Anew Control strategy for an achieving Fast Response of dynamic Voltage Restorer Using Fuzzy Logic

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***Abstract* –PI controller is very common in the control of DVRs. However, one disadvantage of this conventional controller is the fact that by using fixed gains, the controller may not provide the required. To overcome this problem, an adaptive PI controller using fuzzy logic (FL) is proposed to detecting voltage sag on the line and injecting the missing voltage to the system. The simulation results have proved that the proposed control method greatly improves the performance of the DVR compared to the conventional PI controller. The new design is based on two vector control to regulate compensator current and load voltage using 12-switches 12-pulses inverter DVR compared to the conventional inverter control. It shows that the proposed method improved the in-phase compensation technique and improved the time response for nonlinear loads. MATLAB simulation verifies the validity of the proposed technique. Simulation results demonstrated that it can control power and carrier modulated PWM inverter. The control of the compensation voltages in DVR based on dqo algorithm is adopted. Result a source voltage of 11kV (rms) is considered with a source impedance of 3ohms, 11kV/0.415kV step down transformer rated 100MVA with 0.2 Pu is used. A 0.9 MVA 1:1 voltage ratio injection transformer along with a filter of inductance 0.25H and shunt capacitance of 40µF implemented.**

***Index Terms*— Dynamic voltage restorer, fuzzy logic controller, power quality.**

I. INTRODUCTION

The DVR consists of DC energy storage unit, high speed switching pulse width modulation (PWM) inverter, AC harmonic filter and injection transformer. It is able to compensate the voltage sag at sensitive load by injecting an appropriate voltage through an injection [1].

It injects three single-phase voltages in series with the load voltage by synchronizing with the incoming supply voltage. The phase angle and magnitude of the injected voltage varies as a result of variable real and reactive power exchange between the DVR and the distribution system. The amount of real and reactive power supplied by the DVR depends on the type of voltage disturbance [1].

Detecting voltage sag and injecting the missing voltage to the system can be compensated using PI controller, the conventional PI controller is its effectiveness in the control of steady state error of a control system and also its easy implementation. However, one disadvantage of this conventional compensator is its inability to improve the transient response of the system [2]. Most of the PI control is based on multi-loop control due to the dq components of the injected voltage and current. [3]

Fuzzy logic (FL) control is conventional control method and important role because knowledge based design rules can easily be implemented in systems with unknown structure, and it is going to be a since the control design strategy is simple and practical [4].

We aim to present new design based on two vector control to regulate compensator current and load voltage using 12-switches12-pulses inverter DVRs.

II. BASIC CONFIGURATION OF DVR

The DVR consists of DC energy storage unit, high speed switching pulse width modulation (PWM) inverter, AC harmonic filter and injection transformer as shown in Fig 1.

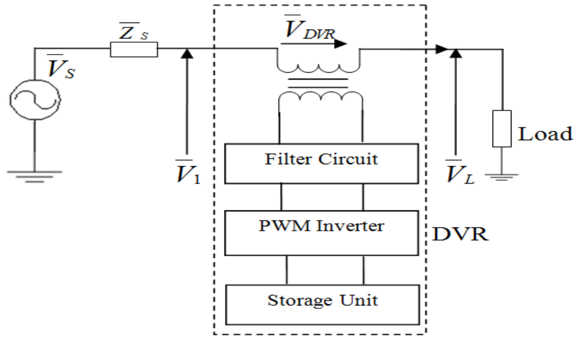

Figure 1. Basic structure of the DVR

$\bar{V}_1$, $\bar{V}_L$ and $\bar{V}_{DVR}$ are the fault supply voltage vector, the restored load voltage vector, and the DVR injection voltage vector, respectively. The DVR injection voltage can be obtained as

$$\bar{V}_{DVR} = \bar{V}_L - \bar{V}_1 \tag{1}$$

where $\bar{V}_L$ is pre-fault load voltage vector. The main sag compensation techniques used in modern DVRs are highlighted in next section.

Experience shows that voltage sag is mostly unbalanced and accompanied with a phase angle shift. In order to restore the voltage rapidly, it is necessary to measure the voltage sags of the system. Fig 2 shows the distribution system during faulty period where the voltage sag and phase angle change can be measured at the point of common coupling (PCC) as follows:

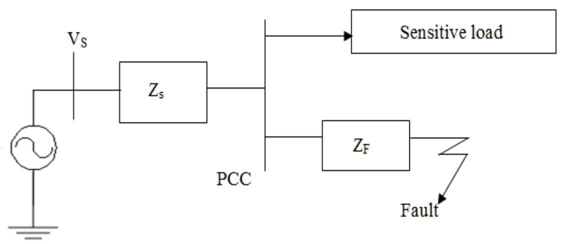

Figure 2. Distribution systems with fault

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} V_S = \frac{Z_F}{Z_S + Z_F} \tag{2}$$

$$\Delta\varphi = \arg(V_{sag}) = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right) \tag{3}$$

where $\bar{V}_{sag}$ is the voltage during the sag at the PCC, $\bar{Z}_F = R_F + jX_F$ is the impedance between the PCC and the fault, $\bar{Z}_S = R_S + jX_S$ is the source impedance at PCC and the source voltage $|V_S| = 1$ p.u.

III. Conventional Method for DVR Voltage Injection

Several conventional methods for voltage sag compensation of DVR have been proposed as described in the following subsections.

A. *Pre-Sag Voltage Compensation*

This strategy is recommended for the non-linear load in which both the voltage magnitude and phase angle need to be compensated. The DVR supplies the voltage which is the difference between the pre-sag and sag voltage. This method tracks supply voltage continuously and compensates load voltage during sag to restore the pre-sag condition, but injected active power cannot be controlled and is determined by external condition such as the type of sags and load condition. Also this technique employs more volts and necessitates a higher inverter voltage rating [5].

Fig 3 shows the restored voltage magnitude and the phase angle using pre-sag voltage compensation technique [6] [7].

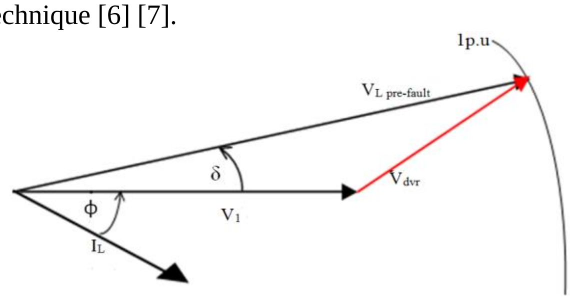

Figure 3. Pre-sag compensation techniques

B. *In-Phase Compensation*

With in-phase compensation, the injected DVR voltage is in phase with sagged voltage as shown in Fig 4 and therefore only the voltage magnitude is compensated. This method minimizes the voltage injected by the DVR. Hence it is recommended for the linear loads. The in-phase compensation algorithm is applied when the reference of the injected voltage is higher than the rated voltage to minimize the injected voltage [8] [7].

Pre-sag voltage compensation and in-phase compensation must inject active power to the load almost at all times. However, the amount of possible injection of active power is confined to the DC link [1] [9]. The steady state injected active power is given by

$$P_{DVR} = 3(V_L - V_1)\, I\cos\o \tag{4}$$

where both V_L and V_1 are phase-to-earth voltages. The DC voltage with in-phase compensation is shown in

Figure 4. The figure shows that the DC voltage decays during the sag and not returns to the 1p.u when the sag is terminated.

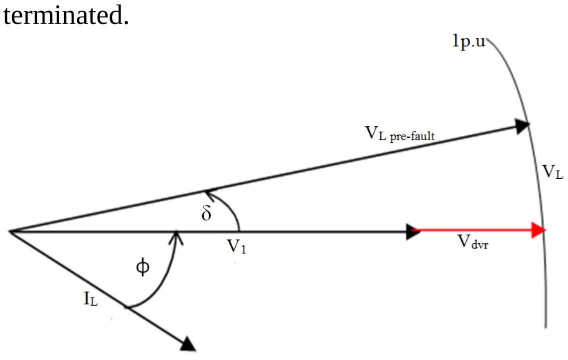

Figure 4. In-Phase compensation techniques

C. *Phase Shift Compensation*

This method is proposed to reduce the size of energy storage system. In this method, active power, P_{DVR}, depends on the angle α. During the sag, the phase of the load voltage will change in a certain steps that cause problems for the load. Figure 5 shows the magnitude of the restored load voltage that is maintained at pre-fault condition. If P_{in} and P_{out} are the input power from the supply and the output load power, respectively, then

$$P_{out} = \sum_{\forall j} V_{LJ} I_{Lj} \cos(\varphi) = 3V_L I_L cos(\varphi) \quad (5)$$

$$P_{in} = \sum_{\forall j} V_{1j} I_{Lj} \cos(\varphi - \alpha + \delta_j) \quad (6)$$

where j = a, b, c, and V1 and VL are the fault supply voltage vector and restored load voltage vector, respectively. δj is the phase angle shift..

Assuming a balance load (I_{Lj} = I_L), fault supply voltage vector ($V_{1j}=V_1$) and a balance output voltage ($V_{Lj} = V_L$) the DVR active power is as follows.

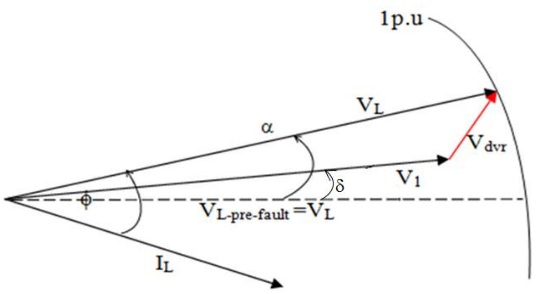

Figure 5. Phase shift compensation technique

Ref [8] shows that during the long or deep sag, the DC voltage decays due to the injection of the active power into the source for pre-sag compensation technique, in-phase compensation technique and phase shift compensation technique.

D. *Voltage Tolerance Method*

This method controls phase angle and magnitude on the tolerance area of the load with small change of voltage magnitude as 90%-110% of nominal voltage and variation is known as 5-10% from normal state [1]. Fig 6 shows the concept of voltage tolerance method.

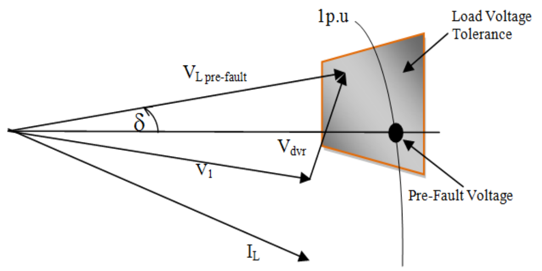

Figure 6. Voltage Tolerance compensation techniques

IV. Conventional Controllers for DVRs

A. *conventional PI controller*

The conventional PI controller is its effectiveness in the control of steady state error of a control system and also its easy implementation. However, one disadvantage of this conventional compensator is its inability to improve the transient response of the system [10]. Most of the PI control is based on multi-loop control due to the dq components of the injected voltage and current. [3]. The conventional PI controller as shown in Fig 7 has the form of

$$U(t) = K_P \varepsilon(t) + K_I \int_T \varepsilon(t) d(t) \quad (7)$$

where U is the control output signal used to PWM generator. K_P and K_I are the proportional and integral gains respectively. These gains depend on the system parameters and ε is the error signal, which is the difference of the injected voltage to the reference voltage.

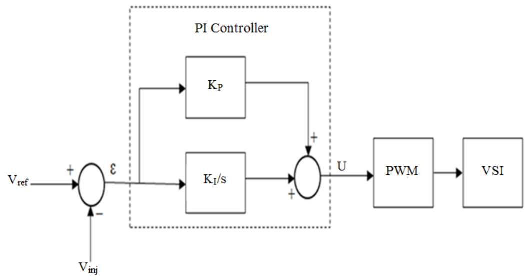

Figure 7. Control of the injected voltage using conventional PI controller

B. FL Control DVR

FL control is conventional control method and important role because knowledge based design rules can easily be implemented in systems with unknown structure, and it is going to be a since the control design strategy is simple and practical [4].

In basic applications, the FL controller is used as a substitute for the conventional PI compensator [10]. FL control is derived from fuzzy set theory introduced by Zadeh in 1965. FL controllers are an attractive choice when precise mathematical formulations are not possible. Other advantages of FL controller are: 1) it can work with less precise inputs: 2) it doesn't need fast processors; 3) it needs less data storage in the form of membership functions and rules than conventional look up table for non-linear controllers; and 4) it is more robust than other non-linear controller [11].

The FL controller provides the state of the switching function. Mamdani's fuzzy inference is the most commonly seen fuzzy methodology. The triangular carrier modulation method is used by deciding the appropriate switching patterns for the converter legs. Thus, the gating of the PWM generator can be correctly decided [11]. The gating signals are generated through a pulse width modulator [12]. Ref [10] proposed the FL control instead of the conventional PI controller to regulate the voltage amplitude at the sensitive load to 98%.

This method has some disadvantages such as the complexity in the implementation of the controller, parameters sensitivity and insufficient compensation under the nonlinear load condition.

V. SIMULATION RESULTS

MATLAB model has been built to simulate the system. It consists of power circuit and control circuit. The power circuit is a DC source and active filter based on 12-switches inverter. The three phase inverter is coupled to the AC system by a three-phase series transformer via low pass filter to eliminate harmonics caused by the switching actions of the inverter. The inverter operates as two 6-pulse inverters with Δ connection to avoid the zero sequences entering into the system from the inverter. The DC terminal of the two inverters is connected together to reduce the rating of DVR and its DC energy storage device. This situation leads to select the DC link voltage as 400V. The DVR is implemented using the FL controller to control the PWM, the load voltage and the response of the PLL which is designed to track the phase change during a fault in every one a cycle and behave as a low pass filter to mitigate the harmonic in the source. The DVR is operated at 11 kV line to line. Result a source voltage of 11kV (rms) is considered with a source impedance of 3ohms, 11kV/0.415kV step down transformer rated 100MVA with 0.2 Pu is used. A 0.9 MVA 1:1 voltage ratio injection transformer along with a filter of inductance 0.25H and shunt capacitance of 40μF implemented.

A FL Controller for DVR

The objective of the FL controller here is to generate and control the PWM. The main parts of the controller are the abc to dq0 transformation, and filter. The dq0 is connected between the Vdc and gain controller to minimize the grid voltage error and to extract the reference voltage for the DVR.

The two continuous vector control algorithm is implemented in the dq-frame and incorporates both current and voltage controller with an inner current control loop and outer voltage control. The current and voltage control are based on two continuous vector controls. The difference between the reference voltage load and the source voltage generate the injected voltage from the DVR. The Park's dqo transformation is shown in [7].

B Comparisons of FL Control of DVR

The FL is proposed instead of conventional PI controller to regulate the PWM of the dynamic voltage restorer. FL control is used to control PWM which generated pulse to control the switches. The control of the PWM can regulate the phase and the magnitude of the injected voltage and can restore the voltage effectively. The PWM that is generated by the FL is presented in Fig 8. As shown in Fig 9, the PLL is tracking the system in every one cycle. The proposed controller can compensate the voltage at 1 p.u during the sag and detect the sag quickly. Furthermore, the quick tracking can control sudden phase angle shift. Fig10 shows the compensated voltage by using FL that is maintained at 99.9%.

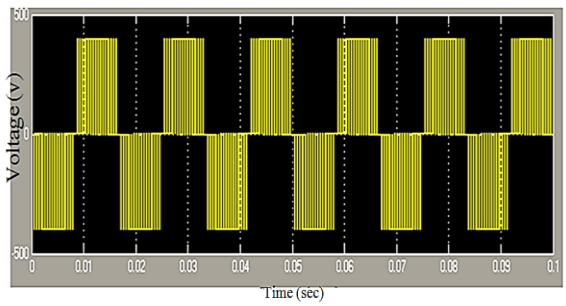

Figure 8. PWM generated by Fuzzy Logic

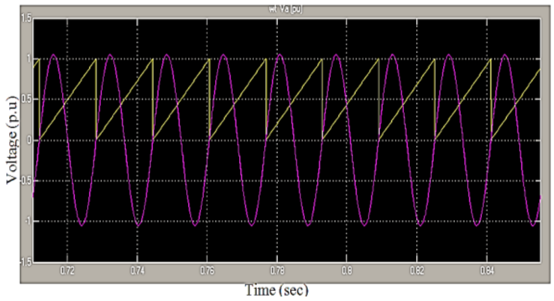

Figure 9. Response of PLL generated by Fuzzy Logic

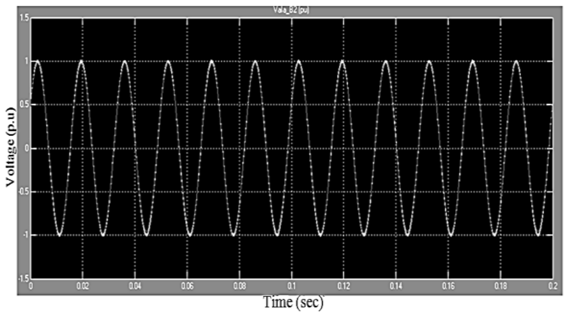

Figure 10. Voltage at the non-linear load with DVR

The controller is designed to compensate the system during the sag even with nonlinear load without harmonic and delay. Fig 11 shows the system during the sag and compensation in the load at the start and end of events.

It can be seen that at time t = 0.05 ms the voltage sag is initiated and the supply voltage is restored 0.15 ms later. At time t =0.2 ms the supply jumps back to the pre-sag condition. The nonlinear load in this design is not affected during the sag and keeps in 0.99 p.u (~1 p.u) and also the figures show that there is no angle shift during the sag. During the sag the system can be detected and compensated with very fast response.

The DVR can sense the sag in the point 0.051 p.u at the time near the 0.05 sec when the sag starts. Also the figures show that the start and the end of compensation voltage is in phase with the source voltage and load voltage respectively. These figures display that the compensation is within 1 ms without any harmonic distortion and phase shift during the sags. The new controller designed can improve the in-phase compensation technique during the nonlinear load when compared to the conventional controller.

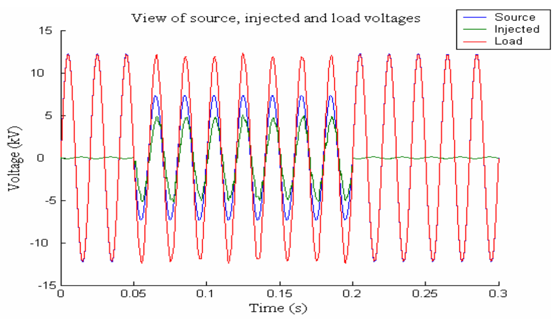

Figure 11. Load voltages (VL) and source voltage (VS) during sag (between 0.05 to2 seconds)

VI. Conclusion

Dynamic voltage restorer is a custom device connected in series to the system to protect the system from the voltage sag, swell and transient.

In this paper, modeling and simulation of a DVR with the control system using MATLAB are presented. The dynamic voltage restorer has been developed as 6-pulses-12-switches inverter connected in parallel to increase the efficiency of the DVR. A Fuzzy Logic Controller with a PWM inverter has been developed to force the injection Voltage to be in-phase with the load voltage and source voltage. The new controller can restore the load voltage up to the 0.99 p.u for nonlinear load.

The simulation results show that the DVR compensates the voltage sag/swell quickly and provides excellent voltage regulation without harmonic distortion. The load voltage has been maintained. Better efficiency is achieved with the proposed control strategies.

The new method optimizes the system by injecting active power during in-phase compensation and tracks the supply voltage continuously by using the two vector control algorithm compared with conventional method. From the results, it can be seen that the two vector controller is effective in tracking the phase, the harmonic and compensates the system within response time (1ms) under various operating condition in case of non-linear load. Finally, the 6-pulses -12-switches inverter and the new controller have given better performance for power quality issues than the conventional method.

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