SIMULATION AND MODELING OF A DYNAMIC VOLTAGE RESTORER

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ABSTRACT

This paper presents modeling and analysis of a Dynamic Voltage Restorer (DVR) with sinusoidal pulse width modulation (SPWM) based controller by using the Matlab / Simulink. The proposed control scheme is simple to design and allows flexibility in cost or robustness constraints. In addition, the performance of the designed DVR is examined under different sag conditions.

I. INTRODUCTION

The voltage generated by power stations has a sinusoidal waveform with a constant frequency. Any disturbances to voltage waveform can result in problems related with the operation of electrical and electronic devices. Users need constant sine wave shape, constant frequency and symmetrical voltage with a constant rms value to continue the production. This increasing interest to improve overall efficiency and eliminate variations in the industry have resulted more complex instruments that are sensitive to voltage disturbances.

The typical power quality disturbances are voltage sags, voltage swells, interruptions, phase shifts, harmonics and transients. Among the disturbances, voltage sag is considered the most severe since the sensitive loads are very susceptible to temporary changes in the voltage. Voltage sag (dip) is a short duration reduction in voltage magnitude between 10% to 90% compared to nominal voltage from half a cycle to a few seconds [4].

The characterization of voltage sags is related with the magnitude of remaining voltage during sag and duration of sag [5]. The magnitude has more influence than the duration on the system. Voltage sags are generally within 40% of the nominal voltage in industry. They can cause damaged product, lost production, restarting expenses and danger of breakdown. Motor starting, transformer energizing, earth faults and short circuit faults will cause short duration increase in current and this will cause voltage sags on the line.

The wide area solution is required to mitigate voltage sags and improve power quality. One new approach is using a DVR [1]-[8]. The basic operation principle is detecting the voltage sag and injecting the missing voltage in series to the bus as shown in Fig.1. DVR has become a cost effective solution for the protection of sensitive loads from voltage sags. Unlike UPS, the DVR is specifically designed for large loads ranging from a few MVA up to 50MVA or higher [5]. The DVR is fast, flexible and efficient solution to voltage sag problems. DVR consists of energy storage unit, PWM inverter, filter and injection transformer as shown in Fig.1, [4], [8].

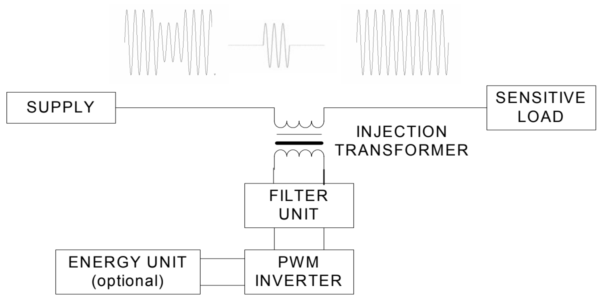

Fig. 1. Typical application of DVR and its output

DVR is connected in the utility primary distribution feeder [2]. This location of DVR mitigates the certain group of customer by faults on the adjacent feeder as shown in Fig.2. The point of common coupling (PCC) feds the load and the fault. The voltage sag in the system is calculated by using voltage divider rule [3].

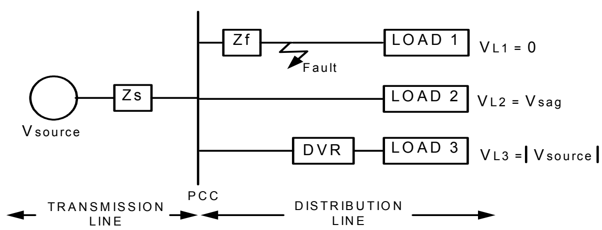

Fig. 2. Location of DVR

II. SELECTION OF DVR COMPONENTS

The main components of DVR are energy storage unit, voltage source inverter circuit, and filter unit and series injection transformers as shown in Fig.1.

Energy Storage Unit: The required energy can be taken from an auxiliary supply (topologies with energy storage) or grid itself (topologies with no energy storage) for compensation of load voltage during sag [8]. The auxiliary supply method is applied to increase the performance when the grid of DVR is weak. In this type, variable DC link voltage or constant DC link voltage topologies are applied. In second topology, the remaining voltage on supply side or load side is used to supply necessary power to the system if the DVR is connected to the strong grid. In load side connected topology, the DC link voltage is almost constant because it is always fed from corrected constant load voltage [4], [6], [8].

If the topologies are analyzed deeply by using some criterions like complexity, cost, drawbacks and performance, they can be arranged in order: 1- Load Side Connected Converter 2- Constant DC Link Voltage 3- Variable DC Link Voltage 4- Supply Side Connected Converter. The load side connected converter topology is selected for this study.

Inverter Circuit: The variable output voltage of the inverter is achieved by voltage source inverter (VSI). Solid-state semiconductor devices with turn off capability are used in inverter circuits. A VSI is energized by a stiff DC voltage supply of low impedance at the input. The output voltage is independent of load current. In VSIs, the values of output voltage variations are relatively low due to capacitor [5]. It is difficult to limit current because of the capacitor. The three phase Pulse Width Modulation (PWM) VSI is most popular and common inverter type and it will be used in this study [4]. The voltage control is achieved by modulating the output voltage waveform within the inverter.

Filter Unit: The nonlinear characteristics of semiconductor devices cause distorted waveforms associated with harmonics at the inverter output. To overcome this problem and provide high quality energy supply, filter unit is used. The inverter side and line side filtering are basic types of filtering scheme [4], [5], [7].

The inverter side filter is closer to the harmonic source and low voltage side thus it prevents the harmonic currents to penetrate into the series injection transformers [7]. This can cause voltage drop and phase shift in the fundamental component of the inverter output. The line side is closer to high voltage side so higher rating on transformer is needed [5]. The filter voltage drop and phase shift problem don't disturb this system. In both filtering schemes, filter capacitor will cause increased inverter ratings. The increased filter capacitor provides better harmonic attenuation but the rating of the inverter is related with the capacitor value. The inverter side filtering method is preferred in this study.

Series Injection Transformers: The three single-phase injection transformers are used to inject missing voltage to the system. The electrical parameters of series injection transformer should be selected correctly to ensure the maximum reliability and effectiveness [4]. To integrate the injection transformer correctly into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required [5].

III. OPERATION MODES OF DVR

Generally, the DVR is categorized into three-operation mode: protection mode, standby mode (during steady state) and injection mode (during sag).

Protection Mode: The DVR is protected from the over current in the load side due to short circuit on the load or large inrush currents [5]. The bypass switches remove the DVR from system by supplying another path for current as shown in Fig.3.

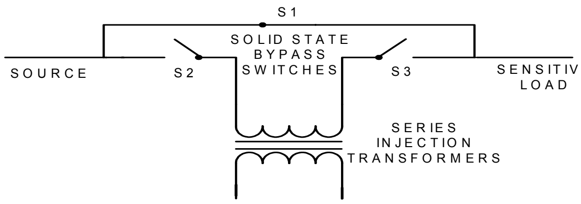

Fig.3. The aspect of power switches

Standby Mode: In standby mode (normal steady state conditions), the DVR may either go into short circuit operation or inject small voltage to compensate the voltage drop on transformer reactance or losses as shown in Fig.4, [5]. Short circuit operation of DVR is generally preferred solution in steady state because the small voltage drops do not disturb the load requirements if the distribution circuit is not weak.

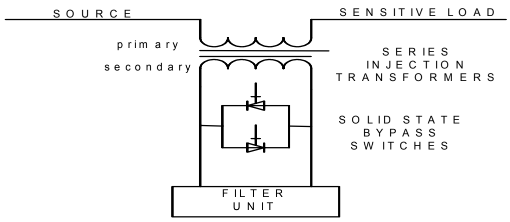

Fig. 4. The view of stand by mode

Injection Mode: The DVR goes into injection mode as soon as the sag is detected [2]. Three single-phase ac voltages are injected in series with required magnitude, phase and wave shape for compensation, [5]. The types of voltage sags, load conditions and power rating of DVR will determine the possibility of compensating voltage sag. The DVR should ensure the unchanged load voltage with minimum energy dissipation for injection due to the high cost of capacitors. The available voltage injection strategies are pre-sag, phase advance, voltage tolerance and in phase method [3].

a) Pre-sag compensation method: This method injects the difference voltage between sag and pre-fault voltages to the system. It is the best solution to obtain the same load voltage as the pre-fault voltage but there is no control on injected active power so high capacity energy storage is required.

b) Phase advance method: The real power spent by DVR is minimized by decreasing the power angle between the sag voltage and load current. The values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage.

c) Voltage tolerance method with minimum energy injection: Generally the voltage magnitude between 90%-110% of nominal voltage and phase angle variation between 5%-10% of normal state do not disturb the operation characteristics of loads. This method can maintain load voltage in the tolerance area with small change of voltage magnitude.

d) In phase voltage injection method: The injected voltage is in phase with supply voltage. As shown in Fig.5 the phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage is satisfied.

$$\left|V_L\right| = \left|V_{Lprefault}\right| \quad (1)$$

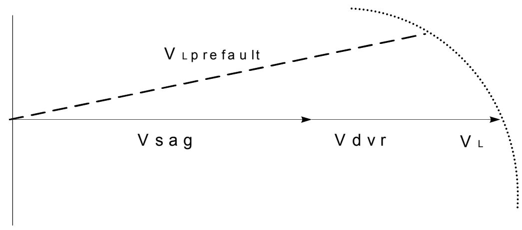

Fig. 5. Vector diagram of in phase method

V_L, V_{sag}, V_{dvr} and $V_{Lprefault}$ represent load voltage vector, remaining voltage vector at PCC, DVR voltage vector (injected) and voltage before sag vector respectively. The rms values of load voltage on the arc are the same (1 p.u) with different phase angles. The method b and c inject smaller active energy than method a and d but the complexity and expenses increases.

IV. MODELING OF DVR

The typical DVR built in Matlab / Simulink program is presented in Fig.6. In this study, the load side connected voltage controlled three leg PWM inverter is used to produce compensating voltage. The model consists of self-commutating IGBT switches with parallel diodes. The sinusoidal pulse width modulation technique (SPWM) forms the control strategy. The control block generates the firing signals for each switch with controllable amplitude, phase and frequency whenever sag is detected. The inverter side filtering is applied to the system because it is closer to harmonic source.

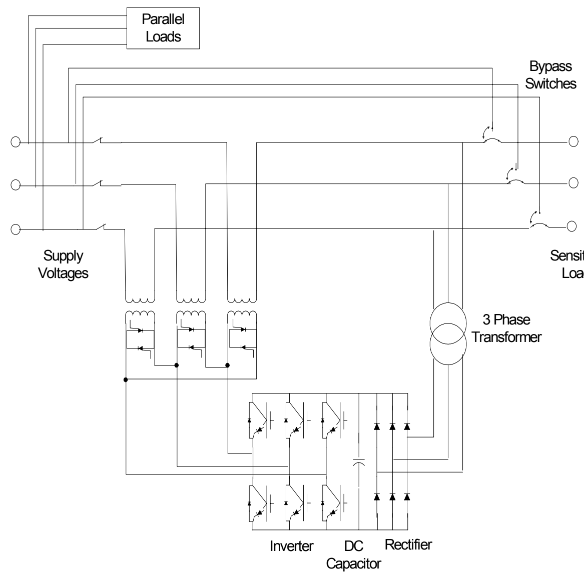

Fig. 6. Configuration of designed system

The main operation principles of DVR can be summarized as shown in Fig. 7

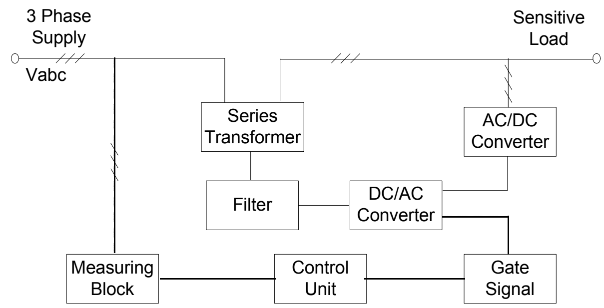

Fig. 7. Function blocks of designed DVR

Direct feed forward type control model is used to minimize the response time and maximize the dynamic performance. Voltage regulation, low harmonic distortions and no interruptions are realized with this type of control architecture.

Using RMS value calculation of the voltages to analyze the sags does not give fast results because at least one half period at the line frequency is required for calculation. In this study reference signal is obtained from the measured parameters by using the Instantaneous Reactive Power Theory method (d-q theory) that is the most popular waveform correction method based on the time domain. [1-2].

The dq method gives the voltage sag depth (d) and phase shift (q) information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from a-b-c reference frame to d-q reference frame. For simplicity zero phase sequence components is ignored.

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) = 0 \qquad (2)$$

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

$$V_q = \frac{2}{3}\left[V_a \cos\omega t + V_b \cos(\omega t - \frac{2\pi}{3}) + V_c \cos(\omega t + \frac{2\pi}{3}) \right] \qquad (4)$$

After conversion, the balanced three-phase voltage Va, Vb and Vc become two constant voltages Vd, Vq. They are easily controlled by PID controller as shown in Fig.8, [6].

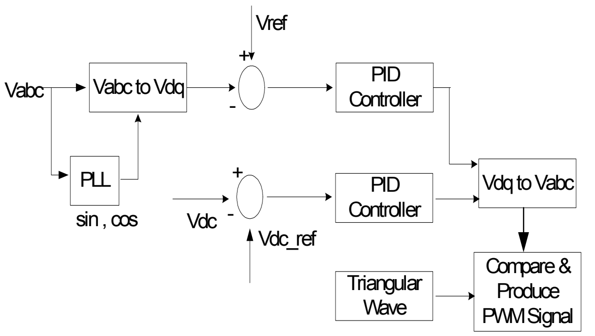

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Fig. 8. Block diagram of Control Unit

The components of the load voltage vectors are compared with the reference values and they are transformed back into Va, Vb and Vc values. The DC link error is used to get optimized controller output signal because the energy on the DC link will be changed during the sag.

The method should not be affected from the harmonics, flickers, frequency variations and unbalanced voltages because the correct detection of the phase of the source voltage is very important for DVR. Using a Phase Locked Loop (PLL) algorithm satisfies these requirements [1-2]. The compensated voltage will be in phase with the pre-sag voltage.

Finally the calculated signal is compared with saw tooth signal at 2 KHz carrier frequency to produce required firing signals for each leg of the PWM inverter that is known as SPWM technique.

V. SIMULATION EXAMPLES

The performance of the designed DVR is evaluated by using the Matlab / Simulink program as a simulation example. The DVR is connected to a 15kVrms, 50Hz distribution system with a load of 15000/380 Vrms, 50kVA, 50Hz, and 0.95 p.f. Maximum single-phase injection capability is %40 of nominal value. The converter type is 3 leg PWM Bridge. The DC link capacitor is 750VDC, 40mF and the injection transformer per phase is 430/3460Vrms, 20kVA, 50Hz.

Fig.10 shows the remaining voltage at PCC, injected voltage and load voltage at 0.4 and 0.2 voltage sags. The first sag occurs between 0.1-0.16 seconds and the second sag occurs between 0.2-0.24 seconds. The sag is mitigated quickly and almost constant load voltage is obtained.

The three phase balanced fault is created by adjacent parallel load1 as shown in Fig.2. The voltage on the faulted phase goes to zero and on the adjacent load2 is V_{sag}. The voltage on load3 is almost the same with pre-fault value and does not affected by sag.

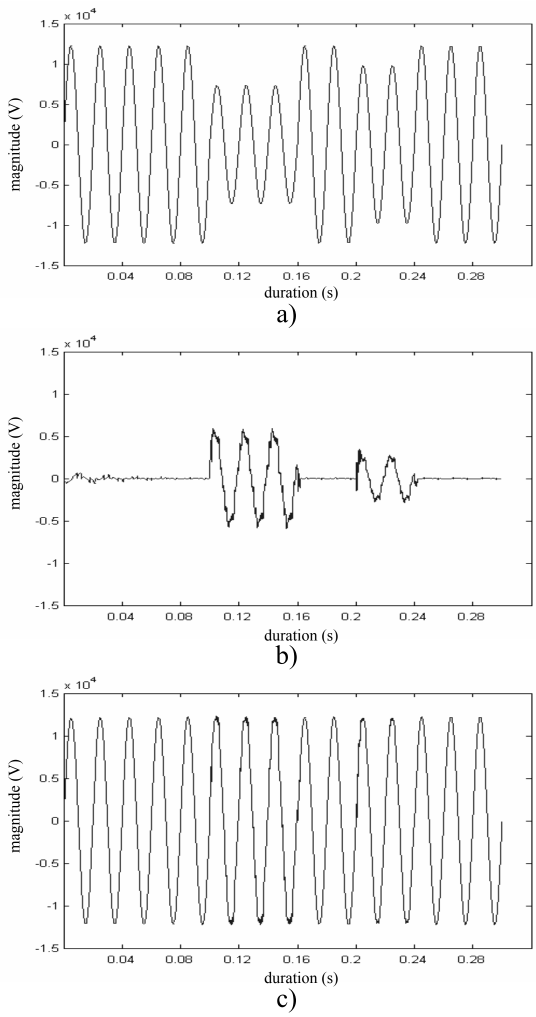


Fig. 10. The remaining (a) injected (b) and load voltage (c) at 0.4 and 0.2 voltage sag

The remaining voltage at PCC is calculated by equation 5. The sag voltage at PCC,

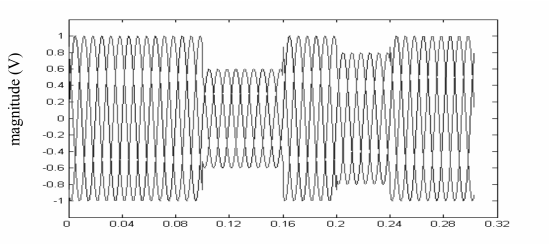
$$V_{sag} = V_{source} \frac{Z_f}{Z_f + Z_s} \quad (5)$$

where Zs is the source impedance and Zf is the fault impedance.

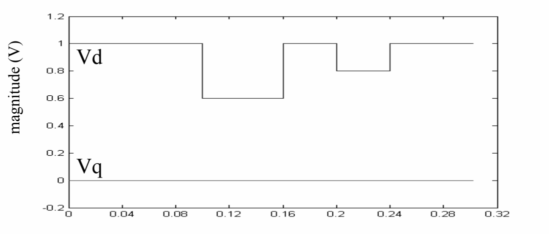
Generally, the systems show the same behavior between 0.95<1<1.05 p.u. voltage values. In this system, the controller is set to recognize the deviations greater than %5 p.u. of nominal value.

In this study, the load side total harmonic distortion is below the standards. The fundamental value of load voltage is almost kept constant thus the continuity of reliable electrical energy is satisfied at load side protected by DVR.

The control unit transforms the source voltage to dq components because source side causes the problem. The d and q values send back the start and end time of sag depth and phase shift. The p.u. values of the source voltage and dq components are shown in Fig. 11.



a)



b)

Fig. 11. The source voltages (a) and extracted dq components (b)

In this simulation study the DC link is fed from load side connected shunt uncontrolled rectifier. In Fig. 12, the magnitude of the DC link decreases during sag because of the voltage drop on the shunt transformer and rectifier switches. By adding the error between set and measured DC link voltage value as another control issue to the control unit, the optimized control is ensured.

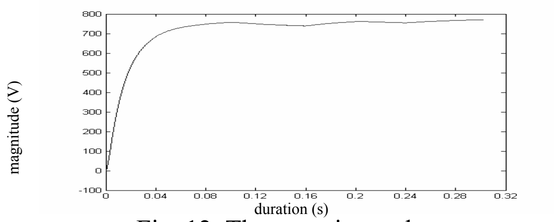


Fig. 12. The capacitor voltage

VI. CONCLUSION

In this study, the modeling and simulation of a DVR with SPWM based controller has been developed by using Matlab/Simulink. The simulation results show that the DVR compensates the sag quickly and provides excellent voltage regulation. The load side connected converter topology has capability of mitigating the long duration voltage sags on the line. The dynamic performance capability of DVR increases the number of sensitive equipments to use in the system.

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