Control Performance of Dynamic Voltage Restorer by V-control

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Abstract—This paper presents the performance improvement of dynamic voltage restorer (DVR) by vector control (V-control), which improves transient performance of DVR. Both current and voltage controllers are incorporated by V-Control, with an inner current control loop and outer voltage control loop. The loop gains are determined according to the system analysis, carried out on closed loop system. Also a review of the reported control techniques that have been implemented to control the injected voltage by DVR is presented. Simulation results have proved that the proposed algorithm is able to improve transient response of DVR.

Keyword—DVR, Power Converters, Power Quality, Vector control.

1. INTRODUCTION

Voltage sags (dips) are considered as the most severe disturbances to industrial equipment. For instance, a paper machine can be affected by disturbances of 10 % voltage drop lasting for 100 ms [1]. Also, voltage sag of 75 % (of the nominal voltage) with duration shorter than 100 ms can result in material loss in the range of thousands of US dollars for semiconductors industry [2]. The voltage source converter (VSC), connected in series with the grid as a dynamic voltage restorer (DVR), is suited to protect sensitive loads against voltage sags. As reported in August 26, 1996, the world's first DVR was installed on the Duke Power distribution system to protect a sensitive textile customer from voltage sags [3]. The basic idea is to inject dynamically a controlled voltage v_{inj} into the grid as shown in Fig.1. Fig.2 illustrates a vector diagram when the grid voltage v_g has voltage sag with a phase angle jump. Fig.3 shows a more detailed single-phase model of a distribution feeder with an DVR, where the supply voltage v_g, the DVR voltage v_{inj} and the load voltage v_{Load} are in series. Here it is worth to mention that small letters are used to denote the instantaneous values while capital letters denote phasors or vectors. So, the DVR is considered as an external voltage source where the amplitude, the frequency, the phase shift of v_{inj} can be controlled. From Fig.1, the load voltage is expressed

$$\underline{v}_{load} = \underline{v}_g + \underline{v}_{inj} \qquad (1)$$

For simplicity, only a single-phase diagram of the DVR details is depicted in Fig.3. The main components of the DVR are:

1) Voltage source converter (VSC),
2) Energy storage,
3) Output filter,
4) Injection transformer and
5) Bypass switch.

The measurement of voltages and currents are the inputs to the control unit in order to generate the reference voltage of the VSC, when the measured quantities differ from the default settings. The voltage references are inputs to pwm modulation unit to generate the modulating signals for the valves of VSC. The energy storage provides the required power to compensate for voltage sags. Installing a filter (LC-filter) reduces the *dv/dt* effect on the windings of the injection transformer and it is necessary to convert the pulse-modulated voltage of the VSC into a sinusoidal voltage. The filtered voltage is injected into the distribution system by the series-injecting transformer. The bypass switch is normally closed to short-circuit the DVR. In case of voltage sag in the grid, the bypass switch is opened and DVR starts the compensation process. In Fig.3, the controlled voltage by the DVR is denoted as v_{inj}.

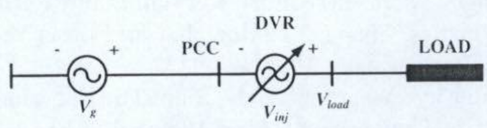

Fig. 1 Simplified circuit diagram of DVR.

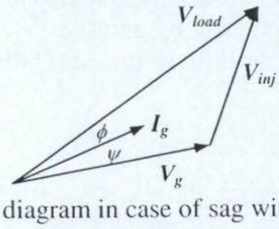

Fig. 2 Vector diagram in case of sag with phase jump.

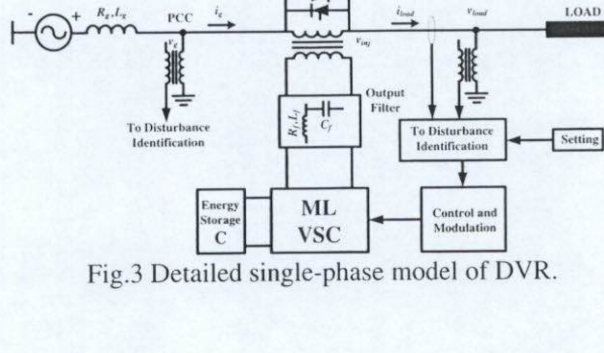

Fig.3 Detailed single-phase model of DVR.

This paper presents and verifies the V-control algorithm when an LC-filter is applied before the injection transformer. The V-Control uses an inner current loop to control the current through the series inductor and an outer voltage loop to track the reference voltage over the capacitor of the LC-filter. In Section 2 a review of the reported control techniques applied to DVR is presented. Section 3 presents the equations of V-Control. In Section 4, the simulation results obtained from a designed MATLAB/Simulink model are introduced. Finally, conclusion is given in Section 5.

2. CONTROL TECHNIQUE OF DVR

The reported control techniques that have been implemented to control the injected voltage by DVR may be classified into two main categories: 1) The scalar; 2) The vector control. By the scalar control, it is meant that only the voltage magnitude is controlled by applying the concept of phasors as in [4,5]. Techniques based on the synchronous reference frame are referred to as V-control where the magnitude and phase of the injected voltage are controlled. The scalar control involves RMS calculation of the fundamental voltage, which requires at least one half period of the fundamental frequency.

To improve the transient response of the DVR and control the injected active and reactive powers separately, the V-control has been implemented in a way similar to the control variable speed drives. Both feedforward/open-loop [6] and feedback/closed loop [7] techniques have been reported.

A block diagram of the basic feedforward control of DVR is depicted at Fig. 4. The grid voltages (v_a, v_b, v_c) are measured and transformed to the stationary reference frame ($v^{\alpha\beta}$). A phase locked loop is exploited to calculate the transformation angle (θ), which is required to transform the grid voltage from the stationary reference frame to the synchronous reference frame (V_{dq})

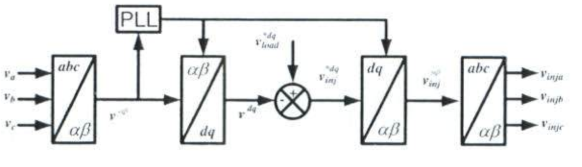

Fig. 4. Feedforward V-control of DVR.

Then the grid voltage is subtracted from the reference of the load voltage (v_{load}) to calculate the reference of the injected voltage (v_{inj}). A backward transformation from the synchronous reference frame to the three-phase is performed in order to obtain the reference of the injected voltage (v_{inja}, v_{injb}, v_{injc}) that should be generated by VSC. The feedforward control is fast but does not guarantee the system stability and may exhibit a steady-state error. Feedback control of the DVR has been proposed in [6] where the injected voltage by the DVR is measured and used in a single loop or a multi-loop control system.

When designing a control algorithm for the DVR, the LC-filter, mounted at the output of the VSC as shown in Fig.3, is important to consider since it affects the dynamic performance of DVR. Moreover, the LC-filter causes a voltage drop on the choke branch, which reduces the injection capability of the DVR and introduces a phase shift in the injected voltage. Such effect has been considered in [9, 10], a simple back calculation of the filter input voltage is applied. The algorithm proposed in [10] compensates for the steady state voltage drop due to the LC filter but it gives poor transient performance and it is sensitive to variations of the LC-filter parameters. To overcome this problem of voltage drop across the LC-filter and improve the performance of DVR, the voltage and current controllers are incorporated in this paper.

3. PROPOSED V-CONTROL

The dynamic performance of the DVR may be improved by controlling both the inductor current and the capacitor voltage of the LC-filter. Thus, a two-loop control algorithm is proposed and is referred to as voltage and current V-control. To reduce the complexity of the system while deriving the V-control equations, the injecting transformer (Fig.3) is assumed ideal, with turns ratio of 1:1 i.e., having zero magnetizing current and zero leakage inductance. Also the transformer, the grid and the load are replaced by an equivalent current source, injecting the grid current. Consequently, the injected voltage by the DVR, v_{inj} is the same as the voltage across the LC-filter capacitor v_C. Hence, the capacitor voltage v_C is controlled to regulate the load voltage. The current through the LC-filter inductor is controlled by an inner control loop. To derive the controllers, the LC-filter is modeled in the stationary $\alpha\beta$-frame and transformed into the synchronous dq-frame as in (2).

$$\frac{d}{dt}\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \qquad (2)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)$$

where

$$x(t) = \begin{bmatrix} i_d & i_q & u_{cd} & u_{cq} \end{bmatrix}^T, \mathbf{u}(t) = \begin{bmatrix} u_d & u_q & i_{gd} & i_{gq} \end{bmatrix},$$

i_d, i_q are the d- and q-components of the inductor current,
u_{cd}, u_{cq} are the d- and q-components of the capacitor voltage,
u_d, u_q are the d- and q-components of the VSC voltage,
i_{gd}, i_{gq} are the d- and q-components of the grid current.

The aim of the controller is to keep the load voltage constant. Thus, the DVR should inject the voltage $\underline{v}_C^{*dq}$ such that

$$\underline{v}_C^{*dq} = \underline{v}_{load}^{*dq} - \underline{v}_g^{dq} \qquad (3)$$

where $\underline{v}_{load}^{*dq}$ is the reference voltage demanded by the load.

The missing voltage $\underline{v}_C^{*dq}$ is injected through the injecting transformer. The inputs to the controller are the grid voltages, the grid currents, the VSC currents and the capacitor voltages of the LC-filter. The proposed controller is a discrete controller and uses a sampling time of T_s . Hence the sampling frequency fs equals to $1/T_s$. The switching frequency f_{sw} is the same as the sampling frequency. The state space equation of the LC-filter, (2) is discretized using the forward Euler method and is then integrated from kT_s to $(k+1)T_s$. The following assumptions are made to derive the controller:

- The grid current is constant independently of variations in currents and voltages of the LC-filter;
- The capacitor voltage and the inductor current change linearly during one sample period;
- The controller uses a dead-beat gain; the output vector $\mathbf{y}(t)$ changes linearly and is equal to the reference output vector $\mathbf{y}^*(t)$ after one sample;
- The average values of the capacitor voltage and the inductor current over the sample period kT_s to $(K+1)T_s$ are each equal to the half sum of the real value and the reference value at sample k.

The controlled variables are the inductor current i^{dq} and the capacitor voltage $\underline{v}_C^{dq}$. Based on the above assumptions and after algebraic manipulation of (2), the equations of the controller are obtained as:

Voltage Controller Outer Loop

$$i^{*dq} = \underline{i}_g^{dq} \pm j\frac{\omega C_f}{2}\left(\underline{v}_C^{*dq} + \underline{v}_C^{dq}\right) + K_v\left(\underline{v}_C^{*dq} + \underline{v}_C^{dq}\right) \qquad (4)$$

Current Controller Inner Loop

$$v^{*dq} = \underline{v}_C^{*dq} + R_f\underline{i}^{dq} \pm j\frac{\omega L_f}{2}\left(\underline{i}^{*dq} + \underline{i}^{dq}\right) + K_i\left(\underline{i}^{*dq} + \underline{i}^{dq}\right) \qquad (5)$$

where i^{*dq} and u^{*dq} are the required reference currents and voltages to track the reference of the injected voltage. The gains K_v and K_i are the dead-beat gains calculated in terms of the filter parameters and the sampling time; $K_v = C_f/T_s$, $K_i = L_f/T_s + R_f/2$. A block diagram of the V-control is depicted in Fig. 5. To stabilize the system, the gains K_v and K_i are altered from the dead-beat gains by the factors K_{vs} and K_{is}, respectively. In other words, the gains of the two loops are given by: $K_v=K_{vs}C_f/T_s$ and $K_i=K_{is}L_f/T_s$. Thus, selecting the values of the two factors K_{vs} and K_{is} determines the system stability.

4. SIMULATION RESULTS

To illustrate a typical response of DVR with the proposed control strategy, a simple 50 Hz power distribution system with a sensitive load as shown in Fig. 1 is considered. The system data and parameters used Thailand power distribution model. The performance of DVR with V-control strategy is shown in Fig. 6 for balanced voltage sag due to a three phase fault that was initiated at 0.2 sec. and lasted for 0.05 sec as presented in the supply voltage graph. The load voltage and the injected voltage by DVR are also shown in Fig. 6. As can be seen from the figure, the proposed control strategy is able to drive the DVR to inject the appropriate three phase voltage component with correct phase to remove the supply voltage anomalies due to three phase fault. It was observed that during the normal operation the DVR is not functioning. It quickly injects necessary voltage components to smoothen the load voltage upon detecting voltage sag. Similar performance is observed for an unbalanced voltage sag case as well.

Figure 7 shows the performance of DVR control for unbalanced voltage sag created by double line fault in the system. As depicted in supply voltage the fault was initiated at 0.2 sec and it was cleared at 0.25 sec. As shown in Fig. 7, DVR with the proposed control strategy is quick in injecting the required unbalanced voltage component for correcting the load voltage and keeps it at nominal value.

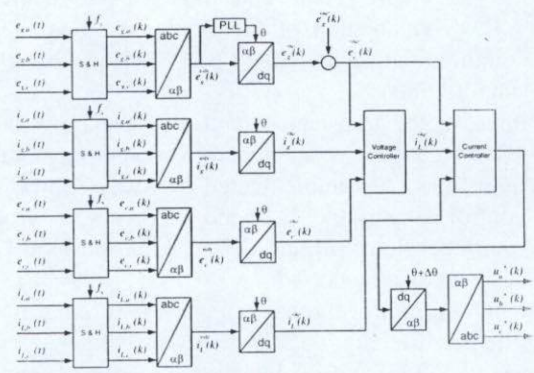

Fig. 5 Block diagram of V-control.

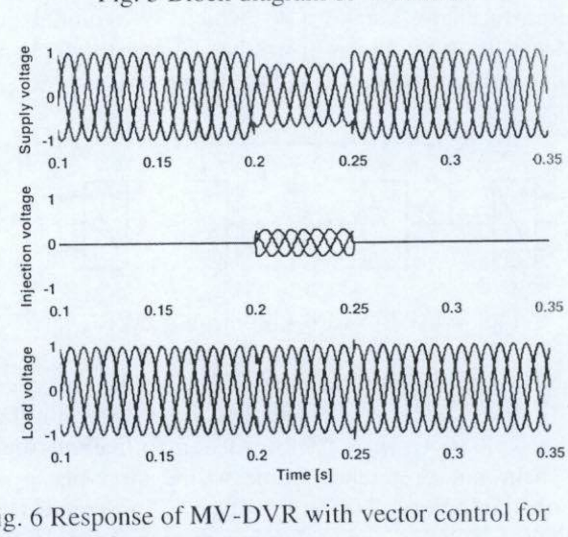

Fig. 6 Response of MV-DVR with vector control for balanced voltage sag.

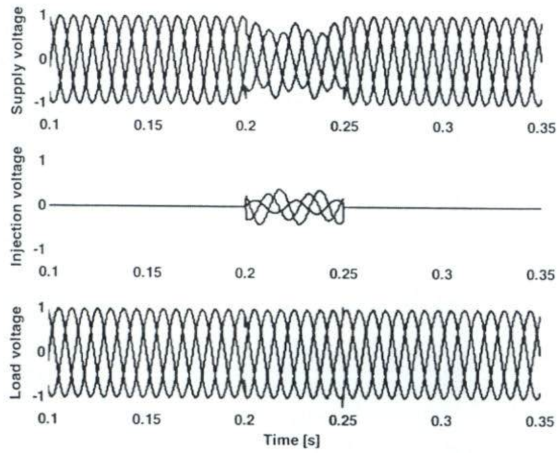

Fig. 7 Response of MV-DVR with vector control for balanced voltage sag.

5. CONCLUSION

A control strategy has been proposed in this paper for DVR control for mitigating voltage sag. The proposed control strategy known as vector control strategy is widely used in Drives. It is implemented in the synchronous frame with two loops, an inner loop which controls the current and an out loop which controls the voltage. The performance of DVR with vector control has been demonstrated through simulation in a simple distribution system with sensitive load for both balance and unbalanced situations. The proposed control strategy proofs to be performed satisfactory, both in terms of response time and smoothness of the injected voltage components. The response time of the DVR with the proposed control strategy was less than half compared to the same of conventional counterparts.

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