DVR Control Strategy for Dynamic Power Quality Disturbance Mitigation

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Abstract- The dynamic voltage restorer (DVR) is a series connected device for mitigating voltage sag/This paper presents with feed forward pre-sag/swell voltage control method to regulate the output voltage of pulse width modulated (PWM) voltage source converter (VSC). The proposed controller maintains a constant load voltage under the multiple balanced/unbalanced dynamic PQ disturbances. The proposed DVR control scheme based on park's transformation is a simpler, lower cost. It is able to compensate multiple sag/swell accurately and can achieve fast response under dynamic load conditions. The detail simulation of 440 volts, 50 Hz distribution system has been carried out to evaluate the performance of DVR for the mitigation of multiple voltage sag/swell with the help of Mathworks Matlab/Simulink for both balanced and unbalanced load conditions. The simulation results are presented for various combinations of dynamic PQ problems.

Index Terms- Power Quality, voltage sag, dynamic voltage restorer, voltage source converter, custom power devices, phase looked loop.

I. INTRODUCTION

In the recent years PQ issues have received much more attention. All categories of power consumers are becoming increasingly sensitive to PQ problems. The increasing use of all electronic voltage sensitive devices has made industrial processes susceptible to the sag/swell. The dynamic PQ problems like voltage sag/swell are always occurring in electrical power distribution system. These are caused by switching of large loads, capacitor switching and remote faults. When such PQ disturbances occur, results in damage to all voltage sensitive equipments, the production which results in huge financial loss. The DVR, which is the most efficient and effective modern custom power device, has been used in power distribution networks to mitigate voltage sag / swell [1]. These PQ disturbances are caused by remote faults or switching of large loads (e.g. motor starting and energize capacitor or transformer). Even though the voltage sag/swell lasts within a few cycles, they can disrupt some sensitive loads such as adjustable speed drives (ASD), programmable logic controllers (PLC), and fine industrial process like semiconductor plants. It was observed that for a load up to few MVA, good solution for sag/swell mitigation is the installation of custom power device such as DVR [2]. Applications of DVR are mainly for protecting the sensitive loads that may be considerably affected by fluctuation in distribution voltage. A fast control strategy is desirable to increase the performance of DVR [1], [2]. The control strategy of DVR can be classified into two parts namely detection of voltage sag/swell and injection of the voltage component [3]. The proportional-integral (PI) control scheme is commonly used in conventional control system due to simple algorithm and structure [4]. The synchronous PI decoupling control scheme is adopted as control strategy for driving DVR against voltage disturbances. This control strategy is derived on the basis of the restoration of linearity in control performance using control variables such as inductor currents in the ripple filter and compensating voltages injected through transformer [5]. Nielsen et. al, proposed various system topologies and are verified and compared for checking the DVR performance [6]. The post fault method control strategy for DVR has been presented by Vilathgamuwa and Perera [7]. In this either minimum voltage or minimum energy DVR operation has been achieved based on using phase-locked loop (PLL). Marei et.al, presented minimum voltage control strategy for DVR based on the symmetrical components [8]. A simple DVR was proposed, in which the Fourier Transform (FT) has been applied for the sag detection [9]. The H-bridge multilevel IGBT VSC with closed loop control scheme is used for mitigation of balanced/unbalanced voltage sag only. In this, DVR structure based on a cascaded H-bridge multilevel inverter topology to eliminate the need of insertion transformer has been used [10]. In the work of M. I. Marei et.al, an energy optimized control scheme for a transformer less DVR has been presented [11]. The D.C. link minimum energy injection control method is presented the work of Il-Yop Chung et.al. The DVR is connected in series with the load and it is a direct voltage control method. The shunt connected compensators are indirect controller in which line current is controlled. Hence DVR is an effective compensator for dynamic PQ disturbances [12]. The design and analysis of the inverter- side filter used for DVR has been presented in the work of S. S. Choi et.al [13]. C. Zang et. al work presents a three dimensional voltage space vector PWM algorithm to analyze the four-wire DVR[14]. Minimum power operation of DVR and its new cascade converter control technique have been presented in [15], [16]. The techniques of the supply voltage compensation with minimum energy are presented in the work of M.R. Banaei et.al [17].

This paper presents a result of proposed controller which is designed for compensating multiple voltage sag/swell. The proposed controller causes DVR to reacts quickly to maintain constant load voltage both for a balanced and unbalanced multiple sag/swell conditions in the distribution systems. One of the main advantages of DVR is that it inject (absorb) energy during sag (swell) to maintain load voltage constant. The DVR, which is a series compensator, protects a sensitive load from the distortion and unbalance in the supply side voltage.

II. DVR: A BRIEF REVIEW

The concept of custom Power was introduced by N.G. Hingorani in 1995. Like Flexible AC Transmission Systems (FACTS) for a power transmissions system, the term custom power uses power electronics controllers in a distribution system, especially, to deal with various power quality problems [2]. The power electronic controllers that are used in the custom power solution can be a network reconfiguring type or a compensating type. The network reconfigurating devices are usually called switchgears which include current limiting, current breaking and current transferring devices. The compensating devices are used to compensate load power factor, unbalance conditions or to improve the power quality of supplied voltage. These devices are either connected in shunt or in series or a combination of both. This class of devices includes the distribution static compensator (D-STATCOM), DVR, and unified power quality conditioner (UPQC)[2]. DVR is 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 [2]. It is normally installed in a distribution system between the supply and the sensitive loads connected at the point of common coupling (PCC).

A. Basic Configuration of DVR

The schematic diagram of DVR system is shown in “Fig.1”,. The DVR has mainly two parts, a) Power circuit b) Control circuit and PI controllers. Power circuit consists of voltage source converter (VSC), series connected injection transformer, passive filter and energy storage device. In DVR, control circuit is used to derive the parameters like magnitude, frequency and phase shift of the control signal that has to be injected through DVR. As per this control signal, an injected voltage is generated by the power circuit. The DVR corrects voltage sags/ swells for both balanced and unbalanced conditions to maintain the load voltage to sensitive loads within acceptable tolerances. The DVR is designed to mitigate voltage sags /swells of a various magnitude for various durations. As the connection of transformer in distribution network is of delta-star type, zero sequence voltage will not propagate through transformer; hence only restoration of positive sequence and compensation of negative sequence voltage is required [14]. The VSC utilizes insulated gate bipolar transistors (IGBTs). It is supplied from an energy source, and provides compensated AC voltage with the help of PWM modulator. A passive filter is used to suppress the switching harmonics and corrects the shape of voltage to be injected. Connection of DVR with the distribution line is made through an injection transformer that is connected in series with the line. The three single phase injection transformer is used to inject the missing voltage at the PCC. The D.C. link capacitor and energy storage battery injects or absorbs the required power to compensate the identified voltage sag/swell. An equivalent circuit diagram of the DVR and the principle of series injection for sag/swell compensation are shown in “Fig. 2”,.

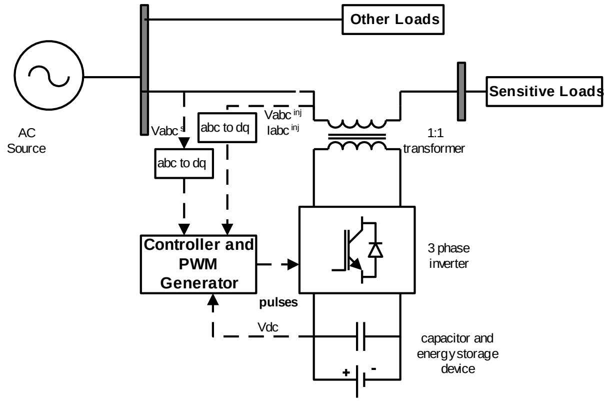

Figure 1. Schematic diagram of DVR System.

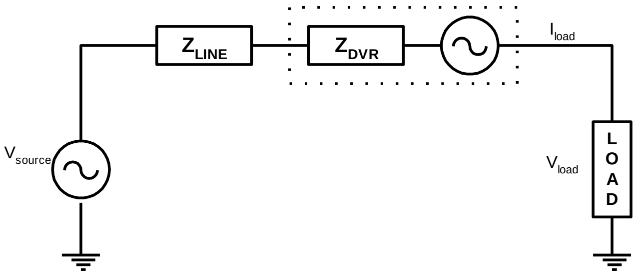

Figure 2. DVR equivalent circuit

The injected voltage by DVR is mathematically expressed by the following equation

$$V_{Inj(DVR)} = V_L + Z_L . I_L - V_s \quad (1)$$

Where,

V_L is the load voltage, V_s is supply voltage during sag and $V_{inj(DVR)}$ is the voltage injected by DVR. Under normal voltage conditions, the load current can be written using the following equation

$$I_L = \frac{S_L}{V_L} = \frac{\left(P_L - jQ_L\right)}{V_L} \tag{2}$$

Where, I_L is the load current, and P_L, and Q_L are the active and reactive power taken by the load respectively during a sag/swell. When DVR inject voltage, then the complex power is given by the following expression

$$S_L = (S_s + S_{Inj}) \tag{3}$$

And the load current can be given by the following equation

$$I_L = \left\lfloor \left(P_s - jQ_s\right) + \left(P_{Inj} - jQ_{Inj}\right)\right\rfloor / V_L \tag{4}$$

The vector diagram of the pre-sag voltage compensation is shown in “Fig. 3”,. It shows the supply voltage vector during the pre-sag stage. The rotating phase angle (RPA) θ_t is obtained from the phase locked-loop (PLL). This method is used to track the supply voltage continuously and it can compensate load voltage during sag to pre-sag conditions.

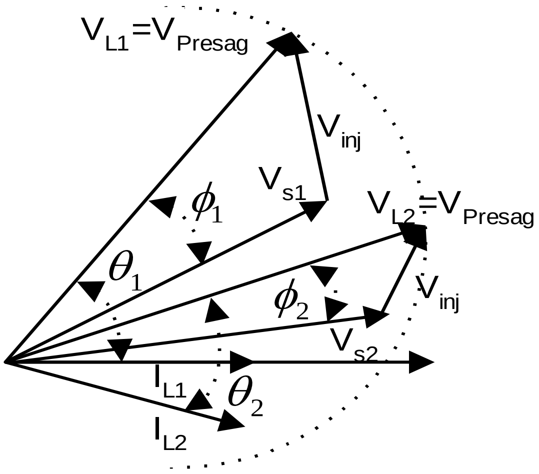

Figure 3. Compensation strategy of DVR for voltage sags.

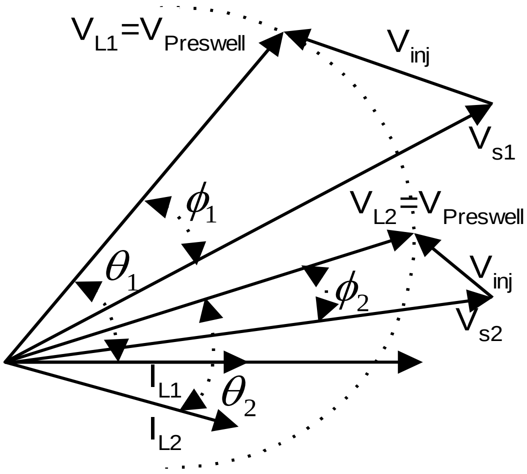

Figure 4. Compensation strategy of DVR for voltage swells.

The phasor diagram of pre-swell voltage compensation for different magnitude of swell is shown in “Fig”, 4.

From the vector diagram, injected voltage magnitude by the DVR for sag and swell compensation is given by the equations (5) and (6) respectively.

$$V_{inj} = \sqrt{V_L^2 - V_S^2 - 2V_L V_S \cos\theta_t} \tag{5}$$

$$V_{inj} = \sqrt{V_S^2 - V_L^2 - 2V_L V_S \cos\theta}_t \tag{6}$$

In this mitigation method, load voltage can be compensated ideally but the injected active power cannot be controlled and is determined by external load conditions.

III. DVR CONTROL STRATEGY

In order to mitigate the multiple voltage sag/swell, the PWM-based control scheme is implemented. This control system only measures the RMS voltage at supply side or load side and no reactive power tracking is required. The open-loop feed forward pre-sag/swell voltage control method is used to restore the load voltage. A 440 volts distribution system is simulated using Mathworks Matlab/Simulink. The discrete proportional plus- integral (DPI) controller has been used in this open-loop feed forward control system to regulate output voltage of the PWM inverter. The measured voltages are given to the input of regulator unit which perform the function of $abc - dqo$ and $dqo - abc$ transform. The regulator also consists of discrete phased locked loop (DPLL), discrete proportional and integral controller (DPI). The DPLL is particularly used to detect amplitude and phase of +ve sequence components of the three phase source voltages. The DPLL must work satisfactorily under abnormal conditions in the power systems such as unbalanced voltage sags/ swells and frequency variations. The response time of the controller is also an important factor. The controller parameters (K_p) and (K_i) are selected properly to fulfill this condition. The DPI controls this variable and the output of this DPI is the supply frequency. The DPI calculates source voltage angle by integrating the source frequency. When the measured supply voltages differ from the reference voltages (kept at 1p.u. constant value) then it gives signal to control unit to trigger the PWM controller for compensating supply voltage. The sag/swell is detected by measuring the error between dqo voltage of the supply voltage and the reference voltage. The d-component is set at rated value and q-component at zero. The park's transformation ($abc-dqo$) has been used to convert stationary frame to rotating frame which can detect the phase angle and magnitude of supply voltages [2], [4]. This transformation method gives the voltage sag/swell depth (direct axis) and phase shift (quadrature axis) information with start and end time. The difference between reference and supply voltages is applied to PWM controlled VSC for injecting proper voltages in series with line by converting again this $dqo-abc$ frame. These quantities are expressed as an instantaneous space vectors and zero sequence component is ignored for simplicity. The park's transformation method is based on error between supply voltage events and reference voltage. This error is used as a modification signal that allows generating a communication pattern for the self commutating IGBT'S VSC. The commutation pattern is generated by using the sinusoidal PWM techniques to control VSC. The DPLL is synchronized with supply voltages to provide the synchronous reference required by the $abc-dqo$ transformation. The control strategy for DVR is shown in "Fig.5",.

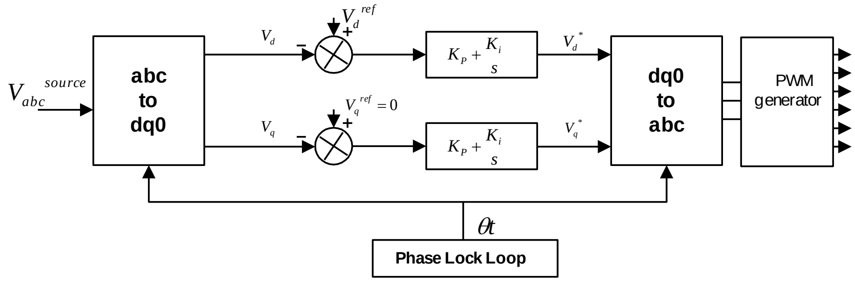

Figure 5. Control scheme for PWM inverter

The PWM inverter can effectively reduce the output voltage distortion and achieve fast dynamic response [7]. As DPI is used in the proposed controller, its sampling frequency can be given by the following relations [11], [12].

$F_s = 1/T_s$, where T_s is the sampling time.

In order to remove errors in non-linearity, noise in the measurements, the DPI is proposed in the controller. The proportional (K_p) and integral (K_i) voltage controller gain can be calculated using the following relations [17].

$K_p = C_f / T_s$, $K_i = K_i . T_s / T_i$, where C_f is the LC filter capacitance.

The DPI controller is a controller which drives IGBT inverter based on difference between the output and the desired set point and the integral of that errors are determined. The main aim of controller is to keep voltage at PCC constant. Hence voltage injected by the DVR is given by the following equation [12], [17].

$$V_{DVR}^{dq} = V_L^{dq} - V_{Synchronous}^{dq} \tag{7}$$

Where $V_{Synchronous}^{dq}$ is synchronous reference frame supply voltage, V_L^{dq} is load reference voltage and V_{DVR}^{dq} is missing voltage injected through series connected transformer by the DVR.

The RPA θ_t obtained from the PLL is provided to the PWM generator to generate desired firing sequences. The firing pulses for VSC have to be synchronized to the supply/load voltage. Under non-disturbance steady state condition, the voltage injected by VSC leads the supply/load voltage by the control angle α . This synchronization is achieved by a PLL whose output is the phase angle of the bus /supply voltage. The RPA θ_t obtained from the PLL and voltage reference from the synchronous frame is compared with the instantaneous voltages of the utility to obtain PWM controlled signal. The output of the regulator represents the modulating signal that drives the PWM inverter. The proposed control system measures supply voltage and no reactive power measurement is required. The VSC switching strategy is based on a sinusoidal PWM technique which offers good response and simple to understand. This PWM technique is an efficient one, because high switching frequencies can be used to improve the efficiency of the converter without incurring significant switching losses. The sinusoidal voltage is phase modulated by means of RPA θ_t and are represented by the following equations

$$V_a = Sin(\omega_0 t + \theta) \tag{8}$$

$$V_b = Sin(\omega_0 t + \theta - 2\pi/3) \tag{9}$$

$$V_c = Sin(\omega_0 t + \theta + 2\pi/3) \tag{10}$$

In this $\omega_0 t$ is the supply frequency in radians/sec. This control strategy converts the voltage from abc synchronous frame to dqo rotating reference frame in which zero phase sequence component is ignored for simplicity. The dqo rotating reference quantities are represented by the following equations

$$V_0 = 1/3(V_a + V_b + V_c) = 0 \tag{11}$$

$$V_d = 2/3[(V_a \sin\theta + V_b \sin(\theta - 2\pi/3 + V_c \sin(\theta + 2\pi/3)] \qquad 12)$$

$$V_q = 2/3[(V_a \sin\theta + V_b \sin(\theta + 2\pi/3) + V_c \sin(\theta - 2\pi/3)] \tag{13}$$

Converting balanced three phase voltages V_a, V_b and V_c, two constant voltages V_d and V_q are obtained and controlled by DPI controller. The voltages at PCC can be obtained using the following equation

$$V_{PCC}(d,q) = \sqrt{3/2}V \begin{pmatrix} \sin(\theta_t) \\ -\cos(\theta_t) \end{pmatrix} \tag{14}$$

Where $\theta_t = \omega_0 t + \Delta\theta = \omega_0 t + (\theta_s - \theta_d)$

In this $\Delta\theta$ is the rotating phase angle of the base voltage which is difference between the supply voltage and direct axis rotating phase angle. The main parameters of the sinusoidal PWM scheme are the amplitude modulation index (m) of the signal, and the frequency modulation index of the triangular signal. By setting the modulation index (m), constant, the output voltage V_d is controlled by PWM controller. The amplitude index is kept fixed at 1p.u. in order to obtain the highest fundamental voltage component V_d at the VSC output.

IV. SIMULATION RESULTS

A 440V, 50Hz, power distribution system configuration is simulated using Mathworks Matlab/Simulink to study the effectiveness and response of suggested DVR control strategy under different supply disturbances. The experimental power distribution system parameters and other constant values are listed in Table 1. A DVR is connected to the system through a series transformer with a transformation turns ratio equal to 1:1. The DVR operation is based on three phase voltage PWM inverter with LC output filter to remove high frequency voltage components. An inductive nature *R-L* load (*R* =200Ω, *L* =1microh) is considered. The simulation results for the both balanced and unbalanced cases of sags/swells are shown below.

TABLE I.
EXPERIMENTAL SYSTEM PARAMETERS FOR SIMULATIONS

Parameters	**Designed Values**
Supply Voltage(Vs)	440V
Supply frequency(F)	50Hz
Load Resistance (R)	200 ohm
Load inductance (L)	1microhenery
Filter inductance (LF)	2microhenery
Filter Capacitance(LF)	300microfarad
Proportional Gain(Kp)	0.4
Integral Gain(Ki)	500
Sampling Time(Ts)	2microsec.
Carrier frequency(KHz)	2KHz
DC link voltage(V)	250V
Circuit breaker resistance (R)	0.001ohm
Series Transformer Turns Ratio	1:1

A. Balanced Multiple Voltage sag

The “Fig.6”, shows response of DVR for a balanced multiple voltage sag. In this, 40% and 20% multiple voltage sags are initiated at 0.05s and 0.25sec respectively. It can be seen, from the results, that the DVR is able to produce the required compensating voltage components for different phases rapidly and help to maintain a balanced and constant load voltage (The load voltage is always kept at 440 volts RMS value.). In the case of voltage sag, which is a condition of a temporary reduction in supply voltage, the DVR injects an equal positive voltage component in all three phases, which are in phase with the supply voltage to correct it. For unbalanced conditions, the DVR injects an appropriate unbalanced three-phase voltage components positive or negative depending on whether the condition is an unbalanced voltage sag or unbalanced voltage swell.

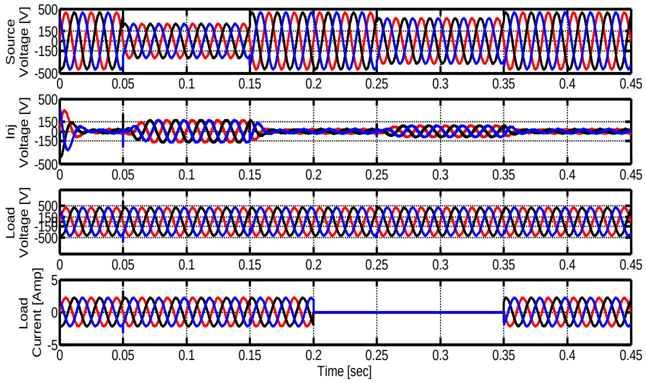

Figure 6. Simulation result of DVR response to balanced multiple voltage sags (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

B Unbalabced Multiple Voltage Sag

The simulation results of DVR response to the unbalanced multiple voltage sag is shown in “Fig.7”,. Only in R phase of three phase voltages ‘40% and 20% sag is created for a durations of 0.1seconds for a different time periods. As in the balanced voltage sag, the proposed control method drives the DVR to compensate for unbalanced voltage sags. During load rejection also the DVR is able to quickly injecting the required unbalanced voltage component to maintain load voltage at it nominal value.

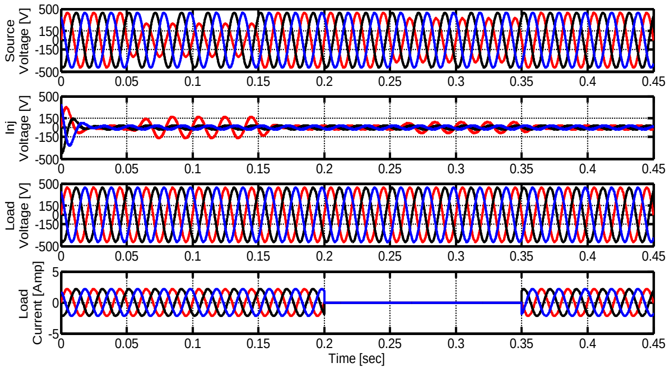

Figure 7. Simulation result of DVR response to an unbalanced multiple voltage sags (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

C Balanced Multiple Voltage Swell

“Fig.8”, gives simulation results of DVR response for a balanced multiple voltage swell. In this simulation balanced multiple voltage swell is created i.e. 60% and 30% for duration of 0.1 second. For a multiple voltage swell case, which is a condition of a temporary increase in supply voltage, the DVR injects an equal negative voltage in all three phases. This injected voltage is always in anti-phase (180 degree opposite) with the supply voltage. During multiple swells also, DVR reacts quickly and maintains voltages at PCC constant.

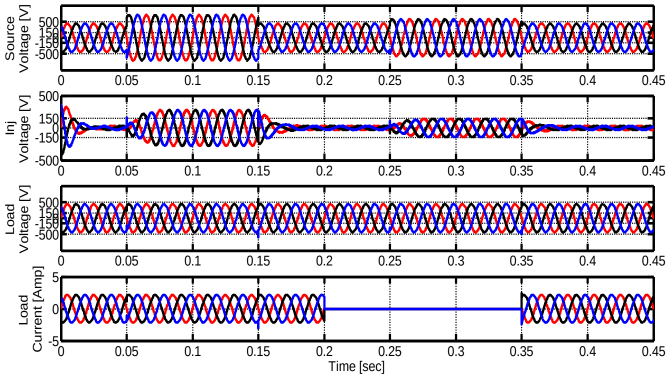

Figure 8. Simulation result of DVR response to balanced multiple voltage swell (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

D Unbalanced Multiple Voltage Swell

“Fig.9”, gives **s**imulation results of DVR response to the unbalanced multiple voltage swell. In this simulation, 60% and 30% unbalanced swell is initiated at 0.05 second and at 0.25second respectively in R phase only. In this type of PQ disturbances also, proposed control method drive DVR effectively and is able to compensate load voltage correctly.

E Balanced Multiple Voltage Sags/Swells

“Fig.10”, gives **s**imulation results of DVR response to the balanced multiple voltage sag/swell. In this simulation 40% sag is generated for a 0.05 second durations and multiple swells are generated (i.e.30% and 40%) during 0.15second to 0.2second and from 0.25second to 0.35second. In this case also, proposed DVR mitigate these PQ disturbances effectively.

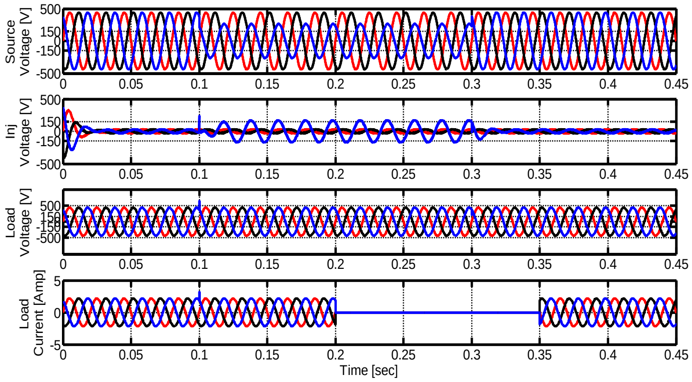

Figure 9. Simulation results of DVR response to unbalanced multiple voltage swell (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

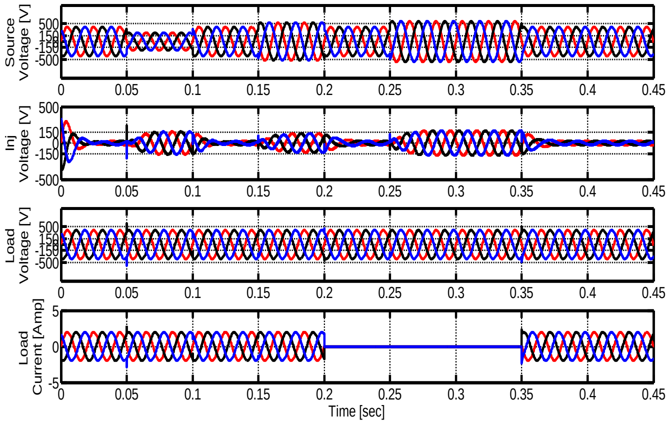

Figure 10. Simulation results of DVR response to balanced multiple voltage sag/swell (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

F Unbalanced Multiple Voltage Sag/Swell

“Fig.11”, gives **s**imulation results of DVR response to the unbalanced multiple voltage sag/swell in one phase of three phase systems. In this case 40% and 20% sag is initiated in phase R at 0.05 second and 0.25second respectively. In Y phase of the same system, 40% and 20% swell is initiated during the same durations. The DVR react quickly for this PQ disturbance also.

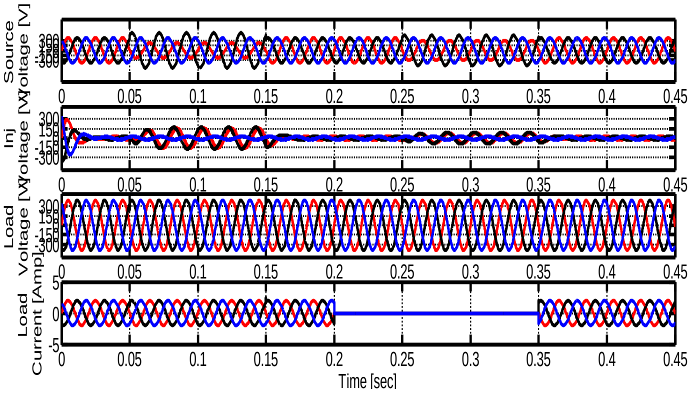

Figure 11. Simulation results of DVR response to unbalanced multiple voltage sag/swell (a) supply voltage, (b) DVR injected voltage, (c) load voltage,(d) load current.

V. PERFORMANCE COMPARISION OF PROPOSED DVR

In Wang et.al. work [10], H-bridge multilevel IGBT VSC is used. For detection of sag/swell, $abc-dqo$ rotating frame parks transformation has been used. The controller based on closed loop control scheme is used for mitigation of balanced/unbalanced sag only. It is particularly suitable for high power applications. In the proposed DVR control strategy, six pulse, three legs IGBT ,VSC is used. The feed forward open loop voltage control method is used for mitigation of multiple balanced as well as unbalanced sag/swell magnitude. It is simple and fast except. In the proposed method even though open loop feed forward method is used, it can mitigate balanced and unbalanced multiple voltage sag/swell for various combinations. The DVR response time of the proposed control strategy is less than one cycle (>2msec). Before application of DVR, the simulated load current total harmonic distortion (THD) was in the range of 12 to 14% in all phases for balanced/unbalanced three phase load conditions. After compensation using DVR, the current THD has been reduced in the range of 3.2% to 4.4% and the voltage THD reduces from 2.1% to 1.2%.

VI. CONCLUSIONS

The modeling and simulation of proposed DVR in mitigating multiple voltage sags/swells is presented. A controller based on a feed-foreword technique is used to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. The presented controller strategy uses the d-q-0 rotating reference frame i.e parks transformation, as it offers higher accuracy as compared to other techniques. In the case of voltage sag/swells, the DVR injects an equal positive/negative voltage component in all three phases to compensate for the supply system. It is also observed that if the sag on one phase results in a swell on another phase, such PQ disturbances in the distribution system is also compensated effectively by the proposed control strategy .

REFERENCES

[1] A. Ghosh,and G. Ledwich, *“Power Quality Enhancement using Custom Power Devices.”* Kluwer Academic Publishers, United States America(USA), 2002.

[2] N. G. Hingorani,“Introducing Custom Power.” *IEEE Spectrum*,vol. 32, no.6, pp. 41-48, 1995.

[3] D. M. Vilathgamuwa, A. A. D. R. Perera, and S. S. Choi, “Performance improvement of the dynamic voltage restorer with closed-loop load voltage and current mode control,” *IEEE Trans. On Power Electronics,* vol.17, pp. 824-834, 2002.

[4] A. Ghosh, A. K. Jindal and A. Joshi, “Inverter control using output feedback for power compensating devices,” ,*Conference on Convergent Technologies for Asia-Pacific Region(TENCON 2003),* pp.48-52, 2003.

[5] H. Awad, J. Svensson and M. H. Bollen, “Static series compensator for voltage dips mitigation,” *IEEE Bologna PowerTech Conf, Bologna,* 2003.

[6] J. G. Nielsen, F. Blaabjerg, “A detailed comparison of system topologies for dynamic voltage restorers,”*IEEE Trans. Industrial Appllication,* vol.41, pp. 1272-1280, 2005.

[7] D. M. Vilathgamuwa, A. A. D. R. Perera, S. S. Choi,“Voltage sag compensation with energy optimized dynamic voltage restorer*,” IEEE Trans. Power Delivery,* vol. 18 ,pp. 928-936, 2003.

[8] M. I. Marei, E. F. El-Saadany, M. M. A. Salama, “A new approach to control DVR based on symmetrical components estimation,” *IEEE Trans. Power Delivery*,vol. 22, pp. 2017-2024, 2007.

[9] I. Tarek, E. F. EI-Shennawy, A. -M. Moussa and M. A. EI-Gammal, “A Dynamic Voltage Restorer for Voltage Sag Mitigation in a Refinery with Induction Motors Loads,”*American J. of Engineering and Applied Sciences* ,vol.3, no.1, pp. 144-151, 2010.

[10] N. H. Woodley, L. Morgan, and A. Sundaram, “Experience with an inverter-based dynamic voltage restorer, *IEEE Trans. Power Delivery,* vol. 14, no. 3, p. 1181, Aug. 1999.

[11] Electric Power Systems Research**,** vol. 83, pp. 110-118, 2012.. Marei, Ayman B. Eltantawy and Ahmed EI-Sattar, J Pedra, “An energy optimized control scheme for a transformerless DVR,” *Electric Power Systems Research***,** vol. 83, pp. 110-118, 2012.

[12] Il-Yop Chung, Dong-Jun Won, Sang-Yong Park, Seung-II Moon and Jong-Keun Park, “The DC link energy control method in dynamic voltage restorer system,” *Electric Power Systems Research***,** vol. 25, pp. 525-531, 2003.

[13] S. S. Choi, D. M. Vilathgamuwa, and B.H. Li, “Design and analysis of the inverter- side filter used in the dynamic voltage restorer,” *IEEE Trans. On Power Delivery,* vol.17, no.3, 2002.

[14] C. Zhan, A. Arulampalam, N. Jenkins,“Four-wire dynamic voltage restorer based on a three dimensional voltage space vector PWM algorithm,” *IEEE Trans. On Power Electronics*, vol.18, no.4, 2003.

[15] H. K. Al-Hadidi, A. M. Gole, D. A. Jacobson, “A novel configuration for a cascade inverter-based dynamic voltage restorer with reduced energy storage requirements, ” *IEEE Trans. On Power Delivery*, vol.23, pp. 881-888, 2008.

[16] H. K. Al-Hadidi, A. M. Gole, D. A. Jacobson, “Minimum power operation of cascade inverter-based dynamic voltage restorer, ” *IEEE Trans. On Power Delivery*, vol.23, pp. 889-898, 2008.

[17] M. R. Banaei, S. H. Hosseini, S. Khanmohamadi, G. B. Gharehpetian, “Verfication of a new control strategy for dynamic voltage restorer by simulation,” *Simulation Modelling Practice and Theory*, vol. 14, pp. 112-125, 2006.

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