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A COMBINED ULTRA CAPACITOR AND DYNAMIC VOLTAGE RESTORER FOR MITIGATING VOLTAGE SAG AND SWELL IN POWER QUALITY OF THE DISTRIBUTION GRID

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ABSTRACT

The most severe power quality problems in electrical systems are called as voltage sag and swell. These power quality problems must be compensated accurately. There are two voltage injection strategies to inject controlled voltage via dynamic voltage restorer (DVR) in electrical systems. The proposed power conditioner has active power capability which is useful in mitigating the grid intermittencies and in improving the voltage sag and swell compensation. Here, energy storage 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, sag/swell compensation and harmonic compensation. The power conditioner operates in five different modes, each of which has been analyzed. The novel contribution of this paper lies in the integration of rechargeable UCAP-based energy storage into the DVR topology. With this integration, the UCAP-DVR system will have active power capability and will be able to independently compensate temporary voltage sags and swells without relying on the grid to compensate for faults on the grid like in the past. UCAP is integrated into dc-link of the DVR through a bidirectional dc–dc converter, which helps in providing a stiff dc-link voltage, and the integrated UCAP-DVR system helps in compensating temporary voltage sags and voltage swells, which last from 3 s to 1 min. Complexities involved in the design and control of both the dc–ac inverter and the dc–dc converter are discussed. The simulation model of the overall system is developed and compared to the experimental hardware setup.
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KEYWORDS: DC–DC converter, d–q control, DSP, dynamic voltage restorer (DVR), energy storage integration, phase locked loop (PLL), sag/swell, Ultra capacitor (UCAP).

INTRODUCTION

Power quality is a major cause of concern in the industry and it is important to maintain good power quality on the grid. [1]. Therefore, there is renewed interest in power quality products like the dynamic voltage restorer (DVR) and the active power filter (APF). The topology which resulted after the integration of dynamic voltage restorer (DVR) and active power filter (APF) [2] through a back-back inverter topology was termed as a unified power quality conditioner (UPQC). DVR prevents sensitive loads from experiencing voltage sags/swells and APF prevents the grid from supplying non sinusoidal currents when the load is nonlinear. The concept of integrating the DVR and APF through a back– back inverter topology was first introduced in and the topology was named as unified power quality conditioner (UPQC). The design goal of the traditional UPQC was limited is 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.

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. 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. Super capacitor is used as auxiliary energy storage for photovoltaic (PV)/fuel cell, and a model-based controller is developed for providing optimal control. a battery energy storage system-based control to mitigate wind/PV fluctuations is proposed. Multi objective optimization method to integrate battery storage for improving PV integration into the distribution grid is proposed theoretical analysis is performed to determine the upper and lower bounds of the battery size for grid-connected PV system's-based control rule is proposed to optimize the battery discharge while dispatching intermittent renewable resources.

Various types of rechargeable energy storage technologies based on superconducting magnets (SMES), flywheels (FESS), batteries (BESS), and ultra capacitors (UCAPs) are compared in [10] for integration into advanced power applications such as DVR. Efforts have been made to integrate energy stor-age into the DVR system, which will give the system active power capability that makes it independent of the grid during voltage disturbances. In [11], cascaded H-bridge-based DVR with a thyristor-controlled inductor is proposed to minimize the energy storage requirements. In [12], flywheel energy storage is integrated into the DVR system to improve its steady-state series and shunt compensation.

Of all the rechargeable energy storage technologies, UCAPs are ideally suited for applications which need active power sup-port in the milliseconds to second's timescale. Therefore, UCAP-based integration into the DVR system is ideal, as the normal duration of momentary voltage sags and swells is in the milliseconds to second's range. UCAPs have low-energy density and high-power density ideal characteristics for compensating voltage sags and voltage swells, which are both events that require high amount of power for short spans of time. UCAPs also have higher number of charge/discharge cycles when compared to batteries and for the same module size, UCAPs have higher terminal voltage when compared to batteries, which makes the integration easier. With the preva-lence of renewable energy sources on the distribution grid and the corresponding increase in power quality problems, the need for DVRs on the distribution grid is increasing [16]. Super-capacitor-based energy storage integration into the DVR for the distribution grid is proposed in [16] and [17]. However, the concept is introduced only through simulation and the experimental results are not presented. In this paper, UCAP-based

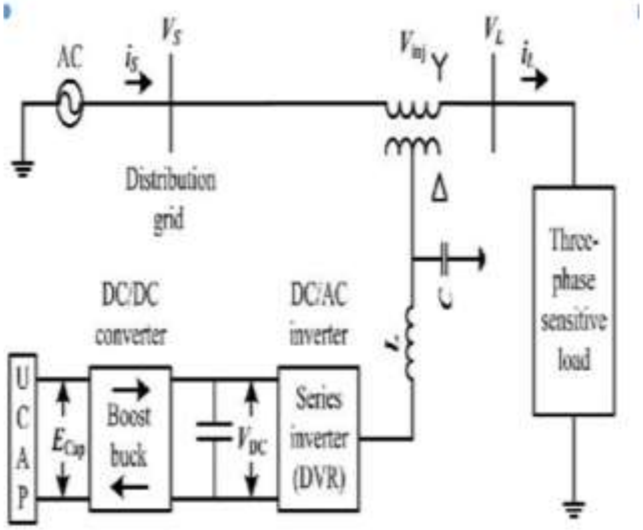


Fig:1.1 One-line diagram of dvr with ucap energy storage.

Energy storage integration to a DVR into the distribution grid is proposed and the following application areas are addressed.

Integration of the UCAP with DVR system gives active power capability to the system, which is necessary for independently compensating voltage sags and swells. Experimental validation of the UCAP, dc–dc converter, and inverter their interface and control. Development of inverter and dc–dc converter controls to provide sag and swell compensation to the distribution grid. Hardware integration and performance validation of the integrated DVR-UCAP system.

WIND POWER

Today's energy situation requires the introduction of new generation methods. A potential new source is distributed generation of electricity from many relatively small and variable sources, harnessing local renewable forms of energy. Whilst centralized electricity generation systems tend to suggest favorable economics due to their scale, distributed generation systems can demonstrate higher efficiency through direct use of heat, lower transmission Such distributed systems will comprise of plant at many sites utilizing multiple sources of renewable energy. These pose a number of challenges to planners, designers and users alike, in particular if the plant is to operate for significant periods of time without an operational grid connection. In this case, performance will be a function of varying sources, load demands, and the ability to store energy. In addition, it is difficult to determine, in advance, the optimum relative proportions of, for example, photovoltaic generation capacity, wind generation capacity and battery capacity, for a given site (weather pattern) and required power availability. Much literature exists recognizing the importance of the optimization of remote renewable energy sites; generally split into three areas, sizing, control and both. Significant work includes [1-5], offering a comprehensive analysis of system components.

Airflows can be used to run wind turbines. Modern utility-scale wind turbines range from around 600 kW to 5 MW of rated power, although turbines with rated output of 1.5–3 MW have become the most common for commercial use; the power available from the wind is a function of the cube of the wind speed, so as wind speed increases, power output increases up to the maximum output for the particular turbine. Areas where winds are stronger and more constant, such as offshore and high altitude sites are preferred locations for wind farms as shown in Fig.2. Typical capacity factors are 20-40%, with values at the upper end of the range in particularly favorable sites. Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand, assuming all practical barriers needed were overcome. This would require wind turbines to be installed over large areas, particularly in areas of higher wind resources, such as offshore. As offshore wind speeds average ~90% greater than that of land, so offshore resources can contribute substantially more energy than land stationed turbines.

TECHNIQUES OF TUNING CONTROLLER

The output from DSTATCOM can be controlled by different types of controllers using various types of control algorithm. Some of them are discussing below.

A. Genetic Algorithm (GAs)

The GAs is well-known close by survive a hundred of works employing the GAs technique to design the controller in various forms. The GAs is a stochastic search technique that leads a set of population in solution space evolved using the principles of genetic evolution and natural selection, called genetic operators e.g. crossover, mutation, etc. With successive updating new generation, a set of updated solutions gradually converges to the real solution. Because the GAs is very popular and widely used in most research areas where an intelligent search technique is applied, it can be summarized briefly as shown in the flowchart. The GAs is selected to build up an algorithm to tune kp parameters. The procedure to perform the proposed parameter tuning is described as follows. First, time-domain results of the load voltage obtained by simulating are collect then is employed to generate a set of initial random parameters. With the searching process, the parameters are adjusted to give response best fitting close to the desired response in the 0dq reference signals [4].

Artificial Immune System (AIS)

Most of the control techniques are offline and require prior knowledge of the system behavior. But AIS, which is inspired by theoretical immunology and observed immune functions, principles and models, has the potential for online adaptive system identification and control. Abnormal changes in the system response are identified and acted upon without having any prior knowledge. AIS controller parameters are first tuned by particle swarm optimization (PSO), so that it can provide innate immunity to common system disturbances

B. Particle Swarm Optimization (PSO)

Particle swarm optimization is a population based search algorithm modelled after the motion of flock of birds and school of fish. A swarm is considered to be a collection of particles, where each particle represents a potential solution to a given problem. The particle changes its position within the swarm based on the experience and knowledge of its neighbors. Basically it 'flies' over the search space to find out the optimal solution .Initially a population of random solutions is considered.

C. Neural Network

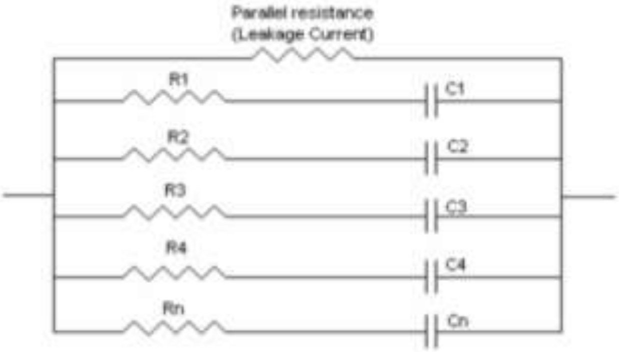
Electrical distribution system suffers from problems like reactive power burden, unbalance loading and voltage regulation. Reactive power burden increases line losses and unbalance loading results in excessive neutral current. The use of distribution static synchronous compensator (DSTATCOM) is well established to cater these problems. Two core issues with the use of DSTATCOM are its control and rating. The heart of the control of DSTATCOM is the derivation of reference currents, which decide the switching of voltage source inverter (VSI) used in DSTATCOM. With neural network based system reference current extractor which operates on LMS algorithm

D. Instantaneous Reactive Power (IRP) Theory

The major power consumption has been in reactive loads, such as fans, pumps etc. These loads draw lagging power-factor currents and therefore give rise to reactive power burden in the distribution system. Moreover, situation worsens in the presence of unbalanced loads. Excessive reactive power demand increases feeder losses and reduces active power flow capability of the distribution system, whereas unbalancing affects the operation of transformers and generators. A Distribution static compensator (DSTATCOM) can be used for compensation of reactive power and unbalance loading in the distribution system. The performance of DSTATCOM depends on the control algorithm used for extraction of reference current components. For this purpose, many control schemes are reported in literature, and some of these are instantaneous reactive power (IRP) theory, instantaneous symmetrical components, synchronous reference frame (SRF) theory and current compensation using dc bus regulation, computation based on per phase basis, and scheme based on neural network technique. Among these control schemes, SRF theories are most widely used [13].

ULTRA CAPACITORS CONSTRUCTION

What makes' Ultra capacitors different from other capacitors types are the electrodes used in these capacitors. Ultra capacitors are based on a carbon (nano tube) technology. The carbon technology used in these capacitors creates a very large surface area with an extremely small separation distance. Capacitors consist of 2 metal electrodes separated by a dielectric material. The dielectric not only separates the electrodes but also has electrical properties that affect the performance of a capacitor. Ultra capacitors do not have a traditional dielectric material like ceramic, polymer films or aluminum oxide to separate the electrodes but instead have a physical barrier made from activated carbon that when an electrical charge is applied to the material a double electric field is generated which acts like a dielectric. The thickness of the electric double layer is as thin as a molecule. The surface area of the activated carbon layer is extremely large yielding several thousands of square meters per gram. This large surface area allows for the absorption of a large amount of ions. The charging/discharging occurs in an ion absorption layer formed on the electrodes of activated carbon



The activated carbon fiber electrodes are impregnated with an electrolyte where positive and negative charges are formed between the electrodes and the impregnant. The electric double layer formed becomes an insulator until a large enough voltage is applied and current begins to flow. The magnitude of voltage where charges begin to flow is where the electrolyte begins to break down. This is called the decomposition voltage. The double layers formed on the activated carbon surfaces can be illustrated as series ofparallel RC circuits. As shown below the capacitor is made up of a series of RC circuits where R1, R2 …Rn are the internal resistances and C1, C2..., Cn are the electrostatic capacitances of the activated carbons. When voltage is applied current flows through each of the RC circuits. The amount of time required to charge the capacitor is dependent on the CxR values of each RC circuit. Obviously the larger the CxR the longer it will take to charge the capacitor. The amount of current needed to charge the capacitor is determined by the following equation.

THREE-PHASE INVERTERS

A. Power Stage

The one-line diagram of the system is shown in Fig. 6. The power stage consists of two back-to-back three phase voltage source inverters connected through a dc-link capacitor. UCAP energy storage is connected to the dc-link capacitor through a bidirectional dc–dc converter. The series inverter is responsible for compensating the voltage sags and swells; and the shunt inverter is responsible for active/reactive power support and renewable intermittency smoothing. The complete circuit diagram of the series DVR, shunt APF, and the bidirectional dc–dc converter is shown in Fig. 2. Both the inverter systems consist of IGBT module, its gate-driver, LC filter, and an isolation transformer. The dc-link voltage Vdc is regulated at 260 V for optimum voltage and current compensation of the converter and the line–line voltage Vab is 208 V. The goal of this project is to provide the integrated power conditioner and UCAP system with active power capability

3.To compensate temporary voltage sag (0.1–0.9 p.u.) and swell (1.1–1.2 p.u.), which last from 3 s to 1 min [18]; and 2) to provide active/reactive support and renewable intermittency smoothing, which is in the seconds to minutes time scale.

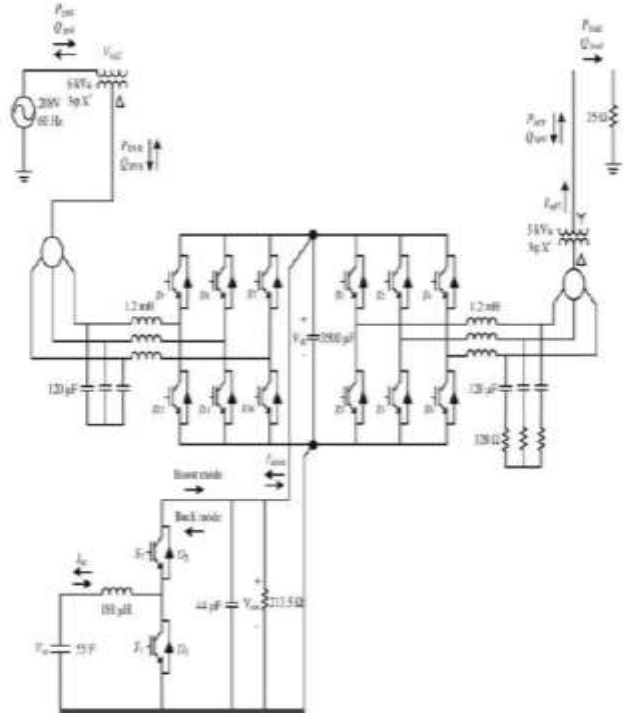


Fig: 4.1 Model of power conditioner with UCAP energy storage.

B. Controller Implementation

The series inverter controller implementation is based on the in-phase compensation method that requires PLL for estimating θ, and this has been implemented using the fictitious power method described in [4]. Based on the estimated θ and the line–line source, voltages Vab, Vbc, Vca (which are available for this delta-sourced system) are transformed into the d–q domain and the line–neutral components of the source voltage Vsa, Vsb, and Vsc which are not available can then be estimated using

$$\begin{bmatrix} Vsa \\ Vsb \\ Vsc \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos(\theta-\pi/6) & \sin(\theta-\pi/6) \\ -\sin(\theta-\pi/6) & \cos(\theta-\pi/6) \end{bmatrix} \begin{bmatrix} Vd/\sqrt{3} \\ Vq/\sqrt{3} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} Vrefa \\ Vrefb \\ Vrefc \end{bmatrix} = m * \begin{bmatrix} (\sin\theta - Vsa/169.7) \\ (\sin(\theta-2\pi/3) - Vsb/169.7) \\ (\sin(\theta+2\pi/3) - Vsc/169.7) \end{bmatrix} \tag{3}$$

$$P_{dvr} = 3V_{inj2a(rms)} I_{La(rms)} \cos\varphi \tag{4}$$

$$Q_{dvr} = 3V_{inj2a} I_{La(rms)} \sin\varphi \tag{5}$$

$$P_{ref} = -3/2V_{sq} i_{qref} \tag{6}$$

$$Q_{ref} = -3/2V_{sq} i_{dref} \tag{7}$$

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{dref} \\ i_{qref} \end{bmatrix} \tag{8}$$

These voltages are normalized to unit sine waves using line– neutral system voltage of 120 Vrms as reference and compared with unit sine waves in-phase with actual system voltages Vs from (2) to find the injected voltage references Vref necessary to maintain a constant voltage at the load terminals, where m is the modulation index, which is 0.44 for this case. Therefore, whenever there is a voltage sag or swell on the source side, a corresponding voltage Vinj2 is injected in-phase by the DVR and UCAP system to negate the effect and retain a constant voltage VL at the load end. The actual active and reactive power supplied by the series inverter can be computed using (3) from the rms values of injected voltage Vinj2a and load current ILa and ϕ is the phase difference between the two waveforms.

The shunt inverter controller implementation is based on the id − iq method, which is modified to provide active and reactive power compensation, such that id controls the reactive power and iq controls the active power. Therefore, based on the references for active and reactive powers Pref and Qref , the reference currents Qref and idref in d–q domain can be calculated using (4), where vsq is the system voltage in q-domain and the reference currents are calculated using (4). The complete inverter control algorithm is implemented in the DSP TMS320F28334, which has a clock frequency of 140 MHz, an inbuilt A/D module, PWM module, and real time emulation, which are all ideal for this application.

C. Bidirectional Dc–Dc Converter UCAP Bank Hardware Setup

UCAPs can deliver very high power in a short time span; they have higher power density and lower energy density when compared with Li-ion batteries [18], [19]. The major Advantage UCAPs have over batteries is their power density characteristics, high number of charge–discharge cycles over their lifetime, and higher terminal voltage per module. These are ideal characteristics for providing active/reactive power support and intermittency smoothing to the distribution grid on a short-term basis. In [20], it is proposed that UCAPs are currently viable as short-term energy storage for bridging power in kilowatt range in the seconds to few minutes timescale. The choice of the number of UCAPs necessary for providing grid support depends on the amount of support needed, terminal voltage of the UCAP, dc-link voltage, and distribution grid voltages. For a 260-V dc-link voltage, it is practical and cost-effective to use three modules in the UCAP bank as shown in Fig.7. Therefore, in this paper, the experimental setup consists of three 48 V, 164 F UCAPs (BMOD0164P048) manufactured by Maxwell Technologies which are connected in series.Assuming that the UCAP bank can be discharged to 40% of its initial voltage (Vuc,ini) to final voltage (Vuc,fin) from 144 to 72 V, which translates to depth of discharge of 74%, the energy in the UCAP bank available for discharge is given by

$$E_{UCAP} = 1/2 * C * \frac{\left(V_{uc,ini}^{2} - V_{UC,fin}^{2}\right)}{60} \text{W min}$$

$$E_{UCAP} = 1/2 * 164/3 * (144^{2} - 72^{2})/60$$

$$= 7128 \text{W min}$$

D. Voltage Swell

Swell is the reverse form of a Sag, having an increase in AC Voltage for a duration of 0.4 cycles to 1 minute's time. For swells, high-impedance neutral connections, sudden large load reductions, and a single-phase fault on a three phase system are common sources. Swells can cause data errors, light flickering, electrical contact degradation, and semiconductor damage in electronics causing hard server failures. Our power conditioners and UPS Solutions are common solutions for swells. It is important to note that, much like sags, swells may not be apparent until results are seen. Having your power quality devices monitoring and logging your incoming power will help measure these events.

Over-voltage:

Over-voltages can be the result of long-term problems that create swells. Think of an overvoltage as an extended swell. Over-voltages are also common in areas where supply transformer tap settings are set incorrectly and loads have been reduced. Over-voltage conditions can create high current draw and cause unnecessary tripping of downstream circuit breakers, as well as overheating and putting stress on equipment. Since an overvoltage is a constant swell, the same UPS and Power Conditioners will work for these. Please note however that if the incoming power is constantly in an overvoltage condition, the utility power to your facility may need correction as well. The same symptoms apply to the over-voltages and swells however since the overvoltage is more constant you should expect some excess heat. This excess heat, especially in data center environments, must be monitored. If you are experiencing any of these power quality problems we have solutions ranging from Power Conditioners / Voltage Regulators to traditional UPS Systems and Flywheel UPS Solutions. Do not hesitate to call on us.

E. Swell Causes

As discussed previously, swells are less common than voltage sags, but also usually associated with system fault conditions. A swell can occur due to a single line-to ground fault on the system, which can also result in a temporary voltage rise on the un faulted phases. This is especially true in ungrounded or floating ground delta systems, where the sudden change in ground reference result in a voltage rise on the ungrounded phases. On an ungrounded system, the line-to ground voltages on the ungrounded phases will be 1.73 p.u during a fault condition. Close to the substation on a grounded system, there will be no voltage rise on un faulted phases because the substation transformer is usually connected delta-wye, providing a low impedance path for the fault current. Swells can also be generated by sudden load decreases. The abrupt interruption of current can generate a large voltage, per the formula: $v = L\, di/dt$, where L is the inductance of the line, and di/dt is the change in current flow. Switching on a large capacitor bank can also cause a swell, though it more often causes an oscillatory transient. The monitor should be thoroughly evaluated in the laboratory, under simulated disturbances, before placing out in the field. Just because it didn't record it, does not mean it didn't happen. Unless there is significant information pointing to the cause of the disturbance before the monitoring begins, it is common practice to begin at the point of common coupling with the utility service as the initial monitoring point.

If the initial monitoring period indicates that the fault occurred on the utility side of the service transformer, then further monitoring would not be necessary until attempting to determine the effectiveness of the solution. If the source of the disturbance is determined to be internal to the facility, the placing multiple monitors on the various feeds within the facility would most likely produce the optimal answer in the shortest time period. Otherwise, the monitor must be moved from circuit to circuit, with particular attention to circuits powering suspected sources, and the circuits of the susceptible devices. Recent developments in artificial intelligence tools, especially fuzzy logic, have allow software vendors to develop products that allow knowledge and reasoning patterns to be stored in the software program. Further analysis of the event, beyond the IEEE 1149 classifications, is possible. These include the severity of the event, relative to the type of equipment that would be effected, and probability factors on the cause of the disturbance. Multiple, successive sags that return to nominal for an adequate time for the power supply capacitors to recharge may not be as severe as a longer duration sag of a higher amplitude.

SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.8 to 16

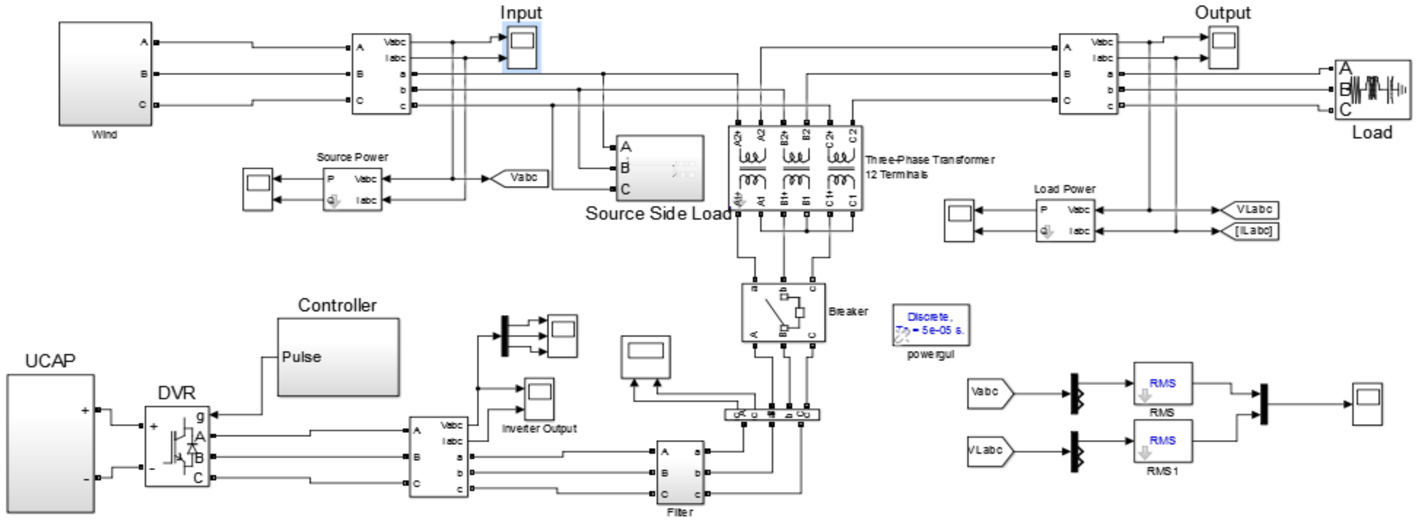


Fig:5 Ultra capacitor arrangement.

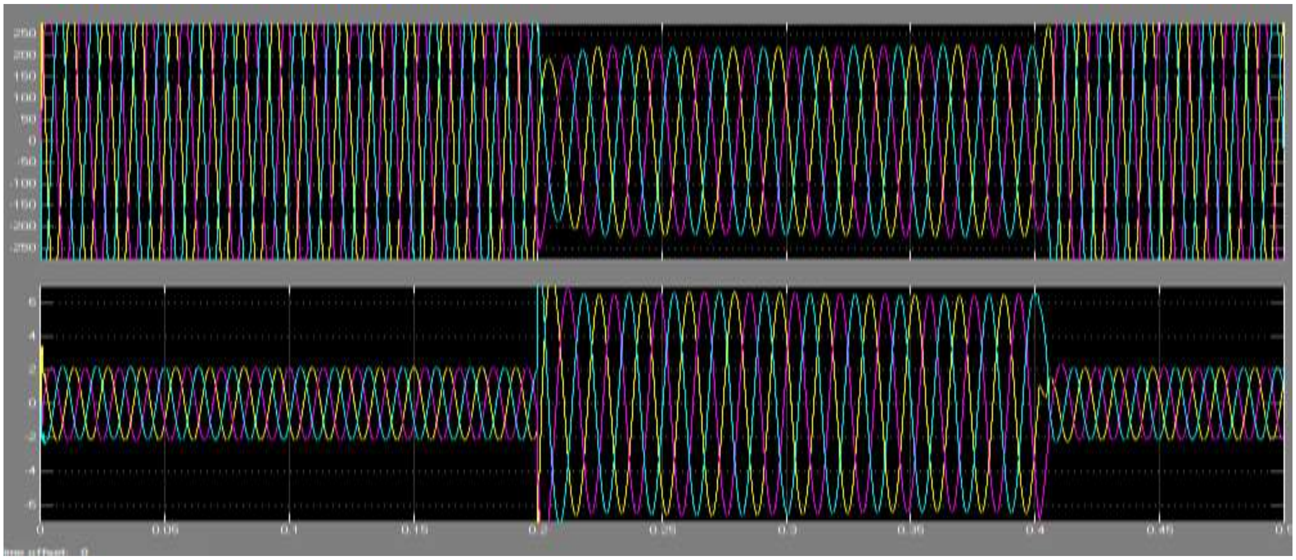


Fig.6.Source voltages V_{sab}, V_{sbc} and V_{sca} during sag.

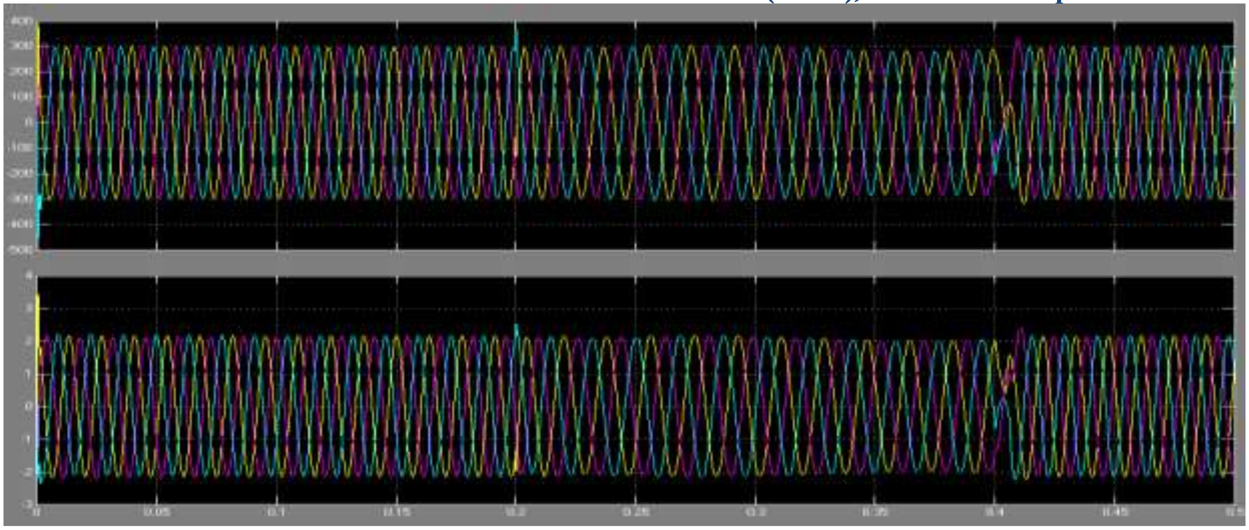


Fig.7. Load voltages V_{Lab},V_{Lbc} and V_{Lac} during sag.

The active power deficit of the grid is met by the DVR power P_{dvr}, which is almost equaled to the input power to the inverter P_{dc} in available from the UCAP. Therefore, it can be concluded from the plots that the active power deficit between the grid and load during the voltage sag event is Conditioner being met by the UCAP-based energy storage system through bidirectional dc–dc converter and the inverter. It can also be noticed that the grid reactive power Q_{grid} reduces during the voltage sag while Q_{dvr} increases to compensate for the reactive power loss in the system. Similar analysis can also be carried out for voltage sags that occur in one of the phases (A, B, or C) or in two of the phases (AB, BC, or CA); however, three-phase voltage sag case requires the maximum active power support and is presented here.

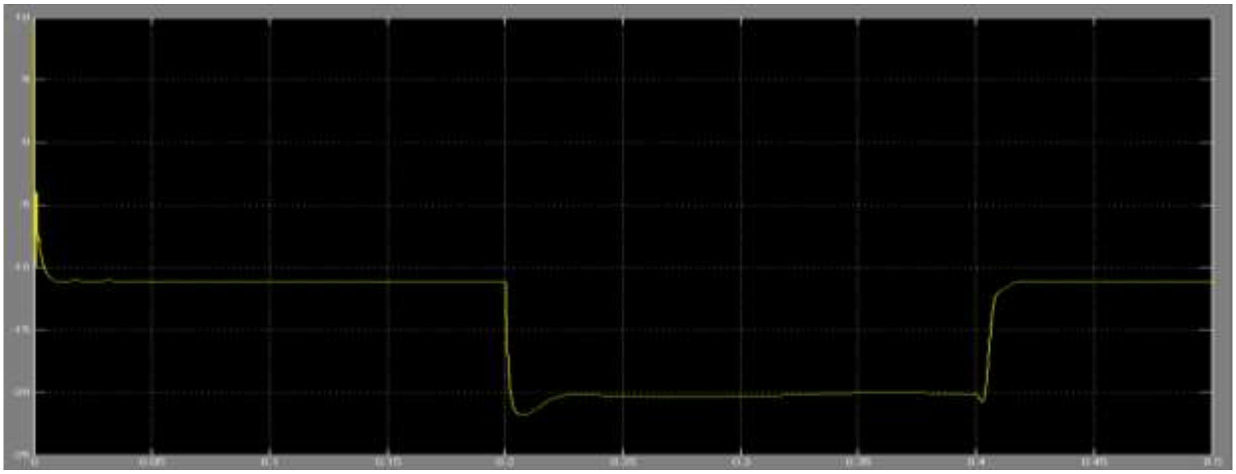


Fig: 8. Wind output dc voltage

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 PSCAD. Hardware experimental setup of the integrated system is presented and the ability to provide temporary voltage sag compensation and active/reactive power support and renewable intermittency smoothing to the distribution grid is tested. Results from simulation and experiment 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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