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Performance Analysis of SRF based PI Controller and Fuzzy Controller on Dynamic Voltage Restorer for Compensation of Voltage Sag and Swell

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ABSTRACT
DVR is a custom power device which is used to protect the sensitive loads from power quality issues like voltage sag and swell at the distribution side.The sensitive loads used at the distribution side are basically electronics based which causes harmonics.In today's scenario, the power quality issues like voltage sag and swell are major concern in power system. To overcome this issue a DVR(Dynamic Voltage Restorer) is proven to be more effective solution with low cost , smaller size and faster dynamic response for the protection of sensitive load.The application of DVR entitlements to be a flawless compensating device for the compensation of voltage sag and swell. This paper presents the modelling and simulation using various controllers like PI controller based on synchronous reference frame algorithm and fuzzy logic controller implemented with DVR to obtain the better performance for sag /swell compensation. The results of both the controllers are verified using Matlab-Simulation.
Keywords - Dynamic Voltage Restorer (DVR), Power Quality, SRF Algorithm based PI controller, Fuzzy logic controller, Voltage sag and swell.

I. INTRODUCTION

The major concern in the field of power quality are voltage sag and swell which include magnitude and time duration.Amongst the various power quality issues like transients, voltage sag, voltage swell , voltage sag/swell mainly affects the performance of system at the distribution side. These power quality issuesmainly arises Due to extensive use of sensitive critical loads these issues arises. Amongst all the power quality issues[1], the variations in magnitude of voltage results in voltage sag and swell.At the point of commom coupling ,DVR a series custom power device is used to protect sensitive loads from the effects of voltage disturbances.DVR basically consists of a series-connected injection transformer, a voltage source inverter, inverter, output filter and an energy storage device connected to the dc-link. To maintain the voltage profile, DVR injects a voltage of the required magnitude, phase angle and frequency in series with distribution feeder.

Voltage sag can be caused by a sudden load change, transformer energizing, overloading, sudden start of motors ,short circuiting and some accidents like lightning in power lines. Voltage sag occurs when there is decrease in rms voltage in between 10 to 90% of nominal voltage for 0.5 cycle to 1 minute.

Voltage swell is defined as an increase in rms voltage/current in between 1.1pu and 1.8pu for durations of 0.5 to 1 minute [2]. Voltage swell can be caused by deenergizing of heavy loads leading to hardware failure of device ,overheating and which could   result to shut-down. To overcome this problem a custom power device, namely dynamic voltage restorer (DVR)[3] is used. A DVR is a power electronic device which is connected in series with the supply and the load to inject the required magnitude of voltage for compensation of voltage sag and swell. DVR mainly inject the difference between the rated voltage in comparison with the voltage variation[4]. It compensates both voltage sag and swell and also improves the regulation. The main roleof DVR is detection and compensation of voltage sag and swell in the voltage at the source side[5] of power supply for the protection of load at distribution side from these power quality issues.

The most common choice for the controlling of the DVR is PI controller because of its simple structure. With the use of PI controller it offers a satisfactory performance over a wide range of operation. The disadvantage of this controller is that this controller may not provide the required control performancewhen there are variations in the system parameters and operating conditions. In order toovercome this disadvantage ,fuzzy logic controller

is considered to be the most promising controller due to its robustness along with a advantage of not having any requirement of mathematical model to describe the system .But, the main problem with the conventional fuzzy controllers is that the parameters associated with the membership functions and the rules depend broadly on the intuition of the experts. If it is required to change the parameters, it is to be done by trial and error only. There is no scientific optimization methodology inbuilt in the general fuzzy inference system [5]Due to the continuous persistence of these problems in power system at the distribution side, various severe effects like complete shutdown of power plant, failure of equipment and unbalancing in the current takes place that shows the adverse impact on the distribution system.Voltage sag also known as voltage dip is defined as reduction in RMS voltage for short duration of time. Voltage sag can be caused by a sudden load change, transformer energizing, overloading, sudden start of motors ,short circuiting and some accidents like lightning in power lines.This paper is systematized in following 6sections i.e section1 has Introduction, section 2 discusses operation of DVR and section3,4discusses Control strategy of DVR, section 5 shows Simulation diagram and results, and section 6 concludes the paper.

II. OPERATION OF DVR

DVR is proven to be more efficient and cost effective.DVR provides high efficiency with more reliable operation.Amongst all the power quality issues voltage sag/ swell are considered to have an severe impact on load at distribution side. To minimize the impact of voltage sag and swell or to protect various components of power system[6], the concept of custom power device were introduced.

The setting of dynamic voltage restorer is mostlysituated at the distribution side i.e. in between distribution feeder and the load.

For proper regulation of the voltage across load, the main role of DVR is injection of extra voltage to transmission system. DVR is a series compensating device which is connected in series between supply and the load at the point of common coupling[7] at the distribution side. It employs voltage boost technology using solid state switches of 3-phase voltage source converter.DVR uses this technology to get the desired output, by rebuilding of load side voltage. Besides the compensation of voltage sag and swell DVR helps in suppression of harmonics in phase voltages, falling of voltage spikes[8] and also in restraining the fault current.

The figure.1 shows the elementary structureof the dynamic voltage restorer(DVR). It comprises of Injection transformer or Boosting Transformesr ,control circuit,filter circuit,Voltage Source Converter,Energy storage devices like Capacitor and Battery which injects power.
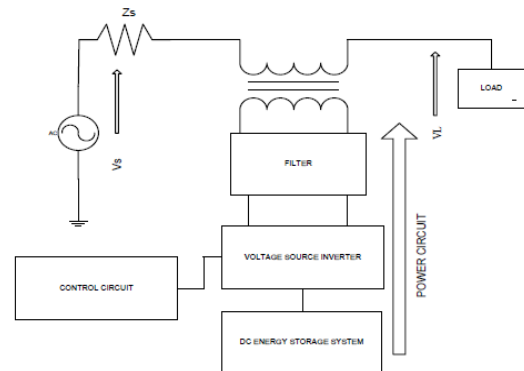

Fig. 1. Elementary construction of DVR[10].

At the point of common coupling during the fault conditions it helps in build up of load voltage profile[11]. Itpermits the exchange of bothactive and reactive power at the distribution side[11] thus it is deliberately consider to be the highly efficient and satisfactory resolution for the compensation of power quality issues like voltage sag and swell at the distribution side.After the detection of the sag for building up of load voltage profile its operation swings from stand by mode to the active mode.For the boosting of 3-phase voltage, restoration of each phase voltage in magnitude and phase is done to the assigned pre-sag value of inverter switches in voltage source converter[12]. In Figure 2 it is clearly represented that the DVR suppliesboth reactive power (Q_{DVR}) or thereal/active power (P_{DVR})[13], where $P_S$and $Q_S$signifies the active and reactive power of the supply mains and P_L& $Q_L$represents the active and reactive power of the load associated.
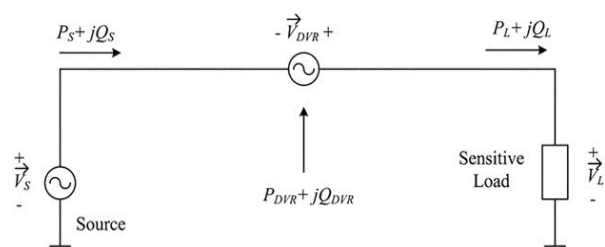

Fig. 2. Schematic diagram of DVR [14].

The main configuration of DVR comprises of power circuit and control circuit[15]. In figure3 the equivalent circuit is shown and the corresponding equations are given below.
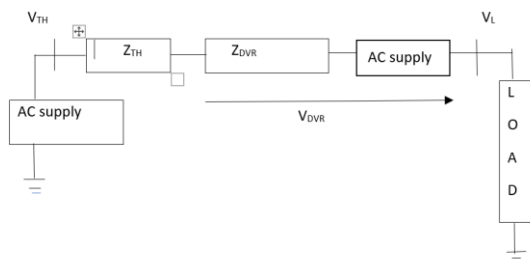
Fig. 3. Equivalent structure of DVR.

$$V_{DVR} = V_{TH} + I_L Z_{TH} + V_L \qquad (1)$$

Where the magnitude of required load voltage is represented by V_L, load impedance by Z_{TH} and load current[16] is represented by I_L, and is shown in equation 2.

$$I_L = \frac{P_L + jQ_L}{V_L} \qquad (2)$$

In equation 3 , α is angle of DVR voltage (V_{DVR}) and β is angle of V_{TH} and in equation 4 power angle of loadbis represented by θ.

$$V_{DVR} < \alpha = V_L < 0 + Z_{TH} I_L < (\beta - \theta) + V_{TH} < \delta \qquad (3)$$

$$\theta = \tan^{-1} \frac{Q_L}{P_L} \qquad (4)$$

The injection of complex power [16] by DVR is given in equation 5 and is represented by S_{DVR}.

$$S_{DVR} = V_{DVR} I_L^* \qquad (5)$$

III. SYNCHRONOUS REFERENCE FRAME THEORY BASED PI CONTROLLER

The capacitor supported DVR employing synchronous reference frame (SRF) theory is shown in figure 4. The control block diagram is shown , where at the point of common coupling (PCC) employing the abc to dq0 conversion, voltages are converted to the rotating reference frame[17]. To eliminate the harmonics and oscillations in voltages the low pass filters are used. The Synchronous Reference Frame (SRF) algorithmic employs Park's transformation in which abc frame load voltages are converted into the rotating reference (dq0) by adopting abc-dq0 conversion as shown in equation 1[18].

$$\begin{bmatrix} v_{ld} \\ v_{lq} \\ v_{lo} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - 2\pi/3) & \frac{1}{2} \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + 2\pi/3) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} (1)$$

The conversion of the rotating reference frame load voltages (v_{ld}, v_{lq}, v_{l0}) into the abc frame load voltages is done by adopting dq0-abc conversion using reverse park's transformation as shown in shown in equation 2.

$$\begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} v_{ld} \\ v_{lq} \\ v_{lo} \end{bmatrix} \qquad (2)$$

For the mitigation of power quality issues like voltage sag, a capacitor-supported DVR connected system is employed which inject the voltage in-quadrature with the load current at fundamental value of frequency[19]. Filters like low pass filters have been used to eliminate the ripples and several oscillations in the source voltages. The various components of point of common coupling (PCC) voltages along d-axes and q-axes are shown in shown in equation 3 and 4 where v_{sddc} and v_{sqdc} are fundamental components respectively of v_{sd} and v_{sq} along d- axis[20]. The harmonic and oscillatory components respectively of v_{sd} and v_{sq} along q-axis are represented as v_{sdac} and v_{sqac}.

$$v_{sd} = v_{sddc} + v_{sdac} \qquad (3)$$
$$v_{sq} = v_{sqdc} + v_{sqac} \qquad (4)$$

The mitigation techniques decide the compensating strategy for voltage compensation for the better power quality. It also specifies that the load terminal voltage should be of rated extent without any distortion. For controlling the DC-link voltage to its reference value i.e v_{dc}=200V the PI controller is employed in the DC link control loop. Due to switching of VSC [21]the output of PI controller consider as active component of voltage resulting in voltage loss v_{loss} as shown in equation 5.

$$v_{loss(n)} = v_{loss(n-1)} + k_{i1}e_{dc(n)} + k_{p1}(e_{dc(n)} - e_{dc(n-1)}) \qquad (5)$$

The difference between the reference DC link voltage $v_{dc}*$and the DC voltage sensed at n^{th} sample[22] is represented by $e_{dc(n)}$and k_{p1} and k_{i1} are the proportional and integral gains of the PI

controller in the loop. Along the d-axis the reference load voltage is shown in equation 6.

$$v_{ld} *= v_{sddc} - v_{loss} \qquad (6)$$

During the voltage sag condition the amplitude of the load terminal voltage (v_{lp}) reduces and thus PI controller is used in the AC-link control loop[23] for controlling the AC-link voltage to its reference value i.e v_{lp}=326 volts. For controlling the AC-link voltagethe reactive component v_{qr} of PI controller [24]is considered. The amplitude of the AC-link voltage i.e v_{lp} at the output of point of coupling is derived from the instantaneous values of the AC load voltages (v_{la}, v_{lb}, v_{lc}) as shown in equation 7.

$$v_{lp} = \sqrt{2/3} + (v_{la}^2 + v_{lb}^2 + v_{lc}^2)^{1/2} \qquad (7)$$

The quadrature section of the load terminal voltage i.e AC-link voltage [25][26] is regulated by PI controller as shown in equation 8.

$$v_{qr(n)} = v_{qr(n-1)} + k_{i2}e_{lp(n)} + k_{p2}(e_{lp(n)} -$$

$$e_{lp(n-1)}) \qquad (8)$$ Along the q-axis the reference load voltage is shown in equation 9. The equation 10 shows the reverse park transformation in which the rotating reference frame load voltages are converted back into the reference load voltages, where the error between the sensed load voltage and the reference load voltages are utilized in PWM to produce gate pulses for the VSC of DVR[27] .

$$v_{lq} *= v_{sqdc} + v_{qr} \qquad (9)$$

$$\begin{bmatrix} v_{la} * \\ v_{lb} * \\ v_{lc} * \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} v_{ld} * \\ v_{lq} * \\ v_{lo} * \end{bmatrix} \quad (10)$$
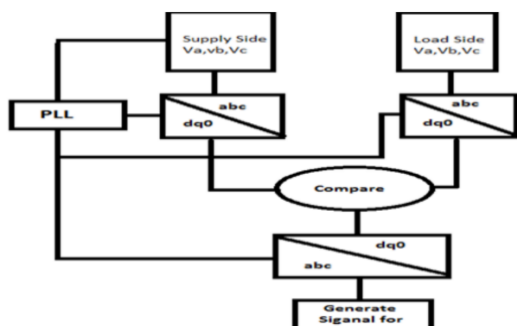
Fig.4. Control block diagram of SRF Baesd DVR[28].

The Performance depends on the tuning of the gains, k_{p2} and k_{i2} of the PI controllers.

IV. FUZZY LOGIC CONTROLLER

In this paper, a conventional fuzzy logic controller based feedback controller is used for controlling the injection of the voltage in the proposed Dynamic Voltage Restorer(DVR).The conventional Fuzzy logic controller is favored over the conventional SRF based PI controller due to its simplicity and easier operation which provide strength in the variation of system parameters. The earlier used PI controller faces problem in controlling the injected voltage as it is more inclined to parameter variation of energy storage system used in DVR as the amount of energy stored varies with the voltagesag/swell events[28]. The energy storage system used in DVR are consisting of capacitors, which are charged directly from thepower supply using rectifier. On the basis of energy stored in dc link capacitors, the output of inverter depends. To overcome the problems faced by PI controller based DVR and to improve the performance in both steady and transient state, a fuzzy logic controller is implemented in the system which let go the system from the precise and bulky mathematical calculations.

The basic block diagram of fuzzy logic controller is shown in figure 5 which comprises of
1.knowledge base
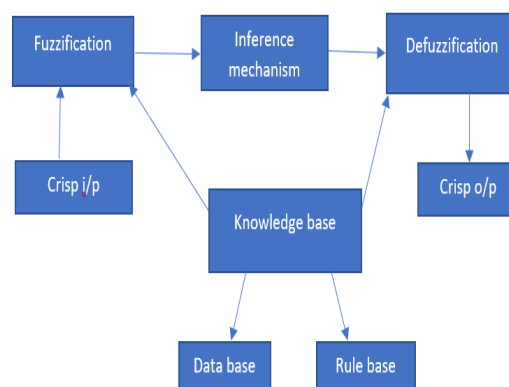2.fuzzification
3. inference mechanism
4. defuzzification

Fig.5. Basic block diagram ofFuzzy logic controller[28].

Fuzzification: In FLC system, there is a need to have that variable linked with input/output state which defines each set have control surface that could have been expressed in notations of fuzzy set using level of linguistic terms. The extent to which a variable belong to a particular level have been denoted through member value of each set of input

and output variables. Fuzzification is defined as the term where the set of input and output have been converted into linguisticvalue.

Inference: The behavior required by the control surface that relates variables at input and output side of the system has been governed with various set of rules. The explanation would be taken with the logistics rule such that if z is A then x is B. When each rule has been read out with input variables that contain any degree of truth in its premise has been fired and which contributed to the forming by modifying approximately of the control surface in it. The constraints related to output of the fuzzy rule base system has been expressed when all rules were firedaccordingly.

Defuzzification: When we convert the value of fuzzy parameter into the corresponding crisp value then it is known asDefuzzification.

Data Base: When membership function stores the value of database required by de-fuzzifier and fuzzifier. There is a compromise between the given memory and mips of the controller chip in digital form which have been given to the storageformat.

Rulebase: Rule evaluator required the rule base in lingtistic level which was created by rule base system.

V. SIMULATION DIAGRAM AND RESULTS

Here, sag/swell events are simulated in the v_{in} (t) abc voltage. The output voltage v_{out} (t) abc is found to be constant due to injected voltage v (t) inj abc which is generated by different controllers. Figure 6 shows the THD analysis at the load side voltage before voltage sag/sell compensation i.e without implementation of DVR.Following test parameters have been considered as given below:

Between t=0.1s and t=0.2s, a voltage sag/swell is introduced at the source side voltage impacting the power quality of load side voltage.To suppress these harmonics various controllers are implemented. The effect of voltage sag (introduced at the source side)on terminal voltage of linear load is compensated using SRF based PI controller, conventional fuzzy Logic controller and a novel technique of type 2 fuzzy controller.
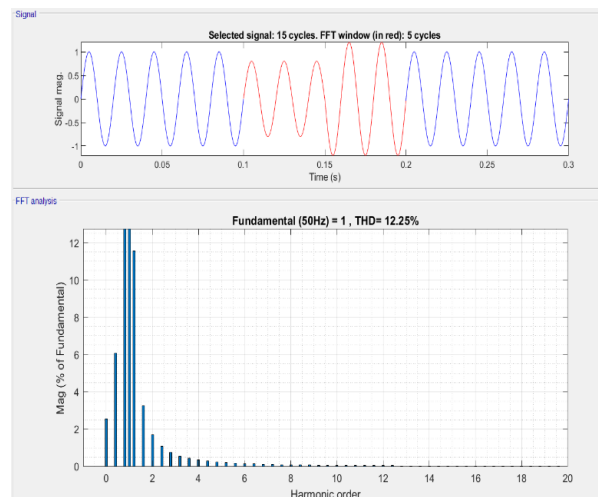

Fig.6 THD at the load side voltage before voltage sag/swell compensation i.e without DVR..

A. Simulation and Result with SRF based PI controller

To suppress thevoltage sag/swell SRFA based PI controller is implemented. The effect of voltage sag (introduced at the source side) on terminal voltage of linear load is compensated using SRF based PI controller. When the source voltage experiences large sag of magnitude as high as 20% voltage sag at that time DVR plays the role of a series compensator. Figure 8 represent the plots of voltage at the point of common coupling (PCC)and load terminal voltage with SRF based controller under the influence of 20% voltage sag in the supply voltage. For the time duration of 0.1–0.2s, a sag is introduced in the supply voltage due to which the load terminal voltage v_{labc} suffers correspondingly with sag. Thus the linear sensitive load would face voltage power quality issues .

It is observed that the sag of 20% for the duration of five cycles is found to be a serious condition. As a result the system would be unable to meet the desired requirement of output voltage at load side without DVR. Thus DVR is employed to inject the voltage to compensate the voltage sag. The basic simulink model of DVR is shown in figure 7.
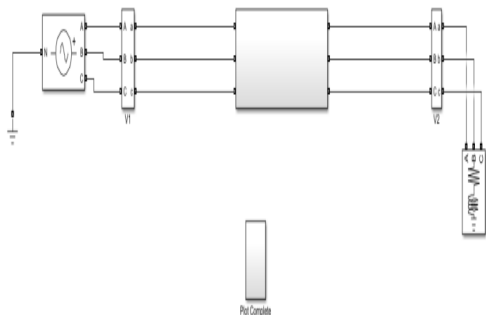
Fig.7 Simulink model of DVR.

The simulation time for sag occurring in the system is 0.1s-0.2s for five cycles. DVR effectively injects the desired magnitude of compensating voltage, $v_{cab\ c}$ to regulate the voltage at load side in the system where v_{labc} is load side voltage and v_{dc} is dc link voltage using SRF based PI controller as shown in figure 8. By proper tuning of k_p and k_i of SRF based PI controller, the desired compensating voltage v_{cabc} can be achieved as shown in figure 9, showing complete simulation results.
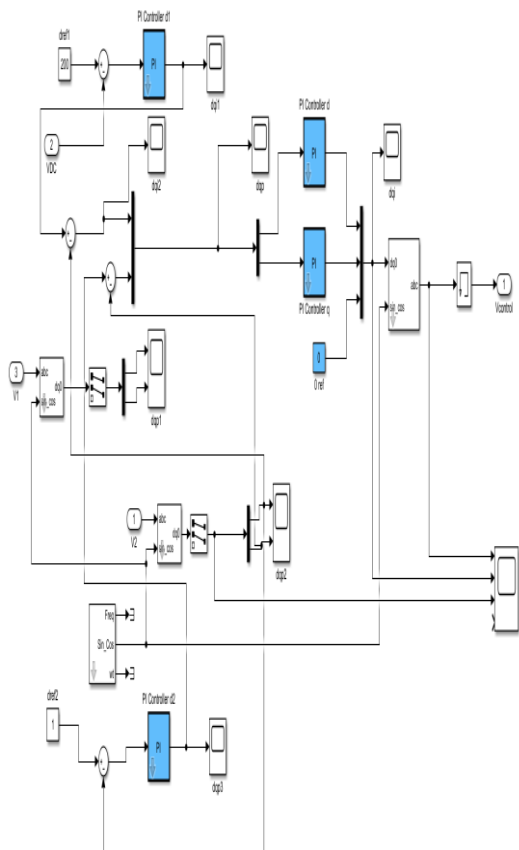

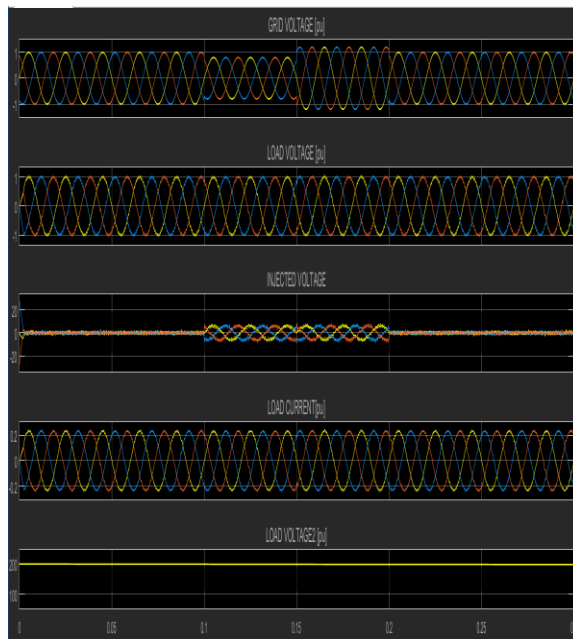**Fig.8** Simulink model of SRFA based PI Controller.

Fig.9 Plot for Grid voltage, Load voltage, Injected voltage ,Load current, dc voltage after sag

compensation using SRFA based PI controller DVR.

The SRF based PI tuned DVR voltage controller gives better result as compared to when used without DVR with THD of 4.42% at the load side as shown in figure 10. For severe voltage sag of 20% at source side, a THD of less than 5% is obtained with a maximum value of only 4.42% using this technique.
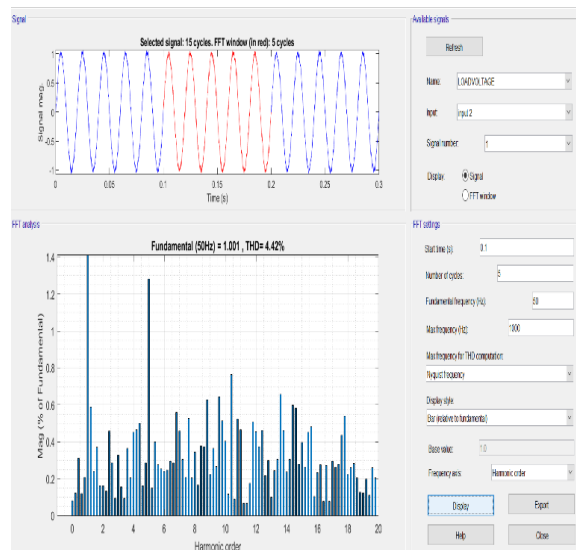

Fig.10 THD at the load side voltage after voltage sag compensation using SRFA based PI controller DVR.

*B.*Simulation and Result with conventional Fuzzy logic controller based DVR

The Simulink model of conventional Fuzzy logic controller is shown in figure 11 which is used in favor over the conventional SRF based PI controller due to its simplicity and easier operation which provide strength in the variation of system parameters. Fig 12 shows the THD improvement of 3.50 % at the load side voltage after voltage sag compensation using conventional Fuzzy logic controller based DVR which is far better performance as compared to SRF based PI controller. A complete comparative analysis is shown in table 1.
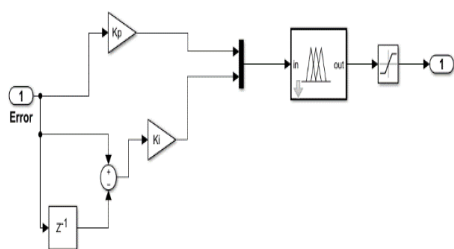

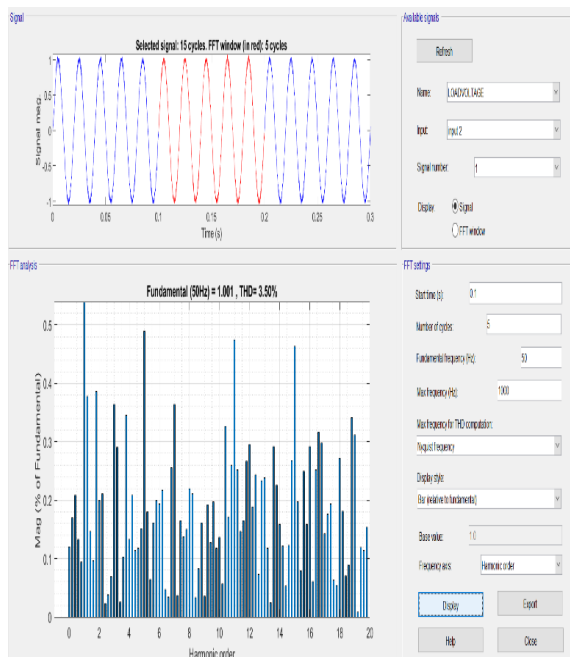Fig.11.Simulink model of conventional Fuzzy logic Controller.

Fig 12.THD at the load side voltage after voltage sag compensation using conventional Fuzzy logic controller based DVR.

factor	With PI controller	With Fuzzy logic controler
SAG of 20% , time=0.1sec-0.15 sec	COMPENSATED	COMPENSATED
SWELL of 20% , time=0.1sec-0.15 sec	COMPENSATED	COMPENSATED
MULTIMODE OSCILLATIONS	OBSERVED	OBSERVED
T.H.D AT SOURCE SIDE	12.25%	12.25%
T.H.D AT LOAD SIDE	4.42%	3.50%

Table1.Comparative analysis of various factors with PI Cntroller and conventional Fuzzy logic controller based DVR.

VI. CONCLUSION

This paper mainly concern with power quality issues like voltage sag and swell affecting the loads at the distribution side. For the compensation of these problems a series compensating device,a PI controller and fuzzy logic controller based DVR is designed for power quality enhancement. Simulation and analysis of DVR for mitigation of voltage sag and swell is obtained and it is found that simulation results obtained proves that DVR is efficient compensating device for both sag and swell. For various controller a comparative analysis is shown in which fuzzy controller based DVR gives better performance than the SRF based PI controller for various voltage fluctuations.

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