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Power Quality Improvement by DVR

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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 a 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.

Index Terms—***Dynamic voltage restorer (DVR), emergency control, voltage sag, voltage swell.***

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.

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. 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 through the DVR, using the flux control algorithm, the series voltage is injected in the opposite direction and, therefore, the DVR acts like a series variable impedance.

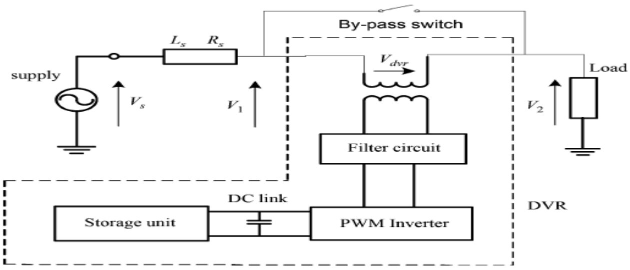


Fig. 1. Typical DVR-connected distribution system.

FACTS

What is most interesting for transmission planners is that FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of the present transmission system. The opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedence, shunt impedence, current, phase angle, and damping of oscillations at various frequencies below the rated frequency. These constraints can not be overcome otherwise, while maintaining the required system stability, by mechanical means without lowering the useable transmission capacity. By providing added flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid-response power electronics.

Static VAR compensators control only one of the three important parameters (Voltage, impedence, phase angle) determining the power flow in the AC power systems viz. the amplitude of voltage at selected terminals of the transmission line. It has long been realized that an all solid-state or advanced, static VAR compensator, which is true equivalent of ideal synchronous condenser, is technically feasible with the use of gate turn-off (GTO) thyristors. The UPFC is a recently introduced FACTS controller which has the capability to control all the four transmission parameters. The UPFC not only performs the functions of the STATCON, TCSC, and the phase angle regulator but also provides additional flexibility by combining some of the functions of these controllers.

Among the FACTS components, Unified Power Flow Controller (UPFC), is the most complete. It is able to control independently the throughput active and reactive powers. The UPFC is capable to act over three basic electrical system parameters: line voltage, line impedance, and phase angle, which determine the transmitted power.

Power Flow through an alternative current line is a function of the line impedance, the magnitude of the sending-end and receiving-end voltage and the phase angle between these voltages. The power flow can be increased,firstly by decreasing the line impedance with a capacitive reactance, secondly by increasing the voltages and finally by increasing the phase angle between these voltages. In our work, the power flow is controlled by controlling the sending and receiving bus voltage. Also, the control of the shunt and series element of the UPFC will be studied.

The Unified Power Flow Controller (UPFC) consists of two voltage sourced converters using power switches, which operate from a common from DC circuit of a DC-storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters and each converter can independently generate (or absorb) reactive power at its own ac output terminal.

FACTS

The term”FACTS” (Flexible AC Transmission Systems) covers several power electronics based systems used for AC power transmission and distribution. Given the nature of power electronics equipment, FACTS solutions will be particularly justifiable in applications requiring one or more of the following qualities:

(a)Rapid dynamic response
(b)Ability for frequent variations in output
(c)Smoothly adjustable output.

FACTS are a family of devices which can be inserted into power grids in series, in shunt, and in some cases, both in shunt and series. Flexible AC Transmission Systems, called FACTS, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice.

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations.

The power electronic based flexible AC transmission systems (FACTS) have been developed and used as economical and efficient means to control the power transfer in the interconnected AC transmission systems. This allows forcing the power transit in the lines with higher transmission capacity.

2.1. TYPES OF FACTS DEVICES

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. Figure 1.2 shows a number of basic devices separated into the conventional ones and the FACTS-devices.

For the FACTS side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of FACTS-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS-devices can equally be static and dynamic.

A power electronic based system & other static equipment that provide control of one or more AC transmission parameters.

The types of FACTS controllers are:

- SERIES
- SHUNT
- SERIES-SHUNT
- SERIES-SERIES

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:

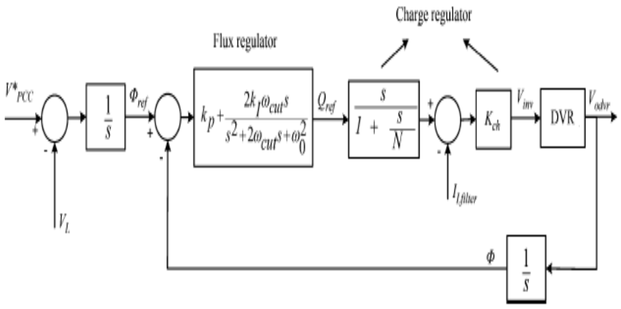


Fig. 8. Proposed method.

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.

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.

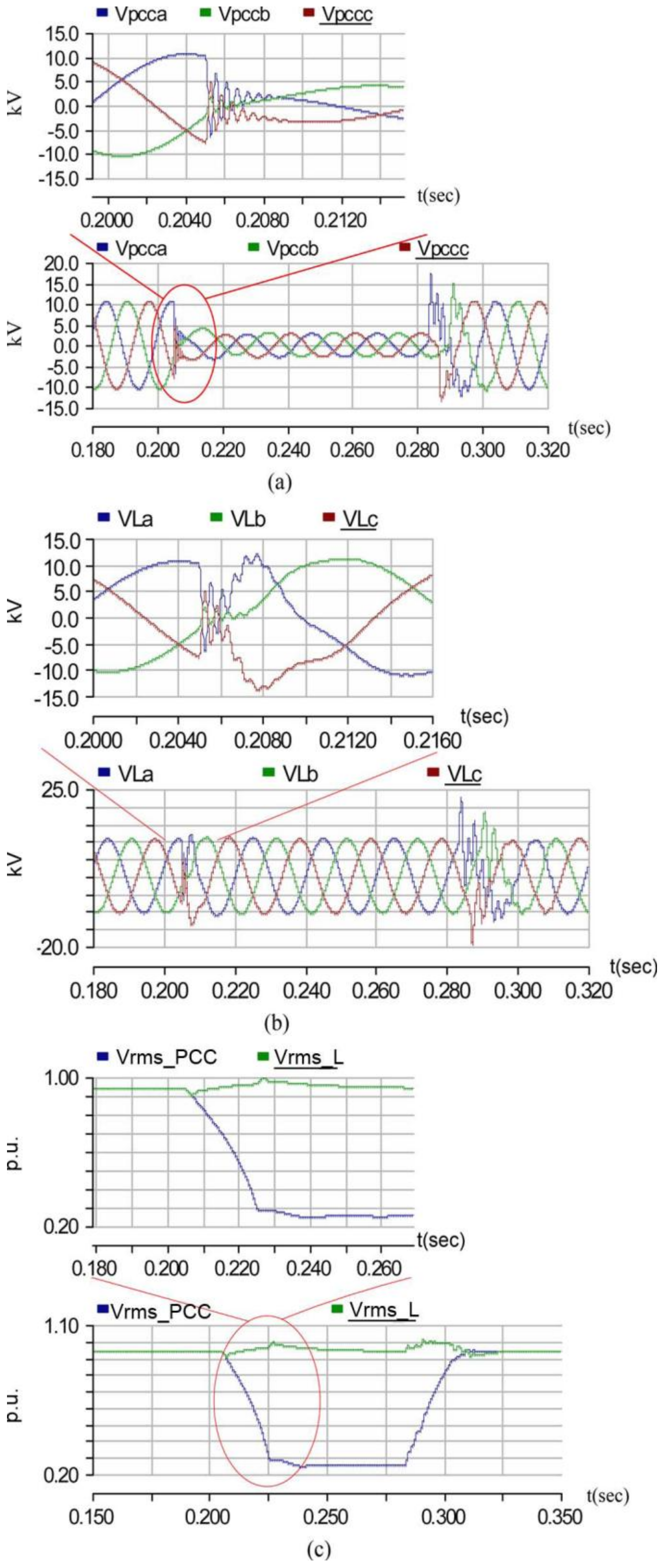
As can be seen in the figure, the rms voltage of PCC drops to about 0.25 p.u. during the fault. It is obvious that this remaining voltage is due to the impedances in the system. The DVR will start the compensation just after the detection of sag. As can be seen in the enlarged figure, the DVR has restored 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. 11. 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. 11, 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. 12, 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. 13 shows the DVR operation during the fault. As can be seen, the rms load bus voltage reaches zero during the fault, and as the enlarged figure shows, in about half a cycle, the DVR has succeeded in restoring the PCC voltage wave shape to the normal condition. It should be noted that the amount and shape of the oscillations depend on the time of applying the fault. As Fig. 13 shows, at this time, the voltage value of phase B is nearly zero; this 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. 12) to 5 kA with DVR compensation.

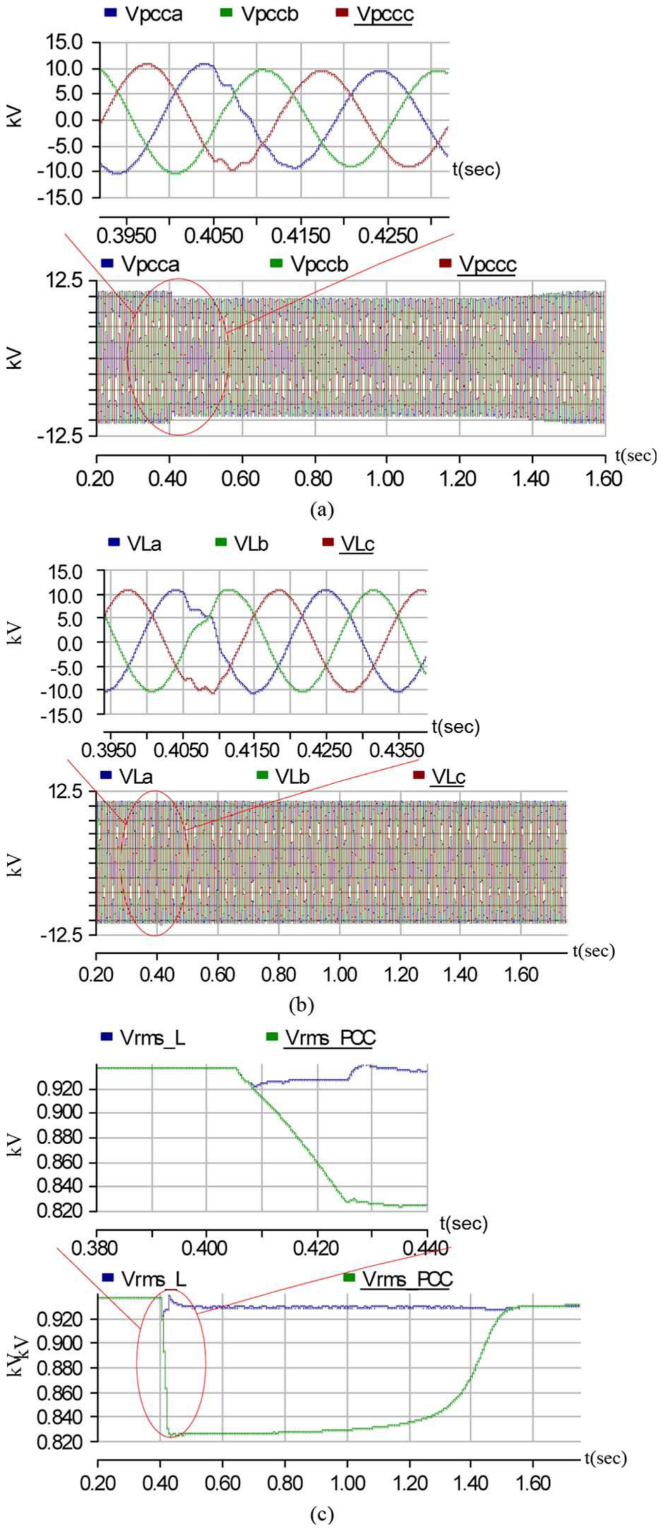


(a)

(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) Threephase PCC voltages. (b) Three-phase load voltages. (c) RMS voltages of PCC and load

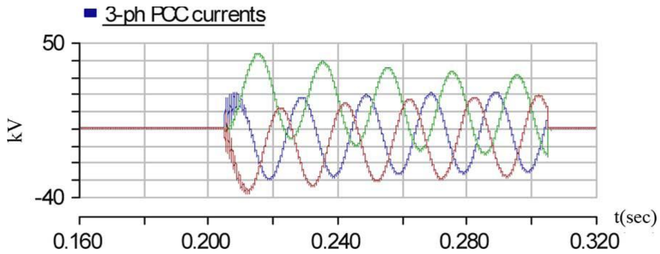
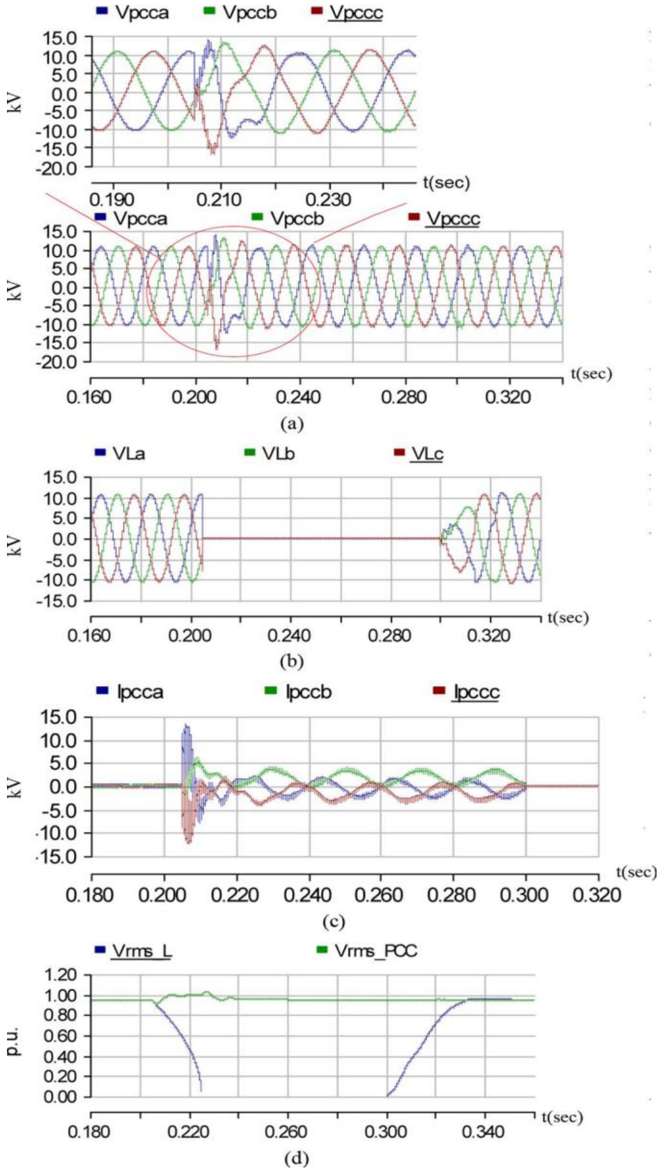


Fig. 12. Current waveshape due to the three-phase short-circuit fault without DVR compensation.



(a)

(b)

(c)

(d)

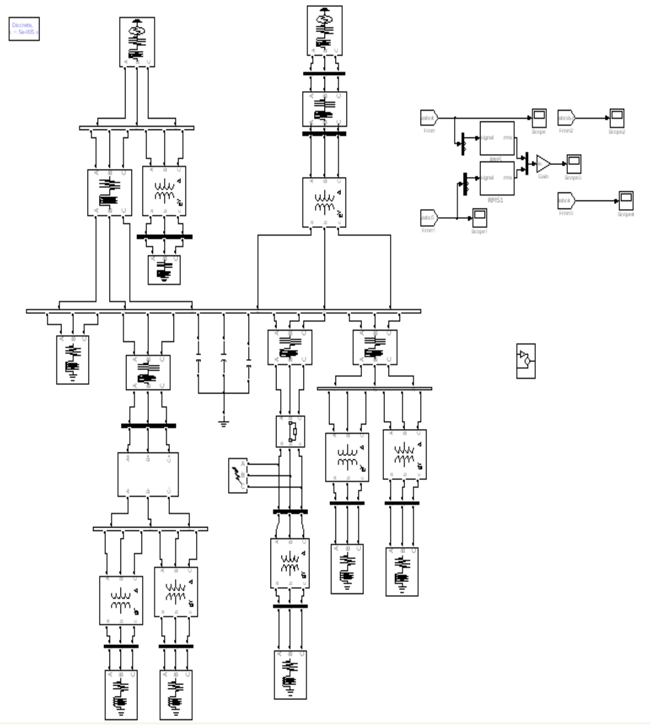
Fig. 13. Fault current limiting by DVR. (a) Three-phase PCC voltages. (b) Three-phase load voltages. (c) Three-phase currents. (d) RMS voltages of the PCC and load.

CONCLUSION

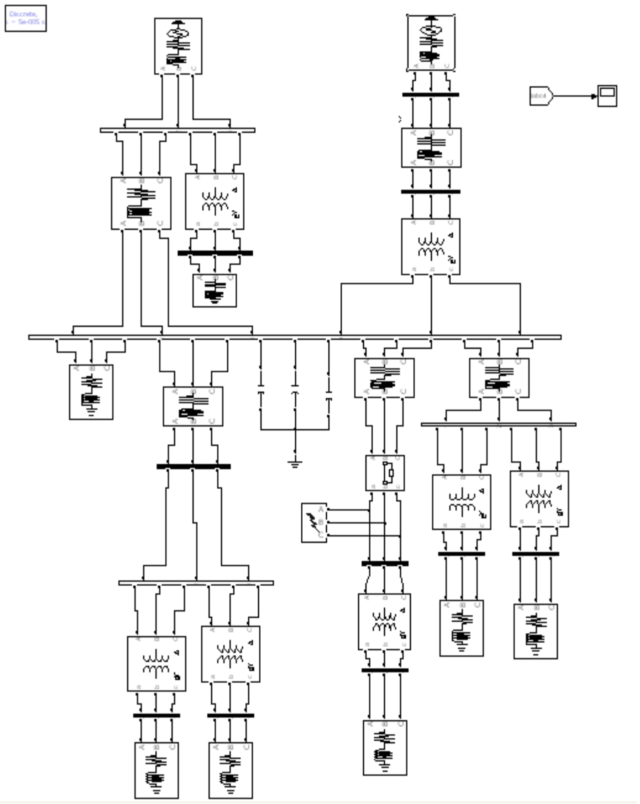
In this paper, a multifunctional DVR is proposed, and a closed-loop control system is used for its control to improve the damping of the DVR response. Also, for further improving the transient response and eliminating the steady-state error, the Posicast and P+Resonant controllers are used. As the second 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.

Simulation results:

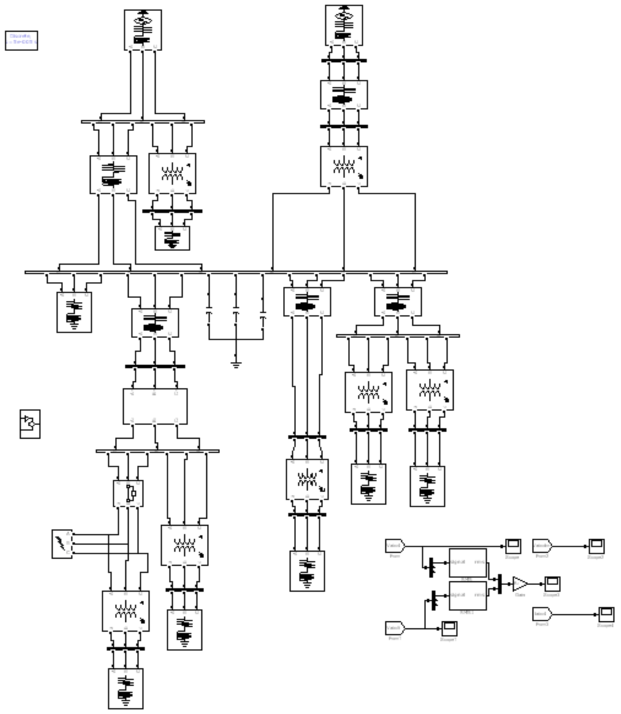
DVR:



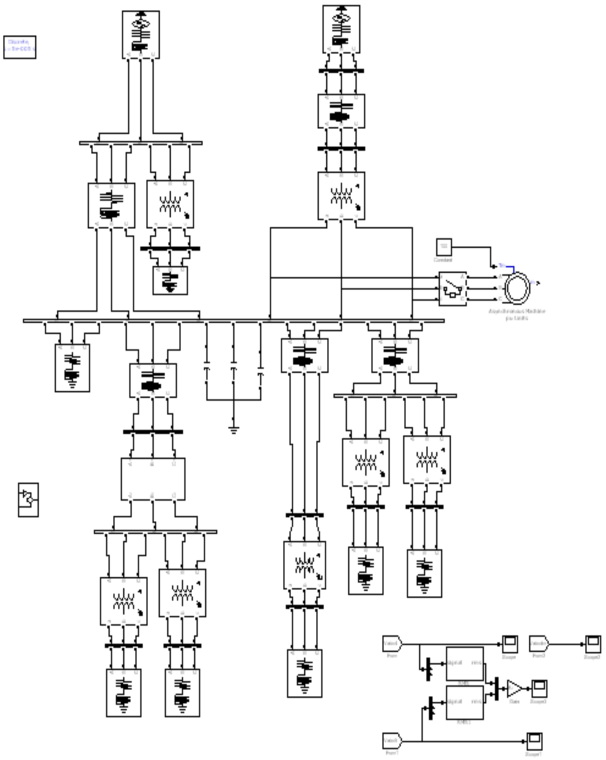
DVR FIG12



DVR fig13:



DVR induction motor



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