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Fault Ride-Through of DFIG Wind Turbine by DVR Using Synchronous Reference Frame Control

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ABSTRACT
Today, wind energy is the world's fastest growing source of renewable energy. Grid connected wind power is growing in leaps and bounds and India is one of them. Among the renewable energy sources, the cost of producing one kilowatt hour of electrical energy from the wind power is the cheapest. All this has become possible because of recent developments in electrical, mechanical, power electronics, materials and other fields which have wide range of applications in renewable energy technology. Wind power, at the one end is very much useful source of energy same time when it is connected to the electric grid creates some quality issues like voltage sag, swell, harmonics etc. Wind power plants are also affected by faults which occur in every power system occasionally. Small power generating capacity plants can be disconnected from the system when fault occurs but large power generating plants cannot be disconnected and remained in operation during fault so manufacturers of wind turbine created some grid codes which defines the fault ride through behaviour of wind turbine. In this research the application of dynamic voltage restorer (DVR) connected to a wind turbine driven by doubly fed induction generator (DFIG) is investigated using synchronous reference frame (SRF) control method. The DVR can compensate the faulty line voltage and DFIG wind turbine can continue its normal operation as demanded in actual grid codes. The DVR can be used to protect wind turbines that do not provide sufficient fault ride through behavior.

Keywords: *Dynamic Voltage Restorer, Doubly Fed Induction Generator, Fault Ride Through, Fuzzy logic controller, Synchronous reference frame*

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I. INTRODUCTION

Consequences of crude oil crises increases the price of fossil fuels and affected the economic growth of developing countries. This has woken up the world to look for the alternate and sustainable energy solutions. Sun, wind, tide, geothermal energy etc. are the alternative or sustainable form of energy which are gaining attention now a days for their natural occurring and other advantages. Since 1980s Indian government promote the use of alternative or renewable energy. Currently, government massively expanding the large scale deployment of both centralized and distributed renewable energy including solar, wind, small hydro, biomass etc. which will ease the strain on the transmission and distribution. Table 1.1 and 1.2 clears the picture about installed grid connected electrical capacity in India and overview of grid connected renewable energy capacity in India.

Table 1.1 Installed grid connected capacity in India

Sl. No.	Technology	Capacity(MW)	Percentage
1	THARMAL	140976.18	66.82
2	HYDRO	39339.40	18.64
3	NUCLEAR	4780.0	2.26
4	RENEWABLE	28522	12.25

Table 1.2 Overview of grid connected renewable energy capacity in India.

Sl. No.	Renewable Source	Grid Connected Capacity(MW)	Percentage
1	Wind	19618	68.78
2	Small Hydro	3447	12.08
3	Bagasse Cogeneration	2337	8.19
4	Solar PV	1760	6.17
5	Biomass	1264	4.43
6	Waste-to-Power	96	0.003

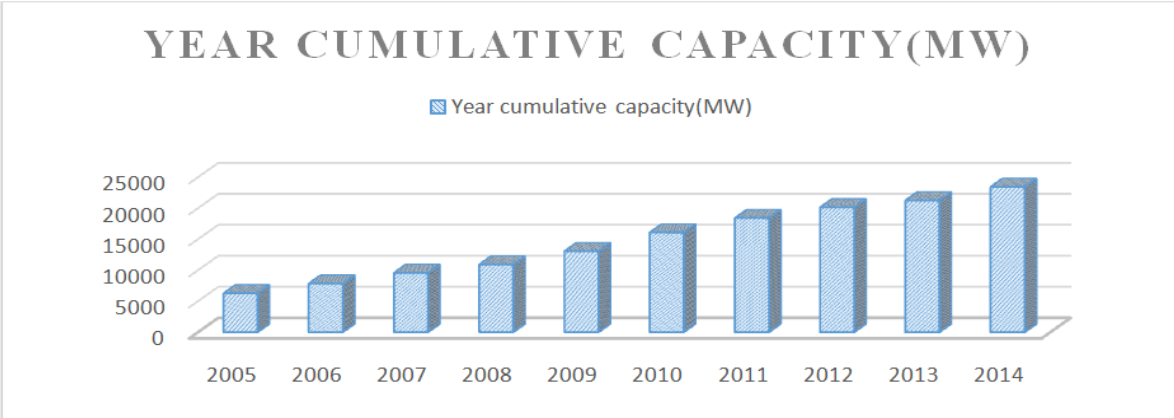

Figure 1.1 Year cumulative capacity of wind power in INDIA

A moderate share of wind power in a power system does not create any problem. When the wind power plants are of smaller capacity and their contribution to the grid is smaller, the rules governing their grid connection are relaxed because major stable feed of electrical power is from the conventional power plants but as the amount of wind power generation increases it raises challenges for various stakeholders involved ranging from generation, transmission and distribution to power trading and consumers. Therefore new regulations for grid connection of WPPs become necessary for stability of power system. These new regulation addresses major issues which are: 1) Interface issue and 2) Operational issue. Short circuit power control, active and reactive power control and voltage control are interface issues. The operational issues are Power system stability, frequency control, short and long term balancing, impact on transmission and distribution and economic dispatch. Power system stability affects by the faults occurring in the system and seeks more attention. Power companies want that all types of power plant would support the grid and provide stability even under faulty condition. Power plant generates needed VARs and maintain the voltage level within certain limits applicable to WPPs. Fault occurring in power system are one-phase, two-phase and three-phase to ground. The three-phase to ground is most dangerous for the generators, if occurred near to the location of WPP. When a three-phase short circuit fault occur in the system the voltage at the generator terminal drops depending upon location of fault and WPP is not able to export needed power because its input is wind dependent. The grid operator's wants that for such faults the WPPs stay on the line for normal clearing time. When fault occurs the voltage at generator terminals drops and also active power reduces which further decreases the mechanical power input and this accelerates the WPP. This acceleration caused by imbalance between input and output power during fault must not compromise the WPP's ability to supply reactive power and ride through the faults.

1.1 FAULT RIDE- THROUGH (FRT)

Grid stability and security of supply are two important aspects for energy supply. Power generating plants should have control capabilities and protection mechanisms to prevent outages. Conventional power plants were fulfilling these requirements in past but presently share of renewable energy sources in the total electricity generation has increased so that these sources too must contribute to the grid stability. Therefore the transmission system operators have established grid codes with certain critical values and control characteristics that the generating plants have to fulfill. Fault Ride through (FRT) or Low Voltage Ride-Through (LVRT) capability of generating plants is one of the most important factor. LVRT is short for Low Voltage Ride-Through and describes the requirement that generating plants must continue to operate through short periods of low grid voltage and not disconnect from the grid. Short-term voltage dips may occur when large loads are connected to the grid or as a result of grid faults like lightning strikes or short-circuits. In the past, wind turbines were allowed to disconnect from the grid during such a fault and try to reconnect after a certain period of time when fault has been removed. Increased share of WPPs this practice has become fatal today. If too many generating plants disconnect at the same time the complete network could break down, a scenario which is also called a "blackout". For this reason the LVRT requirement has been established which is meant to guarantee that the WPPs stay connected to the grid and also support the grid by feeding reactive current into the network and so maintain the voltage during dips. Immediately after fault clearance, the active power output must be increased again to the value prior to the occurrence of the fault within a specified period of time. These requirements which at the beginning only applied to wind turbines, now also have to be fulfilled by Photo Voltaic systems (PV) and most recently, by Combined Heat and-Power Plants (CHP).

WPPs must support the voltage in case of three phase short circuit in the grid. If three phase fault occur close to WPP then there should neither disconnection of WPP nor instability of WPP. WPP operating characteristic is shown in figure 1.2. In this figure V_p is minimum voltage for normal operation of wind turbine and $V_f$is 15% of nominal system voltage. As per grid codes, in the shaded portion the wind turbine must not trip and continue its normal operation against any fault occurring in the system.

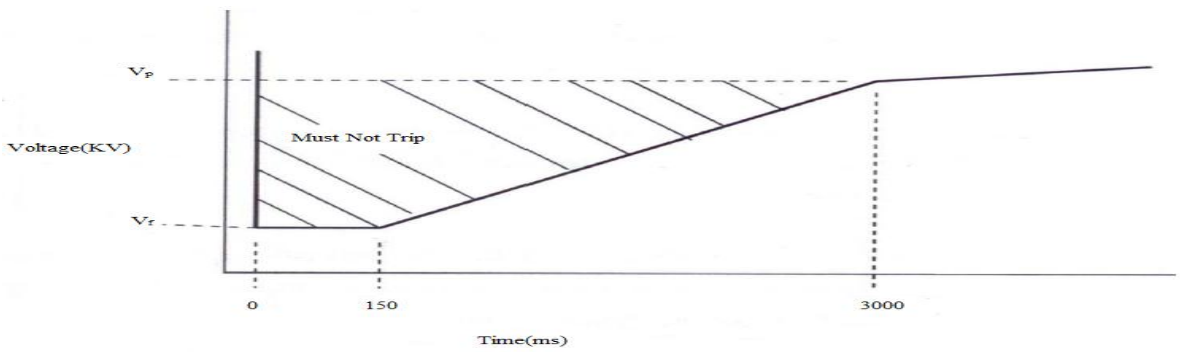

Figure 1.2 WPP operating characteristic (Source: Indian Wind Grid Code, C-WET)

1.2 FRT strategies

The severity of the grid fault to the DFIG based WPP depends on the type of the fault, pre-fault wind speed and DFIG output power. The largest rotor current flows when a sudden symmetrical 3-phase fault occurs and lowers the stator voltage to a small value while the generator delivers its full rated power. Earlier, the wind turbines were required to be disconnected following the occurrence of the network fault and any fault ride-through (FRT) strategy was considered to be successful if it could confine the rotor inrush current and the dc-link over-voltage to within the safe operating areas (SOAs) of the RSPC switching devices and the dc link capacitor, respectively. System voltage regulation e.g. PCC voltage is also an important factor to be dealt with so as to ensure the continuous operation of the DFIG based WT during grid disturbances. Several methods have been proposed that improve the capability of the DFIG based WTs to operate without disconnecting from its point of common connection (PCC) with the grid. These methods are: (i) protection circuit based FRT scheme, (ii) reactive power injecting-devices based FRT schemes and (iii) control approaches based FRT schemes.

Reactive power injecting device, ex., DVR is most effective and efficient solution for fault ride-through. It is a custom power device which injects voltage into the system and regulate the faulty line voltage. Voltage source converter of DVR are controlled by synchronous reference frame control method. In this method the distorted voltages are first converted into stationary coordinates and then these stationary quantities are converted into synchronous rotating frames using cosine and sinus functions from the phase locked loop. This technique is based on conventional a-b-c to d-q-0 transformation.

In this study DVR is used for providing fault ride through behavior to DFIG wind turbine and controlling of DVR is done by using Synchronous reference frame method. Some of the background studies, related to this work are discussed here **[Jayaprakash Pychadathil 2014]** Elaborates new control scheme for DVR with battery energy storage and capacitor supported DVR. Compensation of sag, swell and harmonics in supply system are regulated by using reduced rating DVR. In DVR connected system voltage is injected in such a manner that the load voltage is constant in magnitude and undistorted. This compensation of voltage sags is achieved by injecting or absorbing real or reactive power. **[A.S.A. Awad 2014]** This paper analyses the capability of STATCOM and DVR for LVRT of SCIG wind farm. Partial blackouts, lack of reactive power support are the negative impacts of wind energy generation and its integration to grid. To avoid these impacts grid codes have been developed. LVRT is most important that have been mention in grid codes. **[Sajid Ali 2013]** This paper investigates DVR performance for voltage quality enhancement. DVR topology, DVR operation, DVR compensation technique, control and sag detection technique is presented. **[A. Khoshkbar Sadigh 2012]** High quality power is necessary for sensitive loads such as medical equipment, paper manufacturer and semiconductor device manufacturer. Present days voltage sags are serious threats for power systems and can trip the loads. Voltage variations are suppressed by tap changing transformer and UPS but the cost effective solution is DVR. DVR injects the proper voltage and suppress the voltage variations. **[Wessels Christian 2011]** Grid codes are rules explaining behavior of wind turbines for fault ride through, steady state active and reactive power production. These rules also describe that during faults the wind turbine must connected to grid and support it by producing reactive power to restore the grid voltage after fault. DFIG wind turbine are used due to its variable speed operation and controllable active and reactive power but it is sensitive to grid voltage disturbances. When considering to actual grid codes requirements some solutions are provided for fault ride through problem like crowbar, series dynamic resistance in rotor, changing the control of RSC etc.

all these protection methods can be removed if an external power electronics device is used to compensate faulty grid voltage this is Dynamic voltage Restorer. DVR is used to protect wind turbine that do not provide fault ride through behavior. DVR compensates the fault voltage and DFIG wind turbine continue its operation and this is done without additional protection equipment.

From the literature review, it is observed that researches have attempted to provide the solution for fault ride through by using different technology as STATCOM, UPS etc. but the best one is DVR. There are very few literature on Synchronous reference frame based control of DVR.

II. METHODOLOGY

The investigated wind turbine system, as shown in Fig. 2, consists of the basic components like the turbine, a gear (in most systems), a DFIG, and a back-to-back voltage source converter with a dc link. A dc chopper to limit the dc voltage across the dc capacitor and a crowbar are included. The back-to-back converter consists of a RSC and a LSC, connected to the grid by a line filter to reduce the harmonics caused by the converter. A DVR is included to protect the wind turbine from voltage disturbances. Due to the short period of time of voltage disturbances, the dynamics of the mechanical part of the turbine will be neglected and the mechanical torque brought in by the wind is assumed to be constant

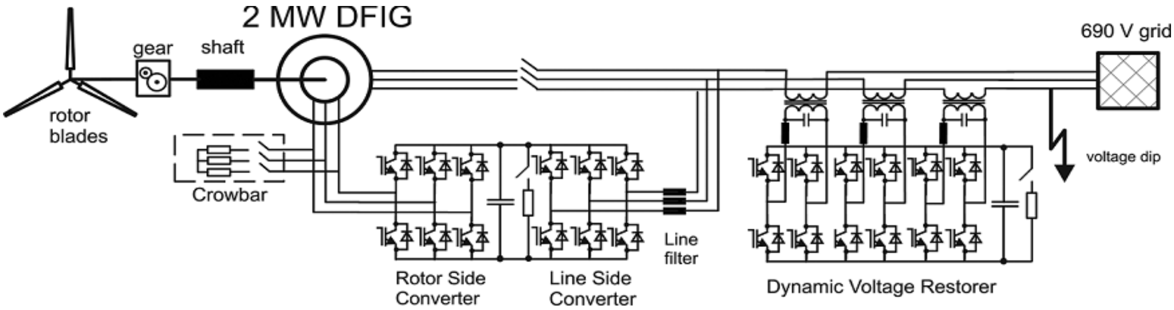

Figure 2.1 Schematic diagram of DFIG wind turbine system with DVR

In this work, the application of a DVR that is connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride through of voltage dips fulfilling the grid code requirements is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Here, asymmetrical faults are investigated. To show the effectiveness of proposed technique MATLAB Simulink model has been developed without DVR and With DVR. Controlling of DVR is done through Synchronous reference frame control method. Stator voltage, stator current and rotor current are plotted without DVR and with DVR. Fault ride through behavior if DVR is also plotted. All this done using these steps

1 .MATLAB Simulink model for fault ride through behavior of wind turbine is created without DVR.
2. Stator voltage, stator current and rotor current has been plotted by scope for LLG fault.
3. MATLAB Simulink model for fault ride through behavior of wind turbine is created with DVR.
4. Stator voltage, stator current and rotor current has been plotted by scope for LLG fault.
5. Study of results.

III. Basics 0f Dynamic Voltage Restorer

Dynamic Voltage Restorer is a series connected device, which corrects the voltage dip and restore the load voltage in case of a voltage dip. Dynamic Voltage Restorer (DVR) is applied to compensate for voltage sags and swells and expected to respond fast (less than 1/4 cycle) and thus employs PWM converters using IGBT devices. Basics of dynamic voltage restorer (DVR) are explained by following sections

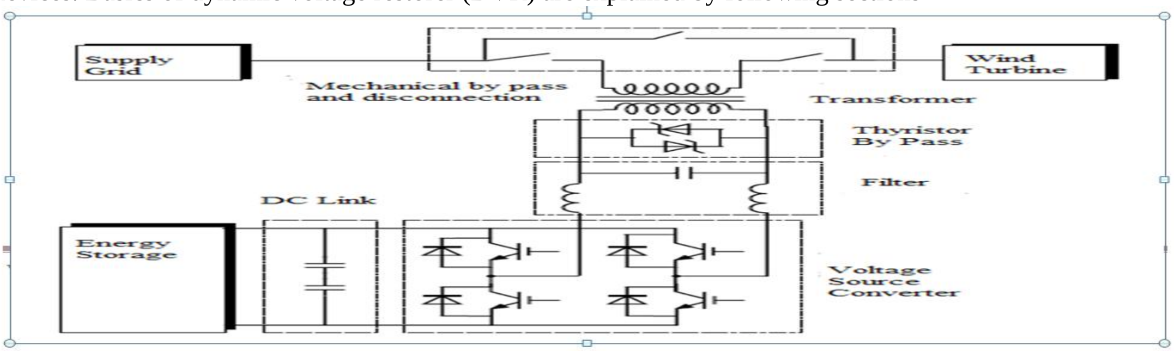

Figure 3.1 Basics blocks of DVR

3.1 Basic Configuration

DVR is a series connected FACTS device which is able to protect a susceptible load against the abnormal and transient disturbances in power system. Basically the DVR consists of two types of circuits, one is power circuit and another one is control circuit. Control circuit is used to derive the parameters as like magnitude, frequency, phase shift, etc. of the control signal that has to be injected by the DVR. Due to control signal, the injected voltage is generated using switching in power circuit. The power circuit of DVR consists of an injection transformer, AC harmonic filter, high speed switching pulse width modulation (PWM) inverter, DC energy storage unit and control unit.

3.2 Principal of operation

Dynamic voltage restorer (DVR) is a series connected device used to compensate voltage sags and swells during abnormal conditions in the distribution systems. DVR is one of the most effective solutions for "restoring" the quality of voltage at its load-side terminals when the voltage at its source-side terminals is disturbed. When problems such as the voltage sag, swell happens; DVR protects the sensitive loads by restoring the load side voltage dynamically. DVR operated in three different operating modes, which here are explained briefly as:

a) Bypass mode: In this mode the DVR is bypassed mechanically or electronically when high load currents and down-stream short circuits occurred and during this mode the DVR cannot inject a voltage to improve the voltage quality.
b) Standby mode: in this mode the supply voltages are at rated level and the DVR is ready to compensate for a voltage dip. During standby mode the DVR can have secondary tasks and operation modes:
   (i) Low loss mode: during this mode the DVR performs no switching and losses in the DVR are minimized to conduction losses.
   (ii) Harmonic blocking mode and voltage balancing mode: during this mode the DVR improves the load voltage and compensate for a poor background voltage quality by switching and it is expected that DVR inject a relatively small voltage in magnitude.
   (iii) Capacitor emulation mode: in this mode the DVR is controlled to operate as an inserted series capacitor compensating for a large line inductance and for the inductance inserted in conjunction with the DVR.
c) Active mode: in this mode the DVR injects the missing voltage after a voltage dip has been detected.

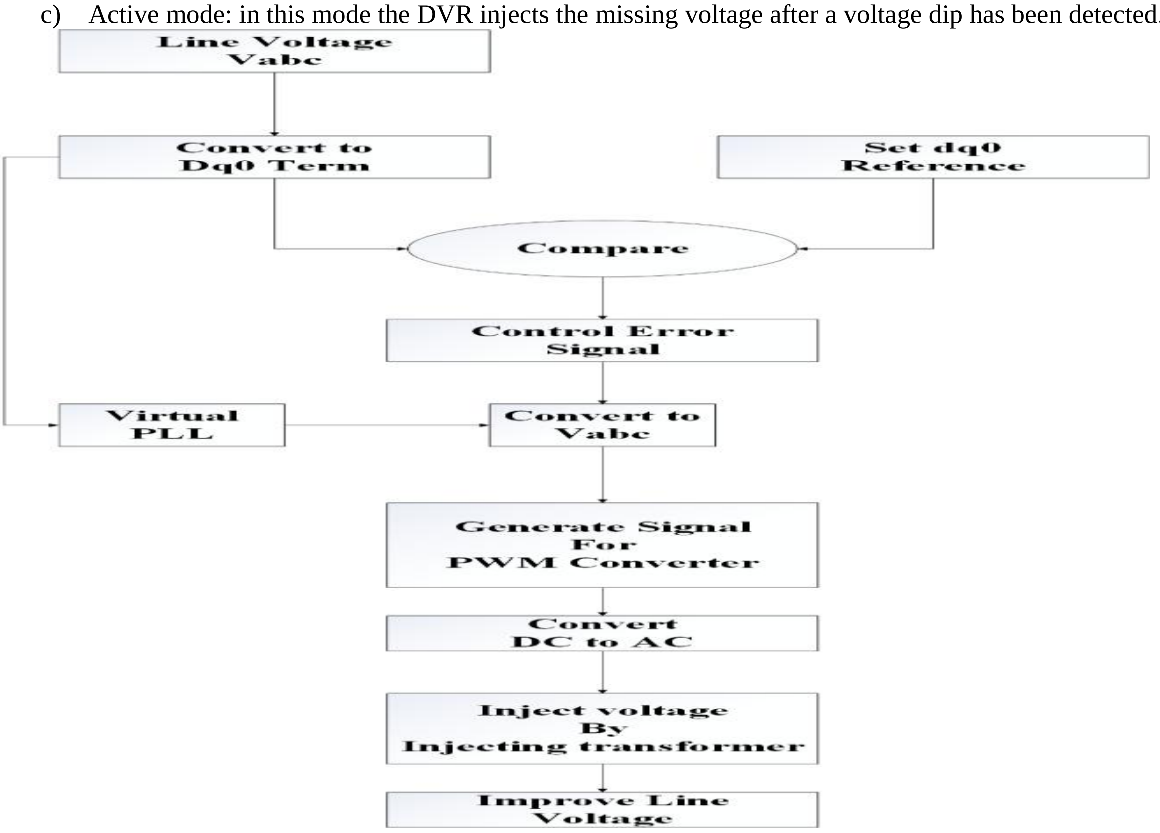

Figure 3.2 flow chart explaining DVR operation

3.3 SRF control of DVR with PI controller

The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power. When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power. However, if the injected voltage is in phase with the current, DVR injects real power, and hence, a battery is required at the dc bus of the VSC.

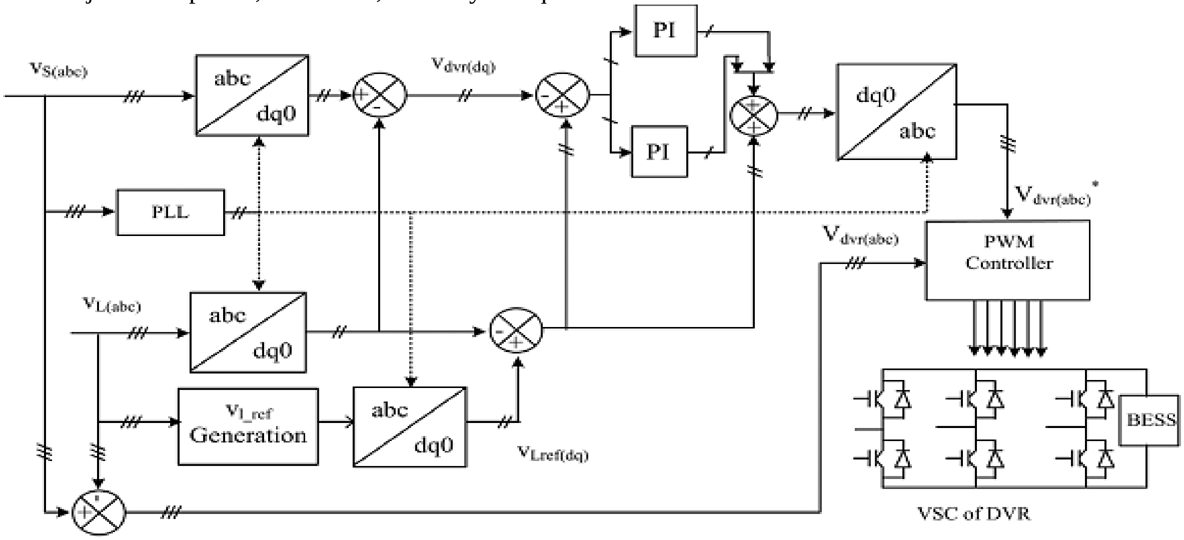

Figure 3.3 Control block of DVR using SRF method

Fig. 4 shows a control block of the DVR in which the SRF theory is used for reference signal estimation. The voltages at the PCC *vS* and at the load terminal *vL* are sensed for deriving the IGBTs' gate signals. The reference load voltage *VL* is extracted using the derived unit vector. Load voltages (*VLa, VLb, VLc*) are converted to the rotating reference frame using *abc−dqo* conversion using Park's transformation with unit vectors (sin*, θ,* cos*, θ*) derived using a phase-locked loop as

$$\begin{bmatrix} v_{Lq} \\ v_{Ld} \\ v_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{La\text{ref}} \\ v_{Lb\text{ref}} \\ v_{Lc\text{ref}} \end{bmatrix}. \quad (1)$$

Similarly, reference load voltages (*V ∗La, V ∗Lb, V ∗Lc*) and voltages at the PCC *vS* are also converted to the rotating reference frame. Then, the DVR voltages are obtained in the rotating reference frame as

$$v_{Dd} = v_{Sd} - v_{Ld} \quad (2)$$

$$v_{Dq} = v_{Sq} - v_{Lq}. \quad (3)$$

The reference DVR voltages are obtained in the rotating reference frame as

$$v^*_{Dd} = v^*_{Sd} - v_{Ld} \quad (4)$$
$$v^*_{Dq} = v^*_{Sq} - v_{Lq}. \quad (5)$$

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two proportional–integral (PI) controllers. Reference DVR voltages in the *abc* frame are obtained from a reverse Park's transformation taking V^*_{Dd} from (4), V^*Dq from (5), V^* *D*0 as zero as

$$\begin{bmatrix} v^*_{\text{dvr}a} \\ v^*_{\text{dvr}b} \\ v^*_{\text{dvr}c} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v^*_{Dq} \\ v^*_{Dd} \\ v^*_{D0} \end{bmatrix}. \quad (6)$$

Reference DVR voltages (v^*dvr*a*, v^*dvr*b*, v^*dvr*c*) and actual DVR voltages (*v*dvr*a*, *v*dvr*b*, *v*dvr*c*) are used in a pulse width modulated (PWM) controller to generate gating pulses to a VSC of the DVR.

3.4 SRF control of DVR with fuzzy logic controller

The objective of fuzzy logic controller is to control the dc link voltage of the grid interfacing inverter. The error signal will be the single input of fuzzy logic controller. This input signal is divided into five groups; mf1, mf2, mf3, mf4, mf5. The fuzzy control rules for error signal are:

If (input1 is mf1) then (output is mf1) (1)
If (input1 is mf2) then (output is mf2) (1)
If (input1 is mf3) then (output is mf3) (1)
If (input1 is mf4) then (output is mf4) (1)
If (input1 is mf5) then (output is mf5) (1)

Shortcomings of PI controller is overcome by Fuzzy controller. In comparison to the linear PI controller, this is a non-linear controller that can provide satisfactory performance during various fault conditions. The fuzzy controller is very useful as it relieves the system from exact & cumbersome mathematical modeling & calculations. The fuzzy controller includes of four main functional modules namely; Knowledge base (Rule base), Fuzzification, Inference Engine and Defuzzification. Fuzzification which converts input data into suitable linguistic values; a knowledge base which consists of a data base with the necessary linguistic definitions and rule base consists control rule set; defuzzification converts the fuzzy outputs to crisp control signals.

In this research, first the PI Controllers are used (figure 3.3) with SRF control for analysis the FRT behaviour of DFIG wind turbine then the PI controller of figure 3.3 are replaced by fuzzy logic controllers to observe the FRT performance of the DFIG wind turbines.

IV. Results

Short-circuit or faulty condition in the power grid reduces the bus voltage at the Point of Common Coupling (PCC) therefore undesirable transients in the stator and rotor currents are developed. This low voltage prevents the full transmission of generated active power into the grid from DFIG wind turbine, leading to significantly increased fluctuations of the dc-link voltage. During unsymmetrical grid fault, the negative sequence stator currents form a clockwise rotating magnetic motive force (MMF) in the machine air gap which in turn induces an electromotive force (EMF) in the rotor circuit with a frequency of $(2 - s)\omega_s$. The more severe the unsymmetrical condition at the stator side, the higher will be the magnitude of the stator voltage, stator current and rotor current harmonics, as shown in figure 4.1, which in turn will lead to the harmonics in the electromagnetic torque also. During symmetrical grid faults stator voltages experience a sudden voltage drop. Hence EMF induced from the stator flux also experiences a sudden drop. This sudden drop can be seen as an impulse in the stator flux as a dc component. This transient dc component in flux linkage will induce an EMF in the rotor circuits, and a surge of rotor current as well. These severe faulty conditions raises the rotor current of DFIG to a high level and the converters in the DFIG system could be damaged. To fulfill the LVRT requirement for DFIG wind turbines, there are two major issues to be addressed properly under a fault condition. The first one is the over-current which may occur in the rotor circuit, while the second one is the dc-link voltage fluctuation. In this research DVR is used to make the stator voltage, stator current and rotor current sinusoidal.

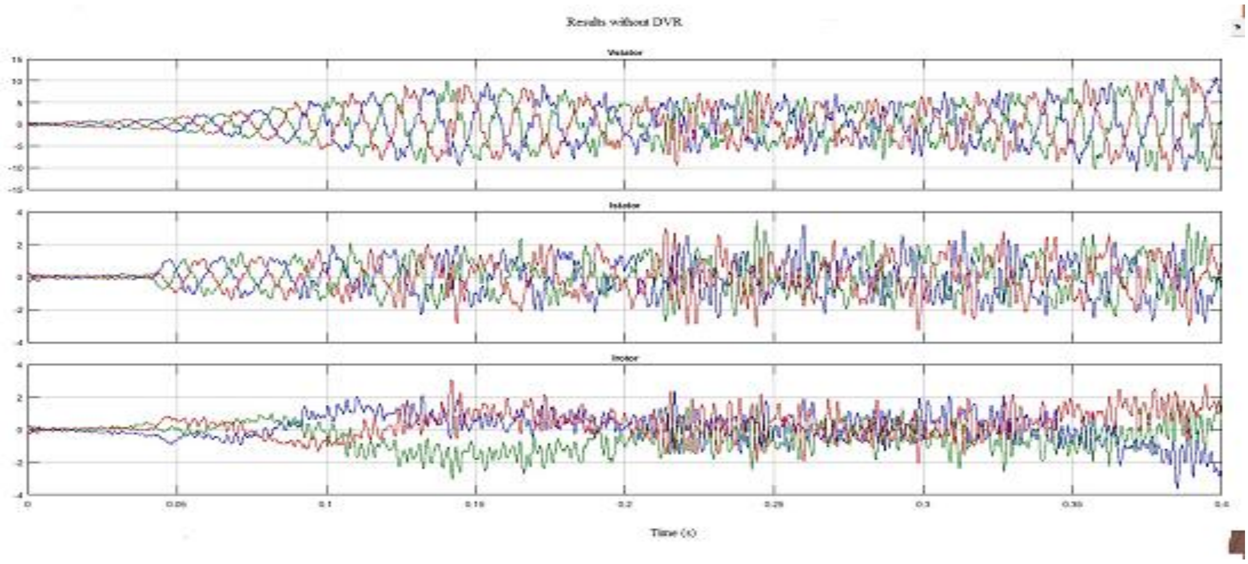

Figure 4.1 stator voltage, stator current and rotor current without DVR when L-L fault occur.

FRT behaviour of wind turbine is shown in figure 4.2 where blue line represents the voltage drop due to a fault (bus voltage B_2) and black line (bus voltage B_3) shows that wind turbine is connected during the fault and continue its normal operation during faulty condition.

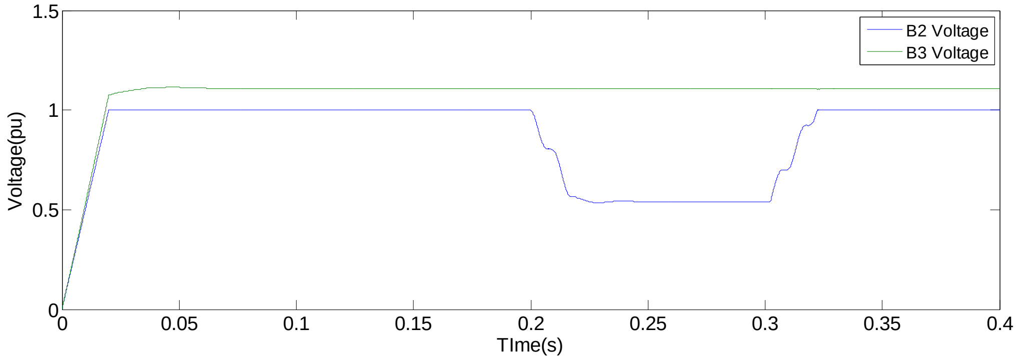

Figure 4.3 effect of fault on bus voltages (B2 & B3)

When a L-L to ground fault occurs in the system, voltage of two phase reduces which is shown in fig 4.4 fault occurs at time t=0.2 sec. to 0.3 sec. From this figure it is clear that voltage of all the phases decreased due to occurrence of fault on those phases and for the compensation of this fault voltage DVR inject voltage. This DVR injected voltage in the faulty line, compensates the faulty voltage and restore it to its previous state and provide fault ride through for DFIG wind turbine. From fig 4.4 it is clear that faulty source voltage is compensated by DVR and stator voltage becomes sinusoidal same as source voltage. Stator and rotor currents which were highly distorted are now sinusoidal. All this is done by injecting active and reactive power in the system these quantities are also shown in the fig 4.4. Using fuzzy logic controller the DVR voltage is more sinusoidal than PI controller also injected active and reactive power is good than PI controller. This is shown in fig 4.5 and 4.6.

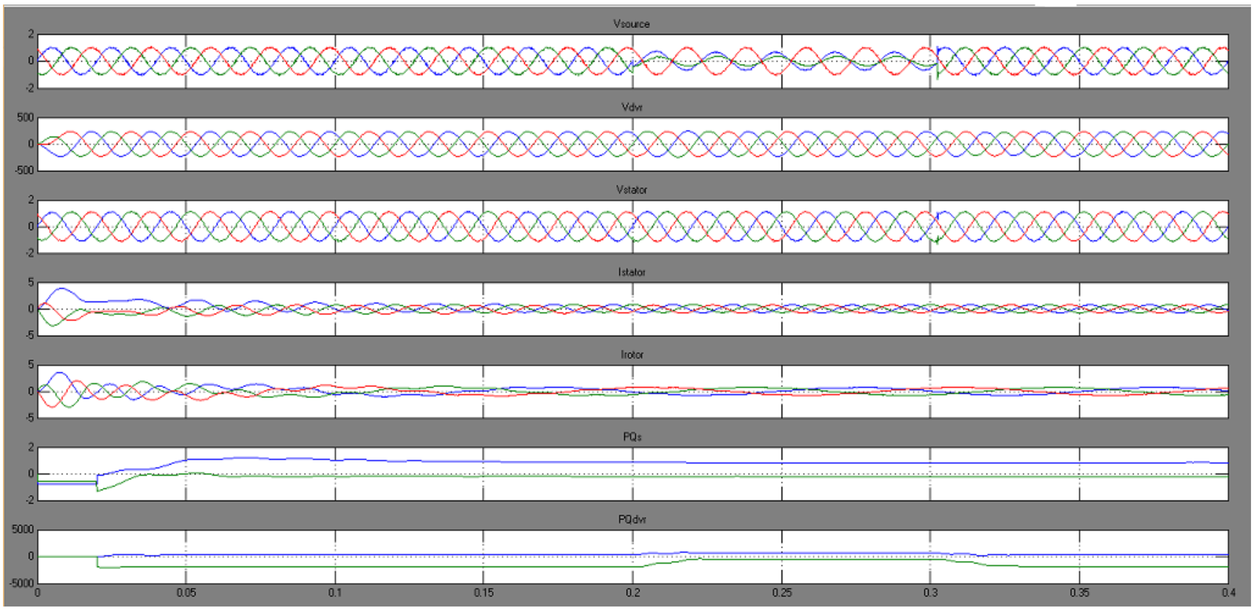

Figure 4.4 source voltage, DVR voltage, stator voltage, stator current and rotor current, P&Q of System, P&Q of DVR with PI controller

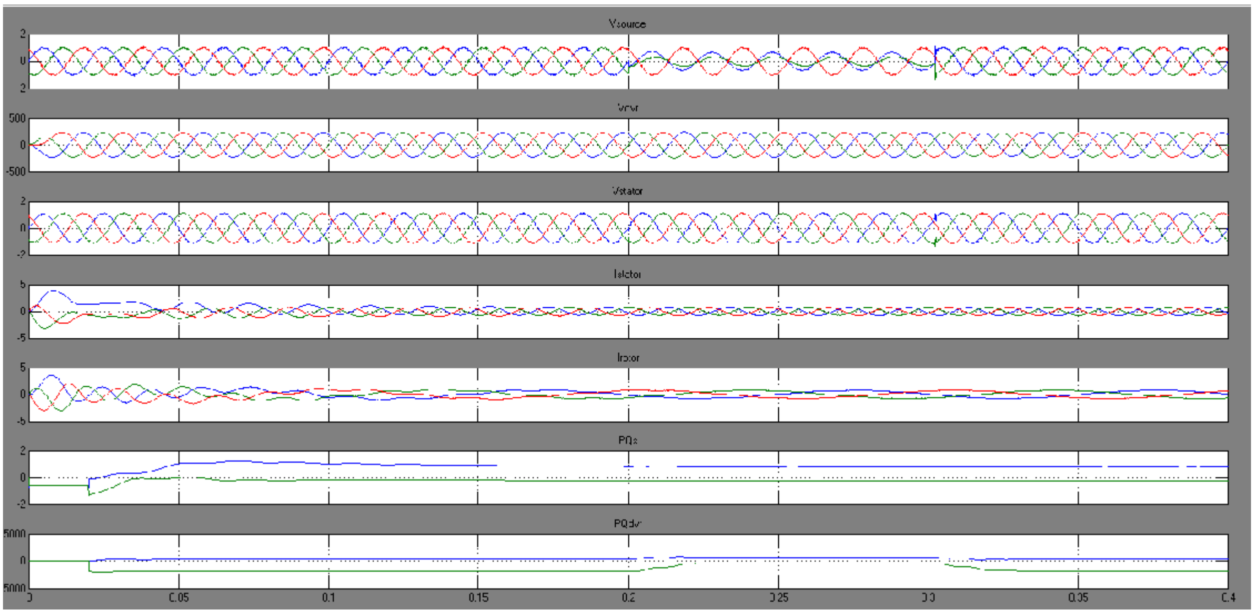

Figure 4.5 source voltage, DVR voltage, stator voltage, stator current and rotor current, P&Q of System, P&Q of DVR with fuzzy logic controller.

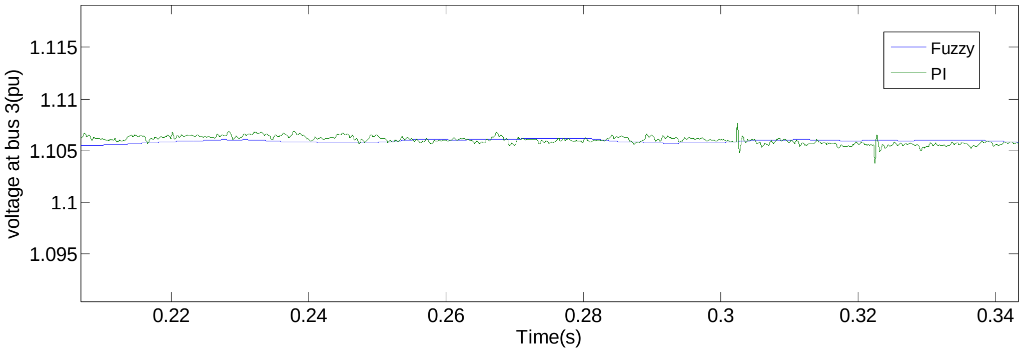

Figure 4.6 bus voltage comparison of fuzzy logic and PI controller for LL fault

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V. Conclusions

From the discussion of results it can be inferred that:

1) DVR connected to DFIG wind turbine provide uninterruptible fault ride-through of grid voltage to fulfill grid code requirements.
2) There is no need of additional hardware for protection of wind turbine to provide fault ride through. DVR can be used to protect already installed wind turbines that do not provide sufficient fault ride-through.
3) It is also observed that fuzzy logic controller has superior performance than PI controller for asymmetrical faults.
4) Active and reactive power of DVR is more constant in fuzzy logic controller than PI controller during fault.

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