A Multi-functional Dynamic Voltage Restorer for Emergency Control 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 multi 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. Simulation results show the capability of the DVR to control the emergency conditions of the distribution systems.

Keywords: **Dynamic voltage restorer (DVR), emergency control, voltage sag, voltage swells.**

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 PQ problems. According to the IEEE 1959–1995 standard, voltage sag is the decrease of 0.1 to 0.9 p.u. in the rms voltage level at system frequency and with the duration of half a cycle to 1 min. Short circuits, starting large motors, sudden changes of load, and energization of transformers are the main causes of voltage sags [3]. According to the definition and nature of 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. 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. Also, the in-phase compensation method can be used for sag and swell mitigation. The multiline DVR can be used for eliminating the battery in the DVR structure and controlling more than one line. Moreover, research has been made on using the DVR in medium level voltage. Harmonic mitigation and control of DVR under frequency variations 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 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. 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).

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

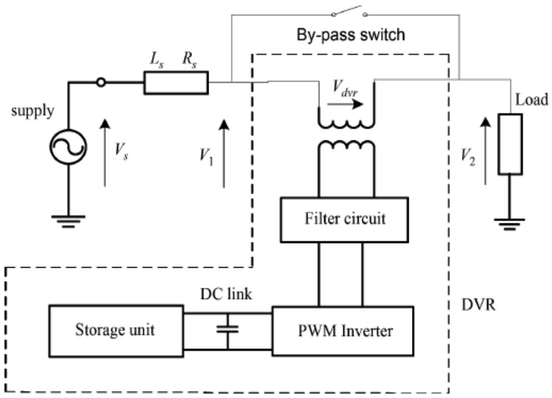


Fig. 1. Typical DVR-connected distribution system.

Through the DVR, using the flux control algorithm, the series voltage is injected in the opposite direction and, therefore, the DVR acts like series variable impedance. The remainder of this paper is organized as follows: The general operation of DVR and its state space description are provided in Section II. The closed-loop control using Posicast and P+Resonant controllers has been presented in Section III. In Section IV, the multifunctional DVR is introduced. The basis of the proposed control method is described in Section V. Finally, the simulation results are provided in Section VI which shows that the control capability of the proposed DVR system is satisfactory.

II. DVR COMPONENTS AND ITS BASIC OPERATIONAL PRINCIPLE

A. DVR Components

A typical DVR-connected distribution system is shown in Fig. 1, where the DVR consists of essentially a series-connected injection transformer, a voltage-source inverter, an inverter output filter, and an energy storage device that is connected to the dc link. Before injecting the inverter output to the system, it must be filtered so that harmonics due to switching function in the inverter are eliminated. It should be noted that when using the DVR in real situations, the injection transformer will be connected in parallel with a bypass switch (Fig. 1). When there is no disturbances in voltage, the injection transformer (hence, the DVR) will be short circuited by this switch to minimize losses and maximize cost effectiveness. Also, this switch can be in the form of two parallel thyristors, as they have high on and off speed. A financial assessment of voltage sag events and use of flexible ac transmission systems (FACTS) devices, such as DVR, to mitigate them is provided in. It is obvious that the flexibility of the DVR output depends on the switching accuracy of the pulse width modulation (PWM) scheme and the control method. The PWM generates sinusoidal signals by comparing a sinusoidal wave with a saw tooth wave and sending appropriate signals to the inverter switches.

B. Basic Operational Principle of DVR

The DVR system shown in Fig. 1, controls the load voltage by injecting an appropriate voltage phasor in series with the

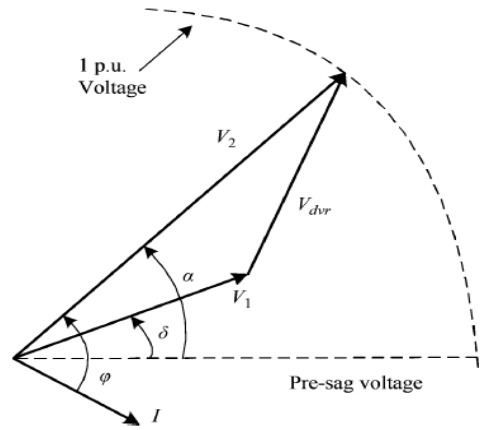


Fig. 2. Phasor diagram of the electrical conditions during voltage sag.

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.

The phasor diagram in Fig. 2 shows the electrical conditions during voltage sag, where, for clarity, only one phase is shown. VoltagesV_1, V_2 and V_{dvr} 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. 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. 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 R_L and an inductance L_L. The DVR harmonic filter has an inductance of L_f, a resistance of R_f , and a capacitance of C_f . Also, the DVR injection transformer has a combined winding resistance of R_t, a leakage inductance of L_t , 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 Point of Common Coupling (PCC)," from now on, V_1 and V_2 will be replaced with V_{pcc} and V_L, 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 is compared with a load-side reference voltage (V_L^{*}) 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.

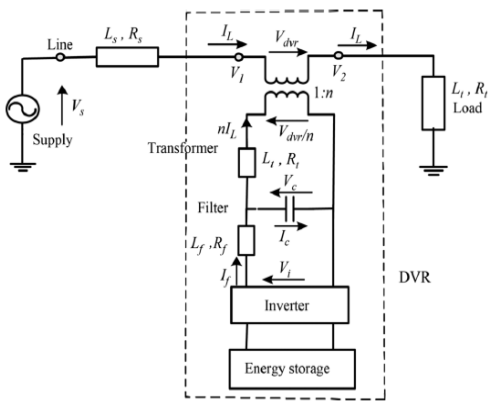


Fig. 3. Distribution system with the DVR

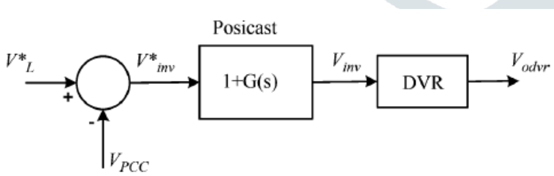


Fig. 4. Open-loop control using the Posicast controller.

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:

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

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.

To find the appropriate values of δ and T_d and, first the DVR model will be derived according to Fig. 3, as follows:

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

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

$$T_d = \frac{2\pi}{\omega_r} = \frac{\pi}{\sqrt{\frac{1}{L_f C_f} - \frac{R_f^2}{4L_f^2}}}$$
$$\delta = e^{\xi\pi/\sqrt{1-\xi^2}} = e^{-R_f\pi\sqrt{C_f}/\sqrt{4L_f - R_f^2 C_f}}. \quad (3)$$

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 multi loop 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. The feedback path consists of an outer voltage loop and a fast inner current loop. To eliminate the steady-state voltage tracking error, a computationally less intensive P+Resonant compensator is added to the outer voltage loop. The ideal P+Resonant compensator can be mathematically expressed as

$$G_R(s) = k_p + \frac{2k_I s}{S^2 + \omega_0^2} \quad (4)$$

Where and are gain constants and is the controller resonant frequency. 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 (non ideal) compensator is therefore used here, and is expressed as

$$G_R(s) = k_p + \frac{2k_I \omega_{cut} S}{S^2 + 2\omega_{cut} S + \omega_0^2} \quad (5)$$

Where is the compensator cutoff frequency which is 1 rad/s .

III. PROPOSED MULTIFUNCTIONAL DVR

In addition to the aforementioned capabilities of DVR, it can be used in the medium-voltage level (as in Fig. 6) 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.

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.

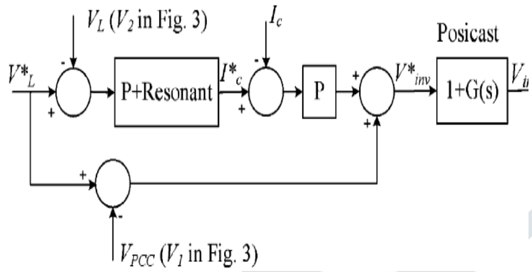


Fig. 5. Multiloop control using the Posicast and P+Resonant controllers.

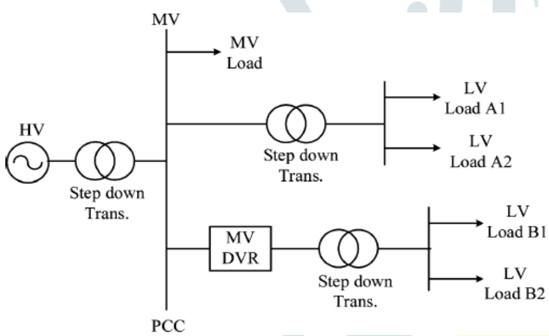


Fig. 6DVR connected in a medium-voltage level power system.

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. 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 a 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.

IV. 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.

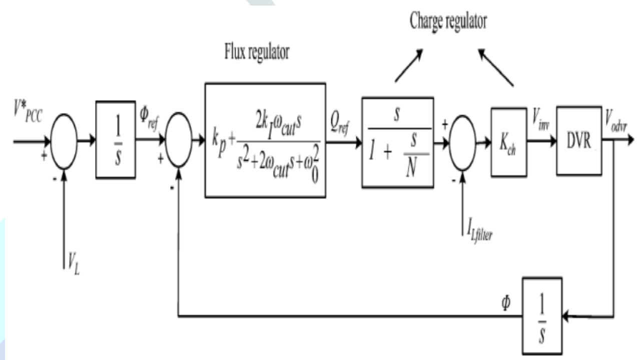


Fig. 7. Proposed method.

The proposed DVR control method is illustrated in Fig. 7. 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:

$$\Phi = \int V_{odvr} dt \tag{6}$$

Where 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

$$G_{charge}(s) = k_{Ch} \frac{S}{1+\frac{S}{N}} \tag{7}$$

Which is actually a practical form of the derivative controller. In this transfer function, the regulator gain is limited to 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) with consideration for measurement noise attenuation, DVR LC-filter transient resonance attenuation, and System stability margins.

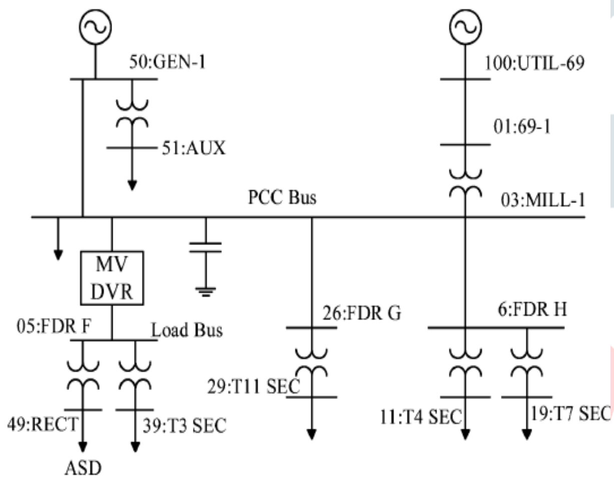


Fig. 8. Under Study test system.

V. SIMULATION RESULTS

In this part, 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.

A. Under Study Test System

In this paper, the IEEE standard 13-bus balanced industrial system will be used as the test system. The one-line diagram of this system is shown in Fig. 9.The test system is modeled in in MATLAB SIMULINK software. Control methods of Figs. 5 and 7 were applied to control the DVR, and the voltage, current, flux, and charge errors were included as the figures show. 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, is 13.8∟-1.52^0 kV.

The equivalent impedance is the subtransient impedance which is0.036+j∟1.3651 Ω. 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 . 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 t=205 ms, the fault is applied at t=285 ms, and the breaker works and separates the line between buses “03: MILL-1” and “26: FDR G” from the system. At

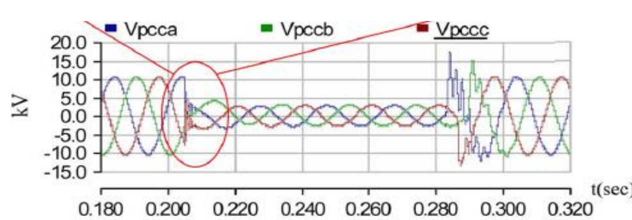
t=305 ms, the fault will be recovered and, finally, at t=310 ms, the separated line will be rejoined to the system by the breaker. The simulation results are shown in Fig. 9. As can be seen in the figure, the rms voltage of PCC drops to about 0.25 p.u. during the fault. The DVR will start the compensation just after the detection of sag.

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. 10. In this simulation, the motor is started at t=405 ms. As can be seen in Fig. 10, 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 t=1.4 s, as the speed approaches nominal, the voltage also approaches the normal condition.

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. 11, the fault current, without the DVR compensation, is shown. 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. 12 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.



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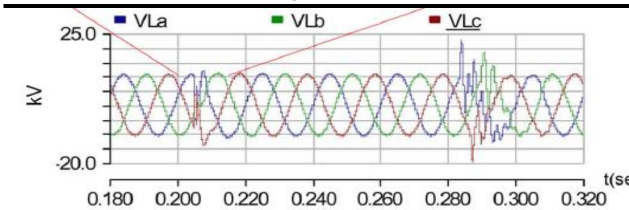

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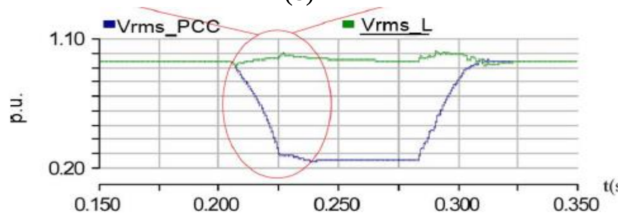
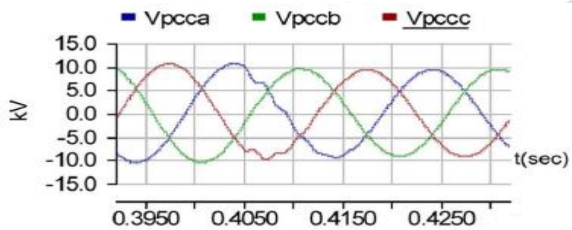


(c)

Fig. 9. Three-phase fault compensation by DVR. (a) Three-phase PCC voltages. (b) Three-phase load voltages. (c) RMS voltages of PCC and load.



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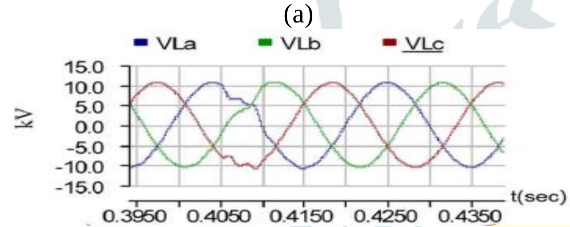

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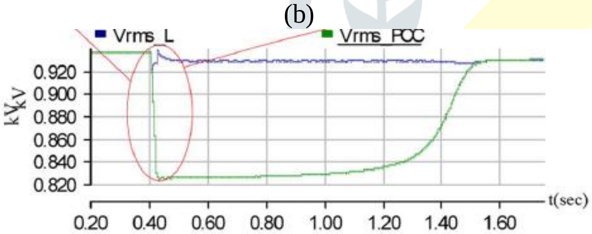


(c)

Fig. 10.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.

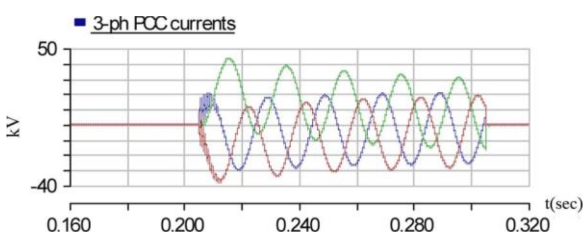
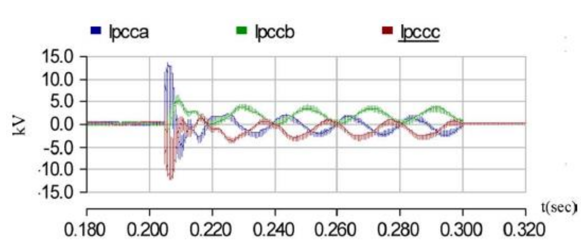


Fig. 11. Current wave shape due to the three-phase short-circuit fault without DVR compensation.



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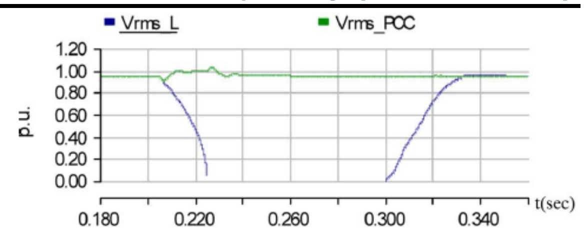

(b)

Fig. 12. Fault current limiting by DVR. (a) Three-phase currents. (b) RMS voltages of the PCC and load.

VI. CONCLUSION

In this paper, for 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 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.

APPENDIX

DVR Parameters:
Filter inductance (L_f) =1mH
Filter capacitance (C_f)=700µF
Inverter modulation ratio=21 mF
Kind of DVR inverter: 12 Pulse
DC-link capacitance: 26 mF
Entered resistance for current limiting: 3 ohms
Entered inductance for current limiting: 2 mH
Supply battery: 12 kV.
Control System Parameters:
δ =1
T_d=41.56
K_p=1
K_i=100
W_0=314rad/s
W_{cut}=1.0 rad/s
Induction Motor Parameters:
Rated power: 2.4 MVA
Rated voltage: 13.8 kV
Moment of inertia: 3.7267 sec
Number of rotor squirrel cages: 1
Base frequency: 50 Hz
Stator resistance: 0.0034 p.u.
Rotor resistance: 0.298 p.u
Stator inductance: 0.0102 p.u.
Rotor inductance: 0.05 p.u
Magnetizing inductance: 0.9 p.u.

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