A NOVEL MINIMAL ENERGY CONSUMPTION STRATEGY FOR THE INTER-LINE DYNAMIC VOLTAGE RESTORER

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ABSTRACT

To restore the load voltage, Dynamic Voltage Restorer (DVR), which is installed between the supply and a sensitive load, should inject voltage and active power from DVR to the distribution system during voltage sag. Due to the limit of energy storage capacity of DC link, it is necessary the minimize energy injection from DVR. In this paper the techniques of the supply voltage sag compensation in a distribution feeder are presented. In addition, a concept of inter-line dynamic voltage restorer (IDVR) that two DVRs in two different voltage distribution system are connected to a common DC link capacitor is proposed. One of these two DVR (low voltage) operates in voltage sag compensation mode and a novel control technique uses to inject minimum energy from DC link capacitor to low voltage distribution system. The other DVRs (medium voltage) controls the voltage of DC link capacitor so that energy flows from medium voltage distribution system to the DC link capacitor. Simulation results carried out by PSCAD/EMTDC, verify the efficiency of the proposed method.

I. INTRODUCTION

One of the most important power quality issues is voltage sags. The increasing usage of voltage sensitivity devices has made industrials processes more susceptible to supply voltage sags [1]. Voltage sags may cause equipment tripping, shutdown for the domestic and industrial equipment, and miss-operation of drive systems. When a fault occurs in the system, the customer voltage drops below its nominal value on one or more phases. Voltage sags of down to 70% are much more common than complete outages. Dynamic voltage restorer (DVR) with energy storage can be used to correct the voltage sag at distribution system [2-6]. A DVR is basically a controlled voltage source installed between the supply and a critical and sensitive load. It injects a voltage on the system in order to compensate any disturbance affecting the load voltage. The compensation capacity of a particular DVR depends on the maximum voltage injection ability and the real power, which can be supplied by the DVR. When DVR restorers voltage disturbances, active power or energy should be injected from DVR to the distribution system. DVR could maintain load voltage unchanged during any kind of faults, if the capability of energy storage of DVR were infinite [2]. Energy storage devices, such as batteries or super-conducting magnetic energy storage systems (SMES) are required to provide active power to the load when voltage sags occur. Because of the energy limitations of these devices, it is necessary to minimize energy injection from DVR.

The inter line dynamic voltage restorer (IDVR) similar to the inter line power flow controller (IPFC) in transmission system uses from several DVRs protecting sensitive loads in different distribution systems to share a common DC link energy storage [7]. In the simplest case, we consider two different voltage distribution system protected by two DVR. Low voltage (400 V) DVR operates in voltage sag mitigation mode and uses a new minimal energy control method to inject active power from DC link capacitor for balanced and unbalanced voltage sags. In the same time medium voltage (20 kV) DVR keeps the voltage of DC link capacitor constant in order to control of active power flow from distribution system to DC link capacitor. The simulations carried out by PSCAD/EMTDC [8] show the capability of the proposed technique.

II. DVR IN DISTRIBUTION SYSTEM

Power circuit of a DVR in a distribution system is shown in Fig.1. The main function of a DVR is the protection of sensitive loads from voltage sags coming from network. Therefore, the DVR is located on approach of sensitive loads. If a fault occurs on other feeders, DVR inserts series voltage, V_{dvr} and compensates load voltage to pre fault value. Distribution systems commonly use a delta-star or a star-star transformer. If delta-star transformer is used in distribution system, zero-sequence voltages will not propagate through the transformer when earth faults occur on the higher voltage level. Therefore, restoration of positive sequence and compensation of negative sequence voltage are necessary.

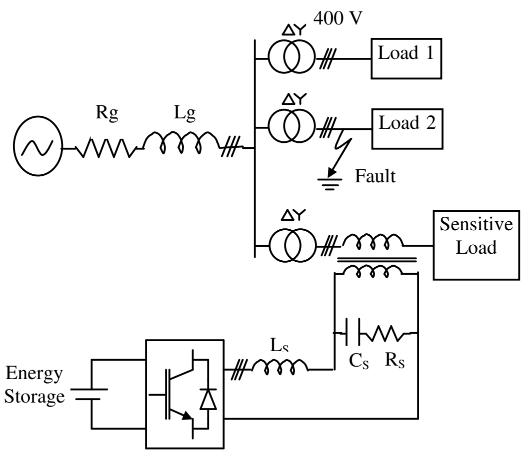


Figure 1. Power circuit of a DVR

The main elements of the three-phase four- wire DVR are the energy storage system, the voltage source converter, the LC filter and the coupling transformers. The AC side of converter is connected to the line through a LC filter. Due to switching, the high order harmonics of converter must be removed by small high pass filters (represented by L_s C_s). The sinusoidal pulse width modulation technique (SPWM) is commonly used to control forced-commutated converters. This method has been used in this paper too.

III. Conventional Control Strategy for DVR1

Several control techniques have been proposed for voltage sag compensation such as pre-sag method [4], in-phase method [4] and minimal energy control [2].

It must be said that the characteristics of the sensitive load determine the control method and the compensation strategy for the DVR. For example, the linear loads are not sensitive to phase angle jump and only magnitude of voltage is dominant. The control techniques should consider the limitations of the DVR such as the voltage injection capability (converter and transformer rating) and energy storage system limitation. The second limitation means that the minimization of exchanged active power from common DC link to the distribution system must be considered.

A. Pre-Sag Compensation Strategy

The most of nonlinear loads such as thyristor-controlled loads, which use the supply voltage angle as a set point, are sensitive to phase jumps. To overcome this problem, this technique compensates the difference between the sagged and the pre-sag voltages by restoring the instantaneous voltages to the same phase and magnitude as the nominal pre-sag voltages. The disadvantage is the capacity limitation of energy storage device for the injection of active power.

Fig. 2 shows the phasor diagram of the pre-sag compensation strategy. In this diagram the subscript i is ith phase, $\boldsymbol{V}_{s1i}$, $\boldsymbol{V}_{L1i}$, $\boldsymbol{V}_{dvr1i}$, $\boldsymbol{I}_{L1i}$, $\Phi_1$and B_i represent the left hand side voltage of DVR1, the load voltage, the DVR1 injected voltage, the load current , load power angle and the phase angle of ith phase respectively.

When a fault occurs in other lines in Fig.1, the left hand side voltage of DVR1, $\boldsymbol{V}_{s1i}$ drops and the DVR1 injects a series voltage, $\boldsymbol{V}_{dvr1i}$ through the injection transformer as:

$$\boldsymbol{V}_{dvr1i}=\boldsymbol{V}_{L1i}-\boldsymbol{V}_{s1i} \quad , \; i=1,2,3 \tag{1}$$

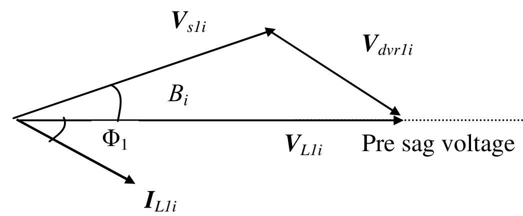


Figure 2. Phasor diagram of pre-sag control

B. In-phase compensation

In this strategy the restored voltage, $\boldsymbol{V}_{dvr1i}$ is in-phase with the left hand side voltage of DVR1, $\boldsymbol{V}_{s1i}$ regardless of the load current and the pre fault voltage. The phasor diagram of this case is shown in Fig.3. The magnitude of $\boldsymbol{V}_{dvr1i}$ is so that the magnitude of $\boldsymbol{V}_{L1i}$ is 1 pu and obtained as:

$$V_{dvr1}=1-V_{s1} \tag{2}$$

The advantage of this method is that magnitude of injected voltage is minimum. Therefore, for a given load current and voltage sag the apparent power of DVR is minimized.

The injected active power from energy storage to load for balanced sag is determined by the following equation,

$$P_{dvr1}=3(V_{L1}-V_{S1}).I_{L1}.\ \mathrm{COS}\ (\Phi_1) \tag{3}$$

C. Minimal Energy Technique

For a given load and balanced sag if voltage phasor, $\boldsymbol{V}_{dvr1}$,is perpendicular to the load current, $\boldsymbol{I}_{L1}$, then the active power injection is not required to restore the voltage by the DVR1 [2]. Fig.4 shows the phasor diagram for the minimal energy control strategy. In this diagram, δ, α are the angle of $\boldsymbol{V}_{L1}$ and $\boldsymbol{V}_{dvr1}$, respectively. In this case, α be obtained as,

$$\alpha=\frac{\pi}{2}-\Phi_1+\delta \tag{4}$$

and the δ is calculated by the following equation,

$$\delta=\Phi_1-cos^{-1}\left(\frac{V_{L1}.cos(\Phi_1)}{V_{s1}}\right) \tag{5}$$

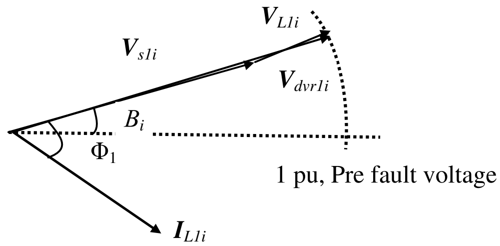


Figure 3. Phasor diagram of In-phase control

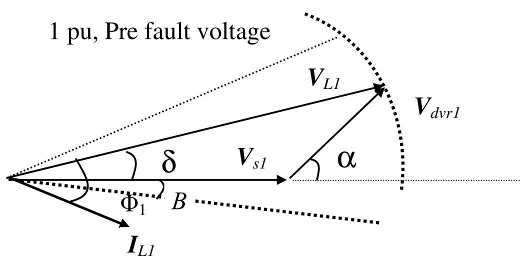


Figure 4. Phasor diagram of Minimal energy control

If the supply voltage parameters satisfy the condition then the value of δ is feasible,

$$V_{L1}.cos(\Phi_1) \leq V_{s1} \qquad (6)$$

Inequality (6) means that the level of voltage sag is shallow sag. Therefore, injected active power of DVR is zero and the optimum α is obtained from (4). If inequality (6) is not satisfied then level of voltage sag will be deep sag and injected real power is not zero.

D. Suggested Control Strategy

As mentioned earlier, for shallow sag injected power, P_{dvr} is zero. However, for deep sag P_{dvr1} is not zero. Considering the Fig.4, for a given load current and $\boldsymbol{V}_{s1}$ increase of δ results increase of $\boldsymbol{V}_{dvr1}$ (i.e., both magnitude and phase angle). The relationship between the injected active power, P_{dvr1}, and the injected voltage $\boldsymbol{V}_{dvr1}$ is illustrated in Fig.5. The parameter of this curve is a balanced three-phase voltage sag, for a given load (with $\cos\Phi_1$=0.8). It is obvious that for a 0.2 pu voltage sag the minimum value of P_{dvr1} can be equal to zero. While, for the shallow sag (less than 0.2 pu) minimum value of P_{dvr1} is negative and for deep sags (more than 0.2 pu) minimum value of P_{dvr1} is positive. In the in-phase compensation strategy the apparent power of DVR is small and injected active power of DVR is considerable. But in the minimal energy technique injected active power is minimum and the apparent power of DVR is considerable.

In this paper, the proposed strategy is the minimization of the injected active power for balanced and unbalanced sag. As an example, Fig.6 presents the relationship between the minimum injected active power, P_{dvr} and the balanced three-phase voltage sag for a DVR1 for a given load (with $\cos\Phi_1$=0.8). It is obvious in Fig.6 that the negative value of minimum injected active power is assumed zero and the positi value of minimum injected active power is estimated as follows:

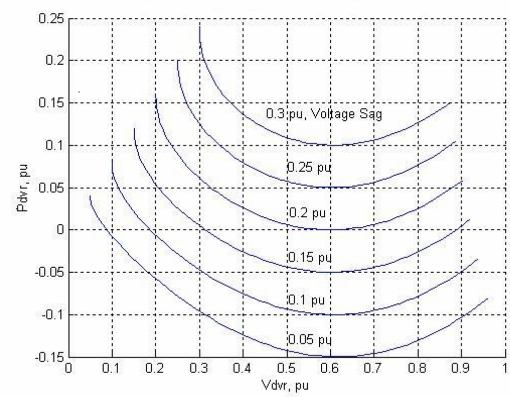


Figure 5. Injected active power vs. injected voltage

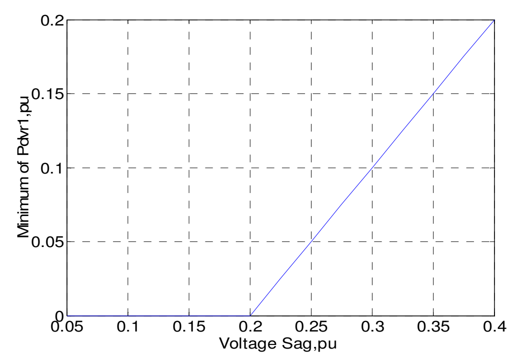


Figure 6. Minimum injected active power vs. voltage sag (apparent power of DVR=0.6 pu)

$$P_{dvr1,pu}=(V_{sag,pu}-0.2) \qquad (7)$$

IV. Inter- Line Dynamic Voltage Restorer (IDVR)

The equivalent circuit on the left hand side of DVR1 shown in Fig.1 is presented by thevenin voltage source, $\boldsymbol{V}_{th1}$ and thevenin impedance, Z_{th1} shown in Fig.7.

When a fault occurs in other lines, the left hand side voltage of DVR1, i.e., $\boldsymbol{V}_{s1}$ drops and the DVR1 injects a series voltage, $\boldsymbol{V}_{dvr1}$ through the injection transformer,

Interline dynamic voltage restorer in the general form uses form several DVRs in different distribution feeder for compensate voltage sag that are connected to a common DC voltage link. Because of the feeders in IDVR system are obtaining from different grid sub stations and perhaps and different voltage levels, voltage sag appearing in one feeder may have lesser influence on the other feeder [7]. The simplest IDVR with two DVR is shown in Fig.8. The voltages of feeder1 and 2 are 400V and 20 kV, respectively. When voltage sag occurs in feeder 1 may have less effect in feeder 2 and they can be supposed as two independent distribution feeder. In this case active power is drawn from common DC link instead of energy storage as shown in Fig.8 and DVR2 that is in normal condition injects active power to common DC link by controlling of DC link capacitor voltage.

As mentioned earlier DVR2 injects active power P_{dvr2} when a long duration voltage sag occurs in line 1 to compensate P_{dvr1} and the converters power looses P_{loos} in steady state as follows,

$$P_{dvr2} = P_{dvr1} + P_{loos} \tag{8}$$

The load 2 in feeder 2 is not sensitive to voltage phase angle. The control strategy for DVR2 is developed so that whenever active power injects to common DC link it maintains the magnitude of load voltage constant as shown in Fig. 9. Where $\boldsymbol{V}_{s2}$, $\boldsymbol{V}_{L2}$, $\boldsymbol{V}_{dvr2}$, $\boldsymbol{I}_{L2}$, Φ_2 and γ represent the left hand side voltage of DVR2, the load 2 voltage, the DVR2 injected voltage, the load 2 current , load 2 power angle and power injected phase angle respectively. By neglecting from harmonics in common DC link voltage all voltage and current in feeder 2 can be supposed harmonic free.

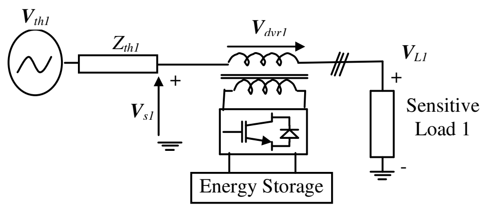


Figure 7. Equivalent circuit of power system

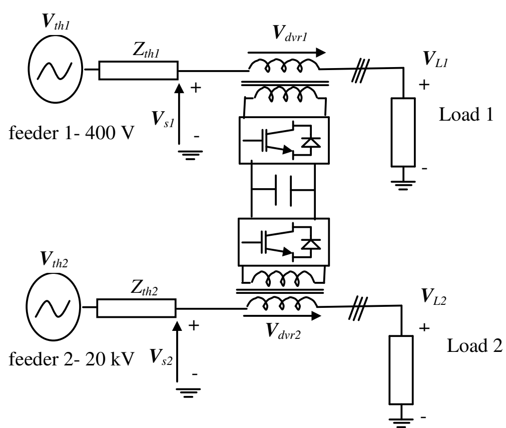


Figure 8. The simplest IDVR with two converter

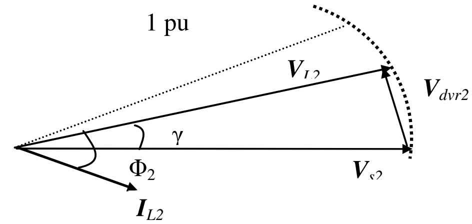


Figure 9. Phasor diagram of DVR2

V. Simulation Results

Simulation results carried out to verify the efficiency of suggested control strategy for system shown in Fig.8 by the PSCAD/EMTDC.

The system parameters are listed in Table.1.

TABLE.1. PARAMETERS OF THE SYSTEM

Parameter	Value
Load 1voltage	400 V
Load 1 apparent power	625 kVA
Load 1 power factor	0.8
Feeder 1 injection transformer ratio	1:1
Load 2 voltage	20 kV
Load 2 apparent power	625 kVA
Load 2 power factor	0.8
Feeder 2 injection transformer ratio	12:1
Base power	125 kVA
Common DC link voltage	600 V
Common DC link capacitor	5000 μF
L_{S1}, L_{S2}	1 mH
R_{s1}, R_{s2}	0.07 Ω
C_{s1}, C_{s2}	300 μF

It is assumed that the voltage magnitude of the load bus in feeder 1, 2 is maintained at 1 pu during the voltage sag conditions in feeder 1. The results of the most important simulations are represented in Fig.10 to Fig.11.

Left side voltage, injected voltage of DVR1, load 1 voltage, load 2 voltage were shown in Fig.10 (a), (b), (c), (d) for two phase earth fault in phase ‘a’, ‘b’. Deep voltage sag with fundamental component of o.23 pu occurs at t=0.1 to t=0.2 and voltage sag in phase ‘a’, ‘b’, ‘c’ is 0.24, 0.13, 0.29 pu. In this case minimal DC component of injected DVR1 and DVR2 active power is 18.75 kW and 43.75 kW respectively. As shown in Fig.10 shallow voltage sag with fundamental component of o.14 pu occurs at t=0.25 to t=0.35 and voltage sag in phase ‘a’, ‘b’, ‘c’ is 0.22, 0.07, 0.05 pu. In this case minimal DC component of injected DVR1 and DVR2 active power is 0 kW and 25 kW respectively. Power losses of two DVR P_{loos} are 25 kW equal 0.04 pu.

Left side voltage, injected voltage of DVR1, load 1 voltage, load 2 voltage were shown in Fig.11 (a), (b), (c), (d) for balanced three phase fault.

Fig.11(a) shows that 0.36 pu deep voltage sag occurs at t=0.1 to t=0.2 and 0.19 pu shallow sag occurs at t=0.25 to t=0.35. In this case minimal component of injected DVR1 and DVR2 active power for deep sag is 100 kW and 125 kW and for the shallow sag is 0 kW and 25 kW respectively.

These simulation results show that based on the suggested control strategy, DVR1 consumes zero injection power during shallow sag and minimizes injection power during deep sag and DVR2 injection active power is controlled by keeping constant common DC link voltage with good dynamic response and in the same time the inserted DVR1 voltage is equal or less than 0.6 pu (according to Fig.5).

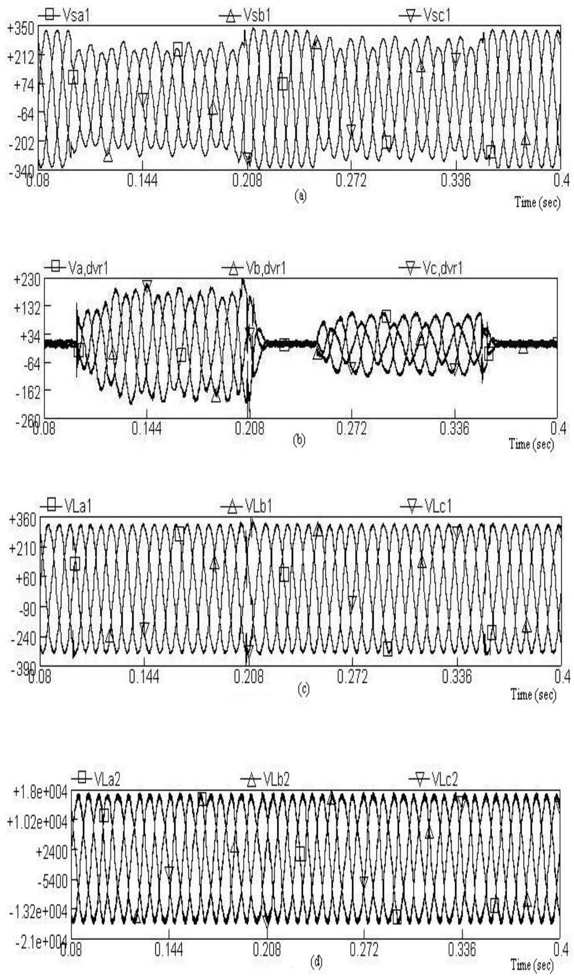
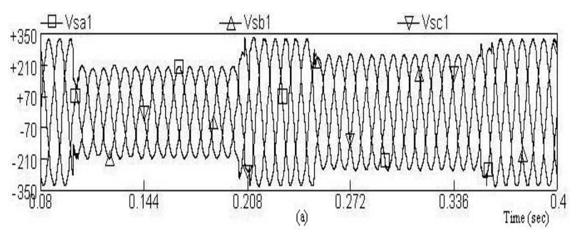


Figure 10. (a) Left side DVR1 voltage, V_{s1} (b) Injection DVR1 voltage, V_{dvr1} (c) Load 1 voltage, V_{L1} (d) Load 2 voltage, V_{L2} for unballance deep sag (t=0.1 to t=0.2) and shallow sag (t=0.25 to 0.35)



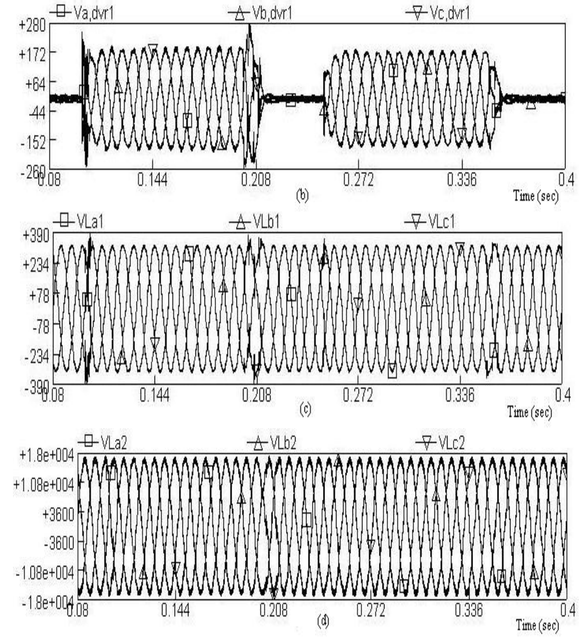


Figure 11. (a) Left side DVR1 voltage, Vs1 (b) Injection DVR1 voltage, Vdvr1 (c) Load 1 voltage, VL1 (d) Load 2 voltage, VL2 for balance deep sag (0.36 pu at t=0.1 to t=0.2) and shallow sag (0.19 at t=0.25 to 0.35)

VI. CONCLUSION

In order to compensate voltage sag it is possible to use dynamic voltage restorer (DVR) in distribution system for a sensitive load. Due to the limit of energy storage capacity of DC link, it is necessary to minimize energy injection from DVR. In this paper the control strategies for the compensation of the supply voltage sag is presented. In addition, a new concept of restoration strategy based on dynamic voltage restorer is proposed to inject minimum energy from common DC-link in unbalance sags.

Proposed control method makes zero injection power during shallow sag and controls DVR1 so that injection of power is minimized during deep sag. In the same time the other DVR injects energy to common DC-link by keeping voltage of common DC-link constant. Simulation results carried out by the PSCAD/EMTDC shows that the proposed method can minimize the injected active power of DVR from one feeder to other feeder.

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