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Design of an Ultracapacitor Based Dynamic Voltage Restorer for Power Quality Enhancement in the Distribution Grid

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Abstract

Dynamic Voltage Restorer is a Power Conditioning equipment that can compensate voltage sag and swell of the source voltage with the integration of Ultracapacitor. The innovative Scheme of this paper is the integration of UCAP with DVR, therefore this configuration of DVR can independently compensate the load voltage without utilization of grid voltage to compensate voltage sag and swell as in the existing system. The UCAP charge or discharge during supplying real power to the DVR. So, it is required to maintain the voltage profile of UCAP, this is achieved by incorporating the Buck-Boost converter between the base of the Inverter and Input stage of UCAP. This DC/DC Bidirectional converter provides the constant dc link voltage for the Voltage Source Inverter (DVR) for satisfying operation. The main complex thing in this work is design and control of DC/DC Buck-Boost Converter and Voltage Source Inverter. The whole model is designed and simulated in MATLAB/Simulink. The control strategies of Bidirectional Converter involve PI controller and DVR is controlled by PWM technique. The performance of DVR is validated with the results.

Keywords- Dynamic Voltage Restorer (DVR), Ultra-capacitor (UCAP), DC-DC converter, sag/swell, PI controller

I. INTRODUCTION

Voltage sags are defined as reductions in voltage magnitude accompanied by phase angle jumps with the typical duration of 0.5 to 30 cycles [1]. They are mostly caused by faults on power system networks and are considered as one of the most severe power quality problems faced by many industrial customers, they are almost impossible to avoid, because of the finite clearing time of the faults that cause the voltage sags and the propagation of sags from the transmission and distribution system to the low-voltage loads. Voltage sags are a common reason for failures in production plants and for end user equipment malfunctions in general [2]. In the standard IEEE-I 159-1995, the definition of voltage swell is quoted: A voltage swell is an increase in the RMS voltage above 1.1 p.u. at the power frequency for duration from 0.5 cycle to 1 minute. For instance, switching off large loads and switching on capacitor banks may cause voltage swell at the grid voltage. Swells can cause overheating, tripping or even destruction of industrial equipment such as motor drives and control relays.

There are several voltage sag/swell mitigation methods available. One of commonly used methods is the use of a DVR (Dynamic Voltage Restorer) at the interface of the customer equipment and the point of electricity supply to mitigate voltage sag/swell for shorter periods. During a sag/swell condition, DVR injects an appropriate voltage magnitude with an appropriate phase angle in series with the distribution line, when voltage sag happens, this voltage injection is achieved through the injection of real and reactive power from the DVR to the distribution network. A form of energy storage unit is used to provide real power and the inverter is used to provide reactive power into the distribution network. If using energy storage as the power supply on the DC bus of the DVR, the energy storage should be able to provide very high peak power during short time duration, the ultracapacitor-based energy storages fulfil above requirement well.

The whole model is designed in MATLAB/SIMULINK software. PI Controller is used to control the bidirectional converter, which operates in two modes; Buck and Boost modes. While charging of UCAP it operates in BOOST mode and during discharging it operates in BOOST mode. Pulse Width Modulation Technique is adopted to convert the DC voltage in to three phase voltages at the output stage of Voltage Source Inverter. Energy storage system like batteries involve high chemical reactions and Superconducting Magnetic energy storage system are still costly, these disadvantages helps to make choice of Ultracapacitor.

II. AUTHOR GUIDELINE FOR MANUSCRIPT PREPARATION

The DVR consists of a series three single-phase transformer, the output is filtered by filters in order to reduce the influence from the switching frequency. The primary side of the series transformer is a PWM (Pulse Width Modulation) inverter bridge, an energy storage unit and a DC/DC converter. Block diagram of the DVR is shown in Fig.1.

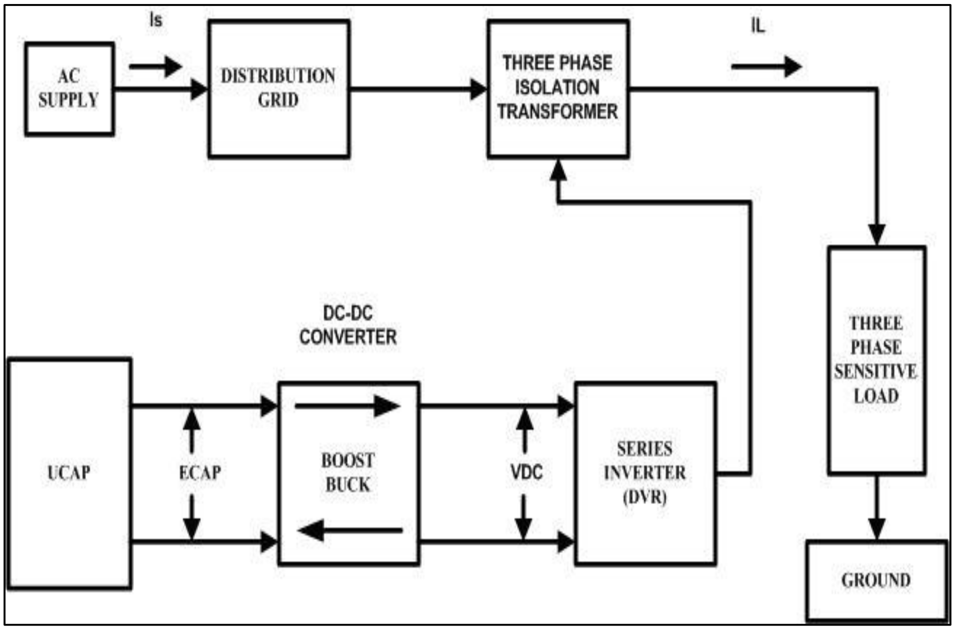

Fig. 1: Block diagram of proposed work

The dc-link of the DVR includes an ultra-capacitor and a DC/DC converter. The power stage is a three-phase voltage source inverter, which is connected in series to the grid and is responsible for compensating the voltage sags and swells. The inverter system consists of an insulated gate bipolar transistor (IGBT) module, its gate-driver, LC filter, and an isolation transformer. The dc-link voltage Vdc is regulated at 260 V for optimum performance of the converter and the line–line voltage Vab is 208 V; based on these, the modulation index m of the inverter is given by

$$m = \frac{2\sqrt{2}}{\sqrt{3}V_{\mathrm{dc}}*n} V_{ab(\mathrm{rms})}. \quad (1)$$

where n is the turns ratio of the isolation transformer. Substituting n as 2.5 in equation (1), the required modulation index is calculated as 0.52. Therefore, the output of the dc–dc converter should be regulated at 260 V for providing accurate voltage compensation. The objective of the integrated UCAPDVR system with active power capability is to compensate for temporary voltage sag (0.1–0.9 p.u.) and voltage swell (1.1–1.2 p.u.), which last from 3 s to 1 min.

$$V_s + V_f = I_s(R_s + jX_s) + V_l$$

$$= \mathrm{I_s Z_s} + \mathrm{V_l} \cdots\cdots (2)$$

Vs is the source voltage of power system and Vf is the injected DVR voltage, Zs is the source impedance.

$$\overline{V}_l = \left(\frac{\overline{V}_s + \overline{V}_f}{Z_s + Z_l}\right) Z_l \quad (3)$$

Vl is the load voltage

III. BIDIRECTIONAL CONVERTER

There arises an increasing need for the systems with the competency of bidirectional transfer of energy between two dc buses, thus bidirectional dc-dc converters have recently received a lot of attention. It acts as an interface circuit in energy storage system for UCAP as a wide range of voltage varies during charging and discharging. Moreover, in the voltage side, if an inverter is connected, there is a need for the UCAP to provide a stable DC voltage for the inverter circuit. Thus, DC-DC converter plays a major role in this system. The model of bidirectional DC-DC converter is shown in Fig. 2. With UCAP as energy storage. During Voltage sag event, the DC-DC converter should be able to withstand the power generated during the discharge mode. Depend on depth and duration of the voltage sag; the grid decides the amount of active power support. Conversely, during voltage swell event the DCDC converter may able to absorb the additional power from the grid. Thus, bidirectional DC-DC converter acts in boost mode while discharging and, on the other hand it acts as a buck converter during charging.

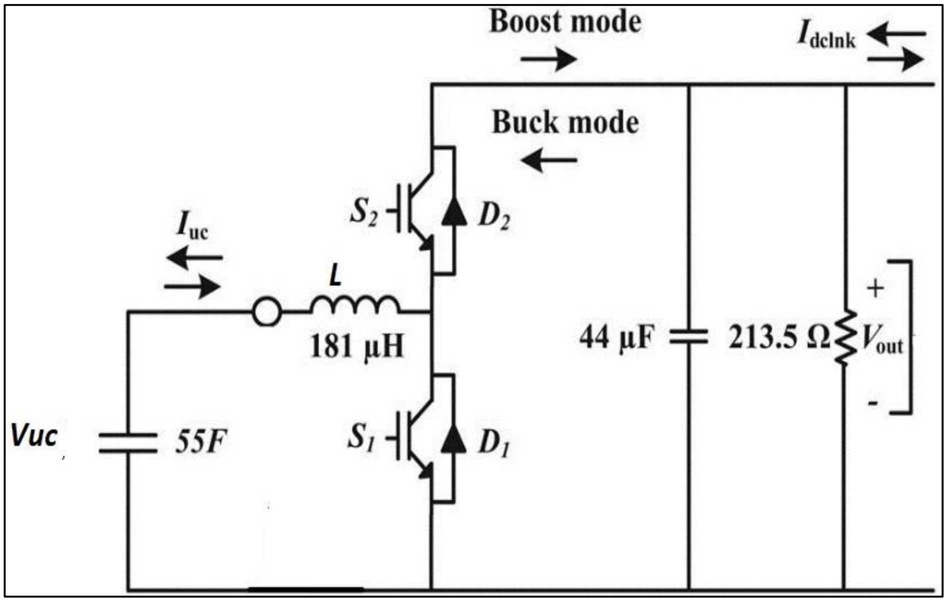

Fig. 2: Model of DC/DC Converter

$$V_{dclink} = \frac{V_{uc}}{1-d} \cdots\cdots \quad (4)$$

In Boost mode, Switch1 is operating, Vdclink voltage is given by equation (4) where d is the duty ratio. Vuc is the Ultra-capacitor voltage. When Switch1 turns on and off the change in inductor current is given by equation (5)

$$\Delta I_L = \left(\frac{V_{uc}}{L}\right) dT \cdots\cdots (5)$$

Equation 5 gives the design of Inductor L

$$\Delta V = \frac{\Delta Q}{C} = \frac{I_{load}\, dT}{C} = \frac{PdT}{CV_{dclink}} \cdots\cdots (6)$$

DC link capacitor voltage changes during charging and discharging of the UCAP through it. Hence, the ripple voltage $\Delta V$of the capacitor C is given by equation 6, where P is the power rating, delta Q is the change in capacitor charge, I load is the load current supplied to the grid.

IV. ULTRA – CAPACITOR

Ultracapacitors, also called as electrochemical double-layer capacitors (EDLCs) or supercapacitors. Parts of Ultracapacitors are electrode, electrolyte, collector, exhaust valve, membrane for isolation, sealing materials and connection pole. As shown above the capacitor is made up of a series of RC circuits where R_1, R_2 …R_n are the internal resistances and C_1, C_2..., C_n are the electrostatic capacitances of the activated carbons. When voltage is applied current flows through each of the RC circuits. In this paper three UCAP each of 48 V are in series connection to obtain 144 V and capacitance of 165F.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 value of the capacitance and equivalent series resistance is given by equation 7 & 8

$$C_{sy} \quad = \frac{cell}{} \cdots\cdots(7)_n$$

$$ESR_{SY} = ESR_{cell} * n\ldots\ldots (8)$$

The amount of current needed to charge the capacitor is determined by the following equation 9

$$I_n = (V/R_n)\exp(-t/(C_n * R_n)) \cdots\cdots (9)$$

The capacitance of the UCAP is directly proportional to parallel plate area A and inversely proportional to distance a between the plates and is given by equation 10

$$C = \frac{\varepsilon_0 \varepsilon_r A}{a} [F] \cdots\cdots (10)$$

Where $\varepsilon_0$is the vacuum permittivity constant and ε_r is the relative constant of insulating dielectric between the plates.

V. SIMULATION MODEL

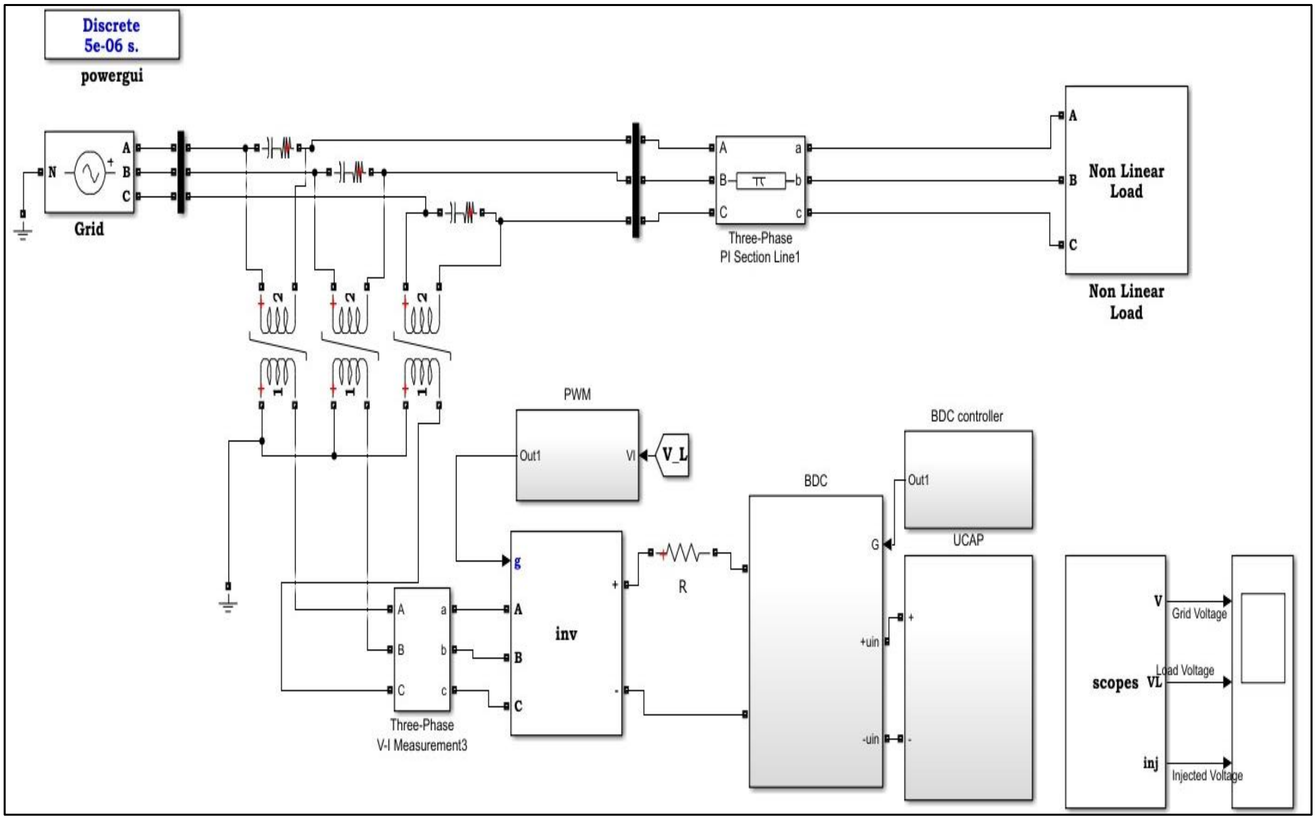

Fig. 3: Simulation model of DVR configuration

The whole model is designed using MATLAB /Simulink software. PI Controller is used to control Bi-directional converter and Pulse width Technique is used to control Dynamic Voltage Inverter (VSI).

VI. RESULTS & DISCUSSIONS

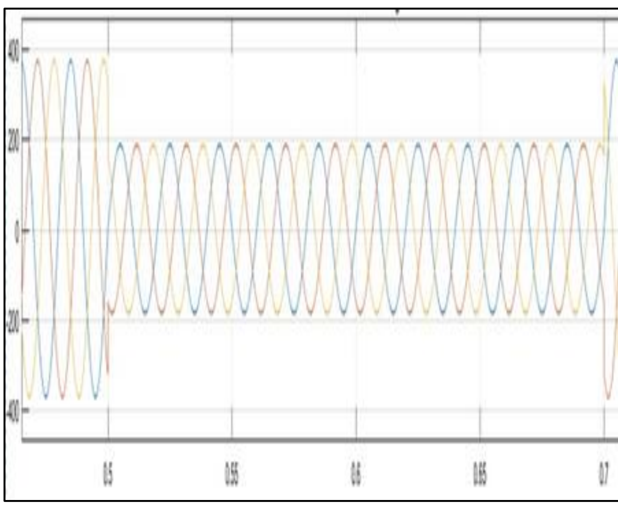

Fig. 5: Sag condition of source Voltage

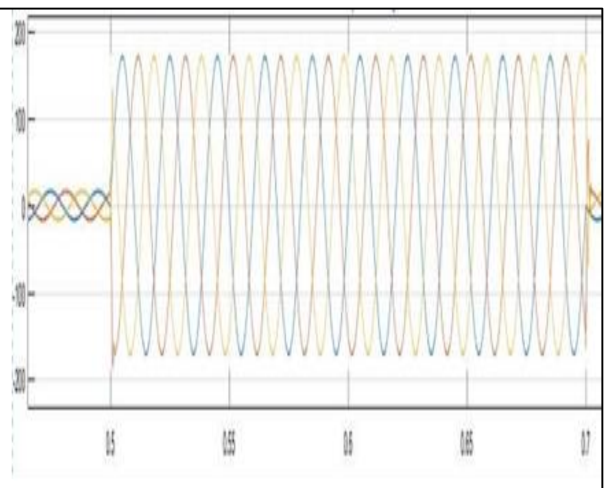

Fig. 6: Injected voltage of DVR

Vinject=220V at t0.5s Vsag=160V at t= 0.5s

When t = 0.5s the sag occurs in the source voltage of the power system, due to this voltage drops from 380Vrms phase to phase voltage to 160V.The source voltage restores at t=0.7s.DVR injects a voltage of 220V in to the grid.

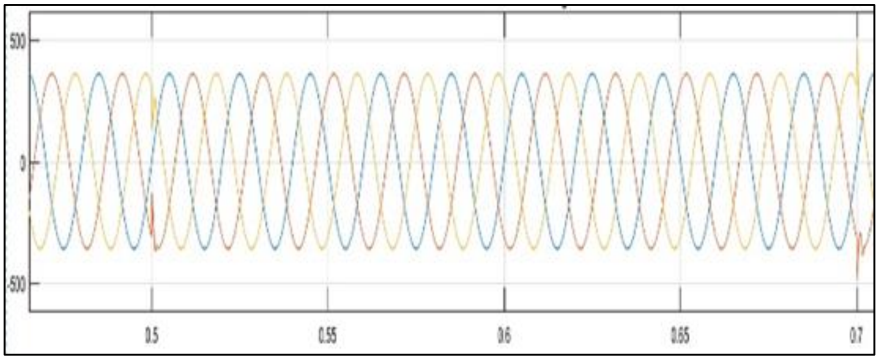

Fig. 6: Compensated load voltage
Vload=380V

The load voltage is maintained at 380 V phase to phase voltage by compensation

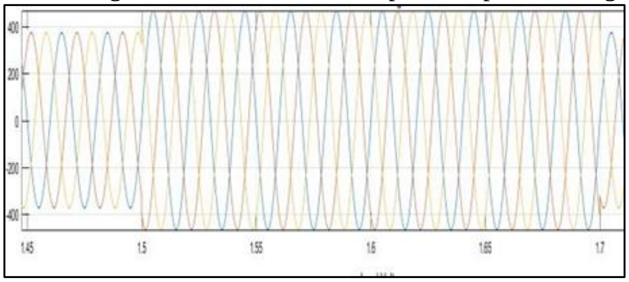

Fig. 8: Swell condition of source voltage
Vswell=460V

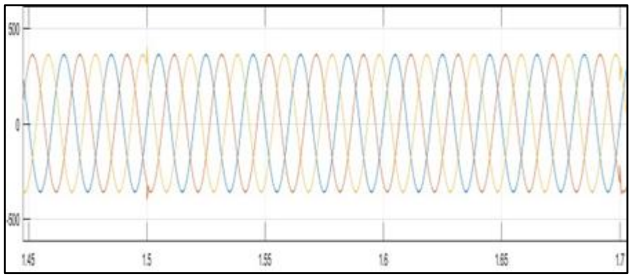

Fig. 9: Injected voltage of DVR
Vabsorb=220V

When t=1.5s voltage swell happens in the source voltage, voltage increase from 380V to 490V.Voltage restoration by DVR absorbs the voltage from the grid of 220 V.

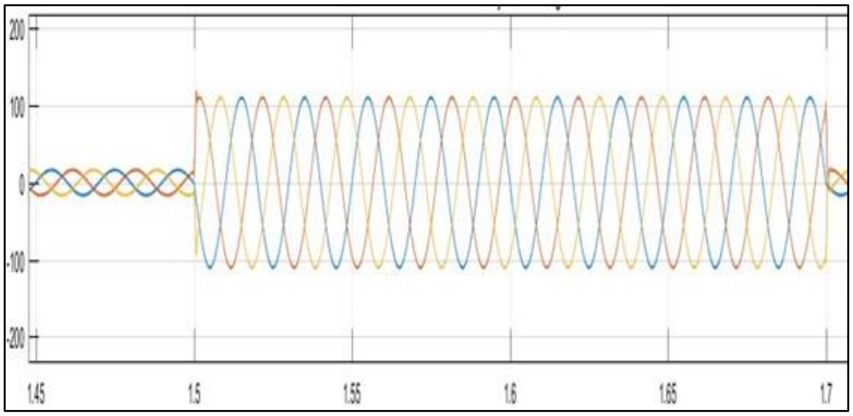

Fig. 10: Compensated voltage
V injection =-160V

Load voltage is maintained constant at 380V line to line voltage.

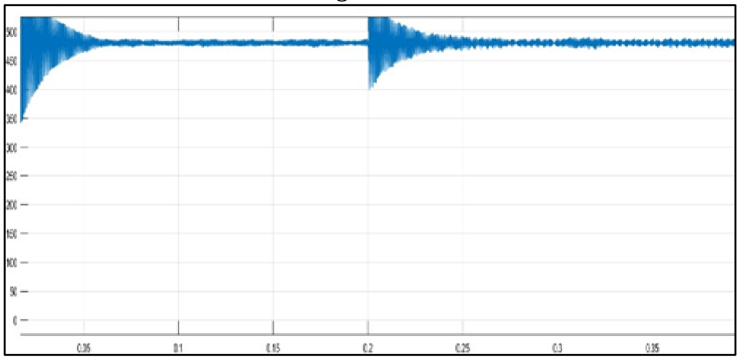

Fig. 11: Output voltage of DC/DC Converter
Vdclink=260V

At t =0.5s during sag condition of source voltage real power is supplied by the UCAP through the Buck Boost Converter to the DVR. Hence at t=0.5s voltage of the DC link of the inverter is maintained constant at 260V, after sag clears it maintains the voltage profile of UCAP

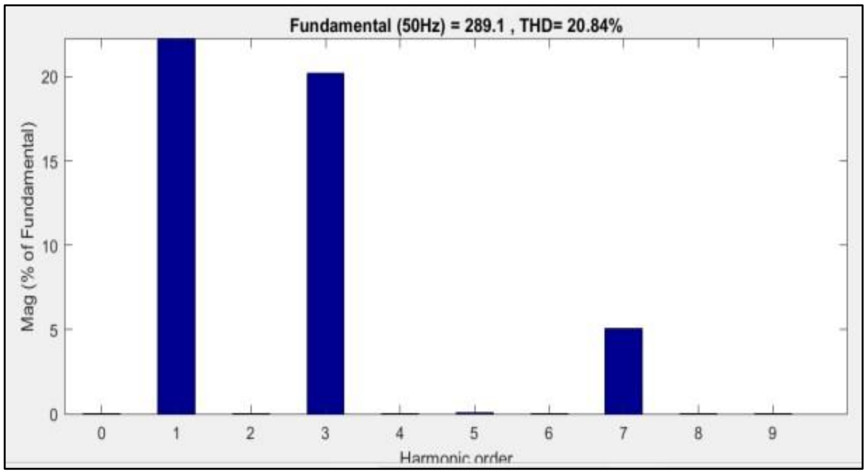

Fig. 12: Total Harmonic distortion without DVR

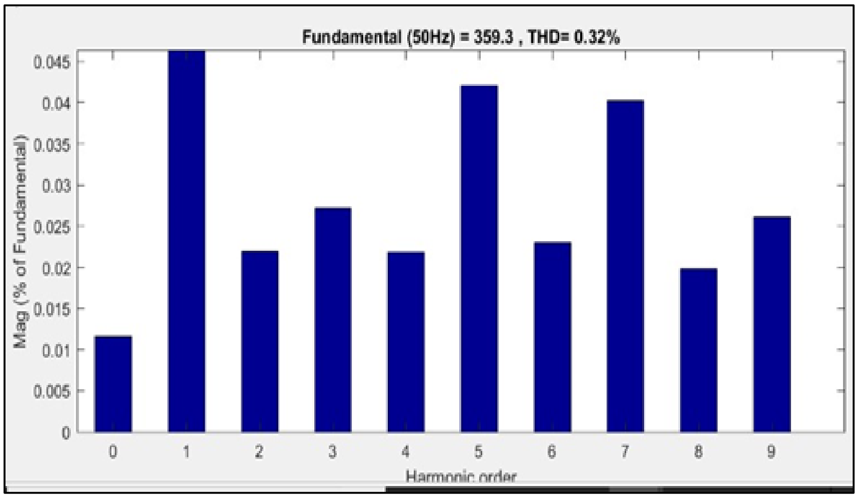

Fig. 13: Total harmonic distortion with DVR

Table 1: THD comparison

	THD Comparison
Without DVR	20.84%
With DVR	0.32%

VII. CONCLUSION

Ultra capacitor-based energy storages are very suitable as the peak power units combined with the VSI based Dynamic Voltage Restorers to compensate the voltage fluctuation in the AC grid due to inconstant power injection from the distributed power generation systems. PI controlling techniques is used for controlling Buck Boost Converter. This technique maintains the constant DC link voltage and maintains the voltage profile of the UCAP. The process of designing the DC/DC Converter is presented. SPWM technique is employed for Voltage Source Inverter is presented also the designing of DVR is discussed.

Table 2: System Specification

System component	Specification
Effective value of line voltage	380V
Three phase loads	10kW
DC link Voltage	400V
DC/DC Converter inductance	181µH
DC/DC Converter capacitance	44µF
PWM switching frequency	1000kHz
Transformer ratio	1:1

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