Very Fast Multifunctional Dynamic Voltage Restorer Implementation for Emergency Control and protect consumers in Distribution Systems

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Abstract
The dynamic voltage restorer (DVR) is one of the modern devices used in distribution systems to protect consumers against sudden changes in voltage amplitude. In this paper, emergency control in distribution systems is discussed by using the proposed multifunctional DVR control strategy. Also, the multiloop 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. Simulation results show the capability of the DVR to control the emergency conditions of the distribution systems.

I. INTRODUCTION
Voltage sag and voltage swell are two of the most important power-quality (PQ) problems that encompass almost 80% of the distribution system .voltage sag, it can be found that this is a transient phenomenon whose causes are classified as low- or medium-frequency transient events. In recent years, considering the use of sensitive devices in modern industries, different methods of compensation of voltage sags have been used. One of these methods is using the DVR to improve the PQ and compensate the load voltage.

The state feed forward and feedback methods, symmetrical components estimation, robust control, and wavelet transform have also been proposed as different methods of controlling the DVR In all of the aforementioned methods, the source of disturbance is assumed to be on the feeder which is parallel to the DVR feeder. In this paper, a multifunctional control system is proposed in which the DVR protects the load voltage using Posicast and P+Resonant controllers when the source of disturbance is the parallel feeders. On the other hand, during a downstream fault, the equipment protects the PCC voltage, limits the fault current, and protects itself from large fault current. Although this latest condition has been described in using the flux control method, the DVR proposed there acts like a virtual inductance with a constant value so that it does not receive any active power during limiting the fault current. But in the proposed method when the fault current passes through the DVR, it acts like series variable impedance (unlike where the equivalent impedance was a constant).

DVR
The major objectives are to increase the capacity utilization of distribution feeders (by minimizing the rms values of the line currents for a specified power demand), reduce the losses and improve power quality at the load bus. The major assumption was to neglect the variations

In the source voltages. This essentially implies that the dynamics of the source voltage is much slower than the load dynamics.

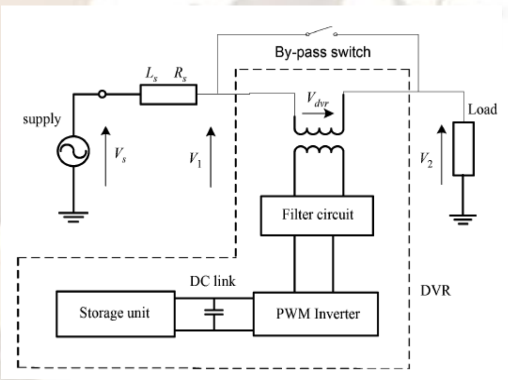


Fig.1Typical DVR-connected distribution system

When the fast variations in the source voltage cannot be ignored, these can aect the performance of critical loads such as (a) semiconductor fabrication plants (b) paper mills (c) food processing plants and (d) automotive assembly plants. The most common disturbances in the source voltages are the voltage sags or swells that can be due to (i) disturbances arising in the transmission system, (ii) adjacent feeder faults and (iii) fuse or breaker operation.

Voltage sags of even 10% lasting for 5-10 cycles can result in costly damage in critical loads. The voltage sags can arise due to symmetrical or unsymmetrical faults. In the latter case, negative and zero sequence components are also present. Uncompensated nonlinear loads in the distribution system can cause

harmonic components in the supply voltages. To mitigate the problems caused by poor quality of power supply, series connected compensators are used.

II. Voltage Source Converter (VSC)

This could be a 3 phase - 3wire VSC or 3 phaes - 4 wires VSC. The latter permits the injection of zero-sequence voltages. Either a conventional two level converter (Graetz bridge) or a three level converter is used.

III. Boost or Injection Transformers

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower voltage level) to the higher distribution voltage level. The three single transformers can be connected with star/open star winding or delta/open star winding. The latter does not permit the injection of the zero sequence voltage. The choice of the injection transformer winding depends on the connections of the step down transformer that feeds the load. If a ¢ ¡ Y connected transformer (as shown in Fig. 14.1) is used, there is no need to compensate the zero sequence volt- ages.

IV. Passive Filters

The passive filters can be placed either on the high voltage side or the converter side of the boost transformers. The advantages of the converter side filters are (a) the components are rated at lower voltage and (b) higher order harmonic currents (due to the VSC) do not °own through the transformer windings. The disadvantages are that the filter inductor causes voltage drop and phase (angle) shift in the (fundamental component of) voltage injected. This can affect the control scheme of DVR. The location of the filter o the high voltage side overcomes the drawbacks (the leakage reactance of the transformer can be used as a filter inductor), but results in higher ratings of the transformers as high frequency currents can flow through the windings.

V. Energy Storage

This is required to provide active power to the load during deep voltage sags. Lead-acid batteries, °wheels or SMES can be used for energy storage. It is also possible to provide the required power on the DC side of the VSC by an auxiliary bridge converter that is fed from an auxiliary AC supply .

Basic Operational Principle of DVR

The DVR system shown in Fig. 1, controls the load voltage by injecting an appropriate voltage phasor (V_{dvr}) in series with the system using the injection series transformer. In most of the sag compensation techniques, it is necessary that during compensation, the DVR injects some active power to the system. Therefore, the capacity of the storage unit can be a limiting factor in compensation, especially during long-term voltage sags.

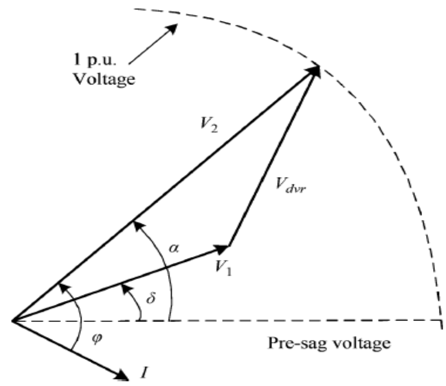


Fig. 2. Phasor diagram of the electrical conditions during voltage sag.

The phasor diagram in Fig. 2 shows the electrical conditions during voltage sagwhere, for clarity, only one phase is shown. Voltages v1, v2, and Vdvr are the source-side voltage, the load side voltage, and the DVR injected voltage, respectively. Also, the operators I, ϕ, δ, and α are the load current, the load power factor angle, the source phase voltage angle, and the voltage phase advance angle, respectively [24]. It should be noted that in addition to the in-phase injection technique, another technique, namely "the phase advance voltage compensation technique" is also used [24]. One of the advantages of this method over the in-phase method is that less active power should be transferred from the storage unit to the distribution system. This results in compensation for deeper sags or sags with longer durations.

Due to the existence of semiconductor switches in the DVR inverter, this piece of equipment is nonlinear. However, the state equations can be linearized using linearization techniques. The dynamic characteristic of the DVR is influenced by the filter and the load. Although the modeling of the filter (that usually is a simple LC circuit) is easy to do, the load modeling is not as simple because the load can vary from a linear time invariant one to a nonlinear time-variant one. In this paper, the simulations are performed with two types of loads: 1) a constant power load and 2) a motor load.

As Fig. 3 shows, the load voltage is regulated by the DVR through injecting V_{dvr}. For simplicity, the bypass switch shown in Fig. 1 is not presented in this figure. Here, it is assumed that the load has a resistance Rl and an inductance L_l . The DVR harmonic filter has an inductance of Lf, a resistance of Rf , and a capacitance of Cf . Also, the DVR injection transformer has a combined winding resistance *of* Rt a leakage inductance of Lf, and turns ratio of 1:n.

The Posicast controller is used in order to improve the transient response. Fig. 4 shows a typical control block diagram of the DVR. Note that because in real situations, we are dealing with multiple feeders connected to a common bus, namely "the

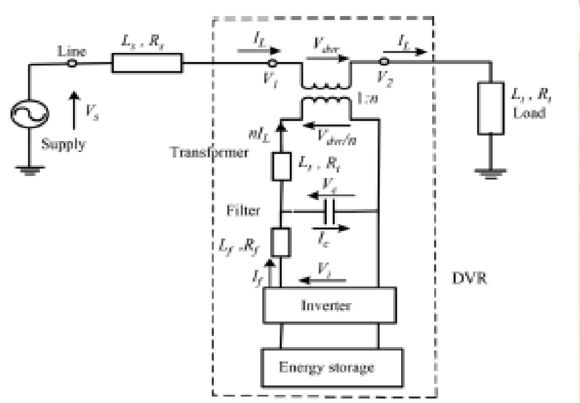


Fig.3 Distribution system with the DVR.

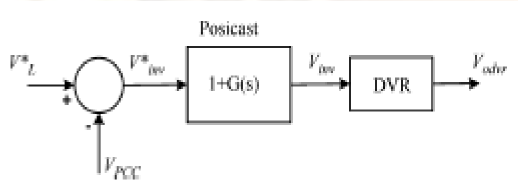


Fig. 4. Open-loop control using the Posicast controller.

Point of Common Coupling (PCC)," from now on V1 and V2 will be replaced with Vpcc and Vl, respectively, to make a generalized sense. As shown in the figure, in the open-loop control, the voltage on the source side of the DVR Vpcc is compared with a load-side reference voltage VL so that the necessary injection voltage V^*_{inv} is derived. A simple method to continue is to feed the error signal into the PWM inverter of the DVR. But the problem with this is that the transient oscillations initiated at the start instant from the voltage sag could not be damped sufficiently. 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:

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

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.

$$\begin{aligned}
V_i &= V_c + I_f R_f + L_f \frac{dI_f}{dt}\\
I_f &= I_c + n.I_l\\
I_c &= C_f \frac{dV_c}{dt}\\
V_{dvr} &= n\left[V_c - n\left(R_t I_t + L_t \frac{dI_t}{dt}\right)\right]\\
V_2 &= V_1 + V_{dvr}.
\end{aligned}$$

Then, according to (2) and the definitions of damping and the delay time in the control literature δ , and T_d are derived as follows:

$$T_d = \frac{2\pi}{\omega_r} = \frac{\pi}{\sqrt{\frac{1}{L_f C_f} - \frac{R_f^2}{4L_f^2}}}$$

$$\delta = e^{\xi\pi/\sqrt{1-\xi^2}} = e^{-R_f\pi\sqrt{C_f}/\sqrt{4L_f-R_f^2C_f}}.$$

The Posicast controller works by pole elimination and proper regulation of its parameters is necessary. For this reason, it is sensitive to inaccurate information of the system damping resonance frequency. To decrease this sensitivity, as is shown in Fig. 5, the open-loop controller can be converted to a closed loop controller by adding a multiloop feedback path parallel to the existing feed forward path. Inclusion of a feed forward and a feedback path is commonly referred to as two-degrees-of freedom (2-DOF) control in the literature. As the name implies, 2-DOF control provides a DOF for ensuring fast dynamic tracking through the feed forward path and a second degree of freedom for the independent tuning of the system disturbance compensation through the feedback path [12]. The feedback path consists of an outer voltage loop and a fast inner current loop. To eliminate the steady-state voltage tracking error $(V_L^* - V_L)$, a computationally less intensive P+Resonant compensator is added to the outer voltage loop. The ideal P+Resonant compensator can be mathematically expressed as

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

Where k_P and k_I are gain constants $\omega_0 = 2\pi \times 50\ \mathrm{rad/sec}$ and is the controller resonant frequency. Theoretically, the resonant Controller compensates by introducing an infinite gain at the resonant frequency of 50 Hz (Fig. 6) 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 ω_{cut} is the compensator cutoff frequency which is 1 rad/s in this application [12]. Plotting the frequency response of (5), as in Fig. 6, it is noted that the resonant peak now has a finite gain of 40 dB which is satisfactorily high for eliminating the voltage tracking error [12]. In addition, a wider bandwidth is observed around the resonant frequency, which minimizes the sensitivity of the compensator to slight utility frequency variations. At other harmonic frequencies, the response of the nonideal controller is comparable to that of the ideal one.

VI. PROPOSED MULTIFUNCTIOAL DVR

In addition to the aforementioned capabilities of DVR, it can be used in the medium-voltage level (as in Fig. 7) to protect a group of consumers when the cause of disturbance is in the

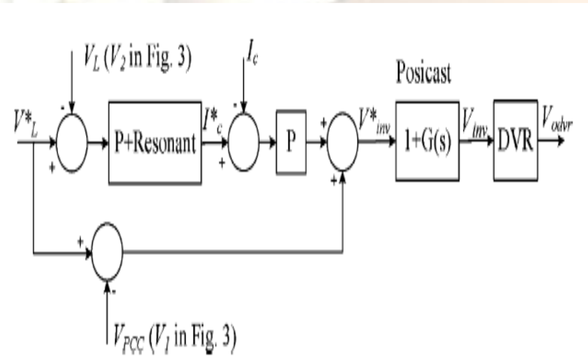


Fig.5.Multiloop control using the Posicast and P+Resonant controllers.

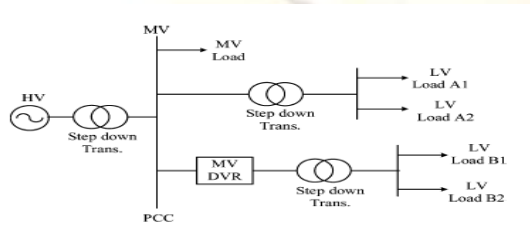


Fig. 6. DVR connected in a medium-voltage level power system.

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.

VII. PROPOSED METHOD FOR USING THE 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 to 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. In this control strategy, the control variable used for the outer flux model is the inverter-filtered terminal flux defined as:

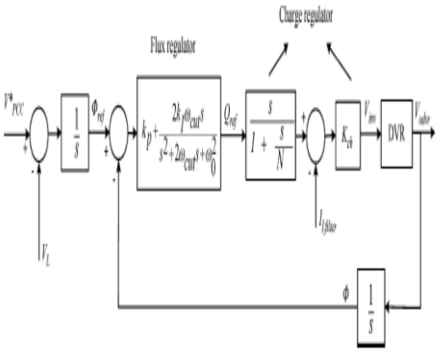


Fig. 7. Proposed method.

$$\Phi = \int V_{\mathrm{odvr}} \mathrm{dt}$$

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 (6). 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. 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 Q_{ref} of the flux regulator. The calculated charge error is then fed to the charge regulator with the transfer function

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

Which 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 $1/1+S/N$. 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.

A. Under Study Test System.

The test system is modeled in PSCAD/EMTDC software. Control methods of Figs. 5 and 8 were applied to control the DVR, and the voltage, current, flux, and charge errors were included as the figures show. Also, the DVR was modeled by its components (instead of its transfer functions) in the PSCAD/EMTDC software to make more real simulation results. A 12-pulse inverter was used so that each phase could be controlled separately. Detailed specifications of the DVR components are provided in the Appendix.

The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. The local (in-plant) generator is represented as a simple Thevenin equivalent. The internal voltage, determined from the converged power-flow solution, $13.8\angle - 1.52^{\circ}$ is kV.

The equivalent impedance is the sub transient impedance which is $0.0366 + j\angle 1.3651\ \Omega$. . The plant power factor correction capacitors are rated at 6000 kvar. As is typically done, leakage and series resistance of the bank are neglected in this study. The detailed description of the system can be found in [25]. In the simulations, the DVR is placed between buses "03:MILL-1" and "05:FDR F."

B. Three-Phase Short Circuit

In this part, the three-phase short circuit is applied on bus "26:FDR G," and the capability of the DVR in protecting the voltage on bus "05:FDR F" will be studied. The DVR parameters and the control system specifications are provided in Appendices A and B. At 205 ms, the fault is applied at 285 ms, and the breaker works and separates the line between buses "03:MILL-1" and "26:FDR G" from the system. At 305 ms, the fault will be recovered and, finally, at 310 ms, the separated line will be rejoined to the system by the breaker. The simulation results are shown in Fig. 10.

As can be seen in the figure, the rms voltage of PCC drops to about 0.25 p.u. during the fault. It is obvious that this remaining voltage is due to the impedances in the system. The DVR will start the compensation just after the detection of sag. As can be seen in the enlarged figure, the DVR has restored the voltage to normal form with attenuation of the oscillations at the start of the compensation in less than half a cycle. It is worth noting that the amount and shape of the oscillations depends also on the time of applying the fault. As can be seen in the enlarged figure, the voltage value of phase B is nearly zero; this phase has minimum oscillation when the fault starts.

C. Starting the Induction Motor

A large induction motor is started on bus "03: MILL-1." The motor specifications are provided in Appendix C. The large motor starting current will cause the PCC voltage (bus "03: MILL-1" 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 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. During this period, the PCC bus is under voltage sag. From 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 (bus "05: FDR F" voltage) at the normal condition. Also, as can be seen in the enlarged version of Fig. 9, the DVR has succeeded in restoring the load voltage in half a cycle from the instant of the motor starting.

D. Fault Current Limiting

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 this purpose, a three-phase short circuit is applied on bus "05: FDR F". In Fig. 10, the fault current, without the DVR compensation, is shown. For the simulation with DVR compensation, the three-phase fault is applied at 205 ms and then removed after 0.1 s. Also, a breaker will remove the faulted bus from the entire system at 300 Ms. Fig. 11 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. 11 shows, at this time, the voltage value of phase B is nearly zero; this phase has the minimum oscillation when the fault starts. Also, the maximum value of the fault current has been reduced from 40 kA (see Fig. 10) to 5 kA with DVR compensation.

SIMULATION RESULTS:

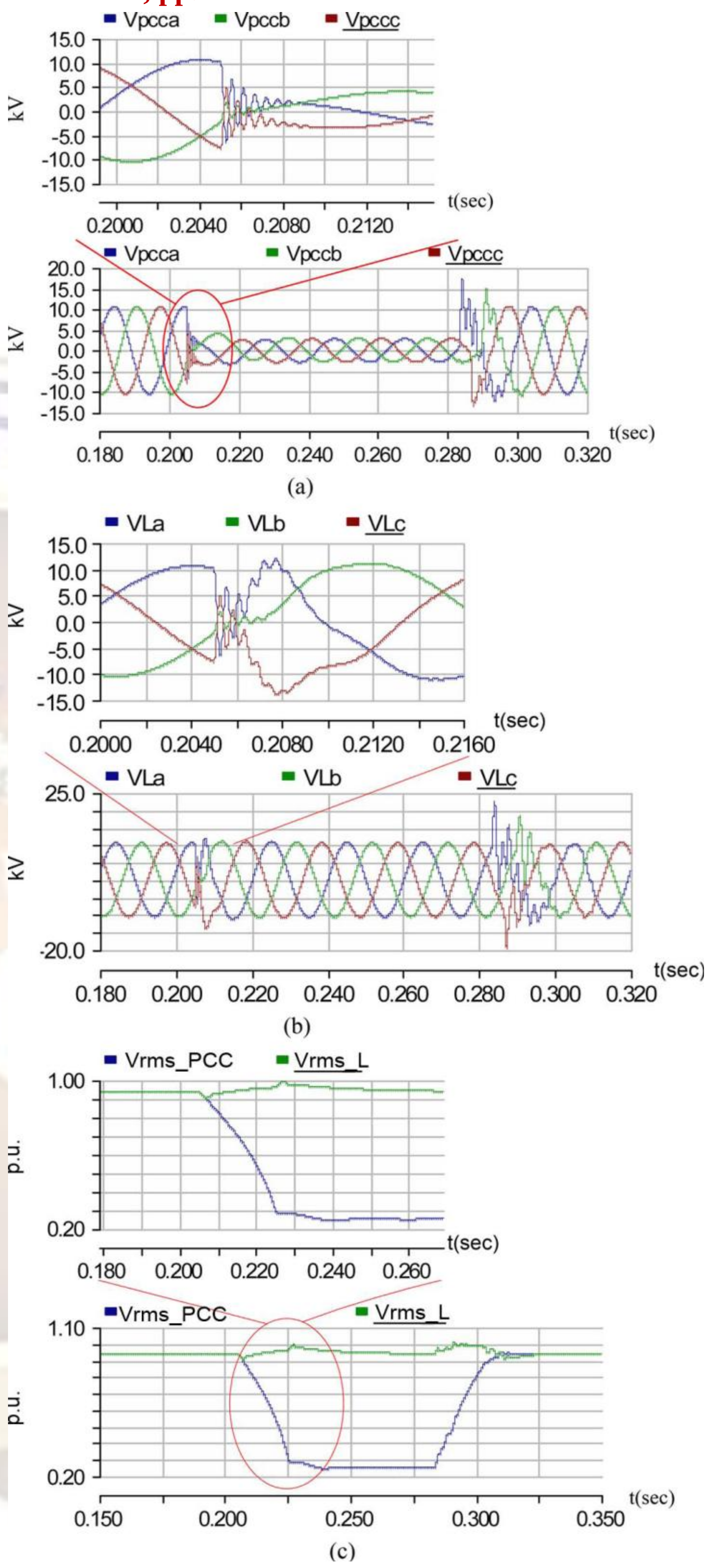


Fig. 8. Three-phase fault compensation by DVR. (a) Three-phase PCC voltages.

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

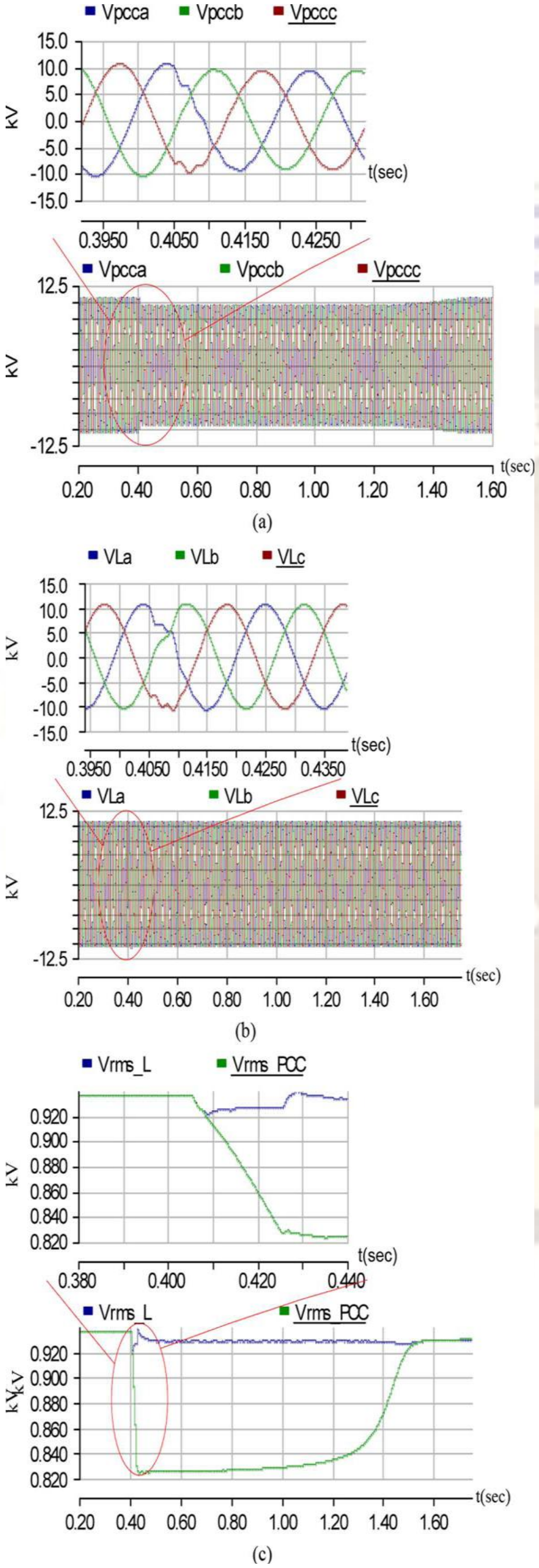


Fig. 10. Current waveshape due to the three-phase short-circuit fault without DVR compensation

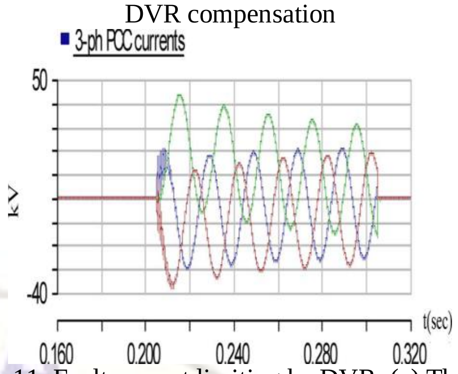
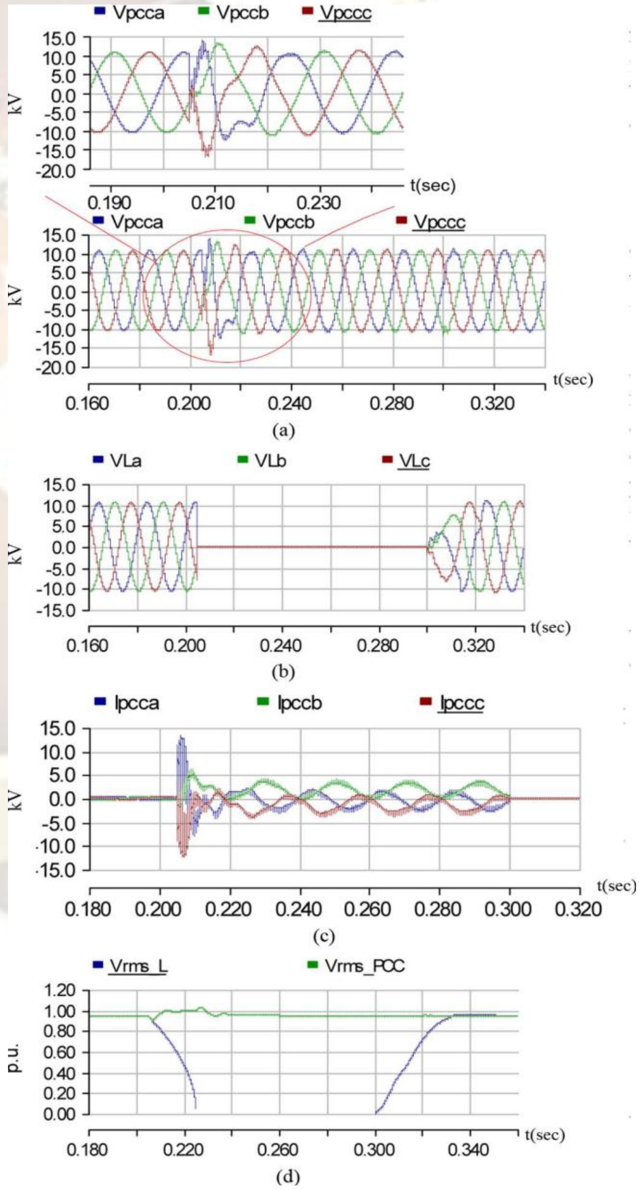


Fig. 11. Fault current limiting by DVR. (a) Three-phase PCC voltages. (b) Three-phase load voltages. (c) Three-phase currents. (d) RMS voltages of The PCC and load



VIII. 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 a variable impedance. The problem of absorbed active power is solved by entering an 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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