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Performance Analysis of Multifunctional Dynamic Voltage Restorer (DVR) for Power Quality Improvement in Distribution System

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Abstract: In recent days, the major concern in distribution system is power quality. The power quality is affected by various factors of the electrical network. Power quality problems such as voltage and frequency variation, harmonic contents affect the performance of Distribution System. Such problem has to be compensated by using CPDs. The energy control in distribution system is discussed by using multi-functional dynamic voltage restorer (DVR) control strategy. For the protection of customers for sudden change in voltage DVR is used. To improve the transient response and to eliminate the steady state error in DVR response, the Posicast and P+Resonant controllers are used respectively. The innovation here is that the DVR acts as a virtual impedance with the main aim of protecting PCC voltage and limits the fault current by using Flux control method. The simulations are performed with two types of loads:1) a constant power load and 2) a motor load using MATLAB/SIMULINK software.

Index Terms: Dynamic voltage restorer (DVR), emergency control, voltage sag, voltage swells.

I. INTRODUCTION

The electric power system is considered to be composed of three functional blocks-generation, transmission and distribution. For reliable power systems, the generation unit must produce adequate power to meet customer's demand, transmission systems must transport bulk power over long distances without over loading system stability and distribution systems must deliver electric power to each customer's premises from bulk power systems. Distribution system locates the end of power system and is connected to the custom directly, so the power quality mainly depends on distribution system. Modern industrial devices are mostly based on electronic devices such as electronic drives and programmable logic controllers. The electronic devices are very sensitive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics. Voltage sag and swell are two of the most important power quality problems that encompass almost 80% of the distribution system PQ problems [1] [2].

According to the IEEE 1959–1995 standard, voltage sag is the decrease of 0.1to 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. 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. Using the DVR to improve the power quality and compensate the load voltage [3].

In this paper, a multifunctional control system is proposed in which the DVR protects the load voltage using Posicast and P+Resonant controllers. During downstream fault, the equipment protects the point of common coupling voltage, limits the fault current, and protects itself from the large fault current 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.

In the proposed method, when the faults current pass through the DVR, it acts like series variable impedance. When the fault current does not pass through the DVR, an outer 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. In case the fault current passes 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.

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II. DVR COMPONENETS AND ITS BASIC OPERATIONAL PRINCIPLES

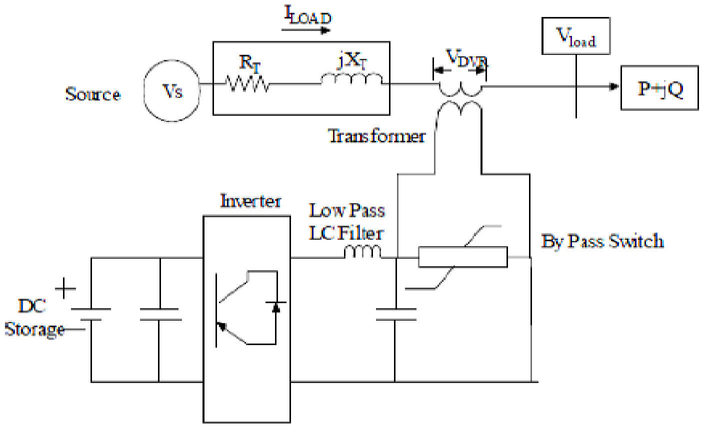


Fig 1. Basic Structure of DVR

The basic structure of a DVR is shown in Fig.1. Basic components of DVR are

Energy storage unit: It is responsible for energy storage in DC form. It is supplies the real power requirements of the system when the DVR is used for compensation.

Capacitor: DVR has a large dc capacitor to ensure stiff DC voltage input to inverter.

PWM inverter: An inverter system is used to convert dc storage in to ac form. The PWM generates sinusoidal signals by comparing a sinusoidal wave with a saw tooth wave and sending appropriate signals to the inverter switches.

Filter circuit: Before injecting the inverter output to the system, it must be filtered so that harmonics due to switching function in the inverter are eliminated.

By pass switch: It is used to protect the inverter from high currents in the presence of faulty conditions.

Voltage injection transformers: it is used for voltage injection purpose [4].

III. POSICAST CONTROLLER AND P+RESONANT CONTROLLER

The Posicast controller is used in order to improve the transient response. Fig. 2 shows a typical control block diagram of the DVR. Note that because in real situations, deal with multiple feeders connected to a common bus, namely "the Point of Common Coupling (PCC)," from now on, V1 and V2 will be replaced with Vpcc 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 (Vpcc) is compared with a load-side reference voltage (V_L) so that the necessary injection voltage 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. 2, 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 follow:

$$G_R(s) = k_p + \frac{2k_1 s}{s^2 + \omega_0^2}$$

Where and 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 sensitive to noise.

POSICAST

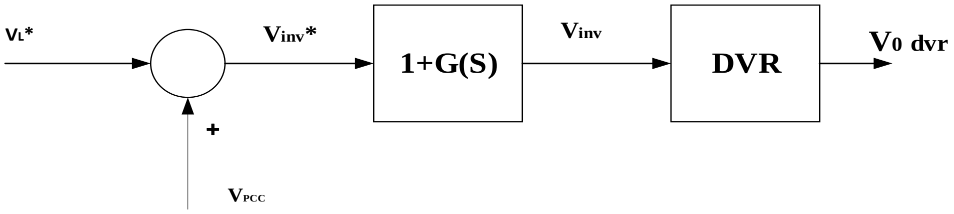


Fig. 2 Open-Loop Control Using The Posicast Controller

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. 2, 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 [7]. The ideal P+Resonant compensator can be mathematically expressed as

$$G_R(s) = k_p + \frac{2k_1 s}{s^2 + \omega_0^2}$$

Where K_P and K_I are gain constants and $\omega_o = 2\pi\times50$rad/sec 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

$$G_R(s) = k_p + \frac{2k_1 \omega_{cut} s}{s^2 + 2\omega_{cut} s + \omega_0^2}$$

Where ω_{cut} is the compensator cut off frequency.

Multifunctional DVR

In addition to the aforementioned capabilities of DVR, it can be used in the medium-voltage level (as in Fig. 3) 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 [8].

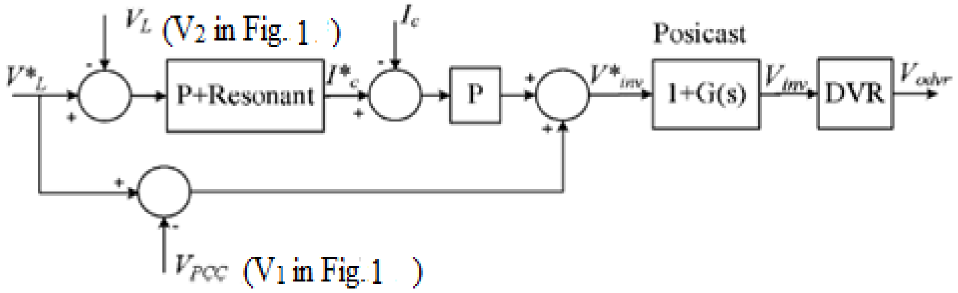


Fig. 3. Multiloop Control Using the Posicast and P+Resonant Controllers.

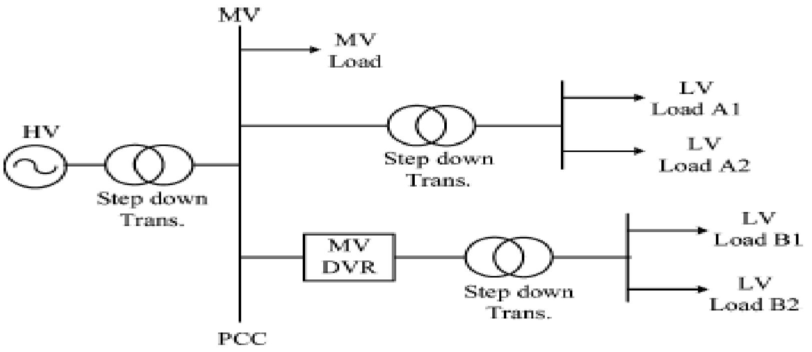


Fig. 4. DVR Connected in a Medium-Voltage Level Power System.

To limit the fault current, a flux-charge model has been 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 [8]. 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 Dissertation, 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, an 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.

By Using the Flux-Charge Model

In this part, an algorithm is used 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. 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 multi-Functional DVR control method is illustrated in Fig. 5. It should also be noted that the reference flux (φ_{ref})s 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:

$$\varphi = \int v_{0\mathrm{dvr}}\, dt$$

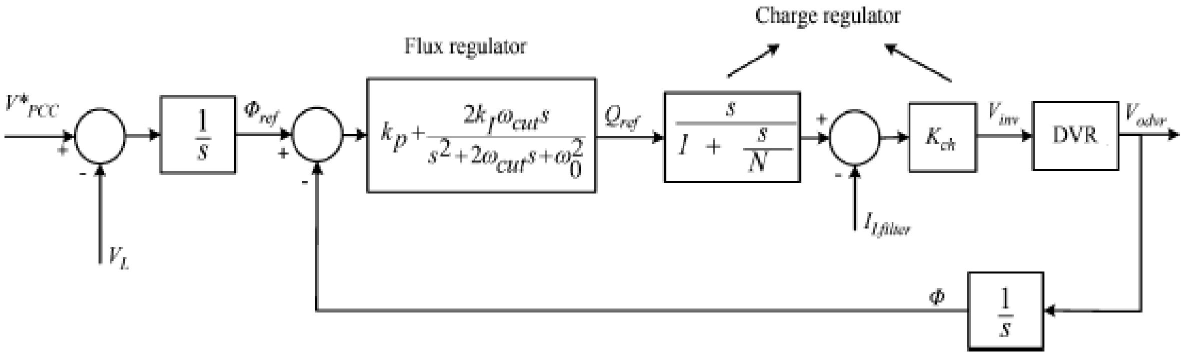


Fig. 5. Multi-Functional DVR Method.

Where V_{odvr} is the filter capacitor voltage of the DVR. The flux error is then fed to the flux regulator, which is a P+Resonant controller, with a transfer function given in [8].

The calculated charge error is then fed to the charge regulator with the transfer function

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

Which is actually a practical form of the derivative controller. In this transfer function, the regulator gain is limited toN at high frequencies to prevent noise amplification. The derivative term in $\frac{S}{1}+\frac{S}{N}$ neutralizes the effects of voltage and current integrations at the inputs of the flux-charge model, resulting in the Multi-Functional DVR algorithm having the same regulation performance as the multi-loop 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 $\frac{1}{1}+\frac{s}{N}$. 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.

IV. PROBLEM FORMULATION AND MODELING

Study Test System

In this Dissertation, 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.6 The test system is modelled in PSCAD/EMTDC software. Control methods of Figs. 3 and 4 were applied to control the DVR, and the voltage, current, flux, and charge errors were included as the figures show. Also, the DVR was modelled 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 theAppendix. 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 $13.8\angle - 1.52^{\circ}$ 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 [15]. In the simulations, the DVR is placed between buses "5 and 6".

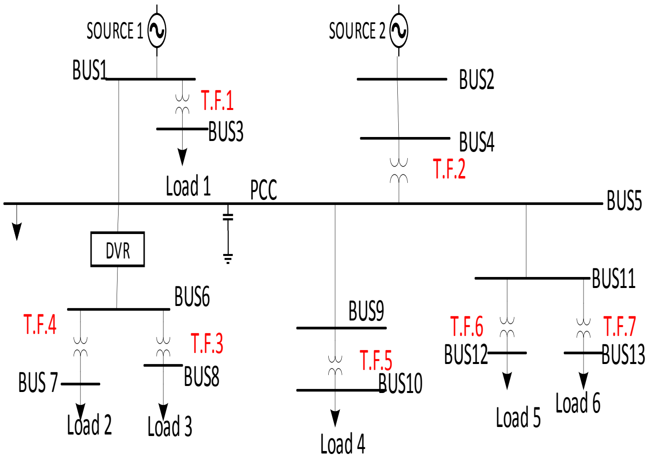


Fig. 6. Study Test System.

Three-Phase Short Circuit

In this part, the three-phase short circuit is applied on bus "9," and the capability of the DVR in protecting the voltage on bus "6" will be studied. Single line diagram is shown in Fig. 7. At t=205ms, the fault is applied at t=285ms Fig. 10 (a), and the breaker works and separates the line between buses "5" and "9" from the system. At t=305ms, the fault will be recovered and, finally, at t=310ms, the separated line will be re-joined to the system by the breaker Fig 10(b). The rms voltage of PCC drops to about 0.25 pu. during the fault Fig 10 (c). The DVR will start the compensation just after the detection of sag.

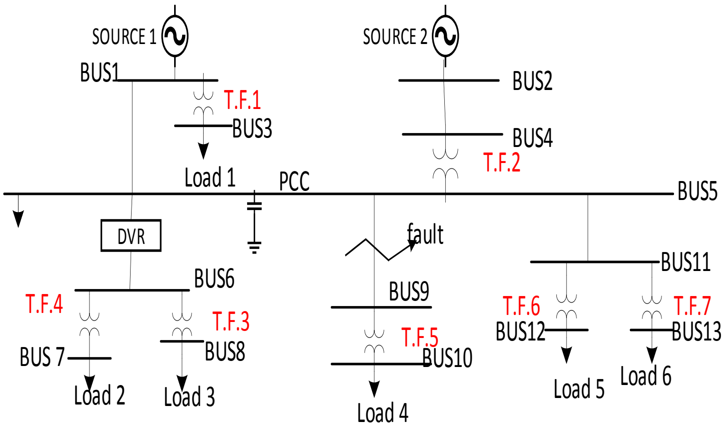


Fig. 7 Single-line simulation diagram, when the 3-phase short circuit occurred in Bus-9 starting the Induction Motor

Starting the Induction Motor

A large induction motor is started on bus “5.” The motor specifications are provided in Appendix C. Simulation one-line diagram is shown in Fig.8. The large motor starting current will cause the PCC voltage (bus “5” voltage) to drop. During this period, the PCC bus is under voltage sag from the Fig. 11 (a). In this simulation, the motor is started at t=405ms., in Fig 11 (b) at this time, the PCC rms voltage drops to about 0.8 pu. The motor speed reaches the nominal value in about 1s. 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 “6” voltage) at the normal condition. As shown in Fig 11 (c) the DVR has succeeded in restoring the load voltage in half a cycle from the instant of the motor starting.

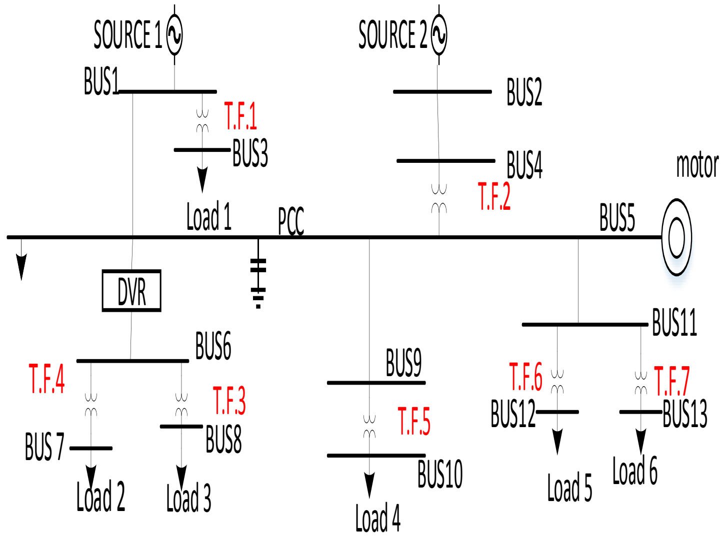


Fig. 8 Single-line simulation diagram, when theinduction motor is started at Bus-5.

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 “6”. Single line diagram is shown in Fig.9. Fig 12 the fault current, without the DVR compensation, is shown. For the simulation with DVR compensation, the three-phase fault is applied at t=205ms and then removed after 0.1s. Also, a breaker will remove the faulted bus from the entire system at t=300ms. 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.

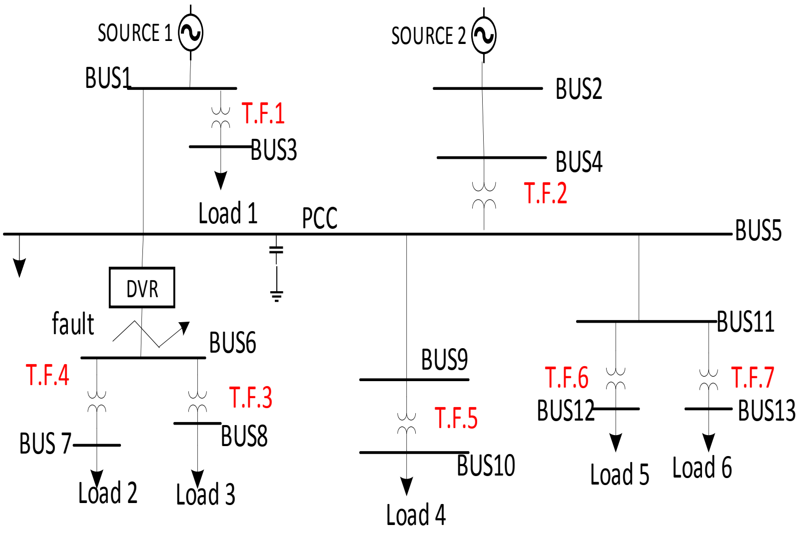
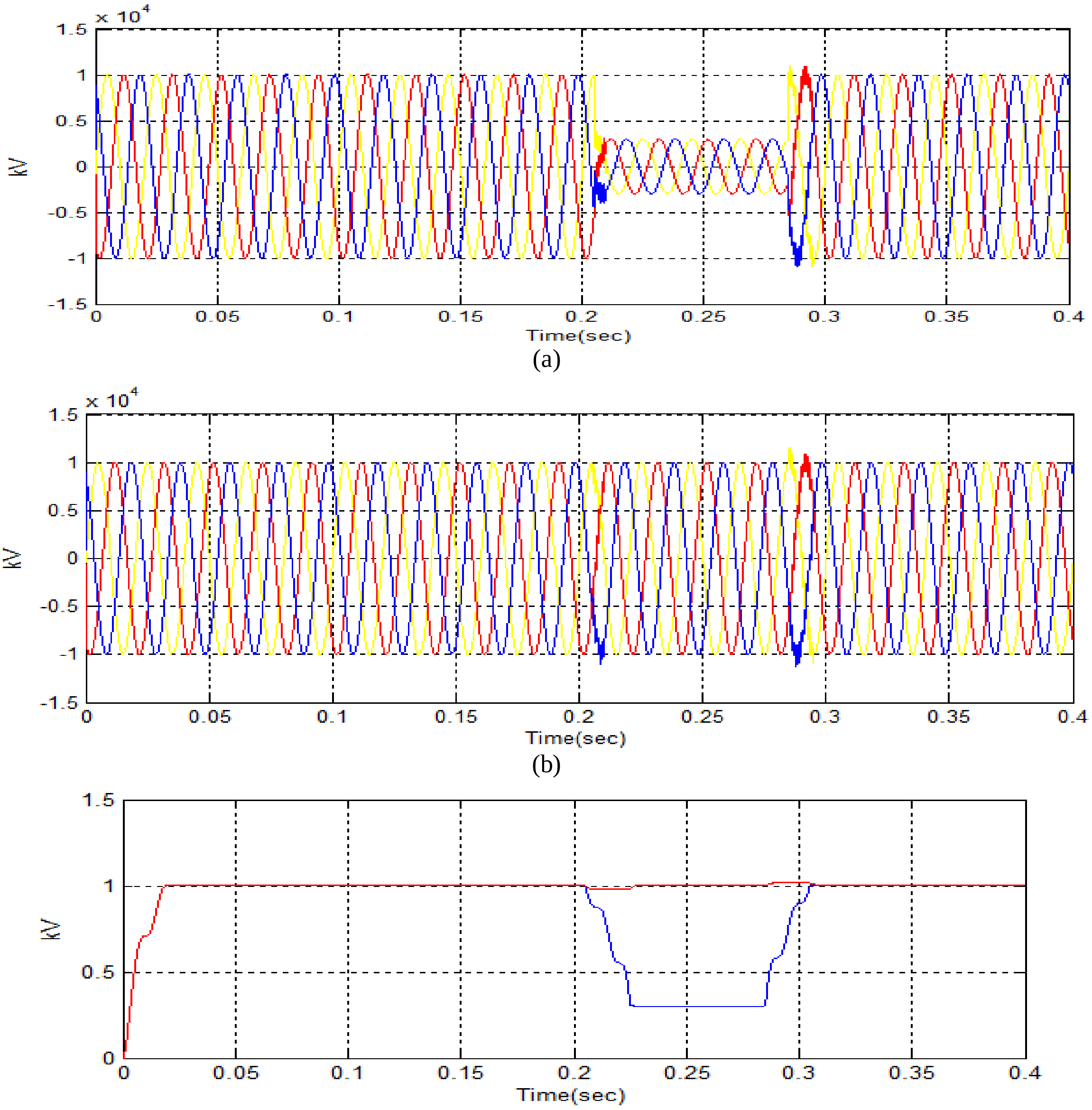


Fig. 9. Single-line simulation diagram, when the3-phase short circuit occurred in Bus-6.

V. SIMULATION RESULTS

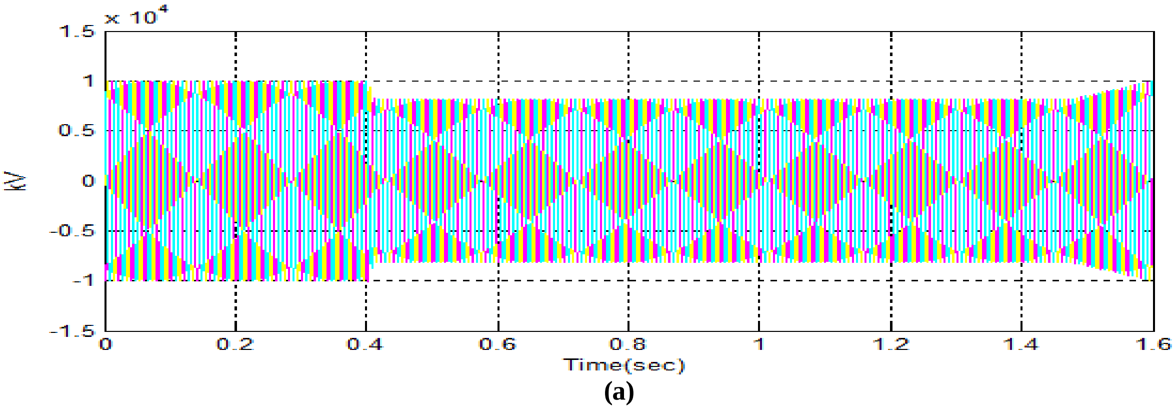


(a)

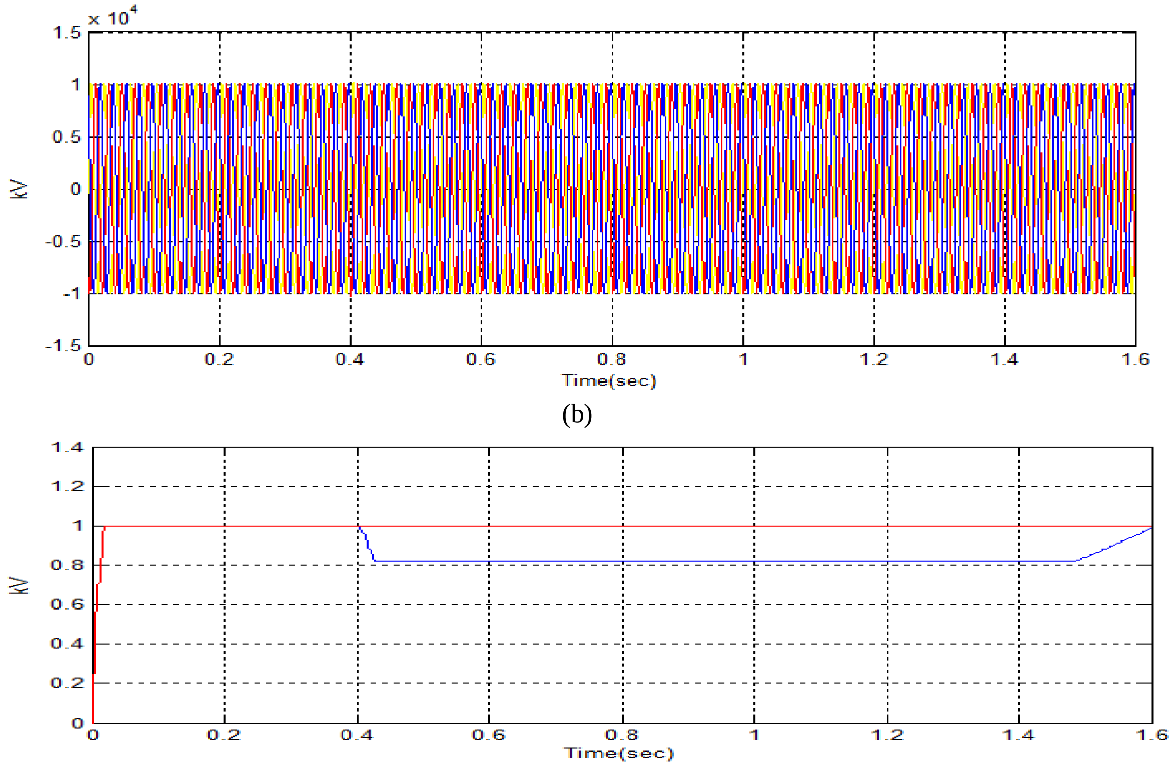
(b)

(c)

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.



(a)



(b)

(c)

Fig. 11. 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

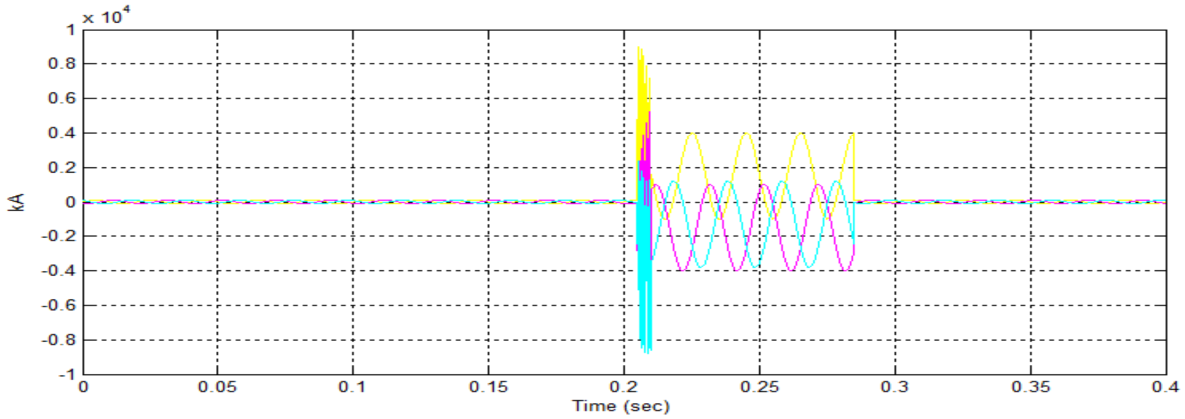
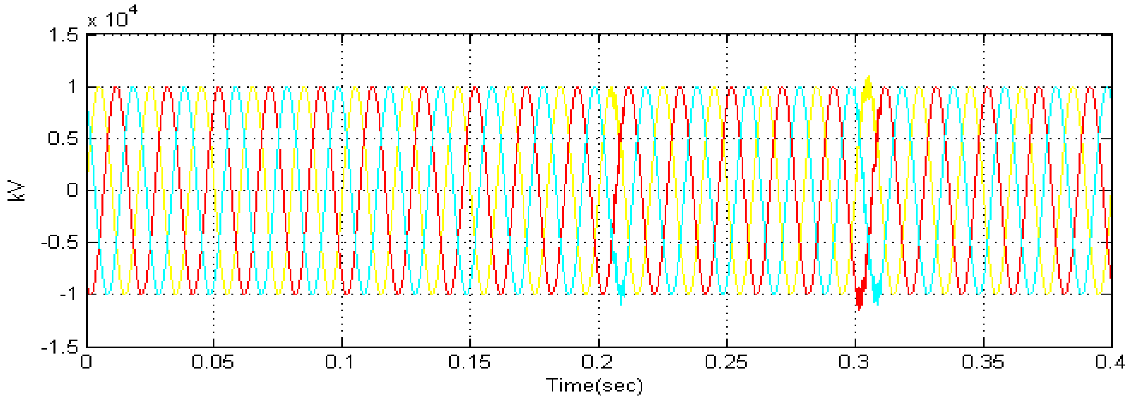
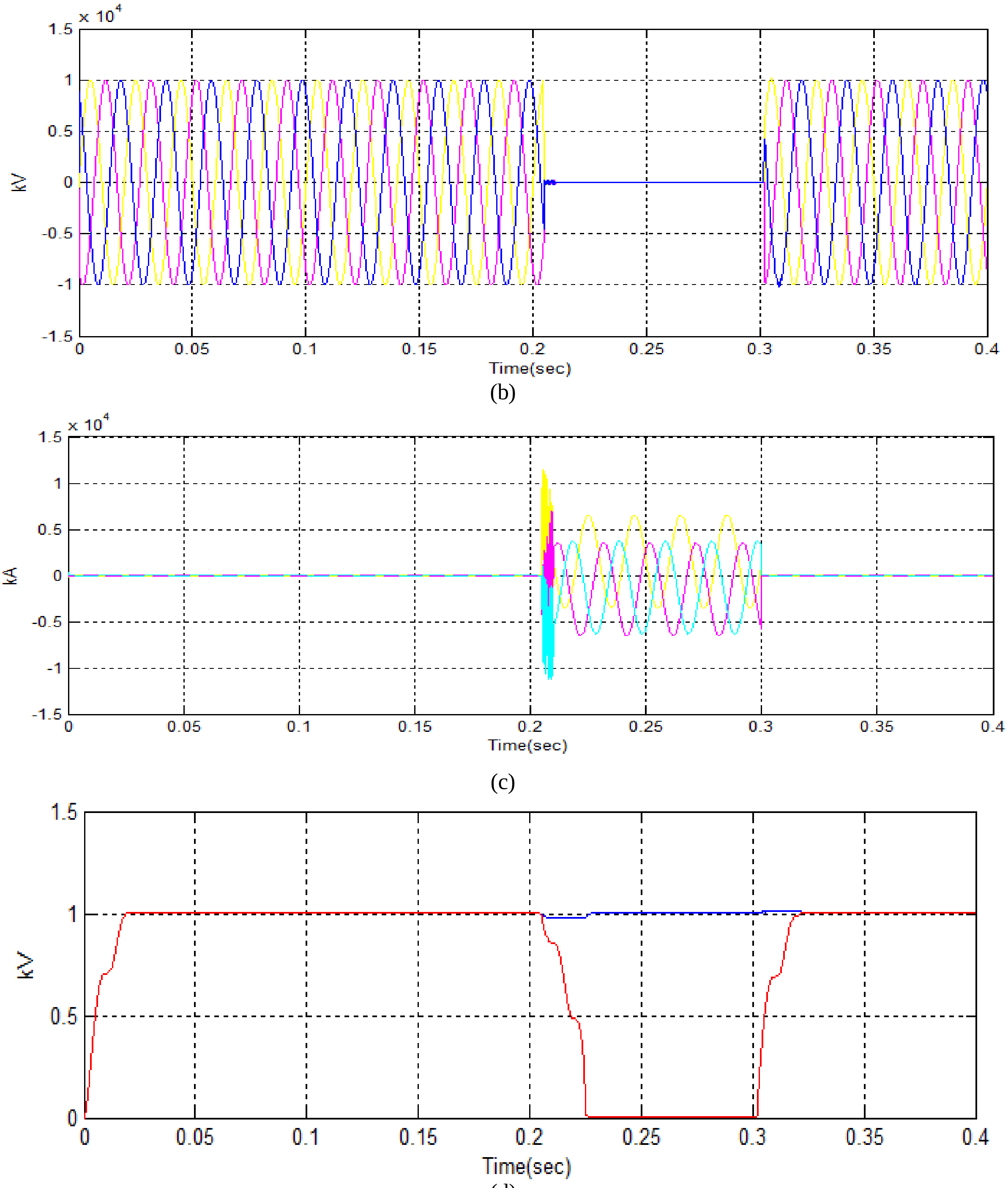


Fig. 12. Current wave shape due to the three-phase short-circuit fault without DVR compensation



(a)



(b)

(c)

(d)

Fig 13. Fault current limiting by DVR. (a) Three-phase PCC voltages. (b) 3-phase load voltages. (c) 3-phase currents. (d) RMS voltages of the PCC and load.

VI. CONCLUSION

In this dissertation, a multifunctional DVR is used, 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

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series with a diode so that the power does not enter it. The simulation results show the effectiveness and capability of the Multi-Functional 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: SYSTEM PARAMETERS

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 = 2mH
Supply battery = 12 kV.

Control System Parameters:

δ = 1
Td = 41.56
Kp = 1
K1 = 100
ω_0 = 314rad/s
ω_{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 pu.
Rotor resistance = 0.298 pu
Stator inductance = 0.0102 pu.
Rotor inductance = 0.05 pu
Magnetizing inductance = 0.9 pu.

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