



An Integrated Dynamic Voltage Restorer- Ultracapacitor for Power Quality Improvement in the Distribution Grid

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KEYWORDS	ABSTRACT
DVR, UCAP, POWER U QUALITY, DISTRIBUTION SYSTEM, VOLTAGE SAG, VOLTAGE SWELL	Cost of various energy storage technologies is decreasing rapidly and the integration of these technologies into the power grid is becoming a reality with the advent of smart grid. Dynamic voltage restorer (DVR) is one product that can provide improved voltage sag and swell compensation with energy storage integration. Ultracapacitors (UCAP) have low-energy density and high-power density ideal characteristics for compensation of voltage sags and voltage swells, which are both events that require high power for short spans of time. 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. MATLAB/SIMULATION Software and sim power systems tools are used. Mainly control system tools, power electronics and electrical elements tools are used.

INTRODUCTION

The concept of using inverter-based dynamic voltage restorers (DVRs) for preventing customers from momentary voltage disturbances on the utility side was demonstrated for the first time by Woodley et al. The concept of using the 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 dc-terminal 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 DVR 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) such as wind, solar, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicle (PHEVs).

Therefore, there has been renewed interest in the literature to integrate rechargeable energy storage again at the dc-terminal of power quality products such as static compensator (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 such as DVR. Efforts have been made to integrate energy storage into the DVR system, which will give the system active power capability that makes it independent of the grid during voltage disturbances.

PROPOSED METHDOLOGY

In, cascaded H-bridge-based DVR with a thyristor-controlled inductor is proposed 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 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 prevalence 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. Supercapacitor based energy storage integration into the DVR for the distribution grid is proposed in and. However, the concept is introduced only through simulation and the experimental results are not presented.

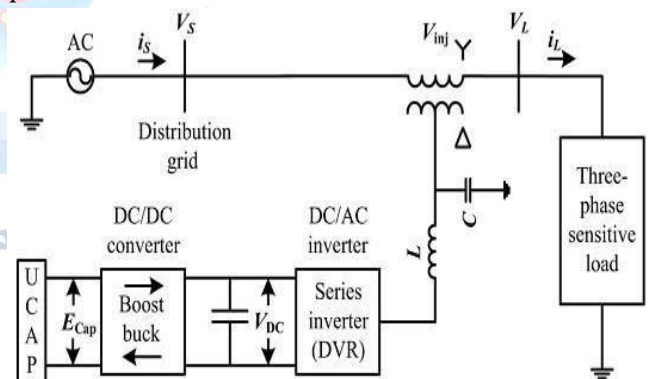


Figure 1:One-line diagram of DVR with UCAP energy storage.

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

- 1) Integration of the UCAP with DVR system gives active power capability to the system, which is necessary for independently compensating voltage sags and swells.
- 2) Experimental validation of the UCAP, dc-dc converter, and inverter their interface and control.
- 3) Development of inverter and dc-dc converter controls to provide sag and swell compensation

to the distribution grid.

The control and protection of a DVR designed to compensate voltage sags must consider the following functional requirements.

1. When the supply voltage is normal, the DVR operates in a standby mode with zero voltage injection. However if the energy storage device (say batteries) is to be charged, then the DVR can operate in a self- charging control mode.
2. When a voltage sag/swell occurs, the DVR needs to inject three single phase voltages in synchronism with the supply in a very short time. Each phase of the injected voltage can be controlled independently in magnitude and phase. However, zero sequence voltage can be eliminated in situations where it has no effect. The DVR draws active power from the energy source and supplies this along with the reactive power (required) to the load.
3. If there is a fault on the downstream of the DVR, the converter is by- passed temporarily using thyristor switches to protect the DVR against over currents. The threshold is determined by the current ratings of the DVR.

The overall design of DVR must consider the following parameters:

1. Ratings of the load and power factor
2. Voltage rating of the distribution line
3. Maximum single phase sag (in percentage)
4. Maximum three phase sag (in percentage)
5. Duration of the voltage sag (in milliseconds)
6. The voltage time area (this is an indication of the energy requirements)
7. Recovery time for the DC link voltage to 100%
8. Over current capability without going into bypass mode.

Typically, a DVR may be designed to protect a sensitive load against 35% of three phase voltage sags or 50% of the single phase sag. The duration of the sag could be 200 ms. The DVR can compensate higher voltage sags lasting for shorter durations or allow longer durations (up to 500 ms) for smaller voltage sags. The response time could be as small as 1 ms.

ULTRACAPACITOR

The electrochemical ultra capacitor is an emerging technology that promises to play an important role in

meeting the demands of electronic devices and systems both now and in the future. This newly available technology of ultra capacitors is making it easier for engineers to balance their use of both energy and power. Energy storage devices like ultra capacitors are normally used along with batteries to compensate for the limited battery power capability. Evidently, the proper control of the energy storage systems presents both a challenge and opportunity for the power and energy management system. This paper traces the history of the development of the technology and explores the principles and theory of operation of the ultra capacitors. The use of ultracapacitors in various applications are discussed and their advantages over alternative technologies are considered.

To provide examples with which to outline practical implementation issues, systems incorporating ultra capacitors as vital components are also explored. This paper has aimed to provide a brief overview of ultra capacitor technology as it stands today. Previous development efforts have been described to place the current state of the technology within an historical context. Scientific background has also been covered in order to better understand performance characteristics. Possible applications of ultra capacitor technology have also been described to illustrate the wide range of possibilities that exist.

Because of the advantages of charging efficiency, long lifetime, fast response, and wide operating temperature range, it is tempting to try and apply ultra capacitors to any application that requires energy storage. The limitations of the current technology must be fully appreciated, however, and it is important to realize that ultra capacitors are only useful within a finite range of energy and power requirements. Outside of these boundaries other alternatives are likely to be the better solution. The most important thing to remember about ultra capacitors technology is that it is a new and different technology in its own right.

There may exist some similarities between ultracapacitor operation and the operation of electrostatic capacitors, but there are fundamental differences that result from the different physical processes involved and these must be appreciated. Problems may be encountered if systems are designed based on the assumption that ultracapacitors behave like normal capacitors.

Ultra capacitors are, at any rate, a part of the new wave of advanced energy storage devices that will further the push towards greater energy efficiency and more sustainable alternatives. They will be a useful tool with which to engineer highly efficient electrical and electronic systems, and as the state of the technology advances they will become progressively more common place.

VOLTAGE SAG

Voltage sags and momentary power interruptions are probably the most important PQ problem affecting industrial and large commercial customers. These events are usually associated with a fault at some location in the supplying power system. Interruptions occur when the fault is on the circuit supplying the customer. But voltage sags occur even if the faults happen to be far away from the customer's site. Voltage sags lasting only 4-5 cycles can cause a wide range of sensitive customer equipment to drop out. To industrial customers, voltage sag and a momentary interruption are equivalent if both shut their process down. A typical example of voltage sag is shown in fig 2. The susceptibility of utilization equipment to voltage sag is dependent upon duration and magnitude of voltage sags and can be define

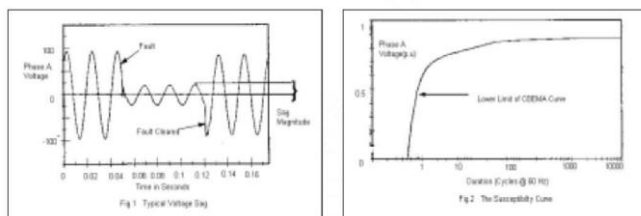


Figure 2 Voltage Sag

RESULTS AND DISCUSSIONS

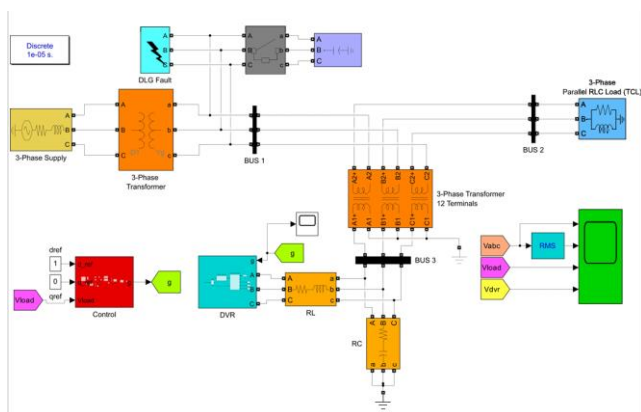


Fig 3: Simulation diagram of the Proposed work

VOLTAGE SAG

SOURCE AND LOAD RMS VOLTAGES

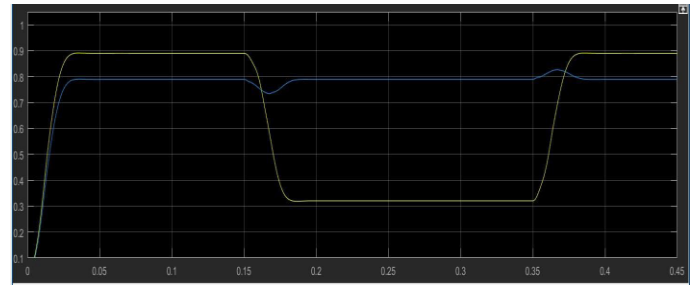


Figure 4(a) Source and load RMS voltages V_{srms} and V_{Lrms} during sag.

SOURCE VOLTAGES

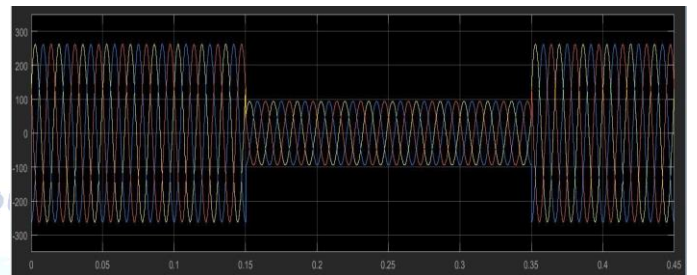


Figure 4(b) Source voltages V_{sab} (blue), V_{sbc} (red), and V_{sca} (green) during sag.

LOAD VOLTAGES

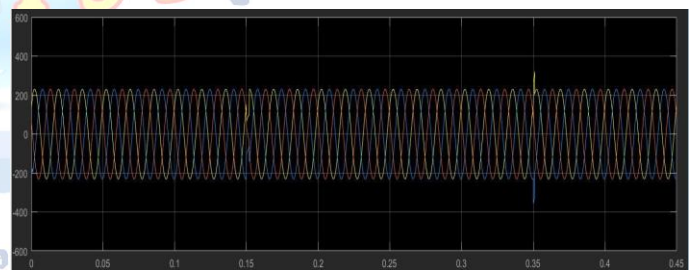


Figure 4(c) Load voltages V_{Lab} (blue), V_{Lbc} (red), and V_{Lca} (green) during sag.

INJECTED VOLTAGES

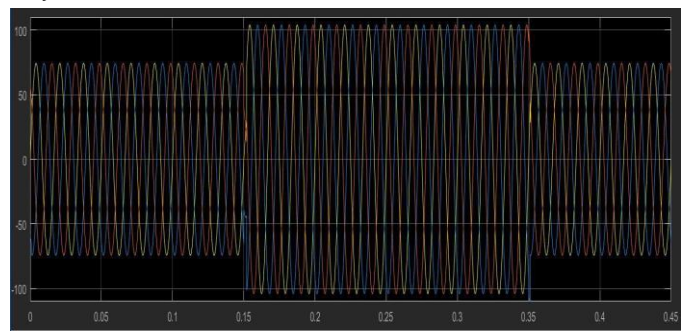


Figure 4(d) Injected voltages V_{inj2a} (blue), V_{inj2b} (red), and V_{inj2c} (green) during sag.

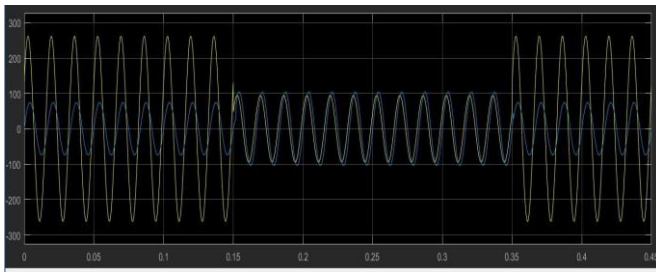
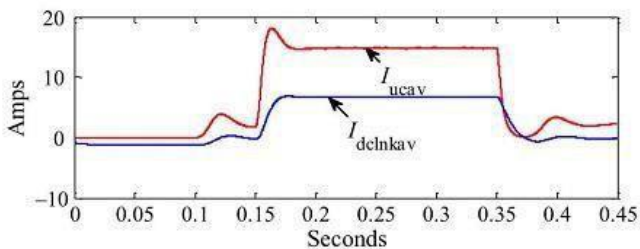
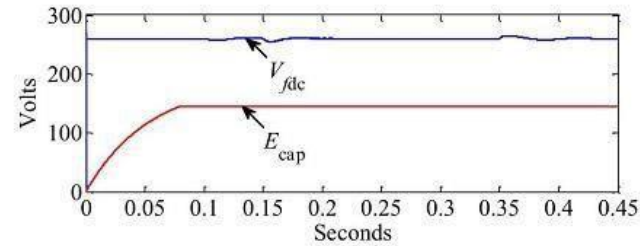
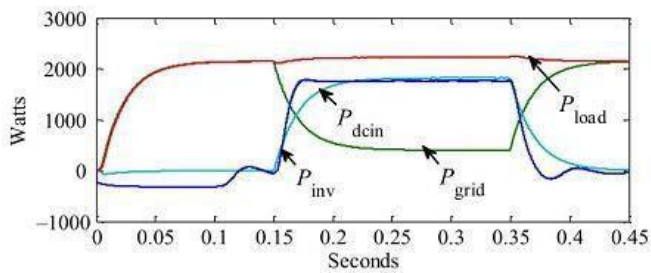


Figure 4(e) Vinj2a (green) and Vsab (blue) waveforms during sag



(a)



(b)

Figure.5 (a) Currents and voltages of dc-dc converter. (b) Active power of grid, load, and inverter during voltage sag.]

VOLTAGE SWELL

SOURCE AND LOAD RMS VOLTAGES

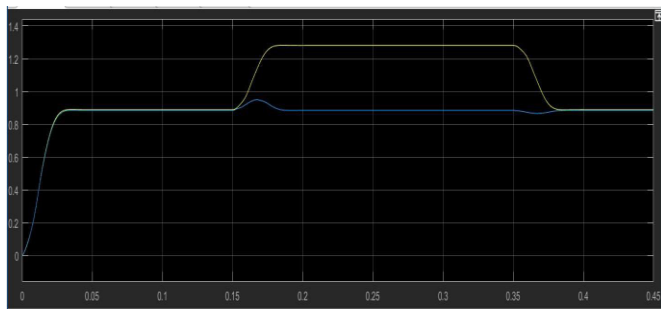


Figure 6(a) Source and load rms voltages Vsrms and VLrms during swell.

SOURCE VOLTAGES

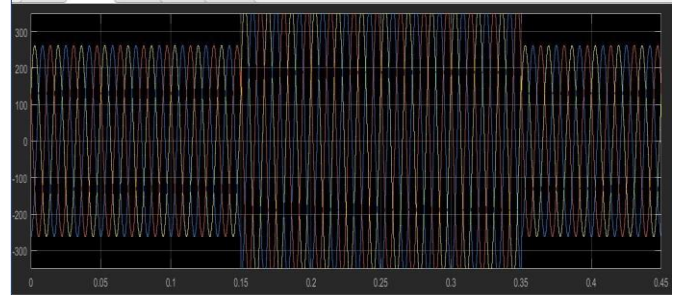


Figure 6(b) Source voltages Vsab (blue), Vsbc (red), and Vsca (green) during swell.

LOAD VOLTAGES

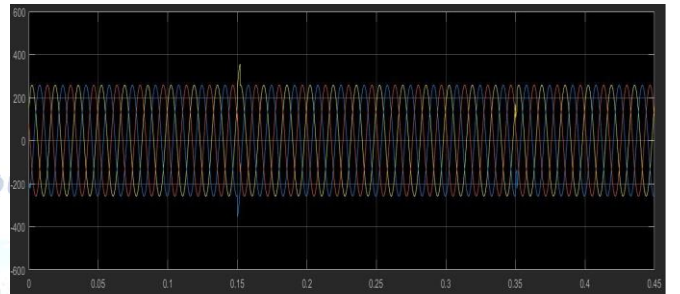


Figure 6(c) Load voltages VLab (blue), VLbc (red), and VLca (green) during swell

INJECTED VOLTAGES

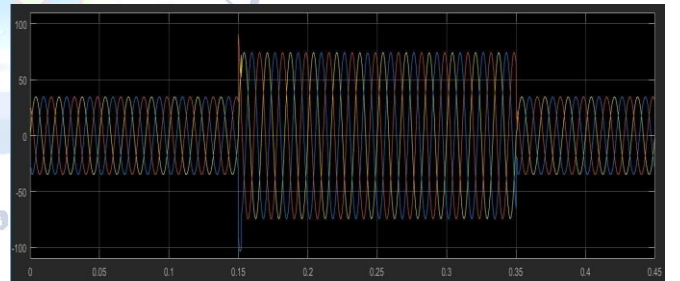


Figure 6(d) Injected voltages Vinj2a (blue), Vinj2b (red), Vinj2c (green) during swell]

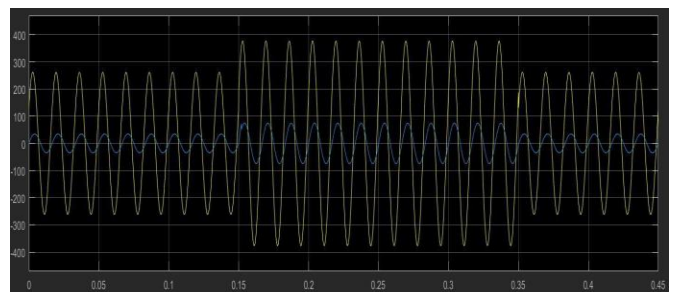


Figure 6(e) Vinj2a (green) and Vsab (blue) waveforms during swell

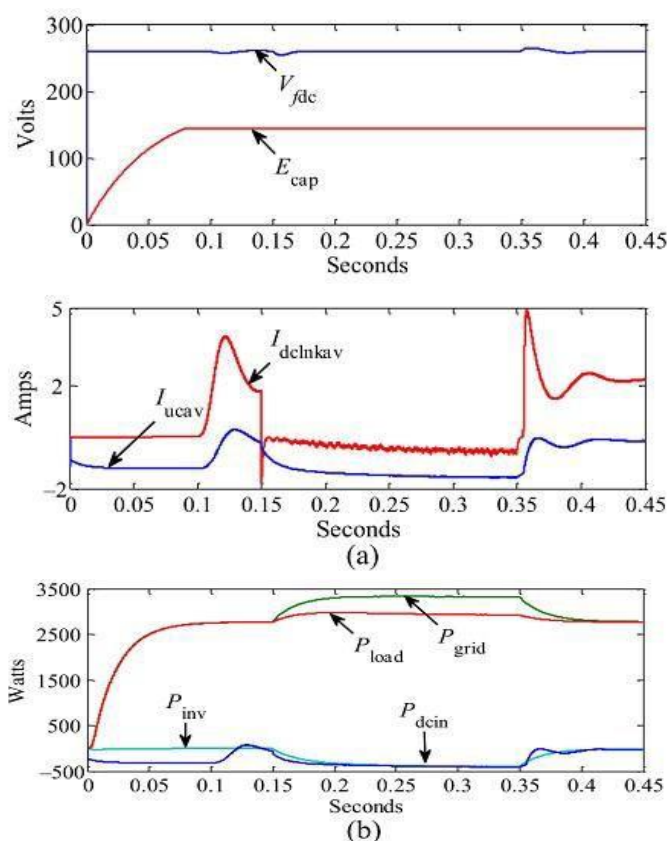


Fig. 7 (a) Currents and voltages of dc-dc converter during swell. (b) Active and reactive power of grid, load, and inverter during a voltage swell.*

The simulation diagram of the proposed work is given in Fig. 3. The system response for a three-phase voltage sag, which lasts for 0.1 s and has a depth of 0.84 p.u., is shown in Fig. 9.7(a)–(e). It can be observed from Fig. 4(a) that during voltage sag, the source voltage V_{rms} is reduced to 0.16 p.u. while the load voltage V_{Lrms} is maintained constant at around 0.9 p.u. due to voltages injected in-phase by the series inverter. This can also be observed from the plots of the line–line source voltages [V_{sab} , V_{sbc} , V_{sca} ; Fig. 4(b)], the line–line load voltages [V_{Lab} , V_{Lbc} , V_{Lca} ; Fig. 4(c)], and the line–neutral injected voltages of the series inverter [V_{inj2a} , V_{inj2b} , V_{inj2c} ; Fig. 4(d)]. Finally, it can be observed from Fig. 4(e) that V_{inj2a} lags V_{sab} by 30° , which indicates that it is in-phase with the line– neutral source voltage V_{sa} .

In Fig. 5(a), plots of the bidirectional dc–dc converter are presented and it can be observed that the dc-link voltage V_{fdc} is regulated at 260 V, the average dc-link current $I_{dc\lnkav}$ and the average UCAP current I_{ucav} increase to provide the active power required by the load during the sag. Although the UCAP is discharging, the change in the UCAP voltage E_{cap} is not visible in

this case due to the short duration of the simulation, which is due to limitations. It can also be observed from the various active power plots shown in Fig.5(b) where the power supplied to the load P_{load} remains constant even during the voltage sag when the grid power P_{grid} is decreasing. The active power deficit of the grid is met by the inverter power P_{inv} , which is almost equal to the input power to the inverter P_{dc_n} available from the UCAP. Therefore, it can be concluded from the plots that the active power deficit between the grid and the load during the voltage sag event is being met by the integrated UCAP-DVR system through the bidirectional dc–dc converter and the inverter. Similar analysis can also be extended for voltage sags, which occur in one of the phases (a, b, or c) or in two of the phases (ab, bc, or ca). However, the active power requirement is greatest for the case where all the three phases ABC experience voltage sag.

The system response for a three-phase voltage swell, which lasts for 0.1 s and has a magnitude of 1.2 p.u., is shown in Fig. 6(a)–(e). It can be observed that during voltage swell, the source voltage V_{rms} increases to 1.2 p.u., whereas the load voltage V_{Lrms} is maintained constant at around 1 p.u. due to voltages injected in-phase by the series inverter. This can also be observed from the plots of the line–line source voltages [V_{sab} , V_{sbc} , V_{sca} ; Fig. 6(a)], the line–line load voltages [V_{Lab} , V_{Lbc} , V_{Lca} ; Fig. 6(b)], and the line–neutral injected voltages of the series inverter [V_{inj2a} , V_{inj2b} , V_{inj2c} ; Fig. 6(c)]. Finally, it can be observed that V_{inj2a} lags V_{sab} by 150° , which indicates that it is 180° out of phase with the line–neutral source voltage V_{sa} as required by the in-phase control algorithm.

In Fig. 7(a), plots of the bidirectional dc–dc converter are presented and it can be observed that the dc-link voltage V_{fdc} is regulated at 260 V, the average dc-link current $I_{dc\lnkav}$ and the average UCAP current I_{ucav} change direction to absorb the additional active power from the grid into the UCAP during the voltage swell event. The overshoot in I_{ucav} and $I_{dc\lnkav}$ during startup at 0.1 s and during mode changes at 0.15 and 0.35 s which is a modeling problem present in the simulation and does not shown in the experimental results. the increase in E_{cap} due to charging of the UCAP during the voltage swell is not visible. This can also be observed

from various active power plots where the power supplied to the load P_{load} remains constant even during

the voltage swell when the grid power P_{grid} is increasing. It can be observed from the inverter power P_{inv} and inverter input power P_{dc_in} plots that the additional active power from the grid is absorbed by the inverter and transmitted to the UCAP. Therefore, it can be concluded from the plots that the additional active power from the grid during the voltage swell event is being absorbed by the UCAP-DVR system through the bidirectional dc-dc converter and the inverter.

CONCLUSION

In this paper, the concept of integrating UCAP-based rechargeable energy storage to the DVR system to improve its voltage restoration capabilities is 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. 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. Designs of major components in the power stage of the bidirectional dc-dc converter are discussed. The simulation of the UCAP-DVR system, which consists of the UCAP, dc-dc converter, and the grid-tied inverter, is carried out using MATLAB SOFTWARE. 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 on the distribution grid to respond to dynamic changes in the voltage profiles of the grid and prevent sensitive loads from voltage disturbances.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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