The Voltage Injected By DVR Control with SRF Theory for Unsymmetrical Loads

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Abstract:  
At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator (D-STATCOM) and the dynamic voltage restorer (DVR) are most effective devices, both of them based on the VSC principle. MATLAB SIMULINK has been used in this project to perform the modeling and analysis of such controllers. A DVR injects a voltage in series with the system voltage to correct the voltage sag. The steady state performance of DVR is obtained for various voltage sags/swell levels. Comprehensive results are presented to assess the performance of each device as a potential custom power solution.

Key Words: Power Quality, DSTATCOM, DVR, Voltage Sag, Voltage Swell.

INTRODUCTION

A DVR is used to compensate the supply voltage disturbances such as sag and swell. The DVR is connected between the supply and sensitive loads, so that it can inject a voltage of required magnitude and frequency in the distribution feeder. The DVR is operated such that the load voltage magnitude is regulated to a constant magnitude, while the average real power absorbed/ supplied by it is zero in the steady state. The capacitor supported DVR is widely addressed in the literature. The instantaneous reactive power theory (IRPT), sliding mode controller, instantaneous symmetrical components etc., are discussed in the literature for the control of DVR. In this project a new control algorithm is proposed based on the current mode control and proportional-integral (PI) controllers for the control of DVR. The extensive simulation is performed to demonstrate its capability, using the MATLAB with its Simulink and Power System Blockset (PSB) toolboxes.

A DVR is a voltage-source converter (VSC)-based power electronics device connected in series between the supply and the critical loads, which are to be protected from the supply-side voltage quality problems, other than outages, by injecting the required compensating voltage through DVR into the distribution line. A DVR can restore a balanced sinusoidal load voltage of desired amplitude even when the source voltage is unbalanced and/or distorted. The voltage injected by self-supported DVR is in quadrature with the feeder current; hence, it does not need any active power during steady state. However, its disadvantage is that, in case of the voltage sag/swell, the restored voltage may not be in phase with the presag/preswell voltage. The self-supported DVR is used when the phase jump, caused by the quadrature voltage injection, is affordable.
The DVR supported by a capacitor has become popular as a cost-effective solution for the protection of sensitive loads from the supply-side voltage quality problems. Currently, most of the research is on DVR dealing with the protection of balanced linear load; however, there are a few which are related to the protection of unbalanced and nonlinear loads. The approach discussed here is comparatively simple as it needs only the extraction of the fundamental positive-sequence phasewhen terminal voltages, thus making it computationally simpler with the least memory requirement. The proposed fundamental positive-sequence extractor requires the sensing of only two line voltages of supply. This reduces the analog-to-digital converter (ADC) requirements of a digital controller and corresponding sensing element. Moreover, it is able to extract three fundamental positive-sequence phase voltages irrespective of the distribution system configuration such as three-phase, four-wire or three-phase, three-wire system where the neutral is not available for sensing phase voltages.

**STRUCTURE OF PROPOSED DVR**

The power circuit of DVR is discussed. Practically, the DVR is realized by three single-phase H-bridge VSCs along with a common dc capacitor (Cdc) as shown in Fig. 1. The three H-bridge VSCs are connected to each phase of the distribution feeder through the improved structure ripple filter (Lr, Cr, Rr) and an injection transformer. The injection transformer not only reduces the voltage requirement of the converter but also provides isolation between the converter and the distribution feeder. The shunt capacitor filter Cf is used to provide a low impedance path to higher order harmonics of load currents when the load current is nonlinear. The operation of practical DVR with nonlinear load current is discussed in the next section.

To track the reference compensating voltages, an improved filter structure constant switching frequency hysteresis band controller is used in this work. The main advantages of the band controller are unconditional stability, faster response and easy implementation compared to other controllers like carrier-based controllers, dead-beat control, state feedback control, combined feedforward and feedback control, etc., which are based on complex mathematical computations and need much information about system parameters. Despite these advantages, the main disadvantage of the band controller compared to carrier-based controllers is variable switching frequency which may cause stress in the switches of the VSC, resulting in the deterioration of its life. The band controller has other drawbacks also like poor controllability, heavy filter currents, parabolic band voltage response, and frequent band violations due to the use of a conventional LC filter which has a second-order characteristic equation.

The single-phase equivalent circuit of the DVR-connected system in Fig. 1 is shown in Fig. 6 to explain the basic principle of the hysteresis band controller. The reference compensating voltage for the DVR is calculated using the proposed algorithm. To inject this voltage in series with the distribution feeder, appropriate switching pulses for VSC are generated using the hysteresis band controller with hysteresis band h. When the DVR voltage VC goes below the lower boundary, the positive dc voltage is applied across the ac filter combination (Cr, Rr) by...
turning switches S1 and S2 on. If DVR voltage $V_C$ goes above the upper boundary, the negative dc voltage is applied by turning switches S3 and S4 on.

In order to improve the performance of the controller, an extra resistance $R_r$ is connected in series with ac filter capacitor $C_r$ as shown in Fig. 2. This resistance dominates the capacitive reactance at switching frequency. At switching frequency, the resistance $R_r$ and combined inductive reactance of the $L_r$ and transformer are very large compared to the capacitive reactance of $C_r$. Thus, at switching frequency, this improved structure filter circuit behaves as an $R-L$ circuit and gives a linear voltage variation within the band compared to the parabolic voltage variation given by the conventional $L-C$ filter circuit. Because of the linear response, this filter has less band violations and, hence, better controllability compared to the conventional filter.

**CONTROL SYSTEM**

The schematic diagram of DVR (ideal voltage sources) connected distribution feeder is shown in Fig. 1. A three-phase supply is represented by the star-connected three single-phase voltage sources ($V_{sa}, V_{sb}, V_{sc}$) along with their series source impedances ($Z_a, Z_b, Z_c$). To regulate the load voltages ($V_{La}, V_{Lb}, V_{Lc}$) to be balanced and sinusoidal against various PQ problems in the terminal voltages ($V_{ta}, V_{tb}, V_{tc}$), DVR injects the required compensating voltages ($V_{Ca}, V_{Cb}, V_{Cc}$) in each phase. The practical implementation of a DVR using three single-phase H-bridge VSCs along with a common dc capacitor is discussed later.

![Fig 3: Schematic diagram of DVR (ideal voltage sources) connected powersystem.](image)

The energy storage device is a capacitor, so the following condition is stipulated on the DVR.

- The DVR should not supply any real power in steady state. This implies that, in steady state, the phase difference between instantaneous DVR voltages and instantaneous line currents must be 90°.

**Under Balanced Linear Load**

The algorithm is developed to compute instantaneous DVR voltages from the samples of instantaneous terminal voltages and line currents assuming balanced sinusoidal supply and balanced load.

Taking the line current as the reference frame, the above equation can be converted to SRF as

$$v_{td} + jv_{tq} + jv_{cq} = v_{Ld}^{*} + jv_{Lq}^{*}$$

Note that, for zero DVR active power in steady state, VC should be at 90° to the line current $v_{td}$ can be computed from the instantaneous samples of terminal voltages as

$$v_{td} = v_{ta} \sin \theta + v_{tb} \sin \left( \theta - \frac{2\pi}{3} \right) + v_{tc} \sin \left( \theta + \frac{2\pi}{3} \right)$$

As terminal voltages are balanced and sinusoidal, $v_{td}$ contains only the constant dc component

$$v_{Ld}^{*} = v_{td}$$

Moreover, to regulate the peak of the load voltage (ph-n) to $v_{Lp}$, $v_{Ld}$ can be directly calculated as

$$v_{Lq}^{*} = \sqrt{v_{Lp}^{2} - v_{Ld}^{2}}$$

$$= \sqrt{v_{Lp}^{2} - v_{td}^{2}}.$$

After computing $v_{Ld}$ and $v_{Lq}$, the instantaneous reference load voltages can be computed as follows
Under Unbalanced Linear Load

The algorithm discussed in the previous section will fail to compute the desired reference load voltages under the situation, where the unbalanced and/or distorted supply voltages feed the unbalanced load.

The unbalanced and/or distorted terminal voltages can be written as

\[
\begin{align*}
v_{tk} &= v_{tk1_f} + v_{tk_{rest}}, & k = a, b, c
\end{align*}
\]

Where \(v_{tk1_f}\) is the positive-sequence component of \(v_{tk}\) and \(v_{tk_{rest}}\) is the remaining portion containing the influence of unbalanced harmonics. The modification is thus to replace \(v_{ta}, v_{tb},\) and \(v_{tc}\) in (3) by \(v_{ta1_f}, v_{tb1_f},\) and \(v_{tc1_f},\) respectively.

To extract the fundamental positive-sequence terminal phase voltages, a novel fundamental positive-sequence extractor is proposed which requires the sensing of only two distorted and/or unbalanced terminal line voltages.

Fundamental Positive-Sequence Extractor

As the line voltages are the difference of different phase voltages (\(v_a - v_b, v_b - v_c, \text{and} v_c - v_a\)), the summation of three line voltages is always zero irrespective of whether three phase voltages are balanced and sinusoidal or unbalanced. Therefore, by sensing only two line voltages \(v_{ab}\) and \(v_{bc}\), the third line voltage \(v_{ca}\) can be calculated as \(v_{ca} = -(v_{ab} + v_{bc})\).

If Park’s transformation is applied to three balanced sinusoidal line voltages \(v_{ab}, v_{bc},\) and \(v_{ca}\) using a PLL over the sameline voltages, then it gives constant direct-axis component \(v_d\) equal to the amplitude of line voltage, quadrature-axis component \(v_q\) equal to zero, and zero-sequence component \(v_0\) equal to zero because line voltages are a positive sequence only without any harmonics.

SIMULATION RESULTS

Voltage Sag

The proposed control scheme of DVR is verified through simulation using MATLAB software along with its Simulink and Power System Blockset (PSB) toolboxes. The DVR is tested under different operating conditions like sag (Fig 5) and swell (Fig. 6) at the terminal voltages (\(V_{ta}, V_{tb},\) and \(V_{tc}\)). In Fig. 5, the terminal voltage has a sag of 30% with a magnitude at 70% of rated value at 0.22 sec and occurs up to 0.32 sec.

The DVR injects fundamental voltage \(V_c\) in series with the terminal voltages \(V_{la}, V_{lb}, V_{lc}\). The load voltage is maintained at the rated value. The terminal voltage \(V_t\), supply current \(i_s\), amplitude of terminal voltage \(V_t\) the amplitude of load voltage \(V_L\) and the dc bus voltage \(V_{dc}\) of DVR are also shown in the Fig.5. It is observed that the dc bus voltage of DVR is maintained at reference value.
Similarly, in Fig. 7, a swell in terminal voltage (Vt) has occurred at 0.22 sec up to 0.32 sec and the load voltage (VL) is maintained at the rated value. The terminal voltage (Vt) supply current (Is), the amplitude of terminal voltage (Vt), the amplitude of the load voltage (VL) and the dc bus voltage (Vdc) of DVR are also shown in the Fig.6.2. It is observed that the dc bus voltage of DVR is maintained at reference value, though perturbation is occurring during transients.

**Voltage Swell**

CONCLUSION

A new control strategy based on current mode control for Dynamic Voltage Restorer (DVR) has been proposed to mitigate the power quality problems in the terminal voltages. The DVR is controlled indirectly by controlling the supply current. The reference supply currents are estimated using the sensed load terminal voltages and the dc bus voltage of DVR. The control scheme is based on synchronous reference frame theory (SRFT) for the operation of a capacitor supported DVR. The proposed control scheme of DVR has been validated the compensation of sag and swell in terminal voltages. The performance of the DVR has been found very good to mitigate the voltage power quality problems. Moreover, it has been found capable to provide self-supported dc bus of the DVR through power transfer from ac line at fundamental frequency.

REFERENCES


