# AN INTEGRATED DYNAMIC VOLTAGE RESTORER - ULTRACAPACITOR DESIGN FOR IMPROVING POWER QUALITY OF THE DISTRIBUTION GRID

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***Abstract***—Energy storage technologies are increasing their presence in the market and integration of these technologies into the power grid is slowly becoming a reality. Dynamic Voltage Restorer has been used in the past to provide voltage sag and swell compensation to prevent sensitive loads from voltage disturbances on the utility side. In this paper the concept of integrating ultracapacitor (UCAP) based energy storage into the dynamic voltage restorer topology has been explored. With this integration the DVR will be able to independently compensate voltage sags and swells without relying on the grid to compensate for faults on the grid. UCAPs have low energy density and high power density ideal characteristics for compensation of voltage sags and voltage swells which are both high power low energy events. UCAP is integrated into dc-link of the DVR through a bi-directional dc-dc converter which helps in providing stiff dc-link voltage and the integration helps in compensating deeper voltage sags, voltage swells for longer durations. 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.

***Keywords— UCAP, DVR, dc-dc converter, DSP, sag/swell, d-q control, PLL, energy storage Integration.***

## 1. INTRODUCTION

The concept of using inverter based Dynamic voltage restorers for preventing customers from momentary voltage disturbances on the utility side was demonstrated for the first time by Woodley etal. The concept of using the dynamic voltage restorer (DVR) as a power quality product has gained significant popularity since its first use. In, the authors propose the usage of the DVR with rechargeable energy storage at the dcterminal to meet the active power requirements of the grid during voltage disturbances. In order to avoid and minimize the active power injection into the grid the authors also mention an alternative solution which is to compensate for the voltage sag by inserting a lagging voltage in quadrature with the line current. Due to the high cost of rechargeable energy storage various other types of control strategies have also been developed in the literature to minimize the active power injection from the DVR. The high cost of the rechargeable energy storage prevents the penetration of the dynamic voltage restorer as a power quality product. However, the cost of rechargeable energy storage has been decreasing drastically in the recent past due to various technological developments and due to higher penetration in the market in the form of auxiliary energy storage for distributed energy resources (DERs) like wind, solar, HEVs and PHEVs. Therefore, there has been renewed interest in the literature to integrate rechargeable energy storage again at the dc-terminal of power quality products like STATCOM and DVR. Various types of rechargeable energy storage technologies based on Superconducting magnets (SMES), flywheels (FESS), batteries (BESS) and Ultracapacitors (UCAPs) are compared in for integration into advanced power applications like DVR. Efforts have been made to integrate energy storage into the DVR system which will give the system active power capability which makes it independent of the grid during voltage disturbances. In cascaded H-bridge based DVR with a thyristor controlled inductor is proposed in order to minimize the energy storage requirements. In 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 support in the milliseconds to seconds 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 seconds range. UCAPs have low energy density and high power density ideal characteristics for compensating voltage sags and voltage swells which are both events which 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. Super-capacitor based energy storage integration into the DVR for the distribution grid is proposed. However, the concept is introduced only through simulation and experimental results are not presented. In the present paper UCAP based 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 the system active power capability which is necessary for independently compensating voltage sags and swells

- Experimental validation of the UCAP, dc-dc converter, 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.

## 2. THREE-PHASE SERIES INVERTER

### A. Power Stage

The one line diagram of the system is shown inThe one line diagram of the system is shown in Fig. 1. The power stage is a 3- phase voltage source inverter which is connected in series to the grid and is responsible for compensating the voltage sags and swells; the model of the Series DVR and its controller is shown in Fig. 2. The inverter system consists of an IGBT module, its gatedriver, LC filter and an isolation transformer. Therefore, the output of the dc-dc converter should be regulated at 260V for providing accurate voltage compensation. The objective of the integrated UCAP-DVR system with active power capability is to compensate for temporary voltage sag (0.1-0.9pu) and voltage swell (1.1-1.2pu) which last from 3s-1min [15].

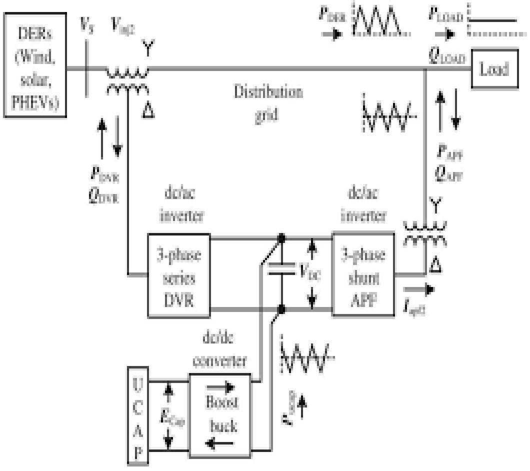

*Fig. 1 One line diagram of DVR with UCAP Energy Storage*

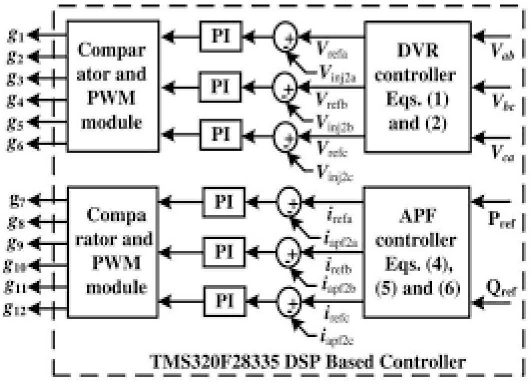

*Fig. 2 Model of three-phase Series inverter (DVR) and its controller*

### B. Controller Implementation

There are various methods to control the series inverter to provide Dynamic Voltage restoration and most of them rely on injecting a voltage in quadrature with advanced phase so that reactive power is utilized in voltage restoration [3]. Phase advanced voltage restorations techniques are complex in implementation but the primary reason for using these techniques is to minimize the active power support and thereby the amount of energy storage requirement at the dc-link in order to minimize the cost of energy storage. However, the cost of energy storage has been declining and with the availability of active power support at the dc-link complicated phase-advanced techniques can be avoided and voltages can be injected in-phase with the system voltage during a voltage sag or a swell event. The control method requires the use of a PLL to find the rotating angle θ. As discussed previously the goal of this project is to use the active power capability of the UCAP-DVR system and compensate temporary voltage sags and swells. The inverter controller implementation is based on injecting voltages in-phase with the supply side line-neutral voltages. This requires PLL for estimating θ which has been implemented using the fictitious power method described. 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. These voltages are normalized to unit sine waves using line-neutral system voltage of 120Vrms as reference and compared to unit sine waves in-phase with actual system voltages Vs from to find the injected voltage references Vref necessary to maintain a constant voltage at the load terminals where m is 0.52. 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 from the RMS values of injected voltage Vinj2a and load current ILa and φ is the phase difference between the two waveforms. The complete inverter control algorithm is implemented in the DSP TMS320F28335 which has a clock frequency of 150MHz, an inbuilt A/D module, PWM module and real-time emulation which are all ideal for this application.

## 3. UCAP AND BI-DIRECTIONAL DC-DC CONVERTER

### A. UCAP Bank Hardware Setup

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 260V dc-link voltage it is practical and cost effective to use 3 modules in the UCAP bank. Therefore, in this paper the experimental setup consists of three 48V, 165F UCAPs (BMOD0165P048) manufactured by Maxwell Technologies which are connected in series. Assuming that the UCAP bank can be discharged to 50% of its initial voltage (Vuc,ini) to final voltage (Vuc,fin) from 144V to 72V which translates to depth of discharge of 75%, the energy in the UCAP bank available for discharge.

B. Bi-directional Dc-dc Converter and Controller

A UCAP cannot be directly connected to the dc-link of the inverter like a battery as the voltage profile of the UCAP varies as it discharges energy. Therefore, there is a need to integrate the UCAP system through a bi-directional dc-dc converter which maintains a stiff dc-link voltage as the UCAP voltage decreases while “Discharging” and increases while “Charging”. The model of the bi-directional dc-dc converter and its controller are shown in Fig. 3 where the input consists of 3 UCAPs connected in series and the output consists of a nominal load of 213.5Ω to prevent operation at no-load and the output is connected to the dc-link of the inverter. The amount of active power support required by the grid during a voltage sag event is dependent on the depth and duration of the voltage sag and the dc-dc converter should be able to withstand this power during “Discharge” mode. The dc-dc converter should also be able to operate in bi-directional mode to be able to “Charge” or absorb additional power from the grid during voltage swell event. In this paper the bi-directional dc-dc converter acts as a boost converter while “discharging” power from the UCAP and acts as a buck converter while “charging” the UCAP from the grid.

Average current mode control which is widely explored in literature [19] is used to regulate the output voltage of the bi-directional dc-dc converter in both Buck and Boost modes while Charging and Discharging the UCAP bank. This method tends to be more stable when compared to other methods like voltage mode control and peak current mode control. Average current mode controller is shown in Fig. 3 where the dc-link and actual output voltage Vout is compared with the reference voltage Vref and the error is passed through the voltage compensator C1(s) which generates the average reference current Iucref. When the inverter is discharging power into the grid during voltage sag event the dc-link voltage Vout tends go below the reference Vref and the error is positive Iucref is positive and the dc-dc converter operates in Boost Mode..

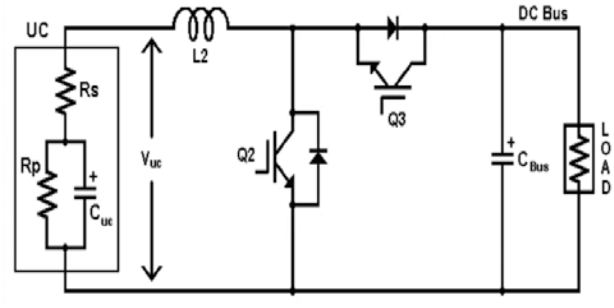

*Fig. 3 Model of the bi-directional dc-dc converter and its controller*

When the inverter is absorbing power from the grid during voltage swell event or charging the UCAP, Vout tends to increase above the reference Vref and the error is negative, Iucref is negative and the dc-dc converter operates in Buck Mode. Therefore, the sign of the error between Vout and Vref determines the sign of Iucref and thereby the direction of operation of the bidirectional dc-dc converter. The reference current Iucref is then compared to the actual UCAP current (which is also the inductor current) Iuc and the error is then passed through the current compensator C2(s). The compensator transfer functions which provide a stable response

## 4. SIMULATION RESULTS

The simulation of the proposed UCAP integrated DVR system is carried out in PSCAD for a 208V, 60Hz system where 208V is 1pu. The system response for a three phase voltage sag which lasts for 0.1s and has a depth of 0.84pu reduced to 0.16pu while the load voltage VLrms is maintained constant at around 0.9pu due to voltages injected in-phase by the series inverter. This can also be observed from the plots of the line-line source voltages (Vsab, Vsbc, Vsca) Fig. 4 (b), the line-line load voltages (VLab, VLbc, VLca) Fig. 4 (c) and the line-neutral injected voltages of the series inverter (Vinj2a, Vinj2b, Vinj2c) Fig. 4 (d). Finally, it can be observed from Fig. 4 (e) that Vinj2a lags Vsab by 30° which indicates that it is in-phase with the line-neutral source voltage Vsa. In plots of the bi-directional dc-dc converter are presented and it can be observed that the dc-link voltage Vfdc is regulated at 260V, the average dc-link current Idclnkav and the average UCAP current Iucav increase to provide the active power required by the load during the sag.

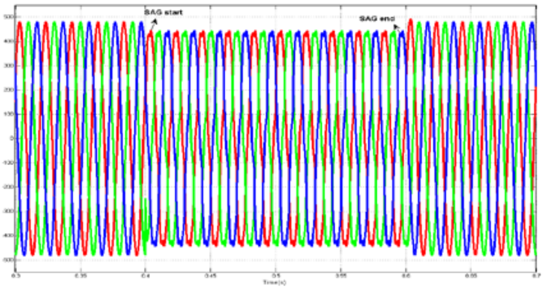

*Fig. 4 a) Grid Voltage*

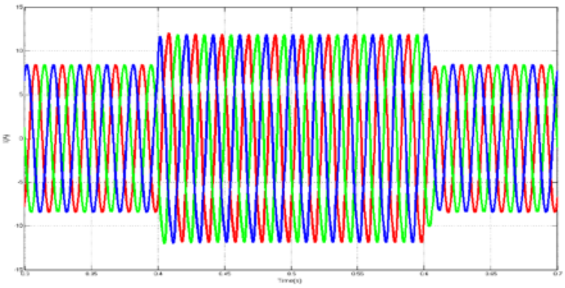

*Fig. 4 b) Grid Current*

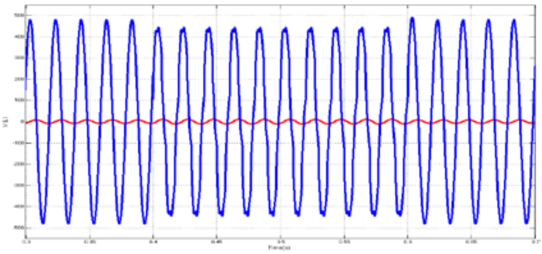

*Fig. 4 c) Voltage & current in mux*

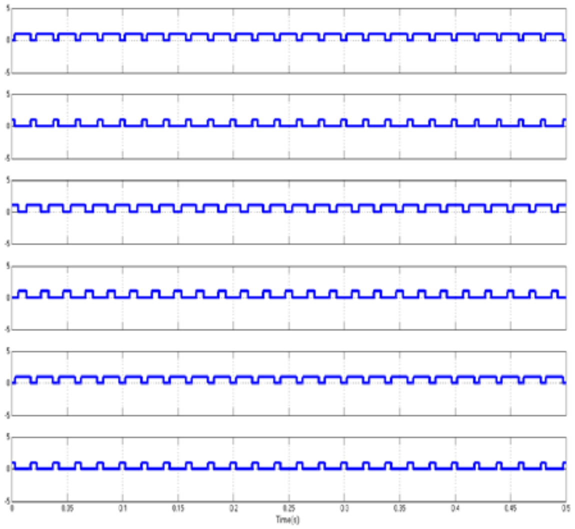

*Fig. 4 d) Gate pulses*

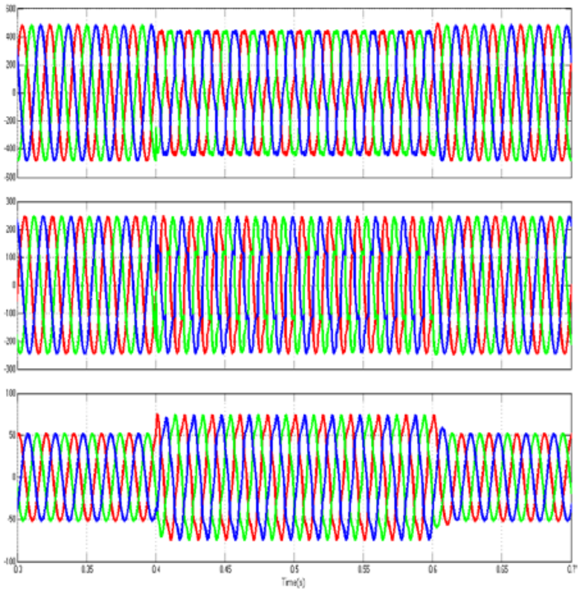

*Fig. 4 e) Grid voltage, load voltage, injected voltage*

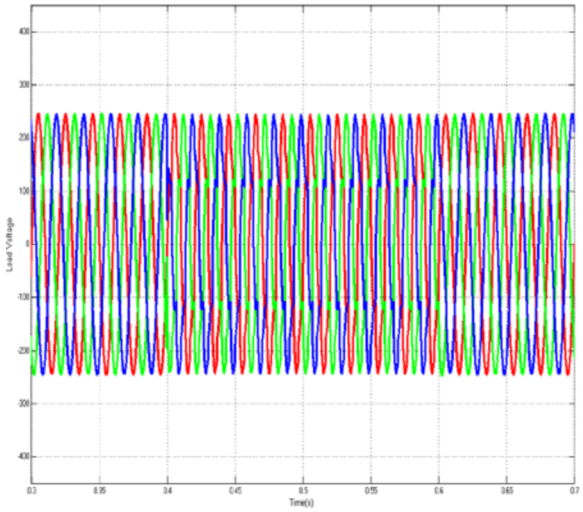

*Fig. 4 f) Load voltage*

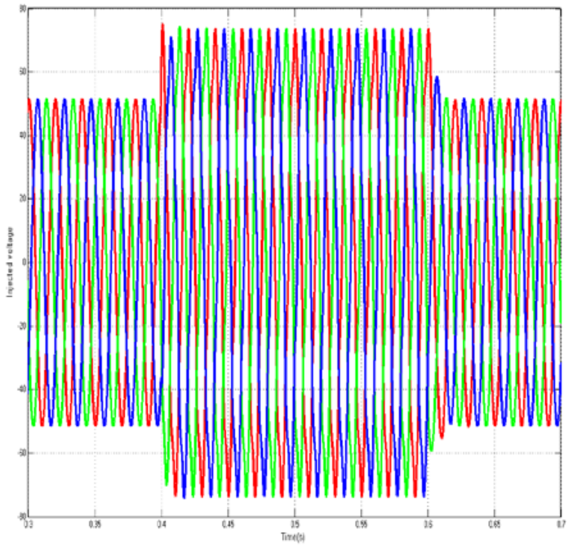

Fig. 4 g) Injected voltage

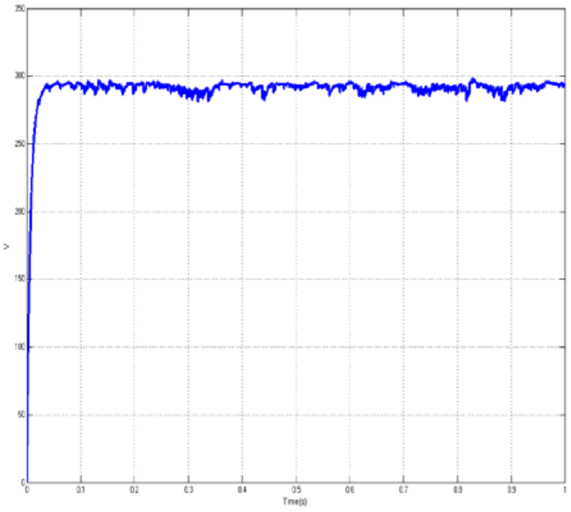

Fig. 4 h) DC link voltage

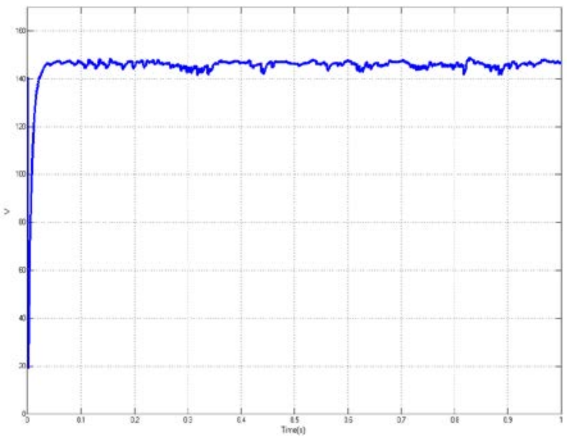

*Fig. 4 i) Voltage from battery*

## 5. CONCLUSION

A new phase advanced multiloop control scheme has been proposed for the dynamic voltage restorer. A Kalman filter is used to determine the supply voltage parameters such that the control scheme can be realized in real time. Through analysis, simulation, and experimental measurements, it is shown that the proposed scheme is superior compared to the conventional in-phase injection technique in terms of energy saving and dynamic performance. Such characteristics are highly desirable as the design is seen to result in a more economical restorer which can improve the ride-through capability of sensitive loads and industrial processes. The UCAP integration through a bidirectional dc–dc converter at the dc-link of the DVR is proposed. The power stage and control strategy of the series inverter, which acts as the DVR, are discussed. The control strategy is simple and is based on injecting voltages in-phase with the system voltage and is easier to implement when the DVR system has the ability to provide active power. A higher level integrated controller, which takes decisions based on the system parameters, provides inputs to the inverter and dc–dc converter controllers to carry out their control actions. The UCAP integration through a bi-directional dc-dc converter at the dc-link of the DVR is proposed. The power stage and control strategy of the series inverter which acts as the DVR are discussed. The control strategy of the inverter is based on in-phase compensation which

is simple and easy to implement when the DVR system has the ability to provide active power. Designs of major components in the power stage of the bi-directional dc-dc converter are discussed. 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. The simulation of the UCAP-DVR system, which consists of the UCAP, dc–dc converter, and the grid-tied inverter, is carried out using PSCAD. Hardware experimental setup of the integrated system is presented and the ability to provide temporary voltage sag and swell compensation in all three phases to the distribution grid dynamically is tested .

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