Renewable Energy Source for Super Capacitor Based UPQC to Improve Voltage Compensation

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Abstract:
This paper presents a technical review of power quality problems associated with the renewable based distributed generation systems and how custom power devices (CPD) such as UPQC play an important role in power quality improvement. IEEE and IEC standards for renewable energy systems are one of the critical points of interest for the selection of custom power devices. PV systems integration issues and associated PQ problems are discussed. The role of CPDs in enhancing the integration of renewables and providing quality power through custom power park are described. One possible way to overcome such problems is through the utilization of active power filters like a Unified Power Quality Conditioner (UPQC). On the other hand, Super Magnetic Energy Storage (SMES) and Super Capacitors (SC) are the most promising energy storage devices, considering its possible applications in power systems. This concept contains a combination of a SC with a UPQC for power quality improvement in an electric grid. Through the utilization of a SC unit, it is possible to increase the stored energy in the DC link of the UPQC, thus improving the system capacity to overcome power quality issues. Voltage sags and current harmonics are simulated and the system behavior is demonstrated.

Keywords: UPQC, SMES; Power Quality, super capacitor, PV system.

I. INTRODUCTION
The term “Power Quality” (PQ) is most important factor of any power delivery system today. Low quality power affects electricity consumers in many ways. The lack of quality power can cause loss of production, damage of equipment or appliances, increased power losses, interference with communication lines and so forth. The widespread use of power electronics based equipment has produced a significant impact on quality of electric power supply by generating harmonics in voltages and currents. Therefore, it is very important to maintain a high standard of power quality [1-3]. Conventional power quality mitigation equipment use passive elements and do not always respond correctly as nature of power system condition change. The term active power filter (APF) is a widely used terminology in the area of power quality improvement. One modern solution that deals with both load current and supply voltage imperfections is the UPQC. The UPQC is one of the APF family members [4,5]. The UPQC is a combination of series and shunt active filters connected in cascade via a common DC link capacitor. The main purpose of a UPQC is to compensate for supply voltage power quality issues such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems such as, harmonics, unbalance, reactive current and neutral current [6]. SMES and SC both are energy storage devices. The stored energy of SMES can be kept for a relatively long time due to the virtually zero resistance of the superconductor. And the voltage given to the SMES system must be greater than the DC capacitor link voltage of UPQC to store energy in SMES. Replacing the SMES with a renewable energy sourced Super capacitor improves the reliability of system and it also decreases the complexity. Here the supply given to Super capacitor is by renewable source (PV array) which is nothing but a Distribution Generator (DG). In charging SC no separate supply is necessary which should be there for SMES where SC is charged by using a renewable source. Solar and wind are the most promising DG sources and their penetration level to the grid is also on the rise. Although the benefits of DG includes voltage support, diversification of power sources, reduction in transmission and distribution losses and improved reliability [7], power quality problems are also of growing concern. This paper deals with a technical survey on the research and development of PQ problems related to solar and wind energy integrated to the grid and the impact of poor PQ. In recent years, FACTS has appeared as solution of many PQ problems. The FACTS concepts applied in distribution systems has resulted in a new generation of compensating devices. A UPQC is the extension of the UPFC concept at the distribution level. UPQC is the integration of Series APF and shunt APF, active power filters, connected back-to-back on the dc side, sharing a common DC capacitor. The series component of the UPQC is responsible for mitigation of the supply side disturbances [10-12] voltage sags/swells, flicker, voltage unbalance and harmonics. It inserts voltages so as to maintain the load voltages at a desired level; balanced and distortion free. The shunt component is responsible for mitigating the current quality problems caused by the consumer: poor power factor, load harmonic currents, load unbalance etc. It injects currents in the ac system such that the source currents become balanced sinusoids and in phase with the source voltages. The overall function of UPQC mainly depends on the series and shunt APF controller [13]. The
System configuration of a single-phase UPQC is shown in figure given below.

![Figure 1. Block Diagram of UPQC.](image)

UPQC consists of two IGBT based VSC, one shunt and one series cascaded by a common DC bus. The main components of a UPQC are series and shunt power converters, DC capacitors, low-pass and high-pass passive filters, and series and shunt transformers. The key components of this system are as follows.

1) Two inverters—one connected across the load which acts as a shunt APF and other connected in series with the line as that of series APF.
2) Shunt coupling inductor L is used to interface the shunt inverter to the network. It also helps in smoothing the current wave shape.
3) A common dc link that can be formed by using a capacitor or an inductor.
4) An LC filter that serves as a passive low-pass filter and helps to eliminate high-frequency switching ripples on generated inverter output voltage.
5) Series injection transformer that is used to connect the series inverter in the network. A suitable turn ratio is often considered to reduce the voltage and current rating of series inverter.
6) The integrated controller of the series and shunt APF of the UPQC to provide the compensating voltage reference Vc and compensating current reference Ic.

**II. SYSTEM OVERVIEW**

The designed system is depicted in Fig. 2. The simulated grid contains a power source, which was simulated using a three phase programmable power source in Simulink, a pure resistive load and the hybrid system consisting of the UPQC+SMES. The series active filter that builds the UPQC is placed close to the power source and the shunt filter is placed close to the load. Although it is possible to choose a reverse configuration (shunt filter close to the source and series filter close to the load) this arrangement was chosen because it allows a better controllability of the DC bus voltage. This is a fundamental characteristic in this hybrid system because the SMES is connected to this DC bus.

![Figure 2. Implemented system.](image)

**A. UPQC**

The UPQC is the main component of the designed system. Fig. 2 shows a schematic of the implemented active power filter. The UPQC flexibility allows a full control of voltage and current. The series power active filter is responsible for voltage control and the shunt filter for current control. This control is possible by measuring the different values of voltages and currents in the grid and comparing them to reference values. The two filters are controlled using PWM generators and follow two different control strategies: the reference signal for the PWM generator of the series filter follows a “feed forward” control method, comparing the voltage of the filter to a well-defined reference value; on the other hand, the reference signal for the PWM generator of the shunt filter is obtained following a Synchronous Reference Frame Method [5]. A major responsibility of the UPQC controller is to maintain the DC bus voltage always above a required level. On this particular case, the chosen value is 700 V, which is higher than the minimum voltage necessary to have full controllability of both active filters at all time. The minimum value in this case is 648V, calculated following the formulation presented. The capacitor used in the DC bus has a value of 50 µF.

![Figure 3. Implemented UPQC](image)
B.SMES

An SMES is a very complex system, composed by three main components: a superconducting (SC) coil (placed inside a cryostat) where energy is stored; a Power Converter System (PCS), which is a power electronics bidirectional converter, responsible for the exchange of energy with the grid to which the SMES is connected, and a Control System (CS) responsible for controlling all energy exchanges with the grid and also for overseeing and protecting the conditions of the SC coil. Fig.4. depicts a typical configuration of the systems.

![SMES system constitution](image)

In this particular case, because it is a simulation work and because the SMES is connected to a DC bus, several simplifications are possible. The PCS becomes simpler than the used one when the SMES is connected to an AC grid. In this case, it is necessary to use only a DC/DC converter. The typical choice is a chopper converter, due to its simplicity. The control strategy used in the PCS also becomes simpler due to this fact, which will also decrease the complexity of the CS. Other simulations are performed on the controller of the SMES: all variables related to the cryogenic system and protection of the SC coil are not considered. However, since the hybrid system is supposed to be able to overcome voltage swells, it is necessary to add a resistor in parallel with the SC coil, so that the excess energy (in case of a voltage swell) can be dissipated. This dissipation of energy will only occur if the SMES is already fully charged. The model used for simulation of the SMES is represented in Fig.5. To simulate the chopper two IGBTs (S1 and S2) were used.

![SMES model](image)

The control of these two switches allows the SMES to work in three different modes:

- S1 and S2 closed – Charging Mode: the coil is charging;
- S1 S2 closed – Discharging Mode: the coil is discharging, due to the occurrence of some fault in the grid;
- S1 open and S2 closed – Persistent Mode: the coil is already full charged and its nominal current value is kept using this mode.

When the SMES is operating alone, the charging process is straightforward. The energy can be extracted from the DC link without any special care. However, in this particular case, since the SMES is connected to the DC bus of an UPQC, it’s the charging process must take into account the fact that the DC voltage cannot decrease below a certain level. Thus, it is only possible to charge the SMES when the DC voltage is above 700 V (the chosen value for the DC bus voltage). The controller of the SMES (which controls the IGBTs S1 and S2) must consider this aspect. The main characteristics from the SMES unit simulated in this work are presented in table I such characteristics were obtained following the method presented. The implemented model also considers a resistor (with 0.1 Ω) in series with the coil, to simulate the existence of connectors in the superconducting tape and a capacitor (with 1nF) in parallel, to simulate capacitance between the single pancake coils.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pancake coils</td>
<td>4</td>
</tr>
<tr>
<td>Number of turns (each coil)</td>
<td>130</td>
</tr>
<tr>
<td>Total inductance (H)</td>
<td>0.28</td>
</tr>
<tr>
<td>Nominal current value (A)</td>
<td>70</td>
</tr>
<tr>
<td>Critical current of SC tape considered (A)</td>
<td>120</td>
</tr>
<tr>
<td>Total length of SC tape necessary to implement this SMES (m)</td>
<td>800</td>
</tr>
</tbody>
</table>

In an UPQC operating alone, in the same conditions as in this case, i.e., the same DC voltage (700 V) and the same capacitor in the DC bus (50 μF), the stored energy is 12.25 J. This is a small value, which strongly limits the range of applications of such system, namely when used for voltage sags compensation. In this case, with an SMES with these characteristics connected to the DC link of the UPQC, the stored energy increases to 698.25 J. This represents an increase of 5700% in stored energy, which greatly expands the range of application of the hybrid system, when comparing to the UPQC alone.

C.FAULT DETECTION

To be able to overcome faults, it is first necessary to correctly and rapidly identify those events in the grid. Voltage sags and swells are detected following a method presented. Briefly, this method detects a voltage sag or swell by comparing the grid voltage value with a reference value. This reference value has the same phase and amplitude as the nominal voltage of the
grid, which is very convenient because this is also used as a reference for the series active power filter.

III. SUPERCAPACITOR

A super capacitor (SC) (sometimes ultra capacitor, formerly electric double-layer capacitor (EDLC)) is a high-capacity electrochemical capacitor with capacitance values much higher than other capacitors (but lower voltage limits) that bridge the gap between electrolytic capacitors and rechargeable batteries. They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable. They are however 10 times larger than conventional batteries for a given charge. Super capacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage or burst-mode power delivery. Smaller units are used as memory backup for static random-access memory (SRAM). Super capacitors do not use the conventional solid dielectric of ordinary capacitors. They use electrostatic double-layer capacitance or electrochemical pseudo capacitance or a combination of both instead:

➢ Electrostatic double-layer capacitor use carbon electrodes or derivatives with much higher electrostatic double-layer capacitance than electrochemical pseudo capacitance, achieving separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte.

➢ The separation of charge is of the order of a few angstroms (0.3 - 0.8 nm), much smaller than in a conventional capacitor.

➢ Electrochemical pseudo capacitors use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudo capacitance. Pseudo capacitance is achieved by Faradic electron charge transfer with redo, intercalation or electro sorption.

➢ Hybrid capacitors, such as the lithium-ion capacitor, use electrodes with differing characteristics: one exhibiting mostly electrostatic capacitance and the other mostly electrochemical capacitance.

Figure 6. UPQC with SC

UPQC with SC

Here the SC is connected directly to PV array (Distributed Generator (DG)) and hence there is no need of a separate supply to Supercapacitor but in the case of SMES, there should be a separate supply (battery) for charging SMES unit. As here we are using a DG, the advantages of the system increases and we can also connect light loads to the DG. The operational procedure of charging/discharging and fault detection of SC is similar to that of SMES. The main advantage of Supercapacitor is, they can accept and deliver charge much faster than batteries.

Figure 7. the voltage behavior of supercapacitors and batteries during charging/discharging differs clearly

IV. PHOTOVOLTAIC SYSTEM

In the crystalline silicon PV module, the complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Fig.6. For that equivalent circuit, a set of equations have been derived, based on standard theory, which allows the operation of a single solar cell to be simulated using data from manufacturers or field experiments.

Figure 8. Equivalent electrical circuit of a PV module.

The series resistance Rs represents the internal losses due to the current flow. Shunt resistance Rs, in parallel with diode, this corresponds to the leakage current to the ground. The single exponential equation which models a PV cell is extracted from the physics of the PN junction and is widely agreed as echoing the behaviour of the PV cell.
\[ I = I_{sc} \left( \frac{V + R_{s}I}{V_{t}} - 1 \right) - \frac{(V + R_{p}I)}{R_{sh}} \]  \hspace{1cm} (1)

The number of PV modules connected in parallel and series in PV array are used in expression. The \( V_t \) is also defined in terms of the ideality factor of PN junction \( (n) \), Boltzmann’s constant \( (K_B) \), temperature of photovoltaic array \( (T) \), and the electron charge \( (q) \).

Applied a dynamical electrical array reconfiguration (EAR) strategy on the photovoltaic (PV) generator of a grid-connected PV system based on a plant-oriented configuration, in order to improve its energy production when the operating conditions of the solar panels are different. The EAR strategy is carried out by inserting a controllable switching matrix between the PV generator and the central inverter, which allows the electrical reconnection of the available PV modules.

V MATLAB/SIMULINK RESULTS

Figure 9. Simulation model of superconducting magnetic energy system of UPQC

Figure 10. Harmonic distortion compensation: source (above) and load (below) voltages during the fault.

Figure 11. Voltage sag elimination: source (above) and load (below) voltages during the fault.

Figure 12. Current in the SMES during three phase voltage sag.

Figure 13. Voltage swells elimination: source (above) and load (below) voltages during the fault.

Figure 14. Simulation model of UPQC with PV system based super capacitor.

Figure 15. PV Voltage.
VI. CONCLUSION

One modern and very promising solution that deals with both load current and supply voltage imperfections is the Unified Power Quality Conditioner (UPQC). This paper presented a review of the UPQC to enhance the electric power quality at distribution level. The UPQC is able to compensate supply voltage power quality issues such as, sags, swells, unbalance, flicker, harmonics, and for load current power quality problems such as, harmonics, unbalance, reactive current and neutral current. In this paper, several UPQC configurations have been discussed. Among all these configurations, UPQC-DG could be the most interesting topology for a renewable energy-based power system. The proposed UPQC compensated the reactive power, harmonic currents, voltage sag and swell, voltage unbalance, and the voltage interruption. In all the operating conditions the THD of source current has been observed within an IEEE 519-1992 standard limit of 5%. This paper researches structure principle and the control strategy of UPQC and arrives at the following conclusions: 1) Super capacitor energy storage and DC/DC converter buffer reactive power, exchange and provide energy for voltage compensation. As a result, decoupling series converter and parallel converter is implemented. Moreover, voltage quality problems of power interruption, which beyond the reach of traditional UPQC, can be resolved successfully. With UPQC, power quality problems in distribution network with high penetration of DGs could be improved.

VII. REFERENCES


