Restoration of single phase distribution system voltage under fault conditions with DVR using sliding mode control

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Abstract: A Dynamic Voltage Restorer (DVR) with Sliding mode control strategy is used to alleviate the voltage sags caused due to faults occurring on the parallel feeders in a single-phase distribution system. The DVR along with the other parts of the distribution system are simulated using MATLAB/SIMULINK.

Keywords—DVR, Sliding mode control, voltage sag, power quality, custom power device.

Introduction
Control of most of the industrial loads is mainly based on semiconductor devices, which causes such loads to be more sensitive against power system disturbances. Thus, the power quality problems have gained more interest recently. Voltage sags are mainly caused due to starting of large induction motors, switching of large inductive loads, short circuit faults in transmission and distribution systems and energizing of large transformers. Therefore, different solutions are examined to compensate these sags and to avoid production losses at sensitive loads. Dynamic Voltage Restorer (DVR) is one of the solutions to realize this goal. For a successful compensation, the Dynamic Voltage Restorer must be able to detect the voltage sag and control the inverter to restore the voltage. The Sliding mode control is used for the Dynamic Voltage Restorer. Using Sliding mode control to the DVR, additional sag detection method is eliminated. This improves the dynamic response of the DVR and also DVR is able to compensate for any variation in source voltage.

Utilities aim to provide their customers with an ideal sinusoidal voltage waveform. By definition ideal sinusoidal voltage waveform has the characteristics: constant magnitude at the required level, constant frequency and balanced in case of three Phase operation. Naturally, this is not always possible because of normal system variations and due to the unavoidable incidents that temporarily can affect the operation, such as short-circuit faults. On the other hand, utilities require that customers should draw sinusoidal current. Fig.1 illustrates the relation between the utilities and their customers in a systematic way. Customers place demands on the voltage $u_g(t)$, while the utilities specify the current $i_g(t)$.

Fig.1. Relation between utilities and customers

Significant deviation from the normal voltage is a problem for sensitive consumers in the grid system. Interruptions are generally considered to be the worst case with the load disconnected from the supply. Voltage sags are characterized by a reduction in voltage, but the load is still connected to the supply. Sags are in most cases considered less critical compared to interruptions, but they typically occur more frequently. Voltage sags have in several cases been reported as a threat to sensitive equipment and have resulted in shutdown, loss of production and a hence a major burden (Bollen, 1999).

Fig.2. Single-Phase Distribution system
The concept of custom power has been developed using advanced power electronic equipment to ensure a high quality of supply. The Dynamic Voltage Restorer (DVR) is one of the custom power devices, which has excellent dynamic Capabilities, and it is well suited to protect critical or sensitive loads from short duration voltage dips (Kara et al., 1998).

Conventional solutions for controller requirements are based on classical control theory or modern control theory (Raviraj & Sen, 1997).
The state space model of DVR with reference to Fig. 3, can be written as:

\[
\frac{d}{dt} [v_c] = \begin{bmatrix}
0 & \frac{1}{C_f} & 0 \\
-\frac{1}{L_f} & -R_f/L_f & 0 \\
0 & \frac{1}{L_f} & \delta(t)dcVt
\end{bmatrix} [v_c] + \begin{bmatrix}
1/C_f \\
-1/L_f \\
0
\end{bmatrix} i_f + \begin{bmatrix}
0 \\
0 \\
1/L_f
\end{bmatrix} i_s
\]

(1)

Where \(i_f\) and \(i_s\) are filter inductor current and source current respectively, \(\delta(t)\) is the switching function of the inverter that can be 1 or -1.

A. Sliding Surface Selection

In order to control the output voltage of inverter we have to find out a suitable sliding surface which will directly affected by switching law. From (1) it is seen that the first time derivative of the output \(dv_c/dt = (i_f - i_s)/C_f = \theta\), does not explicitly contain the control output \(\delta(t)V_{dc}\), therefore the second derivative must be calculated.

\[
\theta = \left[ \frac{-R_f}{L_f} - \frac{1}{L_f}C_f \right] v_c - \left[ \frac{R_f}{L_f} + \frac{1}{L_f}C_f \right] i_f + \frac{1}{L_f} \delta(t)dcVt
\]

(2)

The phase canonical form (2) shows that the second derivative of the output depends on the control input \(\delta(t)V_{dc}\). No further time derivative is needed. Considering that \(e_v = v_c - v_c^{ref}\), a sliding surface \(S(e_v, t)\), can be chosen

\[
S(e_v, t) = k_1e_v + k_2 \frac{de_v}{dt} = 0
\]

(3)

Existence of Sliding Mode

The existence of the operation in sliding mode implies \(S(e_v, t) = 0\). Also, to stay in the regime, the control system should guarantee \(S(e_v, t) = 0\). Therefore, the switching law must ensure the stability condition for the system in sliding mode, written as:

\[
S(e_v, t) \dot{S}(e_v, t) < 0
\]

(4)

The fulfillment of this inequality ensures the convergence of the system trajectories to the sliding surface \(S(e_v, t) = 0\) since if \(S(e_v, t) > 0\) and \(\dot{S}(e_v, t) < 0\), then \(S(e_v, t)\) will decrease towards zero. If \(S(e_v, t) < 0\) and \(\dot{S}(e_v, t) > 0\), then \(S(e_v, t)\) will increase towards zero. Hence, if (4) is verified, then \(S(e_v, t)\) will converge to zero. The condition (4) is called sliding mode existence condition.
**Reaching Condition**

The fulfillment of \( S(e_v, t) S(e_v, t) < 0 \) as \( S(e_v, t) S(e_v, t) = \frac{1}{2} S^2(e_v, t) \) implies that the distance between the system state and sliding surface will tend to zero.

**B. Determination of Control Law**

After verifying the existence condition, the switching law for semiconductor switches can be devised as

\[
\delta(t) = \begin{cases} 
1 & \text{for } S(e_v, t) > 0 \\
-1 & \text{for } S(e_v, t) < 0 
\end{cases}
\]

(5)

In the ideal sliding mode control, at infinite switching frequency, state trajectories are directed toward the sliding surface and move exactly along the discontinuity surface. Practical power converters cannot switch at infinite frequency. So a typical implementation features a comparator with hysteresis \( 2\varepsilon \), switching occurs at \( |S(e_v, t)| > \varepsilon \).

With the above introduced hysteresis comparator the switching law modifies to

\[
\delta(t) = \begin{cases} 
1 & \text{for } S(e_v, t) > \varepsilon \\
-1 & \text{for } S(e_v, t) < \varepsilon 
\end{cases}
\]

(6)

For systems where fixed frequency operation is needed, a triangular wave with frequency slightly greater than the maximum variable frequency is added to the sliding mode controller.

**C. Robustness**

Since the sliding surface and switching does not depend on system operating point, load, circuit parameters, and on power supply, the converter dynamics, operating in sliding mode, is robust.

**Control Strategy for DVR**

Fig. 4 shows the controller block diagram for DVR. The reference voltage to be injected by the DVR is calculated by subtracting the reference source voltage and actual source voltage.

![Fig. 4. Control Block Diagram of DVR](image)

**Simulation Results**

A source voltage of 33 kV (rms) is considered with a source impedance of 2 Ohms, step down transformer rated 500 MVA with 0.02 pu resistance and 0.00459 pu inductance is used. Each feeder having a resistance of 0.169 ohm and Inductance of 1.39 mH is implemented. Resistive load of 50 ohms is used on feeder 1, a series resistance of 50 ohms and Inductance of 10 mH is implemented on feeder 2, a series resistance of 50 ohms and Inductance of 10 mH is taken as a sensitive load.

A 50 MVA 1:1 voltage ratio injection transformer along with a filter of Inductance 40 mH and shunt capacitance of 20 µF implemented. Fig. 5 to Fig. 17 shows the simulation results obtained using MATLAB/SIMULINK.

Fig. 5 shows the voltage across the sensitive load when there is no fault. In Fig.6, a voltage dip of 40% of the supply voltage is occurred between 340ms to 440ms, during the fault at feeder2 during this time interval. In Fig. 6, the voltage is injected by the DVR during fault at feeder2. Fig. 7 & 8 shows the voltage injected by the DVR and the compensated load voltage. Fig. 9, a voltage dip of 40% of the supply voltage is occurred between 140ms to 300ms during fault at feeder1. Fig. 10 shows the voltage injected by the DVR during fault at feeder1 and Fig.11, the compensated load voltage. Fig.12, a voltage dip of 40% of the supply voltage is occurred between 140ms to 300ms and 340ms to 440ms during fault at both the feeders. Fig.13 & Fig. 14 shows the voltage injected by the DVR during fault at both the feeders and the compensated load voltage. Fig.15 shows a voltage dip of 40% of the supply voltage is occurred during fault at both the feeders. In Fig.16 & Fig.17, the voltage is injected by the DVR and the compensated load voltage.

![Fig. 5. Voltage across sensitive load when there is no fault](image)
Fig. 6. Voltage across sensitive load during fault at feeder 2

Fig. 7. Voltage injected by DVR during fault at feeder 2

Fig. 8. Compensated voltage across sensitive load

Fig. 9. Voltage across sensitive load during fault at feeder 1

Fig. 10. Voltage injected by DVR during fault at Feeder 1

Fig. 11. Compensated voltage across sensitive load

Fig. 12. Voltage across sensitive load during fault at both the feeders with different fault time

Fig. 13. Voltage injected by DVR during fault at both the feeders with different fault time

Fig. 14. Compensated voltage across sensitive load

Fig. 15. Voltage across sensitive load during fault at both the feeders with overlap fault time
Fig. 16. Voltage injected by DVR during fault at both the feeders with overlap time

Fig. 17. Compensated voltage across sensitive load

Conclusions
This paper is focused on the performance of dynamic voltage restorer when connected across a sensitive load to alleviate the voltage sag occurring due to fault taking place on the parallel feeder in a given distribution system. Sliding mode control is implemented for the DVR. Control techniques of variable structure systems find a natural application to the Custom Power Devices. In particular, the sliding mode control represents a powerful tool to enhance performance of power converters.

Sliding mode controller is designed for a single phase DVR for the present work. Validity of the sliding mode controller is verified by extensive simulation results. The point of common coupling voltage during sag condition resulting due to a fault occurring on the parallel feeder in a distribution system evidently shows good dynamic response of the DVR achieved through the sliding mode control. It can also be observed that usage of sliding mode control to DVR eliminates the additional sag detection and makes the DVR multifunctional, such as the same control can be used to compensate any variation in the supply voltage.

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