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Fault Current Interruption by the Dynamic Voltage Restore

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ABSTRACT

This paper introduces and evaluates an auxiliary controlstrategy for downstream fault current interruption in a radialdistribution line by means of a dynamic voltage restorer(DVR).The proposed controller supplements the voltage-sag compensationcontrol of the DVR. It does not require phase-locked loop andindependently controls the magnitude and phase angle of the injectedvoltage for each phase. Fast least error squares digital filtersare used to estimate the magnitude and phase of the measuredvoltages and effectively reduce the impacts of noise, harmonics,and disturbances on the estimated phasor parameters, and this enableseffective fault current interrupting even under arcing faultconditions. The results of the simulation studies performed in thePSCAD/EMTDC software environment indicate that the proposedcontrol scheme: 1) can limit the fault current to less than the nominalload current and restore the point of common coupling voltagewithin 10 ms; 2) can interrupt the fault current in less than two cycles;3) limits the dc-link voltage rise and, thus, has no restrictionson the duration of fault current interruption; 4) performs satisfactorilyeven under arcing fault conditions; and 5) can interrupt thefault current under low dc-link voltage conditions.

INTRODUCTION

The Dynamic voltage restorer (DVR) is a custom power device utilized to counteract voltage sags. It injects controlled three-phase ac voltages in series with the supply voltage, subsequent to a voltage sag, to enhance voltage quality by adjusting the voltagemagnitude,waveshape, and phase angle. the main components of a DVR (i.e., a series transformer , a voltage- source converter (VSC), a harmonic filter, a dc-side capacitor , and an energy storage device. The line-side harmonic filter consists of the leakage inductance of the series transformer and the filter capacitor.The DVR is conventionally bypassed during a downstream fault to prevent potential adverse impacts on the fault and to protect the DVR components against the fault current. A technically elaborate approach to more efficient utilization of the DVR is to equip it with additional controls and enable it also to limit or interrupt the downstream fault currents. A control approach to enable a DVR to serve as a fault current limiter is provided in. The main drawback of this approach is that the dc-link voltage of the DVR increases due to real power absorption during fault current-limiting operation and necessitates a switch to bypass the DVR when the protective relays, depending on the fault conditions, do not rapidly clear the fault. The dc-link voltage increase can be mitigated at the cost of a slow-decaying dc fault current component using the methods introduce. To overcome the aforementioned limitations, this paper proposes an augmented control strategy for the DVR that provides: 1) voltage-sag compensation under balanced and unbalanced conditions and 2) a fault current interruption (FCI) function. The former function has been presented in and the latter is described in this paper. It should be noted that limiting the fault current by the DVR disables the main and the backup protection (e.g., the distance and the overcurrent relays). This can result in prolonging the fault duration. Thus, the DVR is preferred to reduce the fault current to zero and interrupt it and send a trip signal to the upstream relay or the circuit breaker (CB). It should be noted that the FCI function requires 100% voltage injection capability. Thus, the power ratings of the series transformer and the VSC would be about three times those of a conventional DVR with about 30%–40% voltage injection capability. This leads to a more expensive DVR system. Economic feasibility of such a DVR system depends on the importance of the sensitive load protected by the by the DVR and the cost of the DVR itself. The performance of the proposed control scheme is evaluated through various simulation studies in the Matlab/simulation platform. The study results indicate that the proposed control strategy: 1) limits the fault current to less than the nominal load current and restores the PCC voltage within less than 10 ms, and interrupts the fault current within two cycles; 2) it can be used in four- and three-wired distribution systems, and single-phase configurations; 3) does not require phase-locked loops; 4) is not sensitive to noise, harmonics, and disturbances and provides effective fault current interruption even under arcing fault conditions; and 5) can interrupt the downstream fault current under low dc-link voltage conditions.

DYNAMIC VOLTAGE RESTORES:

Dynamic voltage restores (DVRs) are nowbecoming more established in industry to reduce theimpact of voltage dips on sensitive loads. A voltagedip is commonly defined as any low voltage drop eventbetween 10% and 90% of the nominal RMS voltage,lasting between 0.5 cycles and 1 min. In comparisonwith interruptions, voltage dips affect a large number ofcustomers and for some cases may cause extremely serious problems. voltage dips are one of the mostoccurring power quality problems. They occur moreoften and cause severe problems and economical losses.There are different ways to mitigate voltage dips, swellsand interruptions in transmission and distributionsystems. At present, a wide range of very flexiblecontrollers which capitalize on newly available powerelectronics components are emerging for custom powerapplications. Among these, the distribution staticcompensator and the dynamic voltage restorer are themost effective devices; both of them based on thevoltage source converter (SVC) principle.

Figure 1 shows a typical DVR series connectedtopology. The DVR essentially consists of a seriesinverter (VSI), inverter output filter and an energystorage device connected to the DC link.The basic operation principle of the DVR is toinject an appropriate voltage in series with the supplythrough injection transformer whenever voltage sag orvoltage swell is detected. In addition to voltage sagsand swells compensation, DVR can also perform other tasks such as harmonic compensation and Power Factorcorrection. Compared to the other Custom Powerdevices, the DVR clearly provides the best economicsolution for its size and capabilities.

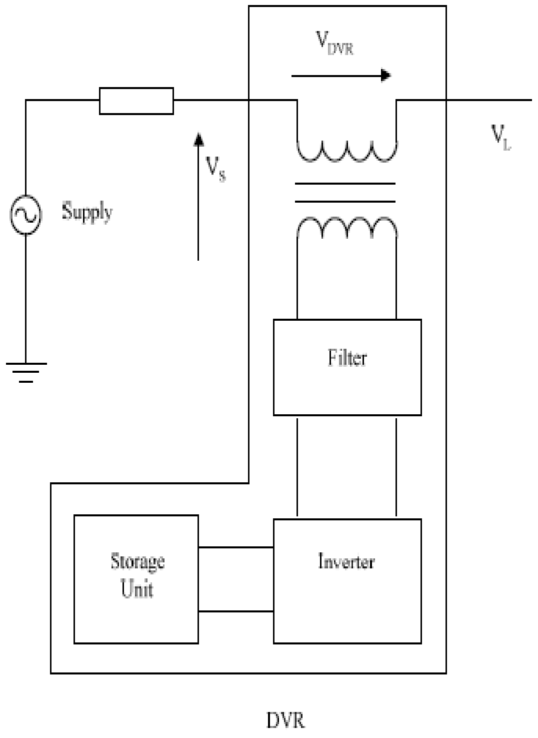

Fig. 1: DVR series connected topology

This research introduced Dynamic VoltageRestorer (DVR) and its voltage compensation methods.At the end, simulation results using MATLAB wereillustrated and discussed.

DYNAMIC VOLTAGE RESTORER

A Dynamic Voltage Restorer (DVR) is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996. It is normally installed in a distribution system between the supply and the critical load feeder. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load. There are various circuit topologies and control schemes that can be used to implement a DVR. In addition to voltage sags and swells compensation, DVR can also perform other tasks such as: line voltage harmonics compensation,reduction of transients in voltage and fault current limitations.

The general configuration of the DVR consists of an Injection/Booster transformer, a Harmonic filter, a Voltage Source Converter (VSC), DC charging circuit and a Control and Protection system as shown in Fig 1.

CONVENTIONAL DVR VOLTAGE INJECTION METHODS

The possibility of compensating voltage sag can be limited by a number of factors including finite DVR power rating, different load conditions and different types of voltage sag. Some loads are very sensitive to phase angle jump and others are tolerant to it. Therefore, the control strategy depends on the type of load characteristics. There are three distinguishing methods to inject DVR compensating voltage:

Pre-Dip Compensation (PDC):

The PDC method tracks supply voltage continuously and compensates load voltage during fault to pre-fault condition. In this method, the load voltage can be restored ideally, but the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions. The lack of the negative sequence detection in this method leads to the phaseoscillation in the case of single-line faults. Figure 2 shows the single-phase vector diagram of this method.

According to Fig. 2, the apparent power of DVR is:

$$S_{1DVR} = I_L V_{1DVR}$$
$$= I_L \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

And the active power of DVR is:

$$P_{1DVR} = I_L (V_L \cos\theta_L - V_S \cos\theta_S)$$

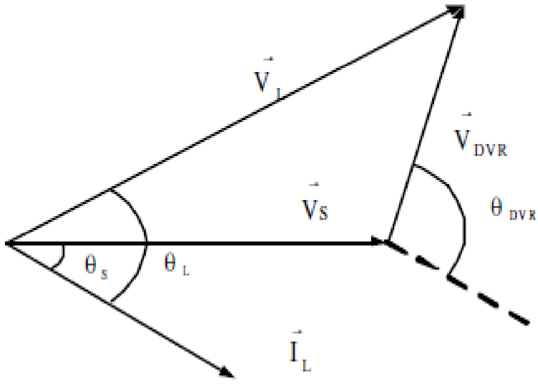

Fig. 2: Single-phase vector diagram of the PDC method

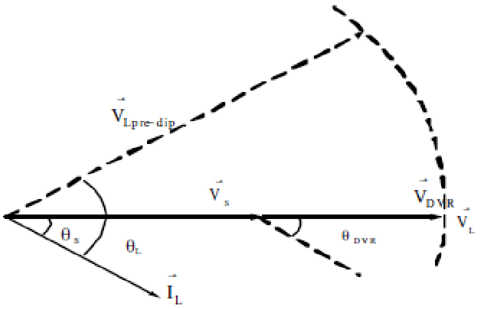

Fig. 3: Single-phase vector diagram of the IPC method

The magnitude and the angle of the DVR voltage are:

$$V_{1DVR} = \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

$$\theta_{1DVR} = \tan^{-1}\left(\frac{V_L \sin\theta_L - V_S \sin\theta_S}{V_L \cos\theta_L - V_S \cos\theta_S}\right)$$

In-Phase Compensation (IPC):

This is the most used method in which the injected DVR voltage is in phase with the supply side voltage regardless of the load current and the pre-fault voltage as shown in Fig. 3. The IPC method is suitable for minimum voltage or minimum energy operation strategies[10]. In other word,this approach requires large amounts of real power to mitigate the voltage sag, which means a large energy storage device.

The apparent and active powers of DVR are:

$$S_{2DVR} = I_L V_{DVR} = I_L \left(V_L - V_S \right)$$

$$P_{2DVR} = I_L V_{DVR} \cos\theta_S = I_L \left(V_L - V_S \right) \cos\theta_S$$

The magnitude and the angle of the DV voltage are:

$$V_{2DVR} = V_L - V_S$$
$$\theta_{2DVR} = \theta_S$$

In-Phase Advance Compensation (IPAC): Pre-Dip and in-phase compensation method must inject active power to loads to correct voltage disturbance. However,the amount of possible injection active power is confined to the stored energy in DC link, which is one of the most expensive components in DVR. Due to the limit of energy storage capacity of DC link, the DVR restoration time and performance are confined in these methods.

For the sake of controlling injection energy, in phase advance compensation method was proposed. The injection active power is made zero by means of having the injection voltage phasor perpendicular to the load current phasor. This method can reduce the consumption of energy stored in DC link by injecting reactive power instead of active power. Reducing energy consumption means that ride-through ability is increased when the energy storage capacity is fixed. On the other hand, the injection voltage magnitude of inphase advance compensation method is larger than those of pre-dip or in-phase compensation methods and the voltage phase shift can cause voltage waveform discontinuity, inaccurate zero crossing and load power swing. Therefore, in phase advance compensation method should be adjusted to the load that is tolerant to phase angle jump, or transition period should be taken while phase angle is moved from pre-fault angle to advance angle.

In short, IPAC method uses only reactive power and unfortunately, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags.

SIMULATION RESULTS:

In order to show the performance of the DVR in voltage sags and swells mitigation, a simple distribution network was simulated using MATLAB (Fig. 1). A DVR was connected to the system through a series transformer with a capability to insert a maximum voltage of 50% of the phase to ground system nominal voltage. In this simulation the In-Phase Compensation (IPC) method was used. The load considered in the study is a 5.5 MVA capacity with 0.92 p.f, lagging.Voltage sags: A case of Three-phase voltage sag was simulated and the results are shown in Fig. 4. Figure 4a shows a 50% voltage sag initiated at 100 ms and it is kept until 300 ms, with total voltage sag duration of 200 ms. Figure 4b and c show the voltage injected by the DVR and the compensated load voltage, respectively.As a result of DVR, the load voltage is kept at 1 p.u. throughout the simulation, including the

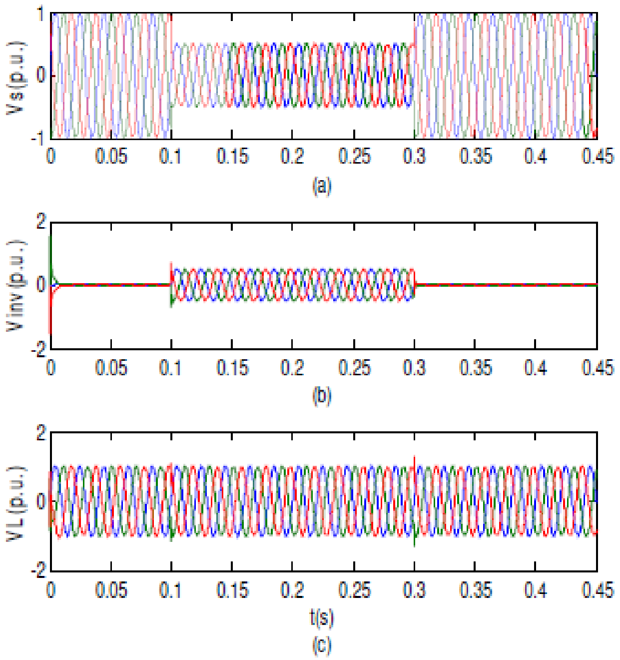

Fig. 4: Three-phase voltage sag; (a): Source voltages, (b): Injected voltages; (c): Load voltages

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 voltage sag. In order to understand the performance of the DVR under unbalanced conditions, Single-phase voltage sag was simulated and the results are shown in Fig. 5. The supply voltage with one phase voltage dropped down to 50% is shown in Fig. 5a. The DVR injected voltage and the load voltage are shown in Fig. 5b and c,respectively. As can be seen from the results, the DVR was able to produce the required voltage component rapidly and helped to maintain a balanced and constant load voltage at 1.00 p .u.

Voltage swells: The performance of DVR for a voltage swell condition was investigated. Here, the supply voltage swell was generated as shown in Fig. 6a. The supply three-phase voltage amplitudes were increased about 125% of nominal voltage. The injected threesphase voltage that was produced by DVR in order to correct the load voltage and the load voltage are shown in Fig. 6b and c, respectively. As can be seen from the results, the load voltage was kept at the nominal value with the help of the DVR. Similar to the case of voltage sag, the DVR reacted quickly to inject the appropriate voltage component (negative voltage magnitude) to correct the supply voltage.

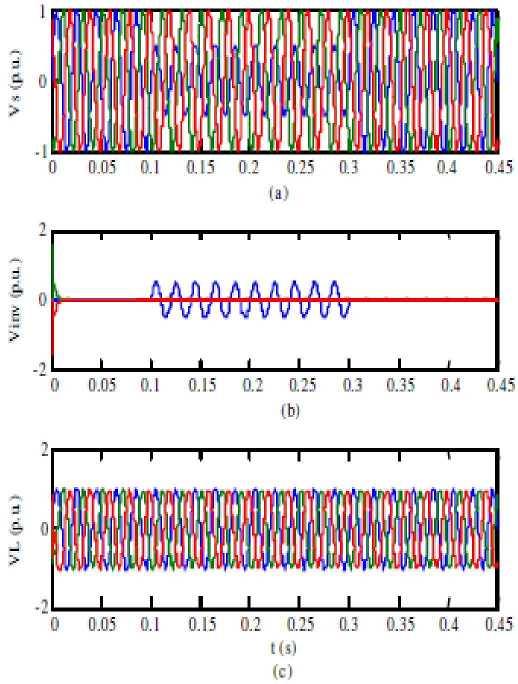

Fig. 5: Single-phase voltage sag; (a): Source voltages; (b): Injected voltage, (c): Load voltages

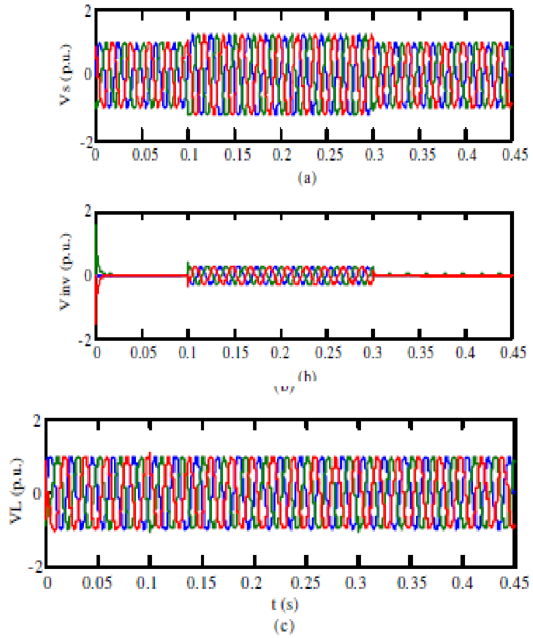

Fig. 6: Three-phase voltage swell; (a): Source voltages; (b): Injected voltages; (c): Load voltages

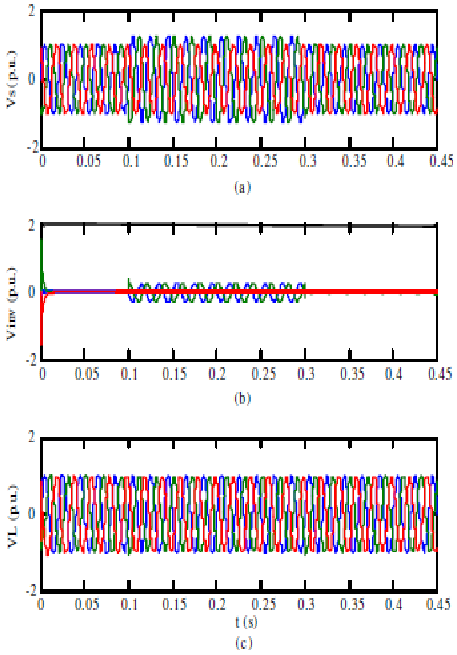

Fig. 7: Two-phase voltage swell; (a): Source voltages; (b): Injected voltages; (c): Load voltages

The performance of the DVR with an unbalanced voltage swell is shown in Fig. 7. In this case, two of the three phases are higher by 25% than the third phase as shown in Fig. 7a. The injected voltage that was produced by DVR in order to correct the load voltage and the load voltage are shown in Fig. 7b and c,respectively. Notice the constant and balanced voltage at the load throughout the simulation, including during the unbalanced voltage swell event.

CONCLUSION

The simulation results showed clearly the performance of the DVR in mitigating voltage sags and swells. The DVR handled both balanced and unbalanced situations without any difficulties and injected the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. The efficiency and the effectiveness in voltage sags/swells compensation showed by the DVR makes him an interesting power quality device compared to other custom power devices.

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