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Implementation of Fuzzy Logic Controller based Dynamic Voltage Restorer (DVR) with DFIG in Distribution System for Power Quality Improvement

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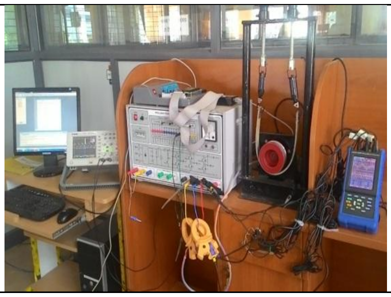
GRAPHICAL ABSTRACT



Abstract: **This paper proposes Fuzzy Logic Controller (FLC) based DVR along with dqo transformation for Power Quality Improvement in a distribution system. Discrete PWM pulse generator with Phase Locked Loop (PLL) was used as a control strategy in this work. In addition to this, to meet the power demand in the distribution system renewable energy resources are employed. Here Doubly fed Induction Generator (DFIG) wind farm as Distributed generation (DG). Simulations are carried out in the MATLAB/SIMULINK software.**

Keywords: **Dynamic Voltage Restorer (DVR) - Discrete PWM pulse generator - Proportional Integral (PI) Controller - Fuzzy Logic Controller (FLC)- Digital Signal Processor (DSP) - Doubly fed Induction Generator (DFIG) - Phase Locked Loop (PLL) - dqo transformation - MATLAB/SIMULINK - Voltage Sag, Harmonics.**

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I. INTRODUCTION

Power quality is one of the major concerns in the present system. It has become important especially with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Hence, there are always demands for good power quality, which positively resulting in reduction of power quality problems like voltage sag, swell, harmonic and flicker. Power quality problem is the occurrence manifested as a nonstandard voltage, current or frequency that results in the failure of end use equipment. Voltage sag is always considered as one of the major power quality problems because the frequency of occasion is so high. These problems can be rectified using electronic devices such as programmable logic controllers and electronic drives which are very sensitive and less tolerant to power quality problems.

A DVR is the power electronic-based equipment that is connected in series with the feeder of sensitive loads between the supply and load buses [1]. DVR usually consist of three single-phase Voltage Source Inverters (VSI), an energy storing unit, passive harmonic filters, injection transformers and a control scheme which itself comprises three parts: an estimation unit, a compensation strategy and a switching pattern, enables the DVR to inject three-phase controllable voltages of required amplitudes and phase angles to maintain the load bus voltage in desired waveform during voltage sags [2] [3]. By using single phase DVR with direct ac/ac converter in order to mitigate harmonics and controls DVR when frequency changes [4] [5]. Mitigation of voltage sags by means of DVRs mainly depends on protected load characteristics. There are three conventional voltage sag compensating strategies, each having distinctive advantages. They are known as in-phase, pre-sag and optimized energy [6]. The adaptive PI controller using fuzzy was proposed in [7] to overcome the drawbacks of PI controller. In some control schemes, for the DVR, the injection voltage for the pre-sag compensating strategy is obtained by comparing the amplitude of the positive sequence component with its reference value and using the frozen angle that is tracked via a Phase-Locked Loop (PLL) [8]. Using optimized control strategy, reducing the needed injection voltage of the DVR and also to mitigate the transient distortions at the load side [9]. Multi-line DVR has been used to remove the battery in DVR structure in order to control more than one line [10]. It illustrates about the digital speed control of permanent magnet brushless dc motor using TMS320F2812 DSP controller. The Control algorithm used for the speed control has been implemented by assembly language programming in TMS320F2812 DSP controller. Here, the Hardware implementation for the speed control has been achieved by programming in the DSP controller TMS320F2812 [11]. In order to achieves voltage regulation with low total harmonics distortion (THD) for both voltage and current, it uses the control technique improvement of a three-phase inverter using direct quadrature-zero (d-q-0) controller based on DSP TMS320F2812 for dynamic voltage restorer (DVR) applications [12].DVR structure is based on a cascaded H-bridge multilevel inverter in order to balanced load-side voltage even during the compensation of unbalanced disturbances with a minimum active power injection [13]. Using DVR, a most cost effective solution method is used to mitigate the voltage sag and swell caused by sensitive loads. And also, using FLC method, it overcomes the drawbacks caused by PI controller method such as improper tunning of K_p and K_i values which will lead to increase in settling time of the system stability and the continuous usage of controller with fixed PI parameters leads to reduce the life time of DVR [14]. Using fuzzy logic controller (FLC), the designs and simulation of DVR is done for improving power quality and reduce the harmonics distortion in sensitive loads [15]. In order to improve the real power of the inverter under any disturbances, DVR is used as three phase four wire based on super capacitor. The controller used in this system is d–q–0 transformation technique and Proportional Integral (PI). Then the proposed controller was then coded into a digital signal processor (DSP) TMS320F2812 board [16]. In order to mitigate the voltage sag created by three-phase fault, a multi-functional DVR is used along with the voltage control loop using Quantitative Feedback Theory (QFT) method. This method can also be used under the emergency control of distribution system by means of DVR [17]. In order to improve grid stability, wind energy systems are expected to ride-through the disturbances in the grid, called as fault ride-through capability. Here the fault ride-through capability of an induction generator based wind generation system is estimated in terms of Critical Clearing Time (CCT) using approximate steady state model and transient model of squirrel cage induction generator [18]. In order to reduce the voltage sag and harmonics created by zero sequence components, the DVR can act as a voltage sag restorer and voltage distortion compensator using zero blocking method along with fuzzy logic controller (FLC) which uses delta connected transformer installed between the supply and the booster transformer [19]. By using single phase dynamic voltage restorer with direct ac/ac converter in order to mitigate harmonics and control DVR when frequency changes [20]. Here, it discusses about the control techniques of dsPIC30F4011 microcontroller and MOSFET which are analysed by mainly focusing with the modelling and Simulation of DC Motor using MATLAB. The prototype hardware set is tested in the power electronics laboratory for motor rating of 1HP. The setup is tested for open & closed loop control of motor [21]. A new fast-converged estimation approach, which directly extracts the amplitudes and phase angles of symmetrical components of desired frequencies from harmonic- distorted network voltages using sensitivity analyses method along with the DVR [22].

This paper introduces Dynamic Voltage Restorer along with DFIG in order to mitigate the voltage sag and harmonics occurring in distribution system. The disadvantage of using Conventional PI controller is that, use of fixed gains in controller structure will cause varying parameters and conditions of the system. And also this setup is implemented in Real Time simulation using DSP Processor based voltage controllers, but the harmonics is higher due to improper earthing and there is no improvement in the voltage profile. In order to rectify these problems, a Proposed dq0 based fuzzy logic controller along with Doubly fed Induction Generator (DFIG) wind farm can be used by replacing the conventional PI controller for DVR. Here, the MATLAB/SIMULINK model based simulated results were presented to validate the effectiveness of the proposed Fuzzy Logic Control method along with DFIG for DVR over conventional method. This is being explained in the following chapters.

II. DYNAMIC VOLTAGE RESTORER (DVR)

DVR is one of the most efficient and effective modern custom power device used in power distribution networks. DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also added other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

A. Basic Configuration of DVR:

In Fig.1, the DVR consist of an injection/booster transformer, a harmonic filter, a Voltage Source Converter (VSC), an energy storage unit and control system.

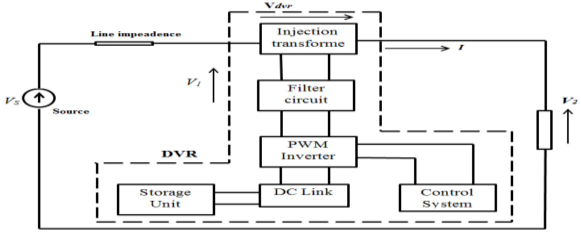

Fig.1 Block Diagram Representation of DVR

The Injection / Booster transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side. Its main tasks are: 1) It connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. 2) In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism). The harmonic filter is to keep the harmonic voltage content generated by the VSC to the permissible level. A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. Here Insulated Gate Bipolar Transistors (IGBT) is used as a switching device. The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. The energy storage circuit has two main tasks: 1) the first task is to charge the energy source after a sag compensation event. 2) The second task is to maintain dc link voltage at the nominal dc link voltage. The control mechanism of the general configuration typically consists of hardware with programmable logic. All protective functions of the DVR should be implemented in the software.

B. Modelling equations of DVR

The system impedance Z_{th} depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage VDVR through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as

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

Where,

V_{DVR} : The desired load voltage magnitude

Z_L : The load impedance.

I_L : The load current

V_{TH} : The system voltage during fault condition

The load current I_L is given by,

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

When V_L is considered as a reference equation can be rewritten as,

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

∝, β, δ are angles of V_{DVR}, Z_{TH}, V_{TH} respectively and θ is Load power angle

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

The complex power injection of the DVR can be written as,

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

It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power.

III. CONTROLLER FOR DYNAMIC VOLTAGE RESTORER (DVR)

In order to mitigate the simulated voltage sags in the test system of each compensation technique, also to compensate voltage sags in practical application, a discrete PWM-based control scheme is implemented, with reference to DVR. The aim of the control scheme is to maintain a constant voltage magnitude at the sensitive load point, under the system disturbance. The main function of controller in the DVR is to detect the voltage sag occurrences in the system and to calculate the compensating voltage, to generate trigger pulses of PWM inverter and stop triggering pulses when the occurrence has passed. Here, the dq0 transformation or Park's transformation is used for voltage calculation. The dq0 method gives the voltage sag depth (d) and phase shift (q) information with start and end times.

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) = 0 \qquad (6)$$

$$V_d = \frac{2}{3}[V_a \sin\omega t + V_b \sin(\omega t - \frac{2\pi}{3}) + V_c \sin(\omega t + \frac{2\pi}{3})] \qquad (7)$$

$$V_q = \frac{2}{3}[V_a \cos\omega t + V_b \cos(\omega t - \frac{2\pi}{3}) + V_c \cos(\omega t + \frac{2\pi}{3})] \qquad (8)$$

In this paper, two controller methods are used they are Proportional Integral (PI) controller and Fuzzy Logic (FL) controller.

1) PI Controller with dq0-Based control scheme

PI controller is the feedback controller which will eliminate forced oscillations and steady state error. It derives the system to be controlled with a weighted sum of the error and integral of that value. The proportional response can be adjusted by multiplying the error by constant K_P, called Proportional gain. The contribution from integral term is proportional to both the magnitude of error and duration of error. The error is first multiplied by integral gain, K_i and then it was integrated to give an accumulated offset value. Here, the K_p and K_i values can be chosen using Ziegler–Nichols tuning method. The below equation shows the Ziegler–Nichols formula for PI controller,

$$u(t) = K_c(\varepsilon(t) + \frac{1}{\tau_i}\int_0^t \varepsilon(t^{'})dt^{'} + \tau_d \frac{d\varepsilon(t)}{dt}) + b \qquad (9)$$

Where,

u is the control signal

ε is the difference between the current value and the set point.

K_c is the gain for a proportional controller.

τ_i is the parameter that scales the integral controller.

τ_d is the parameter that scales the derivative controller.

t is the time taken for error measurement.

b is the set point value of the signal, also known as bias or offset.

TABLE I

ZIEGLER–NICHOLS METHOD

Control Type	**K_p**	**K_i**
Proportional Integral (PI)	$0.45K_u$	$1.2K_p/P_u$

If the stability of the control loop is poor, stability is improved by decreasing Kp. The input to the PI controller is the difference between reference value and error value of the voltage. When comparing these values, PI controller will adjust its proportional & integral gain K_P & K_i in order to reduce the steady state error to zero for the step input. The main disadvantage of using PI controller is that, use of fixed gains in controller structure will cause varying parameters and conditions of the system.

Thus, the error signal is used as a modulation signal that allows generating gate pulse. Then the control block generates the firing signals for each switch with controllable magnitude, phase angle and frequency whenever sag is detected. The discrete virtual phase –lock-loop (PLL) is used to obtain the angle θ of the source voltage. The information extracted from the PLL is used for detection and reference voltage generation. The PI controller processes the error signal and generates the required angle θ to derive the error to zero. The resulting voltage at the load bus equals the sum of the grid voltage and the injected voltage from the DVR.

2) *Fuzzy Logic Controller (FLC) with dq0-Based control scheme*

The drawbacks of PI controller are improper tunning of K_p and K_i values which will lead to increase in settling time of the system stability and the continuous usage of controller with fixed PI parameters leads to reduce the life time of DVR. These drawbacks can be overcome by using Fuzzy Logic controller. In comparison to the linear PI controller, this is a non-linear controller that can provide satisfactory performance under the influence of various fault conditions. There are basically four essential segments in Fuzzy Logic Controller, namely; Knowledge base (Rule Base), Fuzzification block or Fuzzifier, Inference System , Defuzzification block or Defuzzifier.

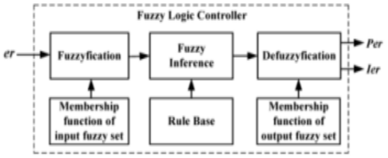

Fig.2 Block diagram of Fuzzy Logic Controller

The Fuzzification block or Fuzzifier converts classical data or crisp data into fuzzy data or Membership Functions (MFs). Fuzzification is the process of making a crisp quantity fuzzy. In the real world, hardware such as a digital voltmeter generates crisp data, but these data are subject to experimental error. Knowledge base has database with necessary linguistic variables and rule base has the set of control rules; defuzzification converts the fuzzy outputs to crisp control signals.

Here, a FLC block is used for error signal-d and error signal-q. The process also same as before except the controller now is Fuzzy Logic. For both error signal-d and error signal-q a Fuzzy Logic Controller consists of 7 linguistic variables for both input and output which is: Z is Zero, N is Negative and P is Positive, NL is Negative Large, NM is Negative Medium, NS is Negative Small, PL is Positive Large, PM is Positive Medium and PS is Positive Small. The FLC controller of the tested system exploits the Mamdani type of inference method. It defuzzifies the crisp input-output variables into fuzzy triangular membership function and reverse process of Defuzzification is based upon the Centroid method. The controller core is the fuzzy control rules as shown in Table II which are mainly obtained from intuitive feeling and experience.

TABLE II

FUZZY ASSOCIATIVE MEMORY (FAM) TABLE

Error/ error rate	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

IV. PROPOSED VOLTAGE CONTROLLER SCHEME USING DSPIC30F4011 DSP KIT

At first Proportional Integral (PI) controller is used as a controller and simulation are done using MATLAB/SIMULINK. By setting the constant values of K_P and K_i at 400 & 0.05, the simulations are done and taken the results for various disturbance condition. But the results does not show the effectiveness of the voltage profile due to the improper tunning of K_p and K_i values which will lead to increase in settling time of the system stability and the continuous usage of controller with fixed PI parameters leads to reduce the life time of DVR. These drawbacks can be overcome by using DSP based voltage controller. DSPIC30F4011 is a new generation controller with high performance 16-bit microcontroller (MCU) architecture which has a main internal oscillator frequency of 7.37 MHz, 512 kHz. It also has a 10-bit high speed analog to digital converter and 6 PWM I/O pins with 3 duty cycle generators. The maximum sampling rate of analog-to-digital converter (A/D) is about 500 kilo samples per seconds which is very much suitable for real time sampling. The formula used to measure the duty cycle is,

$$\text{Duty cycle in }\%=T_{ON}/T_{ON}+T_{OFF}$$

Where,

T_{ON} = ON time

T_{OFF} = OFF time

$T_{CYCLE}= T_{ON}+T_{OFF}$

In this control technique, eZdsp IC30F4011 DSP board is used for PWM control application. Here, the application of the PWM algorithm requires a three process, which are time reference, a comparison mechanism, and digital outputs. The Event Manager Modules of the DSP have the General Purpose (GP) Timer which can be used as time reference, Full Compare/PWM Units can be as a comparison mechanism, and it has an accurate digital PWM outputs. The principles of Event Manager Modules and PWM signal generation process are described in the following sections.

There are two event manager modules in DSPIC30F4011 called EVA and EVB. It has six independent pairs of PWM outputs; three of which are controlled by EVA and the other three are controlled by EVB. Here, the GP Timers, Full Compare/PWM Units and PWM outputs are used to generate the gating pulse for the power circuit. There are two general purpose (GP) timers that can work independently from each other. The GP Timer1 and 2 are controlled by EVA, GP Timer3 and 4 are controlled by EVB. These timers are used to provide a time base for the operation of compare units and associated PWM circuits to generate the PWM outputs. Each GP Timer has up down counter TxCNT, compare register TxCMPR, period register TxPR, control register TxCON, and direction input TDIRx registers. It has six compare units as shown in Fig.3, three of which are in EVA module and the other three are in EVB module. These registers depend on the associated GP Timers to generate PWM signals. The generation of PWM patterns comprises of the following steps: counting mode, GP Timer compare operation, and carrier signal generation. There are two counting modes, controlled by the content of TxCON register that can be applicable to generate the carrier signal: continuous count up mode results in asymmetric and continuous count up down mode results in symmetric carrier waveform. The timer values are incremented by one for each GP Timer clock pulse.

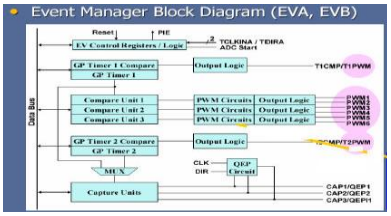

Fig. 3 Event Manager Block Diagram

V. EXPERIMENTAL SETUP

In designing experimental arrangement it consist of four parts namely, the PC, DSP kit, Voltage source inverter (VSI), Intelligent Power Module (IPM) and 3-Phase load (BLDC Motor) shown in Fig. 4. Here, the DSPIC30F4011 eZdsp is programmed to produce Gate pulses by comparing a triangular carrier wave in 5-KHz and a sinusoidal reference wave in 50-Hz.. The reference wave amplitude adjusts the frequency of the generated AC voltage.

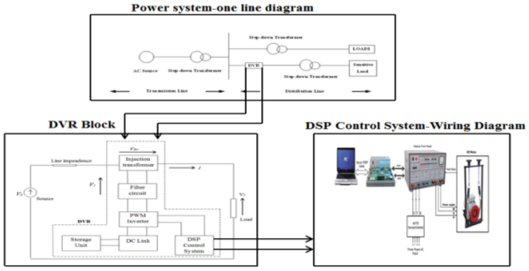

Fig. 4 Overall system block diagram

The experimental setup is done in real time application which are executed under no load and loading conditions whose photo are shown in below Fig.5. In this experimental arrangement, the PC is connected to DSP kit with the help of emulator. And, the DSP kit is connected to Intelligent Power Module (IPM) which has VSI to produce a gate pulse to trigger the PWM signal and it is connected to 3-Phase load using Brush Less DC (BLDC) motor which comprises of Hall element sensor used to position the windings in the inner arrangement of the motor and this setup can be again connected to the DSP kit itself for measuring the speed. Finally, the load i.e. the BLDC motor is connected to speed sensor which is used to measure the actual speed and it is again connected as a feedback signal to the DSP kit.

Fig. 5 Overall Experimental Setup in Real Time with DSPIC30F4011

VI. DSP RESULTS IN REAL TIME

The performance of the proposed DSP based voltage controller technique of DVR is evaluated in real time application using Micro Processor (MP) LAB, Texas Instrument (TI).

Real time simulation:

The program is executed using Coad Composer Studio (CCS) with the DSP kit. The block diagram for this setup is shown in Fig.6.

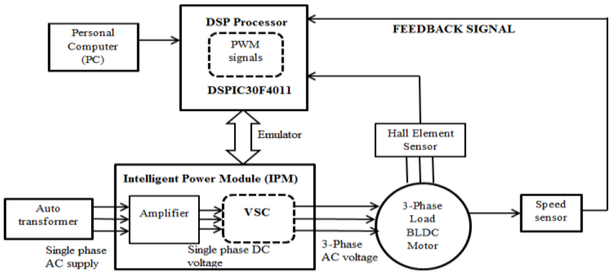

Fig.6 Block diagram of real time controller

TABLE III SYSTEM PARAMETERS

S.No	DEVICES	PARAMETERS	VALUES
1	DVR	Filter inductance	245-455mh
		Filter capacitance	119-221μF.
		DC bus voltage	11KV
2	Intelligent Power Module(IPM)-VSI	**Input:** Three - phase AC supply Single - phase AC supply	(415V±10%) (230V±10%)
		Output: DC Link voltage –DC & Max. Current	750V & 8A
		IGBT Intelligent power module: Switching frequency	20KHz (Max),10K Hz Nominal
3	DSP Kit-DSPIC30F4011	Architecture/CPU Speed (MIPS)	16-bit/30
		Operating Voltage Range (V)	2.5 to 5.5
		I/O Pins/ Pin Count	30/40
		PWM Resolution bits	16
		Motor Control PWM Channels	6
		Timers	5 x 16-bit 2 x 32-bit

Here, the input voltage is given as a single phase AC voltage using auto transformer which is kept as constant voltage i.e. input voltage (V_{in}) at 60 Volts and the speed can be set at constant value at 2060 rpm and the K_p & K_i can also be set at 0.025,0.005 values. By varying the load, the 3-Phase AC output voltage and current is measured and Total Harmonic Distortion (THD) is also measured from the Power Quality (PQ) analyser connected to 3-phases of IPM. Here, the actual speed is measured using tachometer and its PWM waveforms are captured for no load and loading conditions which is shown in below Fig. 7, 8, 9.

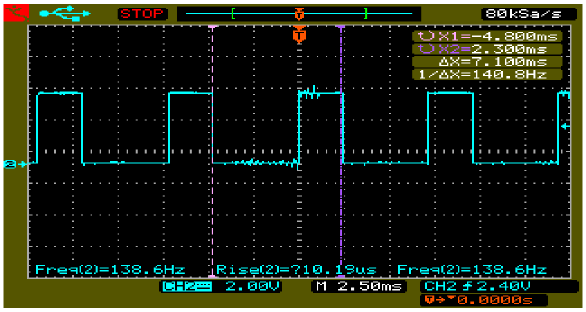

Fig.7 PWM signal at No Load condition.

The above PWM waveform is taken under no load for closed loop arrangement. Here, the width of the PWM signal can be calculated using the above formula i.e. the ON time and OFF time of the PWM signal is 2.300ms & 4.80ms which is used to calculate the duty cycle about 32.3%.

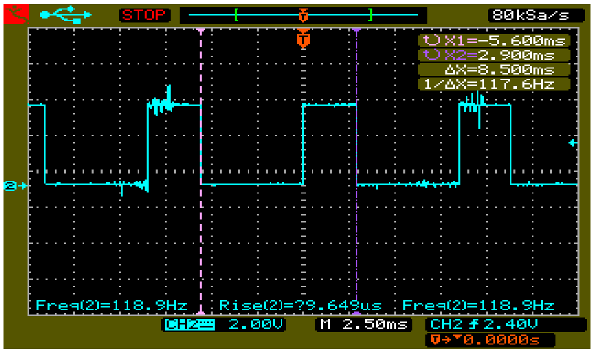

Fig. 8. PWM signal when Load is increased at 110%

The above PWM waveform is taken with the increase in load of 110% for experimental arrangement. Here, the width and duty cycle of the PWM signal is lightly increased comparing to no load condition. It can be calculated using the above formula i.e. the ON time and OFF time of the PWM signal is 2.900ms & 5.60ms which is used to calculate the duty cycle about 34.11%.

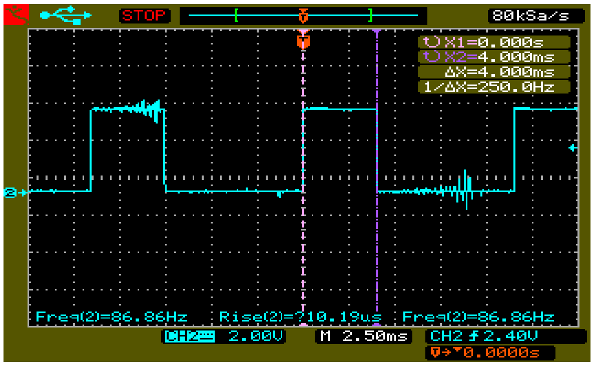

Fig. 9. PWM signal when Load is increased at 120%

The above PWM waveform is taken with the increase in load of 120% for experimental arrangement. Here, the width and duty cycle of the PWM signal is lightly increased comparing to 200 grams increase of loading condition. It can be calculated using the above formula i.e. the ON time and OFF time of the PWM signal is 4.0ms & 7.0ms which is used to calculate the duty cycle about 36.36%.By implementation of other filter techniques, voltage profile can be still improved and the harmonics can be reduced to maintain the performance of the distribution system

TABLE IV
ANALYSIS OF LOAD PARAMETERS WITH DSP CONTROLLERS

S. No	Loading conditions in %	Output voltage V_{out} in per unit	Output current I_{out} in amps	THD in %	PWM Width (Duty cycle) in %
1	Rated Load	0.93	2.68	18.8	32.3
2	110%	0.87	3.11	17.4	34.1
3	120%	0.86	3.6	10.3	36.3

The Table IV shows the readings for load parameters with DSP controllers, it indicates that for constant input voltage and set speed, the 3-Phase output voltage and current are improved when comparing to PI controller. And THD is also completely reduced when comparing to PI controller

VII. DFIG AVERAGE WIND FARM MODEL

To improve the performance of the existing system, additional load has been included. To meet out the load, a 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder. Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter modelled by voltage sources. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. In this model, the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the speed at 1.2 p.u.

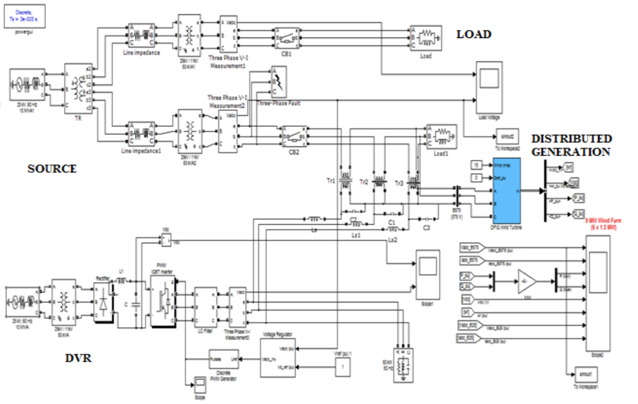

Fig. 10. DFIG Model

The mechanical power and the stator electric power output are computed as follows:

$$P_m = T_m \omega_r \tag{7.1}$$
$$P_s = T_{em} \omega_s \tag{7.2}$$

For a lossless generator the mechanical equation is:

$$J\frac{d\omega_r}{dt} = T_m - T_{em} \qquad (7.3)$$

In steady-state at fixed speed for a lossless generator $T_m = T_{em}$ and $P_m = P_s + P_r$

It follows that:

$$P_r = P_m - P_s = T_m\omega_r - T_{em}\omega_s = -sP_s \qquad (7.4)$$

where

s is defined as the slip of the generator:

$s = (\omega_s - \omega_r)/\omega_s$.

VIII.SIMULATION RESULTS

The proposed system configuration of DVR is composed by a 11 kV, 60 Hz generation system, feeding two transmission lines through a 3- winding transformer connected in Δ/Δ/Δ, 115/25/25 kV. Such transmission lines feed two distribution networks through two transformers connected in Y/Δ, 25/11 kV. To verify the working of DVR for voltage compensation a fault is applied at point X at resistance 0.66 U for time duration of 0.2s. The DVR is simulated to be in operation only for the duration of the fault condition. Thus, DVR will be inserted in series with the load to help improving the supply voltage before to be fed by load.
A detailed system as shown in Fig.4 has been modelled by MATLAB/SIMULINK to study the efficiency of proposed control strategy. The system parameter and constant values are listed in Table III. It is assumed that the voltage magnitude of the load bus is maintained at 1 p.u during the voltage sag condition. The performance of the proposed controller technique of DVR is evaluated using MATLAB/SIMULINK.

Case: Double line-Ground fault (L-L-G) & 120% of change in Load

The simulation was done under three cases without DVR, with DVR using Proportional Integral (PI) Controller and with DVR using Fuzzy Logic Controller (FLC) in order to compensate the voltage sag occurring at the load side. Here a double line to ground fault & 120% of change in Load is applied to the system at point with fault resistance of 0.66Ω for time duration of 0.2 to 0.4s.

When simulating without DVR and with DVR using PI Controller, occurrence of double line to ground fault & 120% of change in Load experiences voltage sag about zero per unit & 0.80p.u of nominal voltage with the duration 0.2s to 0.4s. Introduction of DVR along with FLC Controller mitigates the sag in voltage about 0.99p.u as shown in Fig. 11.

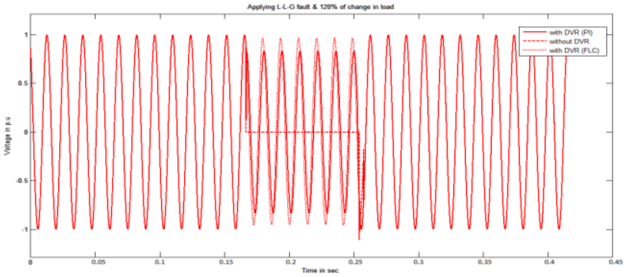

Fig.11: Comparison of voltage generated at load point during Double line-Ground fault (L-L-G) & 120% of change in Load, when using without DVR and with DVR using PI & FLC controller

Due to *L-L-G & 120% of change in Load*, it can generates the harmonics of about 2.36%, 0.62% for without DVR and with DVR using PI controller but the harmonics can reduced up to 0.15% using Fuzzy Logic Controller (FLC) which is shown in Fig. 12,13 and 14.

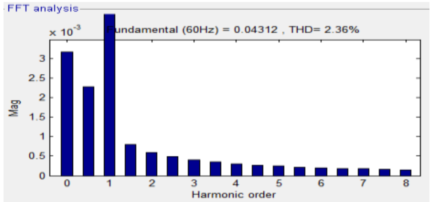

Fig.12: Harmonics generated due to Double line-Ground fault (L-L-G) & 120% of change in Load, using without DVR

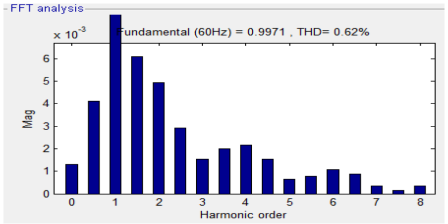

Fig.13: Harmonics generated due to Double line-Ground fault (L-L-G) & 120% of change in Load, using PI Controller (with DVR)

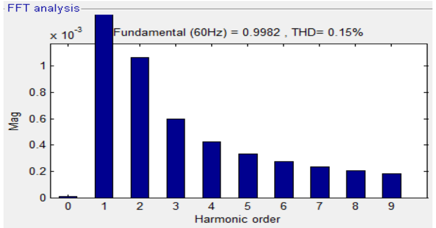

Fig.14: Harmonics generated due to Double line-Ground fault (L-L-G) & 120% of change in Load,, using FLC Controller (with DVR)

The TABLE V describes the effect of DVR in the distribution system for various for various faults and disturbances simulated using MATLAB and SIMULINK software. From the table, it is observed that Fuzzy logic Controller based DVR reduces the harmonics, thereby improve the voltage profile.

TABLE V : IMPACT OF DVR FOR SYSTEM DISTRUBENCE

Conditions	**Controllers**	**Load Voltage in p.u & Total Harmonic Distortion (THD)**
LLG Fault & 120% of change in load	Without DVR	0.00 p.u
		2.36%
	Proportional Integral (PI)	0.80 p.u
		0.62%
	Fuzzy logic Controller (FLC)	0.99 p.u
		0.15%

IX. CONCLUSION

This paper has proposed the modeling and simulation of DVR using MATLAB/SIMULINK. The dq0 based control technique with PI controller and fuzzy logic controller along with DFIG wind farm are proposed in this work. The performance of DVR is studied under voltage sag and voltage harmonics during double line to ground fault and 120% of change in Load conditions. The proposed fuzzy controller technique shows an excellent performance and generates low THD (<5%) when compared to without DVR & PI controller. Fuzzy logic controller compensates about 0.15% of Total Harmonic Distortion (THD) when compared to without DVR & PI controller which compensates about 2.36%, 0.62%, for L-L-G and 120% of change in Load conditions . Thus, the overall simulation result show that the DVR compensates the voltage disturbances such as voltage sags, voltage harmonics quickly and provides excellent voltage regulation.

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