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Grid Independent Power Quality Improvement Technique using Dynamic Voltage Restorer and Ultracapacitor with Fuzzy Logic Control

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Abstract: -- **The reduction of the prices of the storage technologies and development of Smart grid made their integration into the grid easy. Dynamic Voltage Restorer (DVR) along with the energy storage is ideal for compensating the voltage abnormalities i.e., Sags and Swells. Ultracapacitor (UCAP) has high power density and low energy density which is essential for compensation of the voltage fluctuations like Sags and Swells as both these need large power for small amount of time. The rechargeable UCAP integration with DVR is theunique contribution of this paper. With this arrangement the UCAP-DVR system shall be independent of the grid, for compensations during the voltage disturbances, unlike the systems in the past. UCAP is connected into the dc-link of DVR with the help of a Bi-directional dc-dc converter, which retains a stiff dc-link. This whole arrangement can help us in compensating the voltage fluctuations lasting from 3s to 1 min. The Fuzzy Logic Controller is used in the system for smoother operation and less distortion of the output wave. The overall design and simulation models are discussed and developed in detail.**

Keywords:- **Ultracapacitor (UCAP) , Dynamic Voltage Restorer (DVR),Voltage Sag , Voltage Swell, Bidirectional dc-dc converter, Fuzzy logic.**

I. INTRODUCTION

In the modern day power systems, the power quality is a key component. The term power quality refers to the course of action taken to ensure voltage quality and current quality. It also has to ensure that they fulfil the requirements of amplitude and frequency. The power providers are struggling every day for delivering the quality power to the consumers.The introduction of the FACTS devices into the power grid helps us maintain the quality of the power as required to the maximum extent possible. The use of the inverter based DVR on the utility side for maintenance of the power quality was demonstrated earlier by Woodley [1]. Due to the higher costs of storage technologies the active power injection into the system was a challenging task. The authors in the paper also mention an alternative solution for compensation of voltage sag as inserting a lagging voltage in quadrature with the line current. But due to the decrease in the costs of the energy storage technologies the idea of integrating DVR with energy storage devices for providing active power and make the device independent of the grid has become popular again.

There are various energy storage technologies, like, superconducting magnets (SMES), flywheels (FESS), batteries (BESS), and ultracapacitors (UCAPs). Among the different technologies UCAP is best suited for voltage fluctuations that last in the milliseconds to seconds range. The UCAPs have high power density and low energy density which is ideal for correction of voltage sags and swells as they both are the events that need high amount of power for a smallamount of time. Unlike the batteries, UCAPs also have more charge/discharge cycles per unit time and for same module size UCAPs have greater end voltages than batteries, which make the integration easy.

The DVR-UCAP based system is ideal for temporary voltage sags and swells that occur for milliseconds to seconds range, and the system is independent of the grid. This ensures the quality in power delivering to the consumers. In order to improve the quality of the power furthermore, the controller used in the design of the system i.e., PI controller is replaced by more effective and developedFuzzy Logic Controller.

II. THREE PHASE SERIES INVERTER

A. *Power Stage*

The figure 1 displays the single line diagram of the DVR with UCAP based energy storage. The Power Stage comprises of a Voltage Source Inverter connected in series to the grid which is used to compensate the voltage fluctuations. The DVR and its controller are shown in figure 2. The inverter comprises of Insulated Gate Bi-polar Transistor (IGBT) module, its Gate driver, LC filter and an Isolation Transformer.

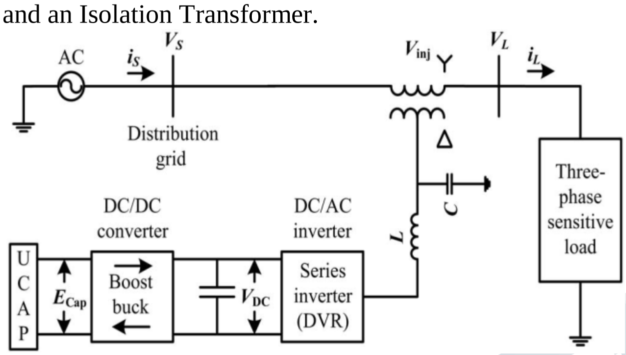

Fig. 1. Single Line Diagram of DVR with UCAP based energy storage.

The modulation index of the transformer is calculated using the following equation

$$m = \frac{2\sqrt{2}}{\sqrt{3}V_{dc*n}} V_{ab(rms)} \text{--(1)}$$

where n is the turns ratio of the isolation transformer. The value of m is calculated as 0.52 based on the values of the source voltage and dc-link voltage.

B. Controller Implementation

For the controller implementation to provide dynamic voltage restoration there are many methods, most of them depend on injecting the voltage in quadrature with advanced phase, sothat reactive power is utilized in voltage restoration [2]. Phaseadvancedvoltage restoration techniques are difficult in putting into practice,but the main reason for using these methods isto decrease the active power support as much as possible and thereby reduce the quantity of energy storage required at the dc-link in order to decrease the money spent on energy storage.With the decrease in the costs of the energy storage these complicated methods can be avoided. The voltages can be directly injected in-phase with the systemvoltage in the event of a voltage sag or swell event. The controlmethod needs a PLL to find the rotating angle.

The inverter controller injects voltages in-phase with the supply-side line–neutral voltages.This requires PLL for estimating θ, which has been implementedusing the fictitious power method described in [3].Based on the estimated θ and the line–line source voltages,Vab, Vbc, and Vca (which are available for this delta-sourcedsystem) are transformed into the d–q domain and the line–neutral components of the source voltage V_{sa}, V_{sb}, and V_{sc},which are not available, can then be estimated using equations 2 and 3.

These voltages are normalisedusing line–neutral voltage of 120Vrms as reference and equatedto unit sine waves in-phase with original system voltages Vsfrom (3) to find the injected voltage references Vref, which areessentialto acquire a stable voltage at the load side.

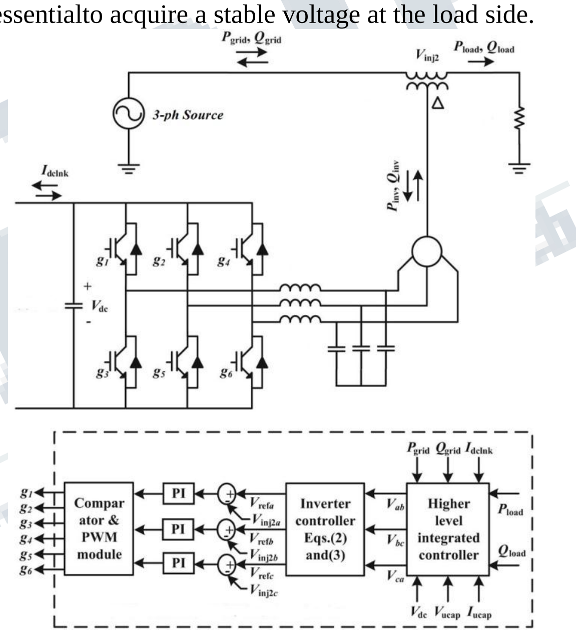

Fig 2. Schematic diagram of three –phase series inverter and its controller

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos(\theta - \frac{\pi}{6}) & \sin(\theta - \frac{\pi}{6}) \\ -\sin(\theta - \frac{\pi}{6}) & \cos(\theta - \frac{\pi}{6}) \end{bmatrix} \begin{bmatrix} \frac{Vd}{\sqrt{3}} \\ \frac{Vq}{\sqrt{3}} \end{bmatrix} \text{--(2)}$$

$$\begin{bmatrix} V_{refa} \\ V_{refb} \\ V_{refc} \end{bmatrix} = m * \begin{bmatrix} (\sin\theta - \frac{Vsa}{169.7}) \\ (\sin\left(\theta - \frac{2\pi}{3}\right) - \frac{Vsb}{169.7}) \\ (\sin\left(\theta + \frac{2\pi}{3}\right) - \frac{Vsc}{169.7}) \end{bmatrix} \text{--(3)}$$

$$P_{inv} = 3V_{inj2a(rms)} I_{La(rms)} \cos\emptyset$$
$$Q_{inv} = 3V_{inj2a(rms)} I_{La(rms)} \sin\emptyset \text{--(4)}$$

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The value of m is 0.52 from (1). Therefore, whenever there is a voltage fluctuation (sag/swell) on the source side, a related voltage V_{inj2} is injected in-phase by the DVR and UCAP system to opposethe effect and maintain a constant voltage V_L at the load end. The real active and reactive power delivered by the series inverter can be estimated fromequation (4) using the rms values of the injected voltage V_{inj2a} and load current I_{La}, and ϕ is the phase angle difference between the two waveforms.

III. DIRECTIONAL DC-DC CONVERTER

As the voltage profile of UCAP changes, it cannot be connected directly to the dc-link. Therefore there was a need of a device which can maintain a stiff dc voltage irrespective of the voltage variations of the UCAP. In order to maintain this voltage stable a Bi-directional dc-dc converter is used. The Bi-directional dc-dc converter and its controller are shown in figure 3. On the input side of thedc-dc converter there is UCAP and on the output side a nominal load is present, in order to avoid no load operation and the output is connected to the dc-link of the inverter. The duration and depth of the sag decides the value of voltage during the sag, this determines the quantity of active power support required by the grid. The dc-dc converter must be able to bear this voltage during the discharge mode of the UCAP. Also in case of Swell event the dc-dc converter should have the ability to absorb the additional amount of power provided by the swell. Here, the bi-directional dc-dc converter works in*boost* mode while the power is discharged from the UCAP and in *buck* mode while the UCAP is charged from grid.

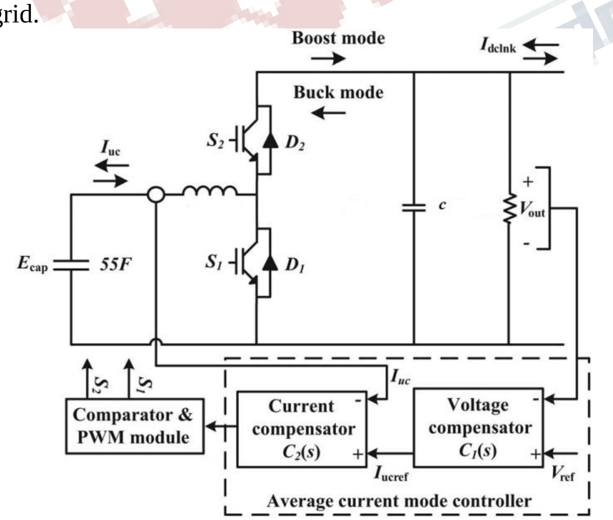

Fig. 3.Bi-directional dc-dc converter and its controller.

Average current mode control [4] is used to regulate the output voltage of the bidirectionaldc–dc converter in both buck and boost modes whilecharging and discharging the UCAP bank. This method ismuch stable over other techniques likevoltage mode control and peak current mode control. Averagecurrent mode controller is shown in Fig. 3, here the dc-linkand actual output voltage V_{out} are compared with the referencevoltage V_{ref} and the error is passed to the voltage compensator$C_1(s)$, where the average reference current$I_{ucref}$is generated.When the inverter is discharging power into the grid duringvoltage sag event, the dc-link voltage V_{out}goes belowthe reference V_{ref} and the error is positive; I_{ucref} is positive andthe dc–dc converter works in boost mode. When the inverteris absorbing power from the grid during voltage swell eventor charging the UCAP, V_{out} increases above the reference$V_{ref}$and the error is negative; $I_{ucref}$is negative and thedc–dc converter functions in buck mode. Hence, the difference between V_{out} and V_{ref} determines the sign of $I_{ucref}$and further the mode of operation of the bidirectional dc–dcconverter. The reference current I_{ucref} is then compared to theactual UCAP current (which is also the inductor current) $I_{uc}$and the error is then passed through the current compensator $C_2(s)$. The transfer functions of the compensators for stable operation are given by the equations

$$C_1(s) = 1.67 + \frac{23.81}{s} \qquad \text{--(5)}$$

$$C_2(s) = 3.15 + \frac{1000}{s} \qquad \text{--(6)}$$

IV. FUZZY LOGIC CONTROLLER

The traditional controllers need specific linear mathematical models to be developed for them to work as desired. But it is not possible to develop a linear model for every time and every situation. In some cases the parameters of the model are uncontrollable and there is no way to determine each and every case. In such cases traditional controllers fail in providing the smooth and effective control. In order to overcome such problems we need to find a controller that is not merely based on mathematical models.

Fuzzy Logic Controller (FLC) is a control method where linguistic variables are used to control the circuit rather than mathematical values. This method is more robust than the traditional controllers and can work with much less information.

In order to increase the quality of power furthermore the FLC has been used as a controller in the project. Any harmonic distortion that might be present in the system due to unknown parameters can be reduced by

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replacing the traditional controllers by FLC to some extent.

In FLC the difference between to chosen parameters is taken and based on the values i.e., linguistic values the output signal is determined. The steps involved in the whole process are Fuzzification, Inference method and Defuzzification. The fuzzy controller is characterised as for each input and output there are seven fuzzy sets. Here the membership function is triangular for ease.

The membership function values are divided into seven sets and they are named as: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB). The value of the input and the shape of the membership function determine the shape of the output.

Error e/change in error Δe	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 1. Fuzzy Rules

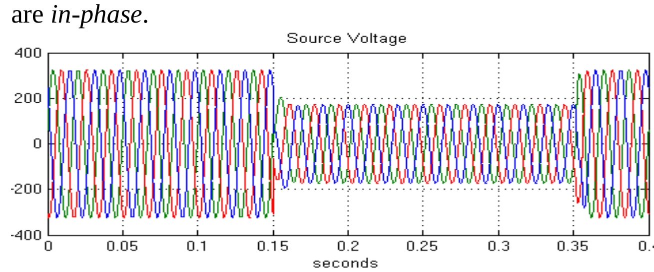
The above Table shows the different relations between the two inputs of the FLC and the output. This table is called the Rule Base of the FLC. In this system the scaling of the values is between -1 and 1. As the membership function is triangular it ensures that any input value has only one dominant fuzzy set, thus eliminating any confusion.

The inference method used is the mandani method. The defuzzification method used is centroid method.

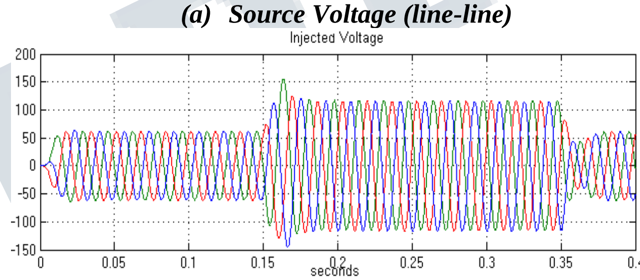
The Fuzzy Logic Controller is used to control the bi directional dc-dc controller in this project.

V. SIMULATION RESULTS

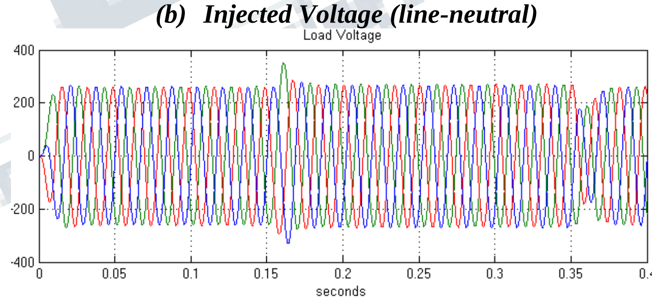
The DVR-UCAP model is simulated using MATLAB-SIMULINK software. The system here is given a three phase power supply and 60hz frequency. The value of the sag applied is 0.72p.u. for the duration of 0.2sec. The values of the various parameters when subjected to such a sag are shown in the figure 4 (a)-(g). The sag caused reduces the source voltage to 0.28p.u. while the Load Voltage is maintain at 0.9-1.1p.u. This is possible as the Voltage is injected by the DVR in-phase with the source voltage to compensate for the sag. This can also be observed from line-line voltages of source(a), line-line voltages of load (c) and line-neutral injected voltages (b). From fig 4 (e) we can observe that injected voltage lags the source by 30^{o} indicating that the Voltages are *in-phase*.



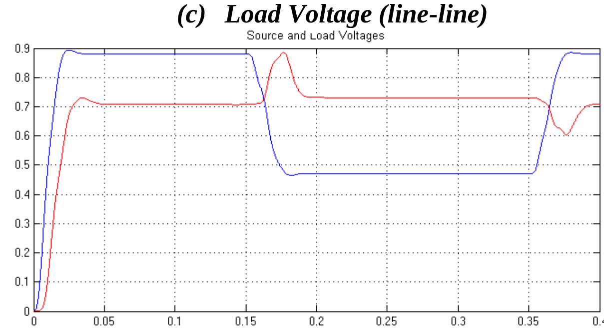
(a) Source Voltage (line-line)



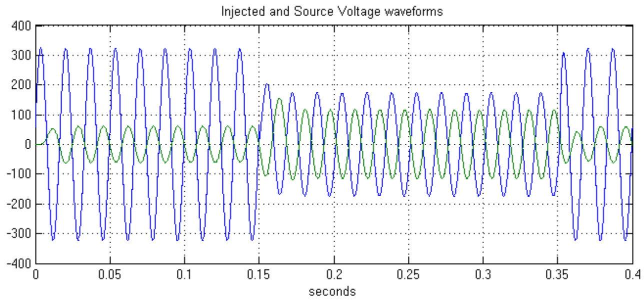
(b) Injected Voltage (line-neutral)



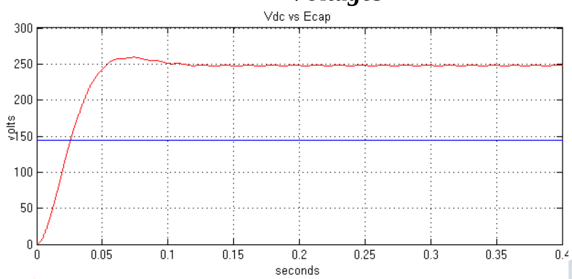
(c) Load Voltage (line-line)



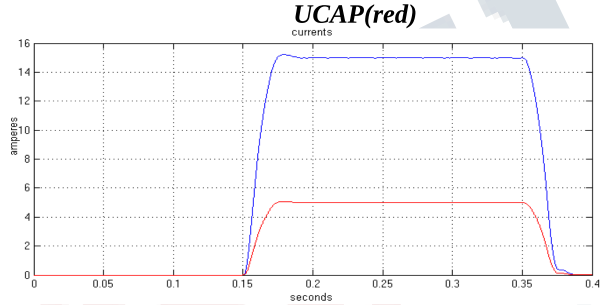
(d) RMS Values of source (blue) and Load (red) Voltages



(e) Waveforms of Source(blue) and Injected(green) Voltages



(f) Voltages of dc-dc converter(blue) and UCAP(red)

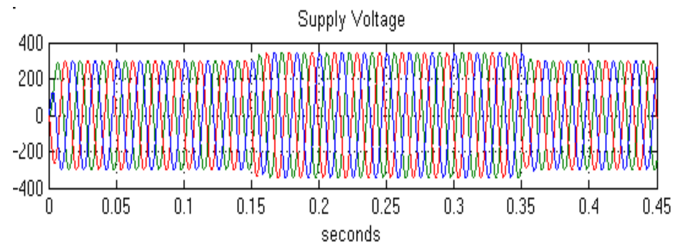


(g) Different currents in the system during sag
Fig. 4. Different Waveforms of a Sag Event

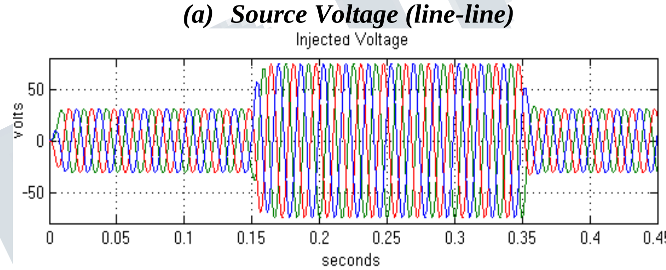
The System responses to three phase voltage swell which exists for 0.2sec and has a magnitude of 1.4p.u. are shown in the figure 5(a)-(g). The swell occurred in the system makes the source voltage 0.4p.u. more than the normal value while the load voltage is maintained from 0.9-1.1 p.u. This can be achieved by the injection of voltage in-phase with the source voltage during a swell. It can be observed that the injected voltage lags the source voltage by 150^{o}, which indicates it is 180^{o} out of phase from the line-neutral voltage of the source, in order to fulfil the in-phase algorithm (fig 5 (e)).

In the figures 4 (f) and 5(f) show the voltage variations in the UCAP and the bi-directional dc-dc converter. Here, we can see that the dc-dc converter regulates the dc-link voltage so that the stiff dc link is maintained irrespective of the fluctuations in the UCAP.

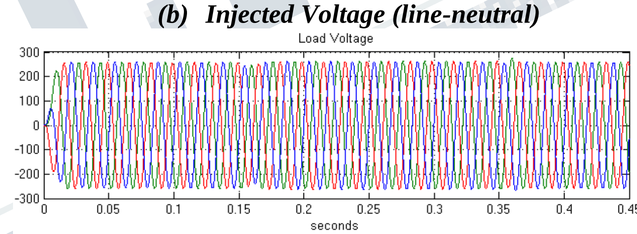
The figures 4(g) and 5(g) show the variations of the currents in the dc –dc converter and the UCAP. During a sag event we can see the increase in the current of the UCAP indicating discharge and in the swell event vice-versa.



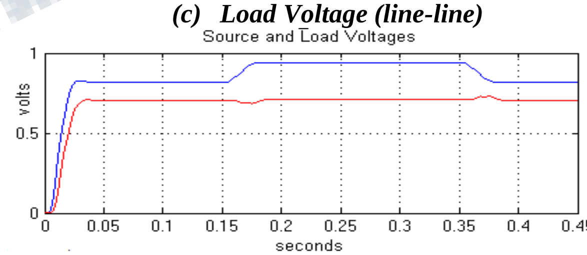
(a) Source Voltage (line-line)



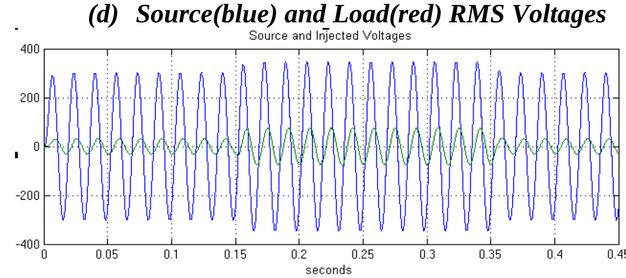
(b) Injected Voltage (line-neutral)



(c) Load Voltage (line-line)



(d) Source(blue) and Load(red) RMS Voltages



(e) Waveforms of Source(blue) and Injected(green) Voltages

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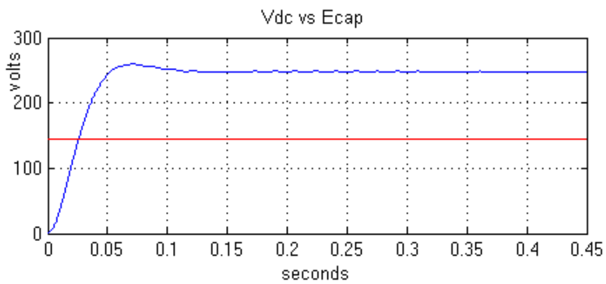
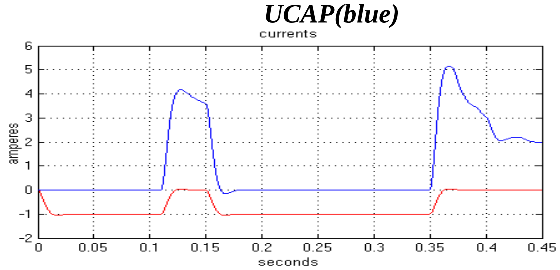


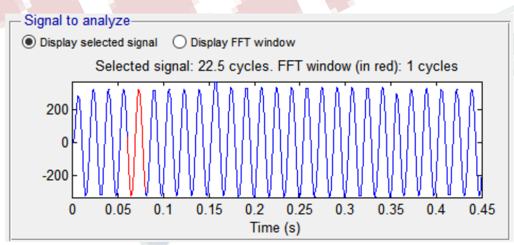
(f) Voltages of dc-dc converter(red) and UCAP(blue)



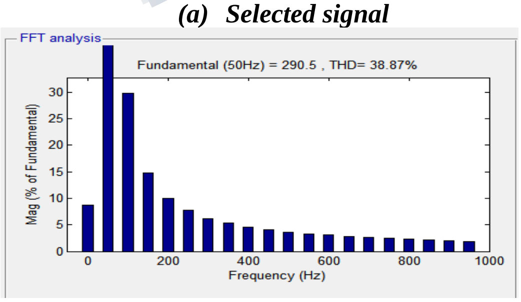
(g) Currents in the system

Fig. 5.Different Waveforms during a Swell Event.

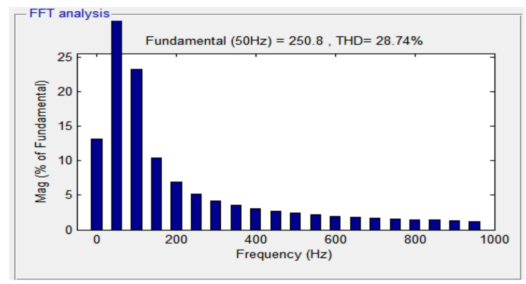
In [5] the system is designed using a traditional controller hence the output voltage might have some harmonic distortion. Now building on the idea of further improving the quality of the power to be supplied, in this project we are using the more advanced and sophisticated controller, Fuzzy Logic Controller. Because of which the Harmonic distortion is reduced to an extent.



(a) Selected signal



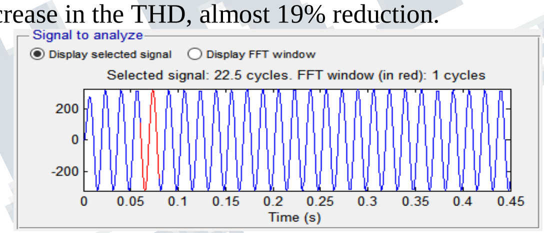
(b) System with PI controller



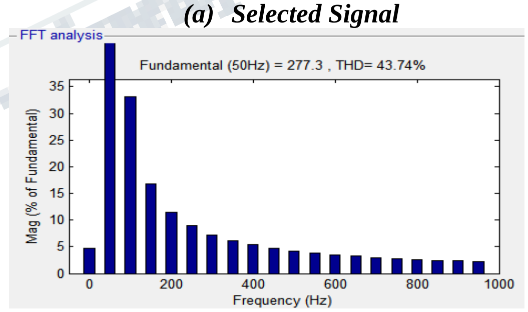
(c) System with FLC

Fig.6. Total Harmonic Distortion (THD) analysis during a sag

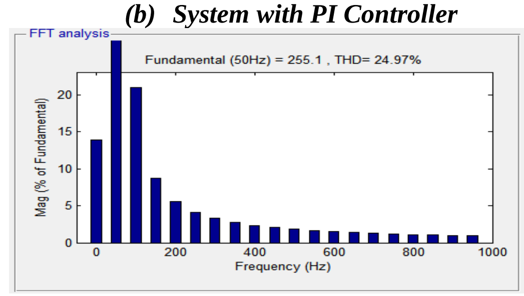
The above figure shows the FFT analysis of the system with traditional controller as well as the FLC. Here we can observe that the THD has reduced over 10% during a sag event further improving the quality of power. Similarly the figure 7 shows the reduction of THD during a swell event. In this case we can observe further more decrease in the THD, almost 19% reduction.



(a) Selected Signal



(b) System with PI Controller



(c) System with FLC
Fig. 7. THD analysis during Swell

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THD Values	Sag	Swell
With PI	38.87%	43.74%
With Fuzzy	28.74%	24.97%

Table 2.Comparison of the THD values.

The above table shows the comparisonof various values of the Total Harmonic Distortion with different controllers. We can observe from the table that because of the FLC there is an enormous reduction of the distortion of the output.

VI. CONCLUSIONS

In this paper we have explored integrating UCAP with DVR along with fuzzy logic as a controller. The integration of rechargeable UCAP with the DVR makes the entire voltage correcting device independent of the grid, as it has its own power source. Also in this paper the system designed ensures the protection from the voltage disturbances, sags /swells which are temporary and have a duration of 3sec to 1min. The addition of the FLC makes the operation of the system smoother and reliable. Furthermore the quality of the power is also increased as the harmonic distortion previously present when a traditional controller is used, is also reduced due to the introduction of FLC. This whole combination of DVR with rechargeable UCAP and FLC ensures that the Quality Power is supplied to the consumers without any interruption.

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