Understanding of Dynamic Voltage Restorers Through MATLAB Simulation

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Abstract

This paper presents the application of dynamic voltage restorers (DVR) on power distribution systems for mitigation of voltage sags/swells at critical loads. DVR is one of the compensating types of custom power devices. An adequate modeling and simulation of DVR, including controls in MATLAB, show the flexibility and easiness of the MATLAB environment in studying and understanding such compensating devices. The DVR, which is based on forced-commutated voltage source converter (VSC) has been proved suitable for the task of compensating voltage sags/swells. Simulation results are presented to illustrate and understand the performances of DVR in supporting load voltages under voltage sags/swells conditions.

Keywords: custom power, power quality, voltage sags, voltage swells, DVR.

1. Introduction

Modern power systems are complex networks, where hundreds of generating stations and thousands of load centers are interconnected through long power transmission and distribution networks [1]. The main concern of consumers is the quality and reliability of power supplies at various load centers where they are located at. Even though the power generation in most well-developed countries is fairly reliable, the quality of the supply is not so reliable. Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency [2]. However, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. Apart from nonlinear loads, some system events, both usual (e.g. capacitor switching, motor starting) and unusual (e.g. faults) could also inflict power quality problems [3]. The consequence of power quality problems could range from a simple nuisance flicker in the electrical lamps to loss of thousands of dollars due to production shutdown.

A power quality problem is defined as any manifested problem in voltage/current or leading to frequency deviations that result in failure or misoperation of customer equipment [3-4]. Power quality problems are associated with an extensive number of electromagnetic phenomena in power systems with broad ranges of time frames such as long duration variations, short duration variations and other disturbances. Short duration variations are mainly caused by either fault conditions or energization of large loads that require high starting currents. Depending on the electrical distance related to impedance, type of grounding and connection of transformers between the faulted/load location and the node, there can be a temporary loss of voltage or temporary voltage reduction (sag) or voltage rise (swell) at different nodes of the system [5].

Voltage sag is defined as a sudden reduction of supply voltage down 90% to 10% of nominal, followed by a recovery after a short period of time. A typical duration of sag is, according to the standard, 10 ms to 1 minute. Voltage sag can cause loss of production in automated processes since voltage sag can trip a motor or cause its controller to malfunction. Voltage swell, on the other hand, is defined as a sudden increasing of supply voltage up 110% to 180% in rms voltage at the network fundamental frequency with duration from 10 ms to 1 minute. Switching off a large inductive load or energizing a large capacitor bank is a typical system event that causes swells [1]. To compensate the voltage sag/swell in a power distribution system, appropriate devices need to be installed at suitable locations. These devices are typically placed at the point of common coupling (PCC) which is defined as the point where the ownership of the network changes. The DVR is one of the custom power devices which can improve power quality, especially, voltage sags and voltage swells. As there are more and more concerns for the quality of supply as a result of more sensitive loads in the system conditions, a better understanding of the devices for mitigating power quality problems is important. This would allow us to make use of the functions of such devices in a better way with efficient control techniques. Hence, in this paper an attempt is made to understand the functions of DVR with the help of MATLAB.

2. Custom Power Technology

The concept of custom power was introduced by N.G. Hingorani in 1995. Like Flexible AC Transmission Systems (FACTS) for transmission systems, the term custom power pertains to the use of power electronics controllers in a distribution system, especially, to deal with various power quality problems. Just as FACTS improves the power transfer capabilities and stability margins, custom power makes sure customers get pre-specified quality and reliability of supply. This pre-specified quality may contain a combination of specifications of the following [1]: low phase unbalance, no power interruptions, low flicker at the load voltage, low harmonic distortion in load voltage, magnitude and duration of overvoltages/undervoltages within specified limits, acceptance of fluctuations, nonlinear and poor factor loads without significant effect on the terminal voltage.

These can be done on the basis of an individual, large customer, industrial/ commercial parks or a supply for a high tech community on a wide area basis. Custom power technology is a general term for equipment capable of mitigating numerous power quality problems. Basic functions are fast switching, and current or voltage injection for correcting anomalies in supply voltage or load current, by injecting or absorbing reactive and active power, respectively [6], [7].

The power electronic controllers that are used in the custom power solution can be a network reconfiguring type or a compensating type. The network reconfigurating devices are usually called switchgears which include current limiting, current breaking and current transferring devices. The solid state or static versions of the devices are called: solid state current limiter (SSCL), solid state breaker (SSB), and solid state transfer switch (SSTS). The compensating devices either compensate a load, i.e. its power factor, unbalance conditions or improve the power quality of supplied voltage, etc. These devices are either connected in shunt or in series or a combination of both. This class of devices includes the distribution static compensator (D-STATCOM), dynamic voltage restorer (DVR), and unified power quality conditioner (UPQC) [2]. Among compensating devices, a DVR can deal with voltage sags and swells which are considered to have a severe impact on manufacturing places such as semiconductors and plastic products, food processing places and paper mills.

3. Dynamic Voltage Restorers

A DVR is a device that injects a dynamically controlled voltage $V_{inj}(t)$ in series to the bus voltage by means of a booster transformer as depicted in Figure 1. There are three single phase booster transformers connected to a three phase converter with energy storage system and control circuit [8]. The amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage $V_L(t)$. This means that any differential voltage caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer.

The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most practical cases, a more economical design can be achieved by only compensating the positive- and negative sequence components of the voltage disturbance seen at the input of the DVR. This option is reasonable because for a typical distribution bus configuration, the zero sequence part of a disturbance will not pass through the step down transformers because of infinite impedance for this component.

For most of the time the DVR has, virtually, "nothing to do," except monitoring the bus voltage. This means it does not inject any voltage ($V_{inj}(t)$ = 0) independent of the load current. Therefore, it is suggested to particularly focus on the losses of a DVR during normal operation. Two specific features addressing this loss issue have been implemented in its design, which are a transformer design with a low impedance, and the semiconductor devices used for switching. An equivalent circuit diagram of the DVR and the principle of series injection for sag compensation is depicted in Figure 2.

Mathematically expressed, the injection satisfies:

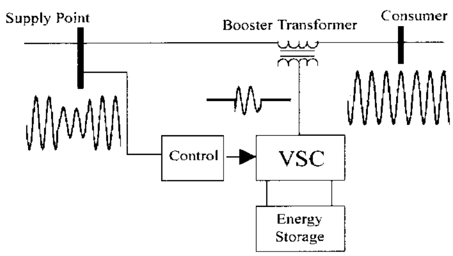

Fig. 1 Schematic diagram of DVR System.

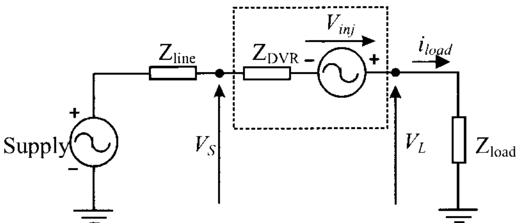

Fig. 2 Equivalent circuit of DVR.

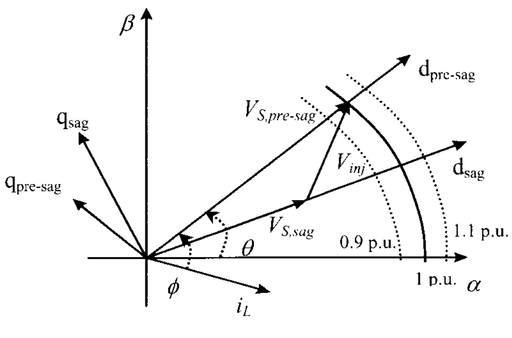

Fig. 3 Compensation strategy of DVR for voltage sags.

$$v_L(t) = v_s(t) + v_{inj}(t) \quad (1)$$

where $v_L(t)$ is the load voltage, $v_s(t)$ is the sagged supply voltage and $v_{inj}(t)$ is the voltage injected by the mitigation device as shown in Fig. 2. Under nominal voltage conditions, the load power on each phase is given by (2):

$$S_L = V_L I_L^* = P_L - jQ_L \quad (2)$$

where I_L is the load current, and P_L and Q_L are the active and reactive power taken by the load, respectively, during a sag/swell. When the mitigation device is active and restores the voltages back to normal, the following applies to each phase:

$$S_L = P_L - jQ_L = (P_s - jQ_s) + (P_{inj} - jQ_{inj}) \quad (3)$$

where the sag subscript refers to the sagged supply quantities. The inject subscript refers to quantities injected by the mitigation device.

4. Modeling of DVR in MATLAB

The compensation of voltage sag/swell can be limited by a number of factors, including finite DVR power rating, loading conditions, power quality problems and types of sag/swell. If a DVR is a successful device, the control is able to handle most sags/swells and the performance must be maximized according to the equipment inserted. Otherwise, the DVR may not be able to avoid tripping and even cause additional disturbances to the loads.

The control strategy should be able to compensate for any of voltage sag/swell and consider the limitation the DVR. Figure 3 shows the supply voltage vector during the pre-sag stage which is representeds as $V_{S,pre\text{-}sag}(t)$ on the $d_{pre\text{-}sag}$ axis, in which the rotating phase angle θ is derived from Phase Lock Loop (PLL) [9], [10]. Initially, the load voltage vector $V_L(t)$ is the same as $V_{S,pre\text{-}sag}(t)$ and is assumed to be 1.0 p.u. if the voltage drops across the series transformer are neglected. When the voltage sags occur, the actual source voltage vector $V_S(t)$ is moved to $V_{S,sag}(t)$. To restore the load voltage vector $V_L(t)$, an injected voltage vector $V_{inj}(t)$ is provided by the DVR. A similar compensation strategy can be drawn in the form of a phasor diagram for voltage swell as well.

Figure 4 shows the basic control scheme and parameters that are measured for control purposes. When the grid voltage is at its normal level the DVR is controlled to reduce the losses in the DVR to a minimum. When voltage sags/swells are detected, the DVR should react as fast as possible and inject an ac voltage to the grid. It can be implemented using a feedback control technique based on the voltage reference and instantaneous values of supply and load voltage. The control algorithm produces a three-phase reference voltage to the series converter that tries to maintain the load voltage at its reference value [10]-[12]. The voltage sag is detected by measuring the error between the *dq*-voltage of the supply and the reference values. The *d*-reference component is set to a rated voltage and the *q*-reference component is set to zero. The MATLAB/Simulink environment is a useful tool to implement this study because it has many tool boxes that can be used in this work and is easy to understand.

In Figure 4, the supply voltage is connected to a transformation block that converts stationary frame to αβ-frame. Output of this block is connected to a phase lock loop (PLL) and another transformation block that converts αβ-frame to rotating frame (*dq*), which detects the phase and changes the axis of the supply voltage. The detection block detects the voltage sag/swell. If voltage sag/swell occurs, this block generates the reference load voltage. The injection voltage is also generated by difference between the reference load voltage and supply voltage and is applied to the VSC to produce the preferred voltage, with the help of pulse width modulation (PWM).

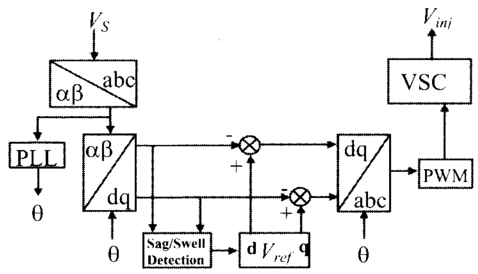

Fig. 4 Control structure of DVR.

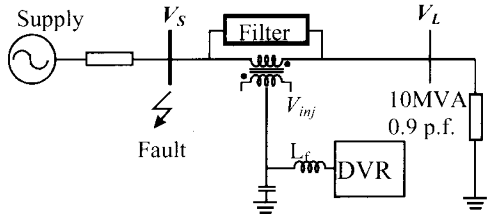

Fig. 5 Simple distribution network with DVR.

5. Simulation results

In order to understand the performance of the DVR along with control, a simple distribution network as shown in Figure 5, is implemented. Voltage sags/swells are simulated by temporary connection of different impedances at the supply side bus. A DVR is connected to the system through a series transformer with a capability to insert a maximum voltage of 50% of the phase-to-ground system voltage. Apart from this a series filter is also used to remove any high frequency components of power. The load considered in the study is a 10 MVA capacity with 0.9 p.f., lagging.

5.1 Voltage Sags

First, a case of symmetrical sag is simulated by connecting a three-phase reactance to the busbar. The results are shown in Figure 6. A 30% voltage sag is initiated at 400 ms and it is kept until 550 ms, with total voltage sag duration of 150 ms. Figure 6 (a), (b) and (c) show the series of voltage components injected by the DVR and compensated load voltage, respectively. As a result of DVR, the load voltage is kept at 1.00 p.u. throughout the simulation, including the voltage sag period. Observe that during normal operation, the DVR is doing nothing. It quickly injects necessary voltage components to smooth the load voltage upon detecting a voltage sag.

In order to understand the performance of the DVR under unbalanced conditions, a single-line-ground (SLG) fault at supply bus bar at 400 ms is simulated. As a result of SLG fault, an unbalanced voltage sag is created immediately after the fault as shown in Figure 7 (a), the supply voltage with two of the phase voltages dropped down to 80%. The DVR injected voltage and the load voltage are shown in Figure 7 (b) and (c), respectively. As can be seen from the results, the DVR is able to produce the required voltage components for different phases rapidly and help to maintain a balanced and constant load voltage at 1.00 p.u.

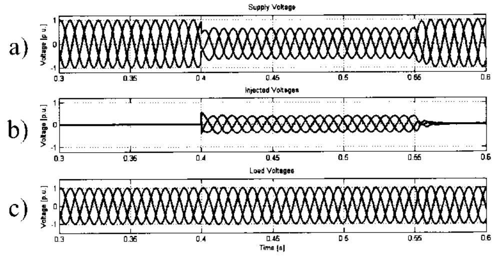

Fig. 6 Simulation result of DVR response to a balanced voltage sag.

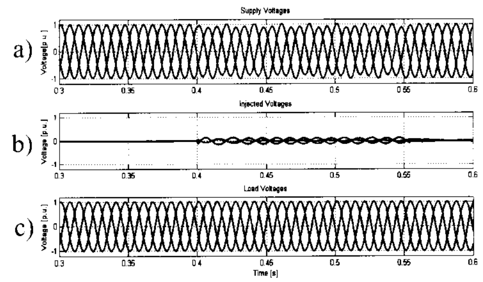

Fig. 7 Simulation result of DVR response to an unbalanced voltage sag.

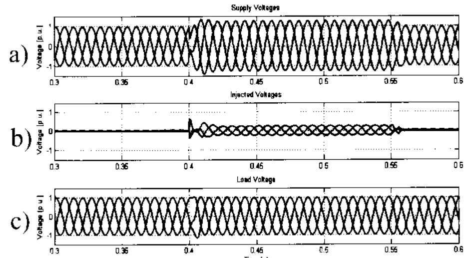

Fig. 8 Simulation results of DVR response to a balanced voltage swell.

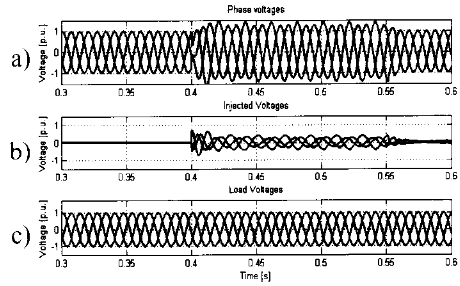

Fig. 9 Simulation result of DVR response to an unbalanced voltage swell.

5.2 Voltage Swells

Next, the performance of DVR for a voltage swell condition is investigated. Here, voltage swell is generated by energizing of a large capacitor bank and the corresponding supply voltage is shown in Figure 8 (a). The voltage amplitude is increased about 125% of nominal voltage. The injected voltage that is produced by DVR in order to correct the load voltage and the load voltage, are shown in Figure 8 (b) and (c), respectively. As can be seen from the results, the load voltage is kept at the nominal value with the help of the DVR. Similar to the case of voltage sag, the DVR reacts quickly to inject the appropriate voltage component (anti phase with the supply voltage or negative voltage magnitude) to correct the supply voltage.

The performance of the DVR with an unbalanced voltage swell is shown in Figure 9. In this case, the unbalanced voltage swell is created by partly rejecting the load. This results in an unbalanced voltage swell where two phase voltages are equal and the other phase voltage is slightly higher that the first two phases voltages. The anti phase unbalanced voltage component injected by the DVR to correct the load voltage is shown in Figure 9(b) and the load voltage is given in Figure 9(c). Notice the constant and balanced voltage at the load throughout the simulation, including during the unbalanced voltage swell event.

6. Conclusion

In this paper, performance of a DVR in mitigating voltage sags/swells is demonstrated with the help of MATLAB. A forced-commutated voltage sources converter is considered in the DVR along with energy storage to maintain the capacitor voltage. The DVR handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. In the case of a voltage sag, which is a condition of a temporary reduction in supply voltage, the DVR injects an equal positive voltage component in all three phases, which are in phase with the supply voltage to correct it. On the other hand, for a voltage swell case, which is a condition of a temporary increase in supply voltage, the DVR injects an equal negative voltage in all three phases, which are anti-phase with the supply voltage. For unbalanced conditions, the DVR injects an appropriate unbalanced three-phase voltage components positive or negative depending on whether the condition is an unbalanced voltage sag or unbalanced voltage swell.

7. References

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