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Emergency Control Using Multifunctional DVR for Distribution Systems

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Abstract
This paper discusses a new multifunctional dynamic voltage restorer (DVR) and closed loop controller using the Posicast and P+Resonant controllers. The closed loop controller using the Posicast and P+Resonant controllers is proposed in order to improve the transient response and eliminate the steady-state error in DVR response, respectively. The proposed algorithm is applied to some disturbances in load voltage caused by induction motors starting, and a three-phase short circuit fault. Also, the capability of the proposed DVR has been tested to limit the downstream fault current. The current limitation will restore the point of common coupling (PCC) (the bus to which all feeders under study are connected) voltage and protect the DVR itself. The innovation here is that the DVR acts as virtual impedance with the main aim of protecting the PCC voltage during downstream fault without any problem in real power injection into the DVR. Results of the simulation studies in the MATLAB/SIMULINK software environment indicate that the proposed control scheme with faults and induction motor under multifunctional DVR.

I. Introduction

Electric power quality is capacity of an electric power system to supply electric energy of a load in an acceptable quality. Power distribution system should provide with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency to their customers. Power systems especially distribution systems, have numerous non linear loads, which significantly affect the quality of power. Apart from non linear loads like capacitor switching, motor starting and unusual faults could also inflict power quality problems. Many problems can result from poor power quality (PQ), especially in today's complex power system, such as the false operation of modern control systems. Voltage sag is an important PQ problem because of sensitive loads growth. Worldwide experience has showed that short circuit faults are the main origin of voltage sag; therefore there is a loss of voltage quality [1]-[2].

Voltage sag is defined as a sudden reduction in supply voltage to between 90% and 10% of the nominal value, followed by a recovery after a short interval (the standard duration of sag is between 10 milliseconds and 1 minute). The most common compensator for voltage sag is the dynamic voltage restorer (DVR). The basic operation of the DVR is based on injection of a compensation voltage with required magnitude, phase angle and frequency in series with the sensitive electric distribution feeder.

Previous works have been done on different aspects of DVR performance, and different control strategies have been found. These methods mostly depend on the purpose of using DVR. In some methods, the main purpose is to detect and compensate for the voltage sag with minimum DVR active power injection [4], [5]. Also, the in-phase compensation method can be used for sag and swell mitigation [6]. The multiline DVR can be used for eliminating the battery in the DVR structure and controlling more than one line [7], [14]. Moreover, research has been made on using the DVR in medium level voltage [8]. Harmonic mitigation [9] and control of DVR under frequency variation [10] are also in the area of research. The closed-loop control with load voltage and current feedback is introduced as a simple method to control the DVR in [15]. Also, Posicast and P+Resonant controllers can be used to improve the transient response and eliminate the steady-state error in DVR. The Posicast controller is a kind of step function with two parts and is used to improve the damping of the transient oscillations initiated at the start instant from the voltage sag. The P+Resonant controller consists of a proportional function plus a resonant function and it eliminates the steady-state voltage tracking error [6]. The state feed forward and feedback methods [7], symmetrical components estimation [8], robust control [10], and wavelet transform [12] have also been proposed as different methods of controlling the DVR.

The basis of the proposed control strategy in this paper is that when the fault current does not pass through the DVR, an outer feedback loop of the load voltage with an inner feedback loop of the filter capacitor current will be used. Also, a feed forward loop will be used to improve the dynamic response of the load voltage. Moreover, to improve the transient response, the Posicast controller and to eliminate the steady-state error, the P+Resonant controller are used. But in case the fault current passes through the DVR, using the flux control algorithm [11], the series voltage is injected in the opposite direction and, therefore, the DVR acts like series variable impedance.

II. Dynamic Voltage Restorer

Dynamic voltage restorer was originally proposed to compensate for voltage disturbances on distribution systems. A typical DVR scheme is shown in Fig. 1. The restoration is based on injecting AC voltages in series with the incoming three-phase network, the purpose of which is to improve voltage quality by adjustment in voltage magnitude, wave-shape, and phase shift. As shown in Fig. 1, the DVR essentially consists of a series-connected injection transformer T_i, a voltage-source inverter (VSI), a harmonic filter, and an energy storage device [4], [13]. Meanwhile, a parallel switch is used to bypass and protect the DVR, when a downstream fault is detected [14], [15]. As shown in Fig. 1, the line-side harmonic filter topology [11] consists of the leakage inductance of the injection transformer and the filter capacitor. Meanwhile, denotes the dc-link capacitor.

The series injected voltage of the DVR, Vdvr, is synthesized by modulating pulse widths of the inverter-bridge switches. The injection of an appropriate Vdvr in the face of an up-stream voltage disturbance requires a certain amount of real and reactive power supply from the DVR. The reactive power requirement is generated by the inverter.

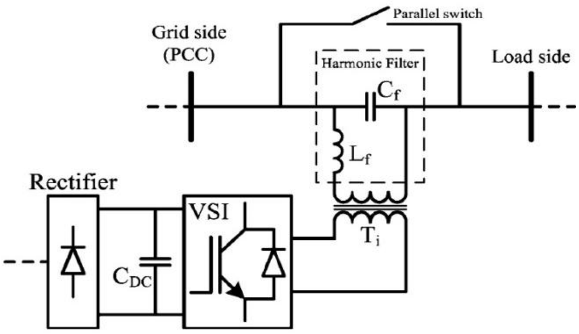


Fig. 1: schematic diagram of the DVR with line side harmonic filter

Widely used in present DVR control is the so-called in phase voltage injection technique where the load voltage V2 is assumed to be in-phase with the pre-sag voltage. As the DVR is required to inject active power into the distribution line during the period of compensation, the capacity of the energy storage unit can become a limiting factor in the disturbance compensation process. In particular, if capacitors are used as energy storage, the DC-link voltage will decrease with the dwindling storage energy during compensation.

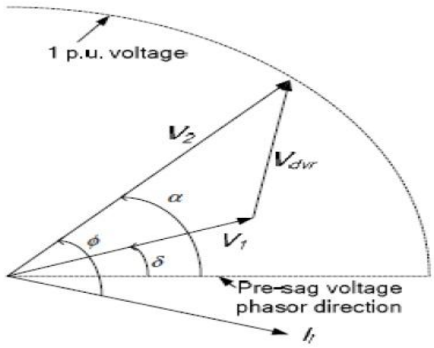


Fig. 2; Vector Diagram of Voltage Injection Method

The corresponding phasor diagram describing the electrical conditions during voltage sag is depicted, where only the affected phase is shown for clarity. Let the voltage quantities Il, φ, δ and α represent the load current, load power factor angle, supply voltage phase angle and load voltage advance angle respectively. Although there is a phase advancement of α in the load voltage with respect to the pre-sag voltage in Fig. 2, only in-phase compensation where the injected voltage is in phase with the supply voltage ($\alpha = \delta$) is considered.

By mounting the battery in DC link of the centralized inverter, the DC/DC converter for battery can be saved as shown in Figure 1(b) [1], [2]. Different from the centralized inverters in Figure 1(a) and (b), the separate grid inverters are used by the two PV systems in Figure 1(c). Thus, the power rating of each inverter becomes smaller, and the inverter is intended to be modular design as well as mass production.

III. Proposed Multifunctional DVR

In addition to the aforementioned capabilities of DVR, it can be used in the medium-voltage level as in Fig. 2 to protect a group of consumers when the cause of disturbance is in the downstream of the DVR's feeder and the large fault current passes through the DVR itself. In this case, the equipment can limit the fault current and protect the loads in parallel feeders until the breaker works and disconnects the faulted feeder.

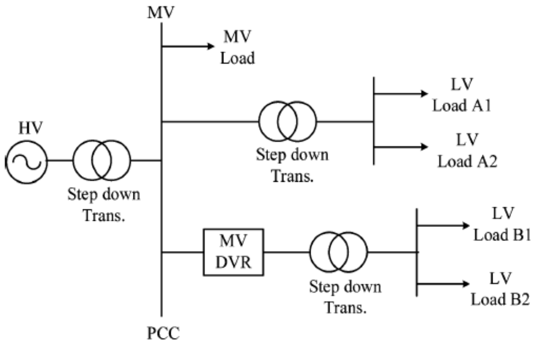


Fig. 2: A multifunctional DVR connected in a medium-voltage level power system.

The large fault current will cause the PCC voltage to drop and the loads on the other feeders connected to this bus will be affected. Furthermore, if not controlled properly, the DVR might also contribute to this PCC voltage sag in the process of compensating the missing voltage, hence further worsening the fault situation [11].

To limit the fault current, a flux-charge model has been proposed and used to make DVR act like a pure virtual inductance which does not take any real power from the external system and, therefore, protects the dc-link capacitor and battery as shown in Fig. 1 [11]. But in this model, the value of the virtual inductance of DVR is a fixed one and the reference of the control loop is the flux of the injection transformer winding, and the PCC voltage is not mentioned in the control loop. In this paper, the PCC voltage is used as the main reference signal and the DVR acts like variable impedance. For this reason, the absorption of real power is harmful for the battery and dc-link capacitor. To solve this problem, impedance including a resistance and an inductance will be connected in parallel with the dc-link capacitor. This capacitor will be separated from the circuit, and the battery will be connected in series with a diode just when the downstream fault occurs so that the power does not enter the battery and the dc-link capacitor. It should be noted here that the inductance is used mainly to prevent large oscillations in the current. The active power mentioned is, therefore, absorbed by the impedance.

3.1 Proposed control scheme for using Flux charge model

In this part, an algorithm is proposed for the DVR to restore the PCC voltage, limit the fault current, and, therefore, protect the DVR components. The flux-charge model here is used in a way so that the DVR acts as a virtual inductance with a variable value in series with the distribution feeder. To do this, the DVR must be controlled in a way to inject a proper voltage having the opposite polarity with respect to usual cases. It should be noted that over current tripping is not possible in this case, unless additional communication between the DVR and the downstream side over current circuit breaker (CB) is available. If it is necessary operate the over current CB at PCC, communication between the DVR and the PCC breaker might have to be made and this can be easily done by sending a signal to the breaker when the DVR is in the fault-current limiting mode as the DVR is just located after PCC [11]. The proposed DVR control method is illustrated in Fig. 8. It should also be noted that the reference flux (ϕ_{ref}) is derived by integration of the subtraction of the PCC reference voltage (V_{PCC}^{*}) and the DVR load-side voltage. This control strategy, the control variable used for the outer flux model is the inverter-filtered terminal flux defined as:

$$\Phi = \int V_{\mathrm{odvr}} \mathrm{dt} \quad (1)$$

Where V_{odvr} is the filter capacitor voltage of the DVR (at the DVR power converter side of the injection transformer). The flux error is then fed to the flux regulator, which is a P+Resonant controller, with a transfer function given in (1). On the other hand, it can be shown that a single flux-model would not damp out the resonant peak of the LC filter connected to the output of the inverter.

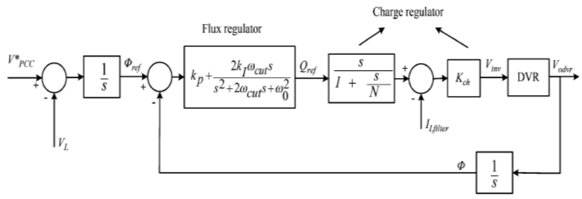


Fig. 3: Proposed method.

To stabilize the system, an inner charge model is therefore considered. In this loop, the filter inductor charge, which is derived by integration of its current, tracks the reference charge output of the flux regulator. The calculated charge error is then fed to the charge regulator with the transfer function

$$G_{\text{charge}}(s) = k_{Ch} \frac{S}{1 + \frac{S}{N}}$$

This is actually a practical form of the derivative controller. In this transfer function, the regulator gain is limited to N at high frequencies to prevent noise amplification. The derivative term in $S/_{1} + S/_{N}$ neutralizes the effects of voltage and current integrations at the inputs of the flux-charge model, resulting in the proposed algorithm having the same regulation performance as the multiloop voltage-current feedback control, with the only difference being the presence of an additional low–pass filter in the flux control loop in the form of $1/_{S} + S/_{N}$. The bandwidth of this low–pass filter is tuned (through varying N) with consideration for measurement noise attenuation, DVR LC-filter transient resonance attenuation, and system stability margins.

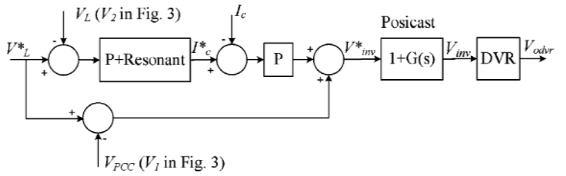


Fig. 4: Multi-loop control using the Posicast and P+Resonant controller

Theoretically, the resonant controller compensates by introducing an infinite gain at the resonant frequency of 50 Hz to force the steady-state voltage error to zero. The ideal resonant controller, however, acts like a network with an infinite quality factor, which is not realizable in practice. A more practical (nonideal) compensator is therefore used here, and is expressed as

$$G_R(s) = k_p + \frac{2k_I \omega_{cut} S}{S^2 + 2\omega_{cut} S + \omega_0^2}$$

Where w_{cut} is the compensator cutoff frequency which is 1 rad/s in this application.

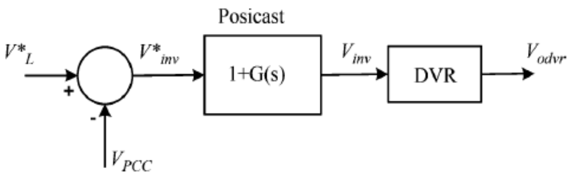


Fig. 5: Open loop control using the Posicast controller

To improve the damping, as shown in Fig. 4, the Posicast controller can be used just before transferring the signal to the PWM inverter of the DVR. The transfer function of the controller can be described as follows:

$$1 + G(s) = 1 + \frac{\delta}{1+\delta}\left(e^{-S^{T_d/2}} - 1\right)$$

Where δ and T_d are the step response overshoot and the period of damped response signal, respectively. It should be noted that the Posicast controller has limited high-frequency gain; hence, low sensitivity to noise.

IV. MATLAB/Simulink modelling and results

In this section, the proposed DVR topology and control algorithm will be used for emergency control during the voltage sag. The three-phase short circuit and the start of a three-phase large induction motor will be considered as the cause of distortion in the simulations.

4.1 Fault Current Limiting

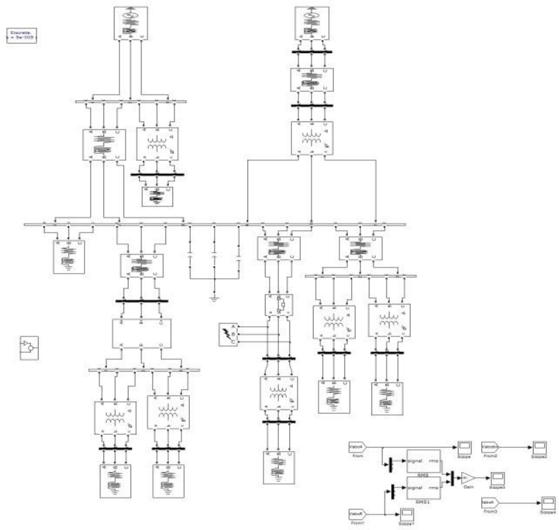
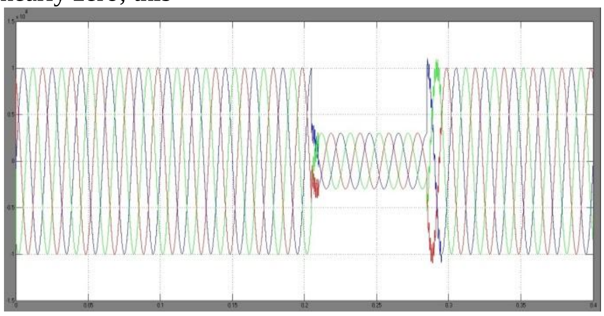


Fig. 6: SIMULINK Model of Proposed a Multifunctional DVR under Three Phase Fault condition.

MATLAB/simulink model of proposed multifunctional DVR under three phase fault in figure.6; The last simulation is run for a symmetrical downstream fault, and the capability of the DVR to reduce the fault current and restore the PCC voltage is tested.

For the simulation with DVR compensation, the three-phase fault is applied at t = 205 ms and then removed after 0.1 s. Also, a breaker will remove the faulted bus from the entire system at t = 300 ms. Fig. 13 shows the DVR operation during the fault. As can be seen, the rms load bus voltage reaches zero during the fault, and as the enlarged figure shows, in about half a cycle, the

DVR has succeeded in restoring the PCC voltage wave shape to the normal condition. It should be noted that the amount and shape of the oscillations depend on the time of applying the fault. As Fig. 13 shows, at this time, the voltage value of phase B is nearly zero; this



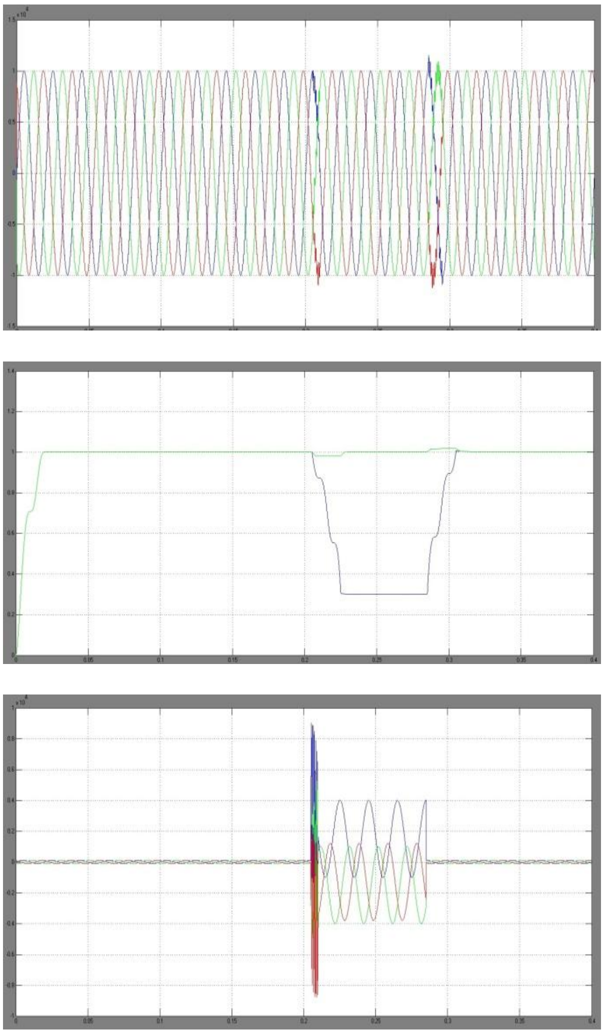


Fig. 7: Fault current limiting by DVR. (a) Three-phase PCC voltages. (b) Three-phase load voltages. (c) RMS voltages of the PCC and load. (d) Three-phase currents.

4.2 Induction Motor

The large motor starting current will cause the PCC voltage to drop. The simulation results in the case of using the DVR are shown in Fig. 9. In this simulation, the motor is started at t = 405 ms. As can be seen in Fig. 11, at this time, the PCC rms voltage drops to about 0.8 p.u. The motor speed reaches the nominal value in about 1 s. MATLAB/simlink model of proposed multifunctional DVR with induction motor in figure8;

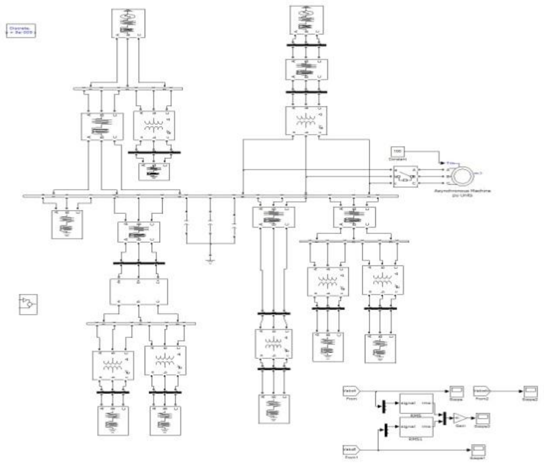


Fig. 8: SIMULINK model of proposed a multifunctional DVR with Induction Motor.

During this period, the PCC bus is under voltage sag. From t = 1.4 s, as the speed approaches nominal, the voltage also approaches the normal condition. However, during all of these events, the DVR keeps the load bus voltage at the normal condition. The DVR has succeeded in restoring the load voltage in half a cycle from the instant of the motor starting.

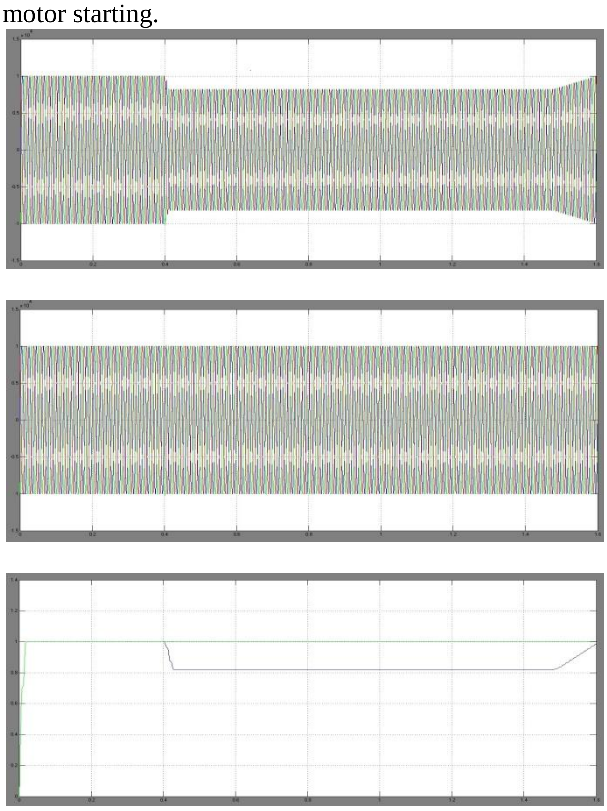


Fig. 9: Starting of an induction motor and the DVR compensation. (a) Three phase PCC voltages. (b) Three-phase load voltages. (c) RMS voltages of PCC and load.

V. CONCLUSION

In this paper, a multifunctional DVR is proposed, and a closed-loop control system is used for its control to improve the damping of the DVR response. Also, for further improving the transient response and eliminating the steady-state error, the Posicast and P+Resonant controllers are used. As the second function of this DVR, using the flux-charge model, the equipment is controlled so that it limits the downstream fault currents and protects the PCC voltage during these faults by acting as variable impedance. The problem of absorbed active power is solved by entering impedance just at the start of this kind of fault in parallel with the dc-link capacitor and the battery being connected in series with a diode so that the power does not enter it. The simulation results verify the effectiveness and capability of the proposed DVR in compensating for the voltage sags caused by short circuits and the large induction motor starting and limiting the downstream fault currents and protecting the PCC voltage.

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