is responsible of the useful work, is associated with the portion of the current which is in phase with the voltage.
- The reactive power Q [kvar], which sustains the electromagnetic field used to make e.g. a motor operate is an energy exchange (per unit of time) between reactive components of the electrical system (capacitors and reactors). It is associated with the portion of the current which is phase shifted by 90° with the voltage.
- The apparent power S [kVA], which gives a geometrical combination of the active and of the reactive powers, can be seen as the total power drawn from the network.

The ratio between the active power and the apparent power if often referred to as the displacement power factor or cos Ø, and giving a measure of how efficient the utilization of the electrical energy is. A cosØ that equals to 1 refers to the most efficient transfer of useful energy. A cosØ that equals to 0 refers to the most inefficient way of transferring useful energy.
Voltage unbalance

In the symmetrical components theory Fortescue has shown that any three phase system can be expressed as the sum of three symmetrical sets of balanced phasors: the first set having the same phase sequence as the initial system (positive phase sequence), the second set having the inverse phase sequence (negative phase sequence) and the third one consisting of three phasors in phase (zero phase sequence or homopolar components).

A normal three phase supply has the three phases of same magnitude but with a phase shifted by 120°. Any deviation (magnitude or phase) of one of the three signals will result in a negative phase sequence component and/or a zero phase sequence component.

The definition of voltage unbalance is usually expressed as the ratio between the negative phase sequence component and the positive phase sequence component. This parameter is expressed in %.

Flicker

According to the International Electrotechnical Vocabulary (IEV) [4] of the International Electrotechnical Committee (IEC), flicker is defined as 'Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time'. From a more practical point of view one can say that voltage fluctuations on the supply network cause change of the luminance of lamps, which in turn can create the visual phenomenon called flicker. While a small flicker level may be acceptable, above a certain threshold it becomes annoying to people present in a room where the flicker exists. The degree of annoyance grows very rapidly with the amplitude of the fluctuation. Further on, at certain repetition rates of the voltage fluctuation, even small fluctuation amplitudes can be annoying.

III. ADDRESSING HARMONIC POLLUTION AND LOAD INBALANCE

Historically passive filters have been and are still being proposed to mitigate harmonic pollution. In LV installations, these solutions become less and less applicable given that:
- LV installations are very dynamic leading over time relatively fast to passive filter overload
- Modern loads (e.g. VFD’s, modern lighting systems, …) have a very good cosØ already (possibly even capacitive) leading to overcompensation when a passive filter is installed. This in combination with limited capability of typical backup generators to run on capacitive cosØ makes that the reliability of an installation may be reduced.
- Passive filters installed in LV installations typically address the lower harmonic orders, whereas nowadays there is tendency to get more problems in installations due to higher frequency harmonics. Hence, the passive filter may not solve the technical problem if present.
- The passive filter filtering efficiency is defined by the impedance ratio of the passive filter impedance and the network impedance and therefore cannot be guaranteed. Hence it is virtually impossible to guarantee compliance with regulations by using passive filters.

For the reasons mentioned above there is a worldwide tendency to move away from passive filtering solutions in favour of active filtering solutions in LV and MV applications.

Most commonly found active filters are power electronics based electrical equipment that are installed in an installation on a parallel feeder to the polluting loads (Fig. 13).

An active filter consists of a power stage and a control system:
- The power stage typically uses a IGBT-based PWM inverter, coupled to the network through a coupling circuit. The IGBT switches are controlled in such a way to amplify the control signals representing the compensating currents and voltages. The coupling circuit contains an output filter section, which acts as a low-pass filter absorbing the high frequency switching components created by the PWM inverter, leaving the compensating harmonic currents to flow.
- The control system relies on current measurements to obtain information on which harmonics are present in the network. The filter control system then calculates the control signals, which represent the compensating current to be injected into the network. These control signals are finally sent to the PWM inverter, which amplifies and couples them to the supply network.

In the more advanced ABB PQF filters, the controller also analyzes the customer requirements programmed by the user, and can then generate for each harmonic frequency a
harmonic current ("compensation current") in perfect opposite phase to the polluting current that was measured. Thanks to the active concept, active filters are not-overloadable but will continue to run at nominal rating if the load demand would be higher than their capacity. Also, active units can be extended quite easily opposite to the difficulty often encountered when trying to extend passive filter units. In order to obtain good performance throughout the filter bandwidth, two control aspects are critical:
- The use of a genuine closed loop control system, and
- The frequency domain approach for the processing and controlling of the polluted current.

These aspects, present in the ABB PQF units, are elaborated on below:
For active filters the closed loop and open loop aspect can be found in the location where the active filter measurement current transformers (CT”s) have to be installed (Fig. 14).

In closed loop systems, the current upstream of the load and filter connection are measured and corrective action is taken. Any measurement or other inaccuracies can be automatically cancelled out and compensated for thanks to the closed loop concept.
In open loop systems, the load current is measured and processed and the inverted signal of the measured image is presented to the IGBT-bridge. As no feedback exists, the resulting line current may typically contain error components which are not seen by the control system.
In summary, the following properties can be assigned to a closed loop control system as opposed to an open loop control system [11]:
- Closed loop systems allow canceling out errors in the control loop and in the behavior upon external disturbance. Open loop systems do not have this capability.
- Closed loop control systems can react as fast as open loop control systems providing that the control loop parameters are set for this behavior.

Another aspect of the control system of an active filter is whether to use a time-domain or a frequency-domain approach.
- In the time-domain approach, the fundamental frequency component is removed from the measured current signal. Then the remaining waveform is inverted and the resulting signal drives the IGBT-bridge of the active filter. In this approach, In this approach it is ignored that the network characteristics are different for different frequencies, as well as the characteristics of the current measuring CT”s and the characteristics of the electronic hardware and software on board of the active filters. As a result, in practice active filters using this control approach have a deteriorating performance with increasing frequency.
- In the frequency-domain approach each harmonic and its corresponding system characteristics is treated individually and performance can be optimized for the harmonic components in the filtering bandwidth. As a result the same (high) filtering performance can be maintained through the filtering bandwidth. Fig. 15 represents schematically the principle of the frequency-domain filtering approach.

Overall it can be concluded that the best filtering performance can be obtained with an active filter using a closed loop control system and an individual frequency domain approach. Other advantages of such filters include:
- User requirements can be preset for each harmonic (e.g. standard compliance requirement).
- Individual harmonics can be selected to allow optimal use of the filter resources (e.g. no need to filter the 5th harmonic if this harmonic is already filtered by another existing filtering device).
- Precise targets for cosØ can be set and maintained. This allows such active filters to operate in applications where accurate cosØ control is required to avoid disturbances in the installation (e.g. tripping of a generator).
- Precise load balancing can be implemented allowing neutral systems to be offloaded and ensuring that neutral to earth voltage is kept to minimal levels. Also, it can be ensured that the load seen by e.g. a UPS is balanced. Fig. 16 gives an example of a balancing application by using a closed loop control ABB PQF active filter.
In addition to the functional aspects, more advanced active filters contain functions that allow minimizing equipment running losses and providing extra reliability to the installation thanks to secondary functions.

IV. FIELD RESULTS
Power Quality products are being used in a variety of applications for a variety of reasons. This section presents some field results obtained with ABB high performance Dynacomp TSC banks and ABB PQF active filters.

A first example considers the Power Quality on offshore rigs. Such applications are often characterized by a low cosØ value, a large reactive power demand and a high harmonic content of voltage and current. This then typically results in an inefficient operation of the rig with possible production stops and associated financial loss, and a non-compliance with certification bureau rules. Fig. 17 shows a typical SLD of such an installation (cf. Table 1).

Given the nature of the problems, it was decided to install an ABB TSC-bank („Dynacomp”) with 7% detuning reactors which main function was to improve the cos Ø drastically and which could also reduce the harmonic pollution to acceptable levels. Table 6 gives the key electrical parameters of the rig with and without the compensator running.

Analysis of Table 6 and Fig. 18 allows concluding that the Power Quality on board of the rig has drastically increased thanks to the compensator installed. The power and current drawn from the power plant has drastically reduced. The harmonic voltage pollution has decreased to acceptable levels. All this resulted in a more efficient and trouble free operation of the installation with higher production rates than ever before: under normal conditions one generator can be switched off, and operating conditions of 110% can be maintained for several weeks without problems. Similar applications on offshore rigs sometimes also include active filters in case the pollution is too high to be handled by a TSC-bank alone or when specific harmonic regulation requirements need to be complied with.

Another problem typically encountered on offshore platforms is that due to the low cos Ø value of the installation, extra required motors cannot be switched on. This is illustrated in Fig. 19 which shows a motor start attempt on an offshore rig. Due to the power limitation of the power plant and the low cosØ of the installation this is not possible however and a potentially dangerous hunting effect is introduced. Therefore the motor has to be switched off.

40 clusters, each with a load in the range of 2 MW. Without the installation of the active filters, the distortion at the LV side of the cluster was about THDV = 12% and the THDI = 27% (Fig. 20).

After the With the compensator installed, the power drawn from the power plant is drastically reduced and sufficient margin is available to start the motor successfully. The
installation could run satisfactory at nominal rating and more efficiently than before.

Another example of Power quality improvement is on the site of an oil field exploitation, made of one central power station feeding many drilling and pumping clusters. The vast majority of the loads were AC drive controlled. There were approximately installation of the active filters, the THDV dropped to THDV = 2% and the THDI = 3% (Fig. 21).

This resulted in a huge improvement of the Power Quality of the clusters allowing the plant to run within IEEE 519 standard limits ensuring trouble free operation of the different clusters.

As seen in previous examples, Power Quality issues often arise in industrial networks due to the presence of a non-negligible number of (large) pollution loads. In commercial applications however, Power Quality is also a concern. In such applications, typically many single phase polluting loads are present which create problems such as:

- Increasing harmonic stress which is put on equipment that is typically more vulnerable than industrial equipment.
- Resonance excitation due to the presence of 3rd harmonic components in combination with capacitor banks with wrongly chosen detuning reactor or no reactor at all.
- Neutral currents in excess of neutral conductors and bus-risers rating.
- Too high neutral to earth voltages which may not be acceptable for product operation and/or from safety point of view.
- The presence of capacitive cosØ due to modern server hardware, this potentially leading to the need to derate UPS-systems etc.

Fig. 22 shows the picture of an office building where Power Quality issues were reported. The elevators regularly broke down, leading to frustration to users, facility management and owner, as well as supply cables running too hot and the presence of other technical failures.

In order to solve the problems ABB installed a combination of suitable power factor correction banks and active filters. This resolved the problems in the building. In addition however, the local Utility has evaluated the solution installed and has concluded that the improvement in Power Quality resulted in a reduction of green house gasses equivalent to taking 25 large cars of the road.

A last example looks at the Power Quality in a prestigious multi-star hotel. This hotel incorporates guest rooms and suites as well as function rooms and business centers. Typical loads encountered are high-speed lifts, dimmer switches and other sophisticated lighting equipment, as well as the typical office equipment including PC’s, printers, etc. As a result of all these loads, the Power Quality had deteriorated to such an extent that the voltage was unstable. As a consequence, changing the operating point of loads in one side of the building would affect also the operation of other loads in other rooms. This was clearly unacceptable as it could lead to loss of customers due to below standard service offered.
A Power Quality solution was sought and after installation of ABB filtering equipment the problems disappeared. Fig. 1 shows a basic system configuration of a general UPQC consisting of the combination of a series active power filter and shunt active power filter. The main aim of the series active power filter is harmonic isolation between a sub-transmission system and a distribution system; it has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). The shunt active power filter is used to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc-link voltage between both active power filters.

Let us first assume that the combination of an ideal series voltage source and an ideal shunt current source represents the UPQC. There are two possible ways of connecting this device at the point of common coupling (PCC). The single-line diagrams of these two schemes are shown in Figures. In these figures the voltage at the PCC is referred to as the terminal voltage $V_I'$. The load voltage, load current and source current are denoted by $V''$, $i'$, and $i$ respectively. The voltage and current injected by the UPQC are denoted by $V''$ and $i''$ respectively. The source voltage is denoted by $V_S$, while $R$ and $L$ constitute the feeder impedance. We shall restrict our discussions to three-phase, four-wire systems only.

![Diagram](image)

**V. RESULTS AND DISCUSSIONS**

**Simulation and Experimental Results**

In this study, a new simplified control algorithm for UPQC is evaluated by using simulation results given in PSIM software. The proposed control algorithm has considerably good simulation results as compared the conventional control algorithms. In the proposed control algorithm, load currents ($i_{Labc}$), mains currents ($i_{Sabc}$), mains voltages ($v_{Sabc}$) and load voltages ($v_{Labc}$) waveforms are shown in Fig. 2, before and after UPQC system is operated.

The feasibility of hardware implementation for the proposed control algorithm was evaluated by design and experimentation of three-phase three-wire UPQC. A three-phase diode-bridge rectifier with the R-L load as the nonlinear load is connected to AC mains to demonstrate the effectiveness of the UPQC with the proposed method. Fig. 3 shows source voltage and current waveform before filtering. After compensation, source current becomes sinusoidal and in phase with the source voltage; hence, both harmonics and reactive power are compensated simultaneously. Before harmonic compensation the THD of the supply current was 29.13% and after the harmonic compensation, it was reduced to 5.75% which complies with the IEEE 519 harmonic standards. In three-phase form source current experimental results for proposed control of shunt active power filter part of UPQC system are shown in Fig. 4 before and after filter operated. These experimental results given above shows that the power quality compensation features of UPQC, by appropriate control of shunt APF can be done effectively. The experimental laboratory prototype series active power filter part is installing and experimental results are planning to publish in future papers.
Fig. 3. Experimental results for source voltage ($v_{sa}$) and source current ($i_{sa}$) before filter operation.

Output side harmonics = 3.126%

Fig. 4. Experimental results for source currents ($i_{sa}$) before and after filter operation.

Input voltage and current vs frequency

5.2 HARMONICS WAVEFORM

5.4 OUTPUT WAVE FORM (without kalman filter)

5.5 OUTPUT WAVE FORM (with kalman filter)
VI. CONCLUSION

This paper reviews the importance of good Power Quality. It presents Power Quality costs and solutions to poor Power Quality. A basic description of Power Quality is given together with its quantification through different parameters. Then, appropriate solutions for each problem type are identified and described. Attention is paid to the importance of the right control systems for the compensating equipment. Field results from different applications are given to give the reader a better insight in the benefits that may be gained by having good Power Quality in installations.

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