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Improving Power Quality of Distribution Grid with Ultracapacitor Integrated Power Conditioner

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Abstract:

Implementation of different types of distributed energy resources (DERs) like solar, wind, and plug-in hybrid electric vehicles (PHEVs) onto the distribution grid is on the increase. There is an equivalent raise in power quality problems and intermittencies on the distribution grid. In order to reduce the intermittencies and develop the power quality of the distribution grid, an ultracapacitor (UCAP) integrated power conditioner is proposed in this paper. UCAP integration gives the power conditioner active power capability, which is useful in tackling the grid intermittencies and in improving the voltage sag and swell compensation. UCAPs have low energy density, high-power density, and fast charge/discharge rates, which are all ideal characteristics for meeting high-power low-energy events like grid intermittencies, sags/swells. In this paper, UCAP is integrated into dc-link of the power conditioner through a bidirectional dc–dc converter that helps in providing a stiff dc-link voltage. The integration helps in providing active/reactive power support, intermittency smoothing, and sag/swell compensation. Design and control of both the dc–ac inverters and the dc–dc converter are discussed. The simulation model of the overall system is developed.

Keywords: ***Distributed energy resources, Hybrid electric Vehicles, UCAP, Charge/discharge, Converters, and Inverters.***

Introduction:

Power quality is major cause of concern in the industry, and it is important to maintain good power quality on the grid. Therefore, there is renewed interest in power quality products like the dynamic voltage restorer (DVR) and active power filter (APF). DVR prevents sensitive loads from experiencing voltage sags/swells, and APF prevents the grid from supplying nonsinusoidal currents when the load is nonlinear. The concept of integrating the DVR and APF through a back–back inverter topology was first introduced in [4] and the topology was named as unified power quality conditioner (UPQC). The design goal of the traditional UPQC was limited to improve the power quality of the distribution grid by being able to provide sag, swell, and harmonic current compensation. In this paper, energy storage integration into the power conditioner topology is being proposed, which will allow the integrated system to provide additional functionality.

With the increase in penetration of the distribution energy resources (DERs) like wind, solar, and plug-in hybrid electric vehicles (PHEVs), there is a corresponding increase in the power quality problems and intermittencies on the distribution grid in the *seconds* to *minutes* time scale. Energy storage integration with DERs is a potential solution, which will increase the reliability of the DERs by reducing the intermittencies and also aid in tackling some of the power quality problems on the distribution grid.

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Applications where energy storage integration will improve the functionality are being identified, and efforts are being made to make energy storage integration commercially viable on a large scale. Smoothing of DERs is one application where energy storage integration and optimal control play an important role. In [11], super capacitor and flow battery hybrid energy storage system are integrated into the wind turbine generator to provide wind power smoothing, and the system is tested using a real-time simulator. In [12], super capacitor is used as an auxiliary energy storage for photovoltaic (PV)/fuel cell, and a model-based controller is developed for providing optimal control. In [13], a battery energy storage systembased control to mitigate wind/PV fluctuations is proposed. In [14], multiobjective optimization method to integrate battery storage for improving PV integration into the distribution grid is proposed. In [15], a theoretical analysis is performed to determine the upper and lower bounds of the battery size for grid-connected PV systems. In [16], a rule-based control is proposed to optimize the battery discharge while dispatching intermittent renewable resources. In [17], optimal sizing of a zinc bromine-based energy storage system for reducing the intermittencies in wind power is proposed.

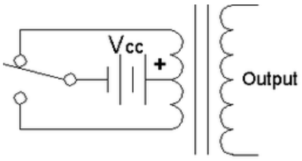
It is clear from the literature that renewable intermittency smoothing is one application that requires active power support from energy storage in the *seconds* to *minutes* time scale. Reactive power support is another application which is gaining wide recognition with proposals for reactive power pricing. Voltage sag and swells are power quality problems on distribution grid that have to be mitigated. sag/swell compensation needs active power support from the energy storage in the *milliseconds* to *1 min* duration. All the above functionalities can be realized by integrating energy storage into the grid through a power conditioner topology. Of all the rechargeable energy storage technologies superconducting magnet energy storage (SMES), flywheel energy storage system (FESS), battery energy storage system (BESS), and ultracapacitors (UCAPs), UCAPs are ideal for providing active power support for events on the distribution grid which require active power support in the *seconds* to *minutes* time scale like voltage sags/swells, active/reactive power support, and renewable intermittency smoothing.

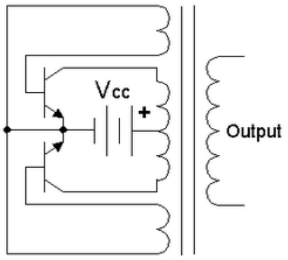
In this paper, UCAP-based energy storage integration through a power conditioner into the distribution grid is proposed, and the following application areas are addressed.

1) Integration of the UCAP with power conditioner system gives the system *active power capability*.
2) *Active power capability* is necessary for independently compensating voltage sags/swells and to provide active/ reactive power support and intermittency smoothing to the grid.
3) Development of inverter and dc–dc converter controls to provide sag/swell compensation and active/reactive support to the distribution grid.
4) Hardware integration and performance validation of the integrated UCAP-PC system.

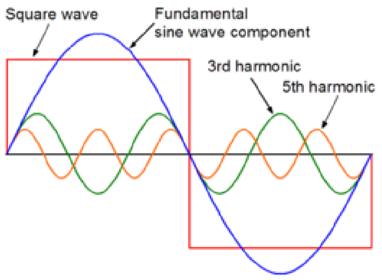
DC- AC Converter (Inverter)

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.





Top: Simple inverter circuit shown with an electro-mechanical switch and automatic equivalent auto-switching device implemented with two transistors and split winding auto-transformer in place of the mechanical switch.



Square waveform with fundamental sine wave component, 3rd harmonic and 5th harmonic.

Power Quality:

Power quality is defined as the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment. There are many different reasons for the enormous increase in the interest in power quality. Some of the main reasons are:

- Electronic and power electronic equipment has especially become much more sensitive. Equipment has become less tolerant of voltage quality disturbances, production processes have become less tolerant of incorrect of incorrect operation of equipment, and companies have become less tolerant of production stoppages. The main perpetrators are interruptions and voltage dips, with the emphasis in discussions and in the literature being on voltage dips and short interruptions. High frequency transients do occasionally receive attention as causes of equipment malfunction.
- Equipment produces more current disturbances than it used to do. Both low and high power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion. There are indications that the harmonic distortion in the power system is rising, but no conclusive results are obtained due to the lack of large scale surveys.
- The deregulation of the electricity industry has led to an increased need for quality indicators. Customers are demanding, and getting, more information on the voltage quality they can expect.
- Also energy efficient equipment is an important source of power quality disturbance. Adjustable speed drives and energy saving lamps are both important sources of waveform distortion and are also sensitive to certain type of power quality disturbances. When these power quality problems become a barrier for the large scale introduction of environmentally friendly sources and users' equipment, power quality becomes an environmental issue with much wider consequences than the currently merely economic issues.

Power quality Terminology:

DSTATCOM means Distribution Static Compensator. STATCOM is a static VAR generator, whose output is varied so as to maintain or control specific parameters of the electric power system.

SAG is a decrease in rms voltage or currents to between 0.1 to 0.9 p.u at the power frequency for duration of time from 0.5 cycles to 1 minute.

Balanced Sag is an equal drop in the rms value of voltage in the three-phases of a three-phase system or at the terminals of three-phase equipment for duration up to a few minutes.

Voltage dip is sudden reduction in the supply voltage by a value of more than 10% of the reference value, followed by a voltage recovery after a short period of time.

Unbalanced Fault is a short circuit or open circuit fault in which not all three phases are equally involved.

Voltage Tolerance it is the immunity of a piece of equipment against voltage magnitude variations (Sags, Swells and Interruptions) and short duration over voltages.

Duration (of Voltage Sag) it is the time during which the voltage deviates significantly from the ideal voltage.

Critical Distance is the distance at which a short-circuit fault will lead to a voltage sag of a given magnitude for a given load position.

Current Disturbance it is a variation of event during which the current in the system or at the equipment terminals deviates from the ideal sine wave.

Voltage Disturbance it is a variation of event during which the voltage in the system or at the equipment terminals deviates from the ideal sine wave.

Power Quality it is the study or description of both voltage and current disturbances. Power quality can be seen as the combination of voltage quality and current quality.

Interruption is the voltage event in which the voltage is zero during a certain time. The time during which the voltage is zero is referred to as the "duration" of the interruption. (OR) A voltage magnitude event with a magnitude is less than 10% of the nominal voltage.

Over Voltage is an abnormal voltage higher than the normal service voltage, such as might be caused from switching and lightning surges. (OR) Abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions.

Under Voltage is a voltage event in which the rms voltage is outside its normal operating margin for a certain period of time. (OR) A voltage magnitude event with a magnitude less than the nominal rms voltage, and a duration exceeding 1 minute.

Swell it is a momentary increase in the rms voltage or current to between 1.1 and 1.8pu delivered by the mains, outside of the normal tolerance, with a duration of more than one cycle and less than few seconds.

Recovery Time is the time interval needed for the voltage or current to return to its normal operating value, after a voltage or current event.

Fault is an event occurs on the power system and it effects the normal operation of the power system.

Voltage Fluctuation is a special type of voltage variation in which the voltage shows changes in the magnitude and/or phase angle on a time scale of seconds or less. Severe voltage fluctuations lead to light flicker.

Voltage Source Converters (VSC):

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual.

Principles for improving power quality:

From the discussion already presented, it is evident that for improving power quality, the steps given in the following figure1.6.1 have to be taken. As also pointed out, the appropriate decomposition of power for purposes of both identification and control of the distortion elimination by filters has to be achieved. Since it is essential to use clear and consistent terminology, the term non-active power filter will be used for equipment that eliminates non-active power. The actual types of these filters are to be discussed in a further chapter of this paper.

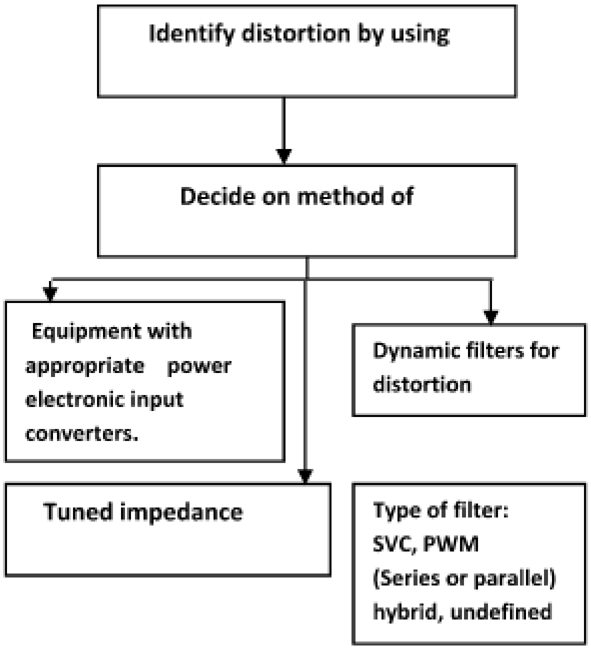


Figure: Improving power quality by distortion elimination.

The non-active power filters to be used can be divided into the classes of input converters, dynamic filters and tuned impedance filters.

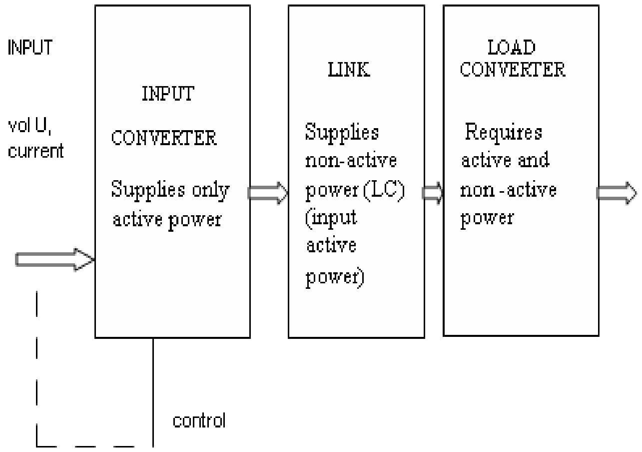


Figure: Principle of input converter to eliminate distortion loads on the power network.

To improve the power quality, some devices need to be installed at a suitable location. These devices are called custom power devices, which make sure that customers get pre specified quality and reliability of supply. The compensating devices compensate a load, its power factor, unbalance conditions or improve the power quality of supplied voltage, etc. some of the power quality improving techniques are given as below.

Simulation Results

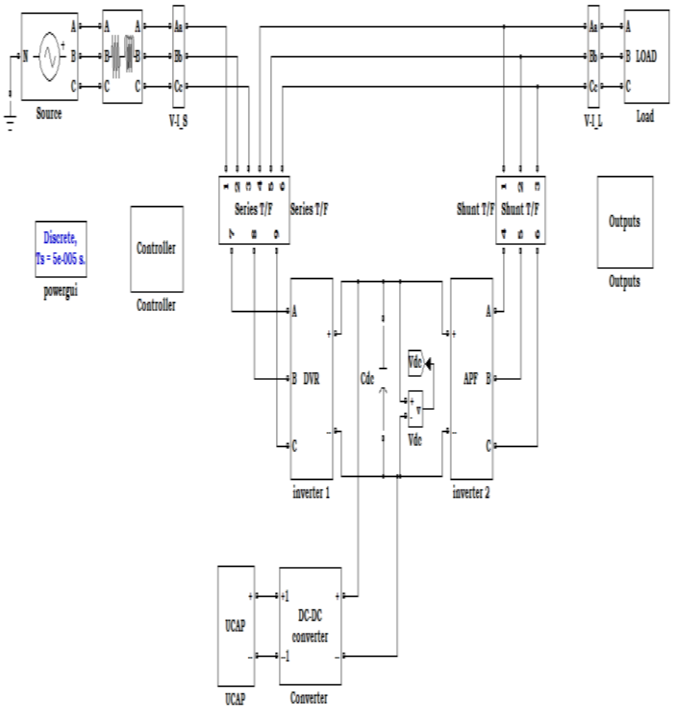


Fig. Simulation Model of power conditioner with UCAP energy storage

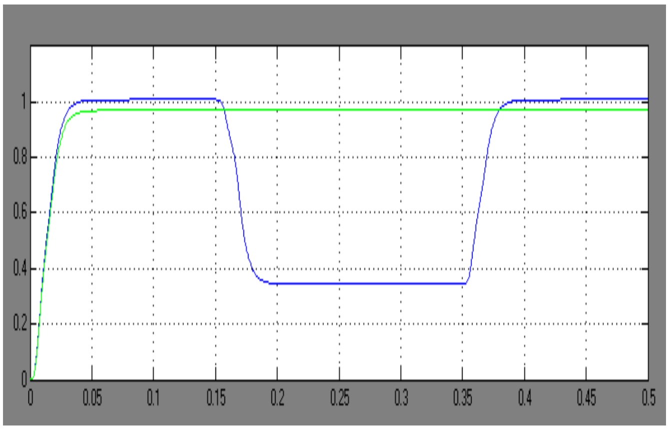


Fig. Source and load rms voltages *V*srms and *V*Lrms during sag

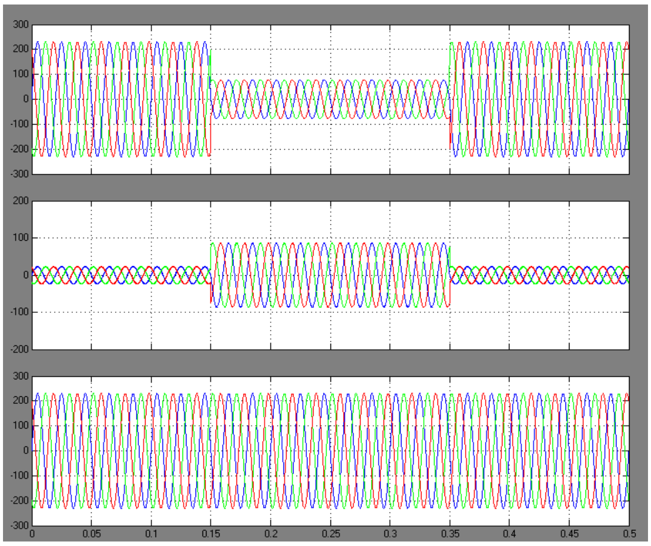


Fig a) Source voltages *Vsab* (blue), *Vsbc* (red), and *Vsca* (green) during sag. (b) Injected voltages Vinj2*a* (blue), *V*inj2*b* (red), and *V*inj2*c* (green) during sag. (c) Load voltages *VLab* (blue), *VLbc* (red), and *VLca* (green) during sag.

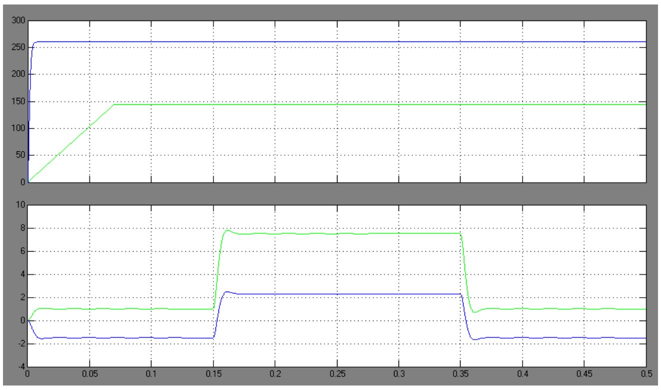


Fig. Currents and voltages of dc–dc converter

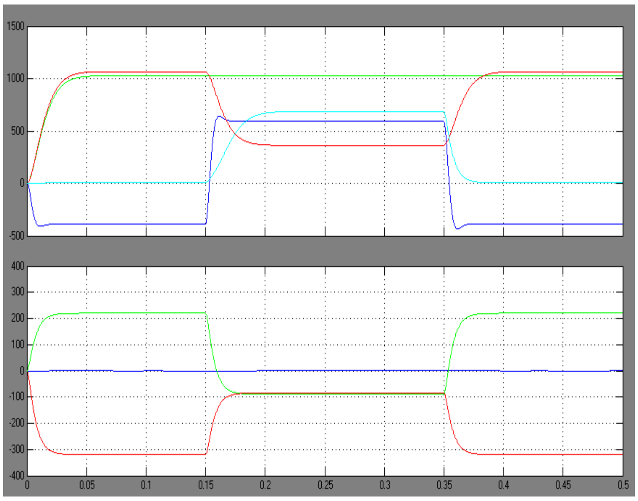


Fig Active and reactive power of grid, load, and inverter during voltage sag.

Conclusion

In this paper, the concept of integrating UCAP-based rechargeable energy storage to a power conditioner system to improve the power quality of the distribution grid is presented. With this integration, the DVR portion of the power conditioner will be able to independently compensate voltage sags and swells and the APF portion of the power conditioner will be able to provide active/reactive power support and renewable intermittency smoothing to the distribution grid. UCAP integration through a bidirectional dc–dc converter at the dc-link of the power conditioner is proposed. The control strategy of the series inverter (DVR) is based on inphase compensation and the control strategy of the shunt inverter (APF) is based on $id - iq$ method.

Designs of major components in the power stage of the bidirectional dc–dc converter are discussed. Average current mode control is used to regulate the output voltage of the dc–dc converter due to its inherently stable characteristic. A higher level integrated controller that takes decisions based on the system parameters provides inputs to the inverters and dc–dc converter controllers to carry out their control actions. The simulation of the integrated UCAP-PC system which consists of the UCAP, bidirectional dc–dc converter, and the series and shunt inverters is carried out using MATLAB. The simulation of the UCAP-PC system is carried out using MATLAB. Results from simulation agree well with each other thereby verifying the concepts introduced in this paper. Similar UCAP based energy storages can be deployed in the future in a microgrid or a low-voltage distribution grid to respond to dynamic changes in the voltage profiles and power profiles on the distribution grid.

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