Mitigation of Voltage Sag by Using Dynamic Voltage Restorer

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***Abstract*— Power quality is one of the important problems in power system due to increasing penetration level of renewable energy sources. Power quality problems begins with nonstandard voltage, current and frequency which causes failure or mis-operation of end user equipments. Among that voltage sag is major problem. To minimize this problem custom power devises are used such as unified power quality conditioner (UPQC), distribution static compensator (D-STATCOM) and dynamic voltage restorer (DVR). This paper gives investigation on DVR which having low cost, small in size and fast dynamic response to the disturbance. Modeling and analysis of dynamic voltage with sinusoidal pulse width modulation (SPWM) based controller using MATLAB/ Simulink is presented. The performance of designed DVR is studied under different fault condition.**

***Keywords*- Dynamic voltage restorer (DVR), Components of DVR, Voltage sag , Synchronous PI decoupling control strategy**

I. INTRODUCTION

The advanced production plants are subjected to unwanted failure or malfunction because of problems in power quality. One of the most important power quality problem is voltage sag. It is almost impossible to avoid the voltage sag produced in an electric grid due to finite fault clearing time that causes the voltage sag and propagation of sag from grid to low voltage loads. Failure of equipments in production line produces interruption and loss of cost production [1].

The big sources of voltage sag are utility line short circuits and earth faults. Reduction in magnitudes of short circuit fault produces some power quality enhancement because major industrial processes are able to mitigate sag of limited amplitude [2-4].

Voltage dip can be defined as quick reduction of voltages between 10% and 90% at point from half cycle to 1 minute. Voltage sag become important power quality requirement in sophisticated electronic equipment because of their sensitivity to voltage dip like variable speed drives, PLC and computers. These sensitive devices trips when there is reduction of voltages below 90% of its rated voltage in few cycles. In most of countries the wind power plant has increased its penetration in last year. This increased integration produces new challenges in terms of power quality and fault ride through capability. Voltage sag produces unfavorable effects on wind turbine; it requires disconnecting wind turbine from grid when sag occurs within certain limit. Also relays and contacts of motor starter are sensitive to voltage dip [5].

The control system used to control the DFIG in unbalanced condition and different line faults are tested including symmetrical and unsymmetrical voltages in [6]. The performance of induction generator connected to weak electric grid with balanced voltage sag using unified power quality conditioner (UPQC) is studied in [7]. The feed forward control algorithm to minimize voltage sag using dynamic voltage restorer (DVR) is presented in [8]. This scheme is capable for minimizing unbalanced voltage sag.

The description about various shortcomings like phase angle jump and limitations of circuit breaker and analyze the effect of symmetrical voltage dip on DFIG connected wind turbine system in [9]. The use of DVR to improve low voltage ride through ability of DFIG connected wind power plant is suggested in [10]. The control algorithm used for DVR is capable to mitigate balanced and unbalanced voltage sag consequently improve low voltage ride through (LVRT)/ fault ride through (FRT) grid code.

This paper presents the mathematical model of DVR in section II general components of DVR system in section III, control strategy used to mitigate voltage sag in section IV, proposed model developed in MATLB/ Simulink platform including different types of faults and application of DVR to enhance FRT/ LVRT capability of DFIG based wind turbine system in section V, and finally section VI concludes the paper.

II. DYNAMIC VOLTAGE RESTORER (DVR)

DVR is voltage source converter it injects the controlled voltage in series with the grid voltage by using series injection transformer. The magnitudes of DVR injected voltages are controlled in such so as to regulate the load-side voltage. In other words any different voltage produced by fault in the bus will be compensated by an equivalent voltage that can be generated by the VSC and injected through the booster transformer. The DVR was first developed in 1966. Figure 1 and figure 2 shows the basic block diagram and equivalent circuit of DVR respectively. It normally connected in distribution system in between source and the feeder of critical load. Various topologies and control strategies are used to develop DVR. It can perform multifunctions like compensation of voltage sags and swells along with harmonic compensation or reduce voltage transients and fault currents [11]. Most of the time DVR only monitors the bus voltage that is perform nothing to do action.

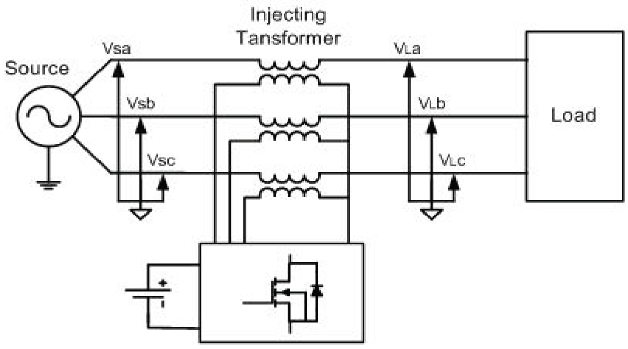

Fig.1. Basic block diagram of DVR

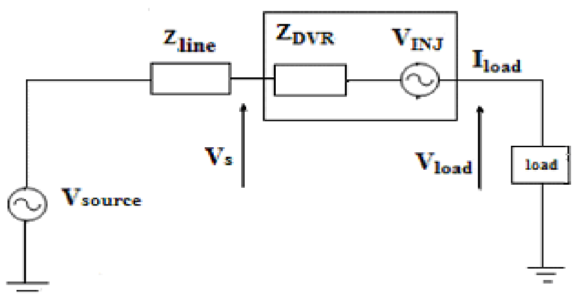

Fig.2.Equivalent circuit of DVR

Mathematically this can be expressed as:

$$V_L(t) = V_s(t) + V_{inj}(t) \quad (1)$$

Here $V_L(t)$ is the voltage across load, $V_s(t)$ is the supply voltage with sag and $V_{inj}(t)$ is the compensating voltage injected by DVR.
Under normal condition the per phase power taken by load is given by

$$S_L = I_L V_L^* = P_L - jQ_L \quad (2)$$

Here I_L is the load current, P_L and jQ_L are active and reactive power of load respectively.
In sagged the DVR restores the voltage back to the normal expressed as

$$S_L = P_L - jQ_L = P_s - jQ_s + P_{inj} - jQ_{inj} \quad (3)$$

Here P_s and jQ_s are sagged supply quantities, P_{inj} and jQ_{inj} are injected quantities by DVR [12].

III. SELECTION OF DVR COMPONENTS

The DVR consists of an injection/ booster transformer, filter, a voltage source inverter (VSI), DC charging circuit/ energy storage circuit and control and protection system. Some of these components are briefly explained as follows.

A. *Energy storage Unit:*

The voltage source converter require some energy to operate this can be taken from grid or any other auxiliary supply to compensate load voltage in dip condition. If DVR is connected to weak grid then auxiliary supply method is used to improve the performance. In this category variable or constant dc capacitor voltage topologies are used. In second category that is if DVR is installed at strong grid then the required supply is provided from grid to DVR. This category also divided into two types, one is supply provided from load side and other is supply provided from source side. If types of energy storage system is depends on some conditions like cost, complexity limitations and behavior they can arranged as i)Load side connected converter ii)constant dc link voltage iii)variable dc link voltage iv)supply side connected converter. The constant dc voltage is selected in this paper.

B. *Inverter circuit:*

The required amount o voltage is supplied by voltage source inverter (VSI). The semiconductor devices having self commutation capacity like insulated gate bipolar transistors (IGBTs) are used in inverter circuit. These inverters are energized by dc voltage having low input impedance. In voltage source inverters the value of voltage variations are low but difficult to limit the current due to capacitors. The 3 phase pulse width modulation (PWM) is used in this study which is most popular type.

C. *Filter unit:*

The distortion of waveforms with harmonics is produced at the output of inverter due to nonlinear behavior of semiconductor devices. To minimize this drawback and improve the power quality of supply the filter circuits are used. There are two types of filter circuits used depends on location. The inverter side and grid side are the two types. The first type is closure to harmonic source so it able to prevent the injection of harmonics in injecting transformer. This type produces the I*R drop and phase shift in output inverter voltage. But this voltage drop and phase shift unable to disturb the system. The inverter rating depends on capacitor. For better harmonic compensation filter capacitor rating is increased. The inverter side connected filtering scheme is used in this paper.

D. *Series Injection Transformer:*

The injection transformer is used to inject saged voltage in grid. The reliability and effectiveness of voltage depends on rating of transformer. To interface the DVR with injection transformer the turn's ratio, MVA rating, short circuit impedance, primary winding voltage and currents are necessary [13].

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IV. SYNCHRONOUS PI DECOUPLING CONTROL STRATEGY

i) Positive-Sequence Component and Phase Angle

The positive sequence voltage components extracted from unbalanced voltages can be written as

$$\begin{bmatrix} v_{ga}(+) \\ v_{gb}(+) \\ v_{gc}(+) \end{bmatrix} = \begin{bmatrix} \frac{1}{3}\left(v_{ga} - \frac{v_{gb}}{2} - \frac{v_{gc}}{2}\right) - \frac{1}{j2\sqrt{3}}(v_{ga} - v_{gc}) \\ \frac{1}{3}\left(v_{gb} - \frac{v_{gc}}{2} - \frac{v_{ga}}{2}\right) - \frac{1}{j2\sqrt{3}}(v_{gc} - v_{ga}) \\ \frac{1}{3}\left(v_{gc} - \frac{v_{ga}}{2} - \frac{v_{gb}}{2}\right) - \frac{1}{j2\sqrt{3}}(v_{ga} - v_{gb}) \end{bmatrix} \quad (4)$$

Here v_{ga}, v_{gb}, v_{gc}, and $v_{ga}(+), v_{gb}(+)$ and $v_{gc}(+)$ are instantaneous voltages of grid and positive-sequence components, respectively.

From these positive-sequence component of $v_{ga}(+), v_{gb}(+)$ and $v_{gc}(+)$ that is a balanced voltage set, the grid phase angle is found by conventional PLL system, using the *dq* synchronous reference frame as follows

$$\theta_c = \tan^{-1}\left(\frac{-v_d^s(+)}{v_q^s(+)}\right) \quad (5)$$

Here

$$v_d^s(+) = \frac{(2v_{ga}(+) - v_{gb}(+) - v_{gc}(+)}{3}$$

$$v_q^s(+) = \frac{(v_{gc}(+) - v_{gb}(+)}{sqrt\,(3)} \quad (6)$$

ii) Voltage Sag compensation

The DVR injects the compensating voltages, the reference for these voltages can be calculated as:

$$\begin{bmatrix} v_{ca}^* \\ v_{cb}^* \\ v_{cc}^* \end{bmatrix} = \begin{bmatrix} v_{ga,presag} - v_{ga} \\ v_{gb,presag} - v_{gb} \\ v_{gc,presag} - v_{gc} \end{bmatrix} \quad (7)$$

Here $v_{ga,presag}$, $v_{gb,presag}$, and $v_{gc,presag}$ are the voltages prior to voltage sag and v_{ga}, v_{gb}, and v_{gc} are those after the voltage sag occurs in system.

iii) Voltage controller

In PI synchronous decoupling control strategy the voltage reference is obtained from equations (6) and (7) as:

$$V_{fdqp}^* = (K_p + \frac{K_i}{s})e_p \quad (8)$$

$$V_{fdqn}^* = (K_p + \frac{K_i}{s})e_n \quad (9)$$

Where

$$V_{fdqp}^* = \begin{bmatrix} V_{fqp}^* \\ V_{fdp}^* \end{bmatrix} \qquad V_{fdqn}^* = \begin{bmatrix} V_{fqn}^* \\ V_{fdn}^* \end{bmatrix}$$

$$e_p = \begin{bmatrix} V_{cqp}^* - V_{cqp} \\ V_{cdp}^* - V_{cdp} \end{bmatrix} \qquad e_n = \begin{bmatrix} V_{cqn}^* - V_{cqn} \\ V_{cdn}^* - V_{cdn} \end{bmatrix}$$

Here, K_p and K_i are the PI controller gains. V_{cdp}, V_{cqp}, V_{cdn}, and V_{cqn} are the *dq* components of the positive and negative sequence voltages across the filter capacitor of the DVR. V_{fdqp}^* and V_{fdqn}^* are the *dq* components of the inverter output sequence voltages of the DVR.

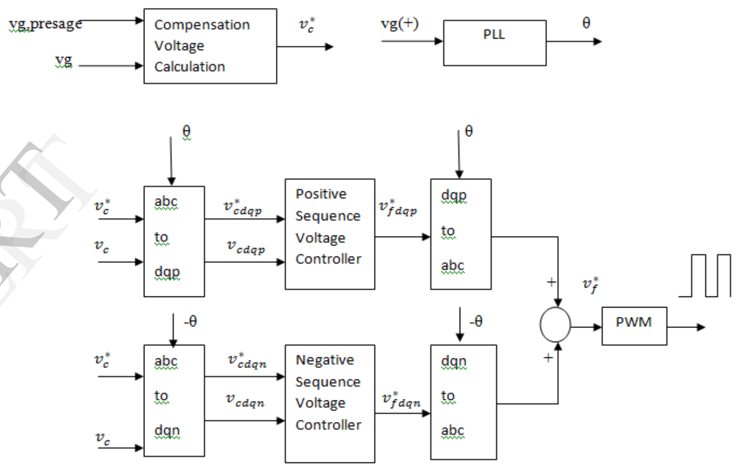


fig. 3. Control system of DVR

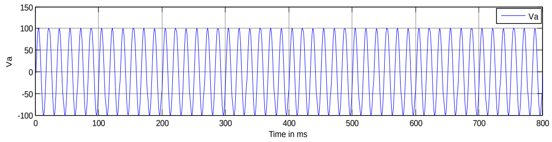
The control system of DVR consists of positive and negative sequence voltage controllers derived in dq reference frame. The positive sequence controller is used to handle balanced voltage sag. The dq component of this controller is not dc quantities so these controllers are not capable to handle unbalanced voltage sag. Therefore negative sequence controller is used to handle unbalanced voltage sag. The subscript 'p' expresses positive sequence whereas 'n' express negative sequence component of voltage. The zero sequence components are neglected [10].

V. SIMULATION RESULTS AND DISCUSSION

The proposed model of dynamic voltage restorer is developed in MATLAB/ simulink platform. The three phase voltage source is sued as supply system. The voltage source converter produces compensation voltage which is feed to primary of injecting transformer. The proposed control system compares the normal voltage with saged voltage and error is produced. By comparing this error with actual voltage of DVR using positive and negative sequence controller produces switching pattern for voltage source converter using PWM technique. The PLL block is used to calculate angle.

A. Three phase balanced fault

The three phases to ground fault occurs on system at 0.3 sec and it is cleared at 0.5 sec as shown in fig 4. The DVR can inject the compensating voltage during this period and rest of the time DVR undergoes nothing to do mode



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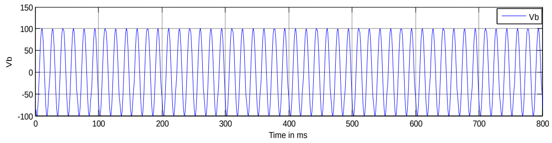

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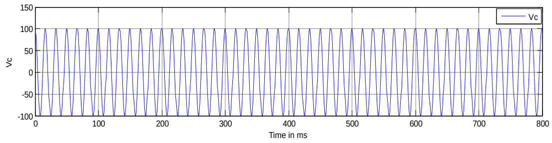

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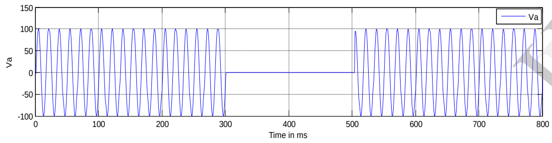

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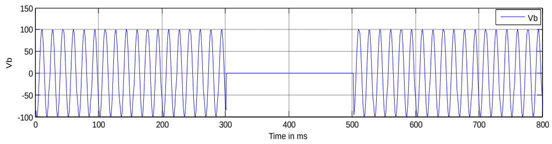

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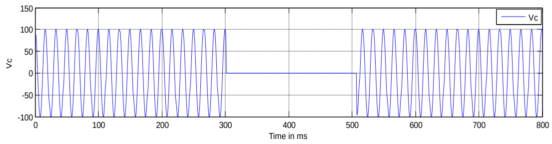

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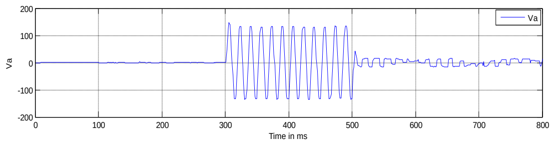

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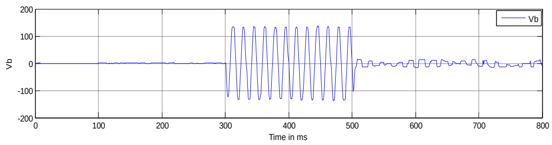

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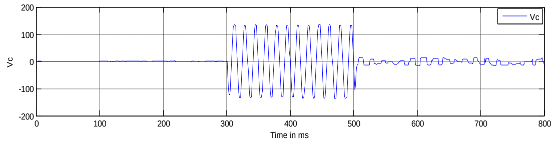
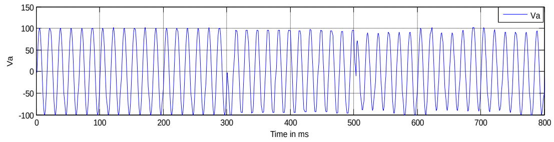


(i)



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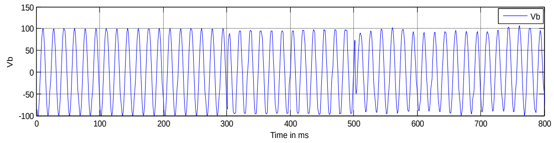

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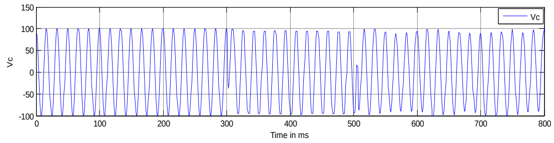
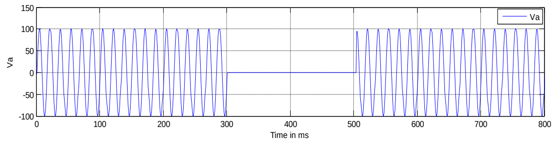


(l)

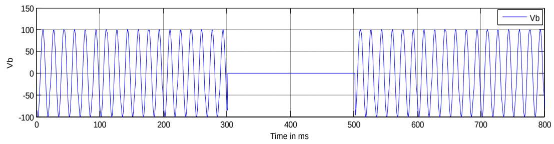
fig.4. Simulation of three phase balanced fault:(a),(b) and (c) voltages of phases a, b and c in normal condition;(d), (e) and (f) saged voltages of three phases; (g), (h) and (i) DVR injected voltage and (j), (k) and (l) compensation of three phase voltages.

B. Uunbalanced fault

In this case the fault is occurs on phases ‘a’ and ‘b’ so there is no sag on phase ‘c’. In this condition the negative sequence voltage controller is working. The DVR can provide compensating voltage for only two phases as shown in fig.5.



(a)



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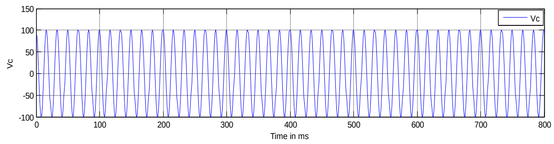

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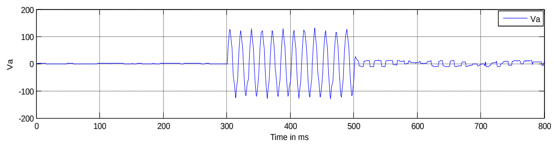

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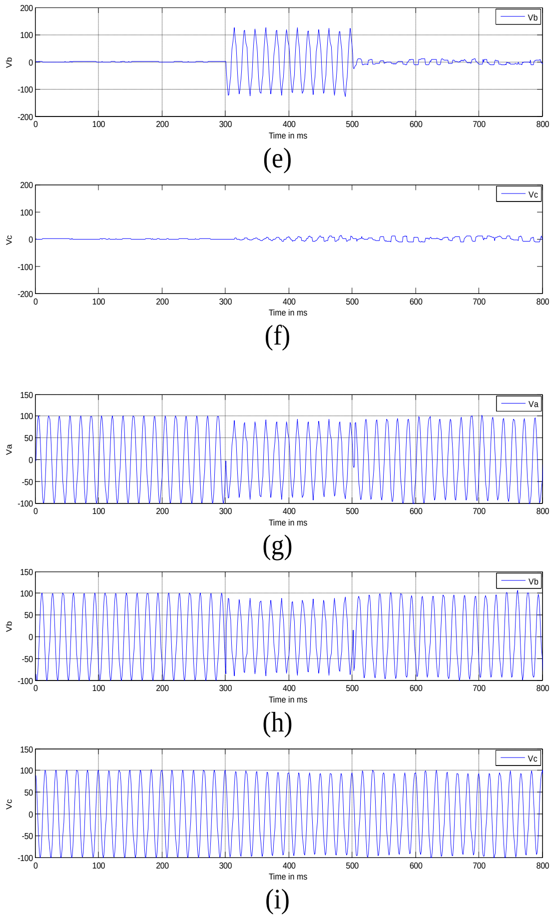

fig. 5. Simulation of three phase balanced fault: (a), (b) and (c) saged voltages of phases a, b and c during two phases to ground fault; (d), (e) and (f) DVR injected voltage and (g), (h) and (i) compensation of three phase voltages.

VI. CONCLUSION

The DVR is simple and cost effective device. It is most commonly used to enhance power quality due to its various advantages. The DVR model is developed in MATLAB / Simulink platform. The synchronous PI de-coupling control strategy is used to minimize the sag. The proposed control scheme is simple and able to compensate balanced as well as unbalanced voltage sag effectively.

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