An Emergency Control in Distribution Systems by Multifunctional Dynamic Voltage Restorer

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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 eliminate the steady-state error response and to improve the transient response in DVR, 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) 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 swell.**

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 [1]. 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.[2]. 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 [2]. 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 [6]–[13]. Previous works have been done on different aspects of DVR performance, and different control strategies have been found. 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 variations [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 [16].

The state feed forward and feedback methods [17], symmetrical components estimation [18], robust control [19], and wavelet transform [20] have also been proposed as different methods of controlling the DVR.

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. 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.

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.

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 show that the control capability of the proposed DVR system is satisfactory.

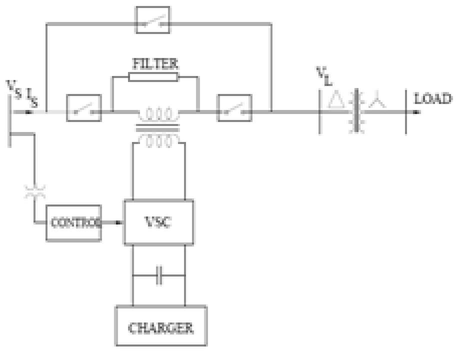


Fig. 1. Typical DVR-connected distribution system.

II. DVR COMPONENTS AND ITS BASIC OPERATIONAL PRINCIPLE

1. Voltage Source Converter (VSC)

This could be a 3 phase - 3 wire VSC or 3 phase - 4 wire 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.

2. 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 trans- former 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.

However if Y/Y connection with neutral grounding is used, the zero sequence voltage may have to be compensated. It is essential to avoid the saturation in the injection transformers.

3. 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 °ow through the windings.

4. Energy Storage

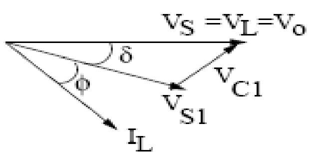
This is required to provide active power to the load during deep voltage sags. Lead-acid batteries, °ywheel or SMES can be used for energy storage. It is also possible to provide the required power on the DC side of the VSC by an auxiliary bridge converter that is fed from an auxiliary AC supply.

III. CONTROL STRATEGY

There are three basic control strategies as follows.

1. Pre-Sag Compensation

The supply voltage is continuously tracked and the load voltage is compensated to the pre-sag condition. This method results in (nearly) undisturbed load voltage, but generally requires higher rating of the DVR. Before a sag occur, VS = VL = Vo. The voltage sag results in drop in the magnitude of the supply voltage to VS1. The phase angle of the supply also may shift see Fig. 14.2). The DVR injects a voltage VC1 such that the load voltage (VL = VS1 + VC1) remains at Vo (both in magnitude and phase). It is claimed that some loads are sensitive to phase jumps and it is necessary to compensate for both the phase jumps and the voltage sags.



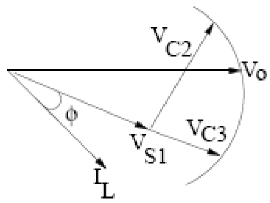
2. In-phase Compensation

The voltage injected by the DVR is always in phase with the supply voltage regardless of the load current and the pre-sag voltage (Vo). This control strategy results in the minimum value of the injected voltage (magnitude). However, the phase of the load voltage is disturbed. For loads which are not sensitive to the phase jumps, this control strategy results in optimum utilization of the voltage rating of the DVR. The power requirements for the DVR are not zero for these strategies

3. Minimum Energy Compensation

Neglecting losses, the power requirements of the DVR are zero if the injected voltage (VC) is in quadrature with the load current. To raise the voltage at the load bus, the voltage injected by the DVR is capacitive and VL leads VS1 (see Fig. 14.3). Fig. 14.3 also shows the in-phase compensation for comparison. It is to be noted that the current phasor is determined by the load bus voltage phasor and the power factor of the load.

Implementation of the minimum energy compensation requires the measurement of the load current phasor in addition to the supply voltage. When VC is in quadrature with the load current, DVR supplies only reactive power. However, full load voltage compensation is



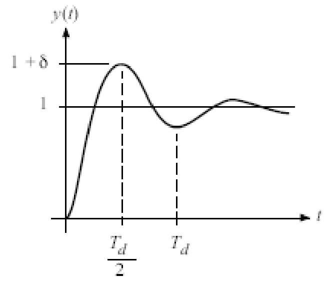
not possible Unless the supply voltage is above a minimum value that depends on the load power factor.

When the magnitude of VC is not constrained, the minimum value of VS that still allows full compensation is where Á is the power factor angle and Vo is the required magnitude of the Load bus voltage. If the magnitude of the injected voltage is limited (V max C), the mini-mum supply voltage that allows full compensation is given by The expressions (14.1) and (14.2) follow from the phasor diagrams shown in Fig. 14.4. Note that at the minimum source voltage, the current is in phase with VS for the case (a).

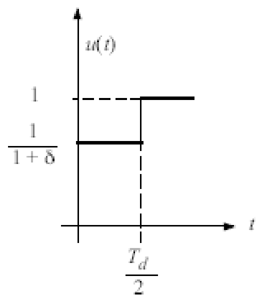
IV. POSICAST CONTROL

INVENTED in the late 1950's, Posicast is a feed forward control method that dampens oscillations in systems whose other transient specifications are otherwise acceptable. When properly tuned, the controlled system yields a transient response that has deadbeat nature.

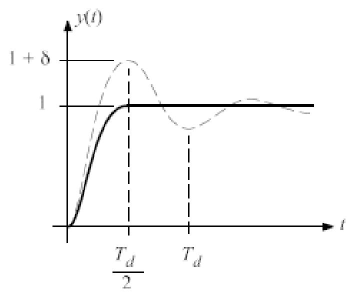
Consider a system having a lightly damped step response as shown in Fig. 1(a). The overshoot in the response can be described by two parameters. First, the time to the first peak is one half the under damped response period Td. Second, the peak value is described by 1 +δ, where δ the normalized overshoot, which ranges from zero to one is. Zero overshoot corresponds to critical damping.



(a) A lightly damped transient response.



(b) Posicast command



(c) System output (dashed is uncompensated)

Fig. 1. Natural response (a), Posicast command (b) and resulting output (c)

Posicast splits the original step input command into two parts, as illustrated in Fig. 1(b). The first part is a scaled step that causes the first peak of the oscillatory response to precisely meet the desired final value. The second part of the reshaped input is full scale and time-delayed to precisely cancel the remaining oscillatory response, thus causing the system output to stay at the desired value. Such is the idea behind "half-cycle Posicast," which can be modeled using just the two parameters δ and Td. The resulting system output is sketched in Fig. 1(c; the uncompensated output is also shown for comparison.

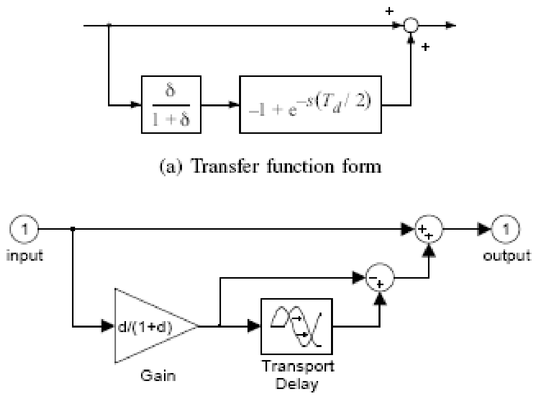


Fig. 3. Block diagrams for half cycle Posicast

$$P(s) = \frac{\delta}{1+\delta}\left[-1 + e^{-s(T_d/2)}\right]$$
………(1)

1. Frequency Domain Analysis of Posicast

Half-cycle Posicast is equivalent to an all-zero filter, with an infinite set of zeros spaced at odd multiples of the damped natural frequency. Solving for the roots of 1+P(s) = 0, the real part of the zeros is given by:

$$\text{Real part } = -\frac{2}{T_d}\ln\delta$$
………..(2)

and the imaginary part is given by:

$$\text{Imaginary part } = \frac{2\pi}{T_d}(2n+1), \quad n = 0, 1, 2, \cdots$$
……(3)

The frequency response of Posicast with δ = 0.8 and Td = 1 is shown in Fig. 4. The first pair of zeros cancels the dominant pair of poles in the lightly damped system.

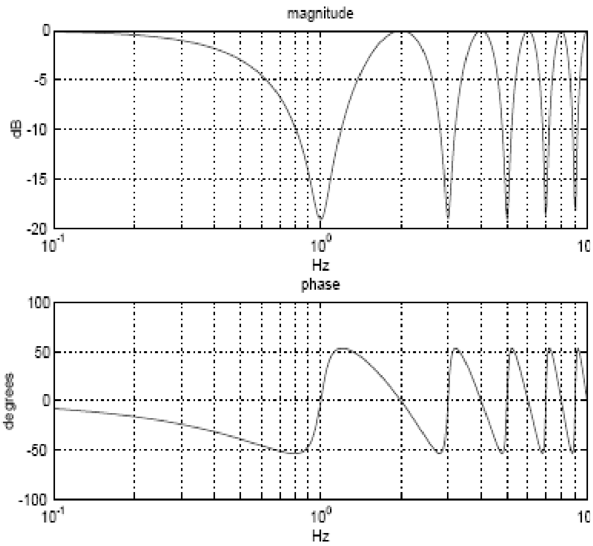


Fig. 4. Posicast frequency response for _ = 0.8, Td = 1

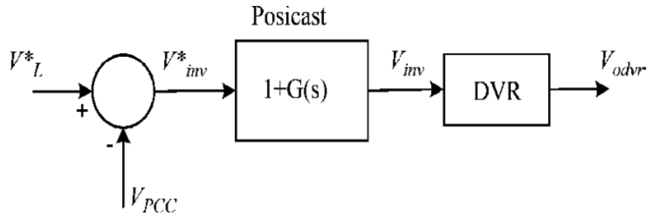


Fig. 4. Open-loop control using the Posicast controller.

The Posicast controller is used in order to improve the tran-sient 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 withV_{PCC} and V_L , respectively, to make a gen-eralized sense. As shown in the figure, in the open-loop control,

the voltage on the source side of the DVR (V_{PCC}) is compared with a load-side reference voltage(V_L^*)so that the necessary in-jection 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 suf-ficiently. To improve the damping, as shown in Fig. 4, the Posi-cast controller can be used just before transferring the signal to the PWM inverter of the DVR. The transfer function of the con-troller can be described as follows:

$$1 + G(s) = 1 + \frac{\delta}{1+\delta}\left(e^{-sT_d/2} - 1\right)$$
….(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 , first the DVR model will be derived according to Fig. 3, as follows:

$$\begin{aligned} V_i &= V_c + I_f R_f + L_f \frac{dI_f}{dt} \\ I_f &= I_c + n.I_t \\ I_c &= C_f \frac{dV_c}{dt} \\ V_{dvr} &= n\left[V_c - n\left(R_t I_t + L_t \frac{dI_t}{dt}\right)\right] \\ V_2 &= V_1 + V_{dvr}. \end{aligned}$$
………..(2)

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:

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

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

…….(3)

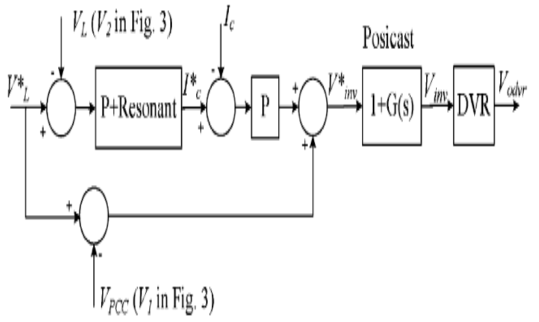


Fig. 5. Multiloop control using the Posicast and P+Resonant controllers.

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 (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

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

where K_P and K_I 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 (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 (non ideal) compensator is therefore used here, and is expressed as

V. PROPOSED MULTIFUNCTIONAL 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 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.

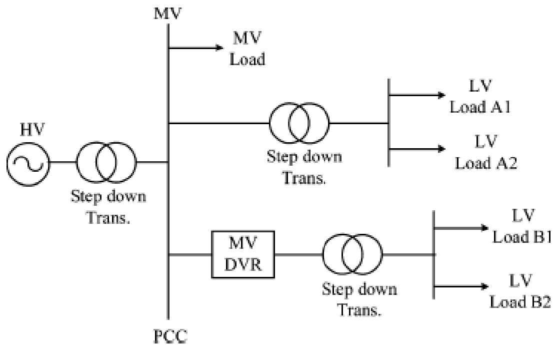


Fig. 7. DVR connected in a medium-voltage level power system.

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.

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 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.

VI. 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. The proposed DVR control method is illustrated in Fig. 8. It should also be noted that the reference flux ($Ø_{ref}$) 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:

$$\Phi = \int V_{odvr} dt \qquad \text{..........(6)}$$

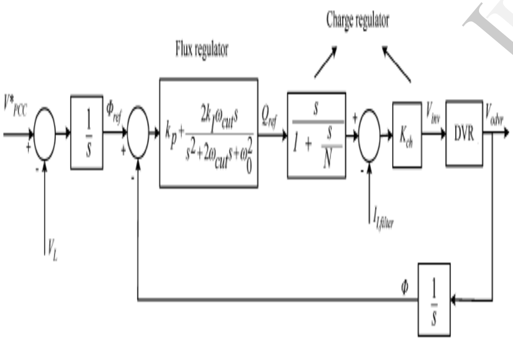


Fig. 8. Proposed method.

Where V_{0dvr} 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

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

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.

VII. 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 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.

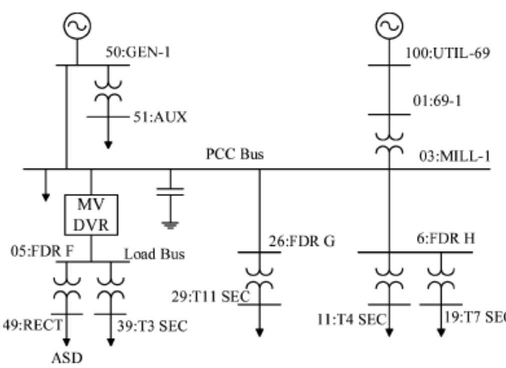


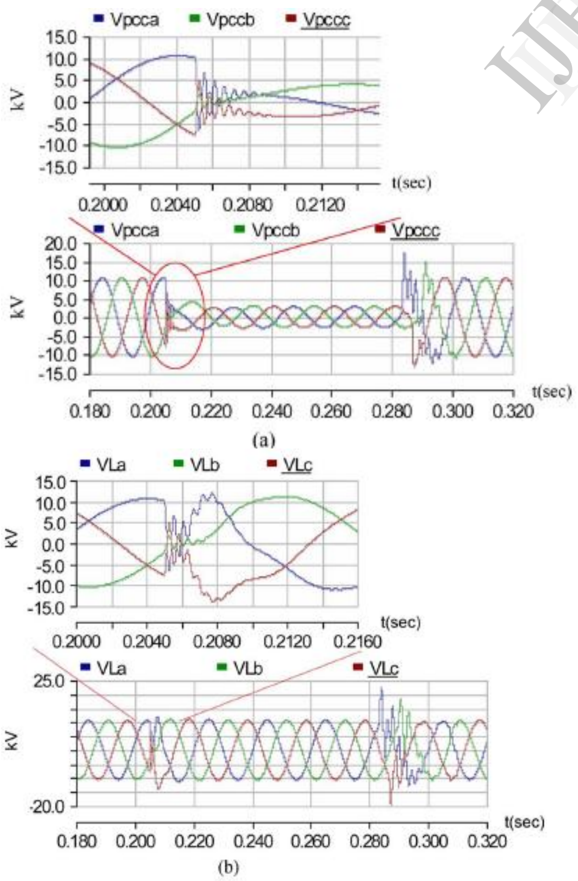
Fig. 9. Under study test system

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° kV.

The equivalent impedance is the subtransient impedance which is 0.0366+j∟1.3651. 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 t=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 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. 10.



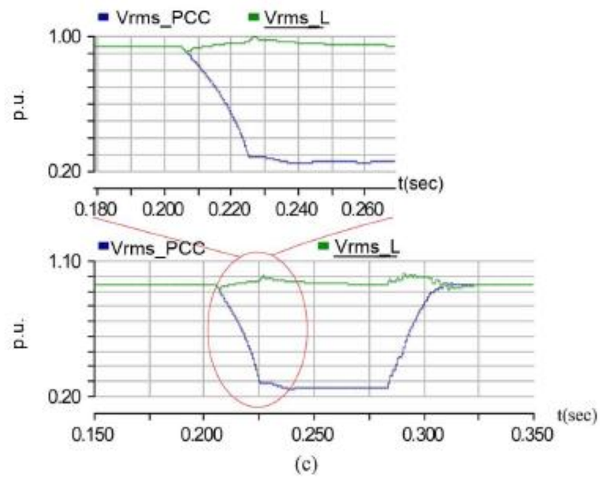


Fig. 10. Three-phase fault compensation by DVR. (a) Three-phase PCC voltages.
(b) Three-phase load voltages. (c) RMS voltages of PCC and load.

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. Thelarge 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. 11. 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.

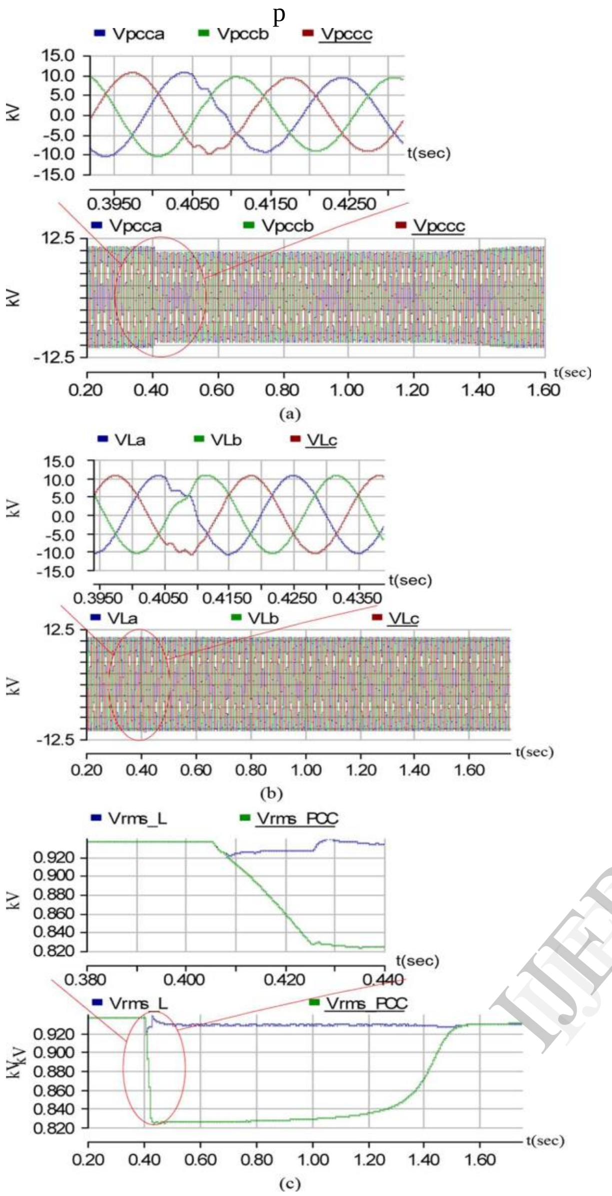


Fig. 11. Starting of an induction motor and the DVR compensation. (a) Threephase PCC voltages. (b) Three-phase load voltages. (c) RMS voltages of PCC and load.

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 (bus "05:FDR F" voltage) at the normal condition. Also, as can be seen in the enlarged version of Fig. 11, the DVR has succeeded in restoring the load voltage in half a cycle from the instant of the motor starting.

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.

APPENDIX

DVR Parameters:

Filter inductance (L_f)=1 mH
Filter capacitance (C_f)=700 μF
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=41.56μs
K_P=1
K_I = 100
ω_0 = 314 rad/sec
ω_{cut} =1.0 rad/sec

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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