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Power Quality Improvement By A D-FACT Device Using Repetitive Controller

Rashmi Kapoor
Asst. Proff. EEE Dept.
CVR College of Engg.
Hyderabad

Dr. M. Sushama
Professor and Head, EEE Dept.
JNTU College of Engg.
Kukatpally, Hyderabad

Abstract

This paper proposes a repetitive controller for a two-level DVR, that not only compensate key voltage-quality disturbances, namely, voltage sags, harmonic voltages, and voltage imbalances, but also simultaneously control current during downstream fault. Repetitive control is a simple control method as conventional methods like PID, also it removes tracking problems associated with PID controllers. MATLAB/SIMULINK is used to carry out all modelling aspects of repetitive controller and test system.

1. Introduction

Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Modern industrial processes are based a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances [1] and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, and harmonics. Voltage dips are considered one of the most severe disturbances to the industrial equipment. Swells and over voltages can cause over heating tripping or even destruction of industrial equipment such as motor drives. Electronic equipment's are very sensitive loads against harmonics because their control depends on either the peak value or the zero crossing of the supplied voltage, which are all influenced by the harmonic distortion.

The DVR is essentially a voltage-source converter connected in series with the ac network via an interfacing transformer, which was originally conceived to ameliorate voltage sags [1]. However, as shown in this paper, its range of applicability can be extended very considerably when provided with a suitable control scheme. The basic operating principle behind the DVR is the injection of an in phase series voltage with the incoming supply to the load, sufficient enough to re-establish the voltage to its pre-sag state. Its rate of success in combating voltage sags in actual installations is well documented [2], this being one of the reasons why it continues to attract a great deal of interest in industry and in academic circles.

The repetitive control system is a type of servomechanism for periodic reference input. That is, the repetitive control system follows the periodic reference input without steady state error, even if a periodic disturbance or uncertainty exists in the plant. It is difficult to design stabilizing controllers for the plant; because the repetitive control system follows any periodic reference input without steady state error is a neutral type of time-delay control system [3].

During downstream fault occurrence, the voltage of point of common connection (PCC) falls and in consequence, DVR might try to compensate voltage sag, which would lead to fault current increase. If this current passes through DVR, the power electronic devices may face with heavy defects. In conventional DVRs, the passive methods are used to bypass DVR via a parallel switch in order to avoid such miss operations [4] [5]. In [6] and [7], active methods are presented to reduce fault current in devices connected in series with grid. In [8] and [9] DVR is applied for fault current reduction applying such methods.

Repetitive control was first introduced in [10] to eliminate periodic disturbances and to track periodic reference signals with zero tracking error. A detailed analysis of various repetitive control configurations is reported in [11]. The repetitive control was originally applied to eliminate speed fluctuations in electric motors but it has since been adopted in a wide range of power-electronics applications. In [12], a repetitive controller is applied to obtain an output voltage with low distortion in a constant voltage, constant frequency three-phase PWM inverter. In [13], a repetitive controller is used to achieve zero tracking error in the output current of a three-phase rectifier in order to improve its power factor**.** A more recent example is found in [14], where a repetitive controller is used to compensate for key power-quality disturbances, namely voltage sags, harmonic voltages, and voltage imbalances, using a dynamic voltage restorer (DVR). The present work is extension to this paper by adding an extra feature of controlling the downstream fault current.

In this paper, by adding a control function to DVR control unit, the downstream fault current is reduced as fault occurs. In fact, DVR is maintained in the grid and is not separated from distribution system and therefore, the control strategy is changed. This control strategy change makes DVR to perform as a great inductor during fault occurrence that leads to fault current limitation and dc link stress suffer minimization. Due to high expenses of DVR manufacturing, installation and utilization in power system, applying DVR with dual functionality will overcome the fault current limiters (FCL) application.

2. Model of the DVR

A Dynamic Voltage Restorer (DVR) is basically a controlled voltage source converter that is connected in series with the network. It injects a voltage on the system to compensate any disturbance affecting the load voltage. The compensation capacity depends on maximum voltage injection ability and real power supplied by the DVR. Energy storage devices like batteries and SMES are used to provide the real power to load when voltage sag occurs. If a fault occurs on any feeder, DVR inserts series voltage and compensates load voltage to pre-fault voltage. The two most popular strategies to compensate voltage sags [15] are: 1) pre-sag compensation. The injected DVR voltage is calculated to simply compensate the load voltage to its pre-sag condition; 2) in phase compensation. The DVR voltage is always in phase with the grid voltage.

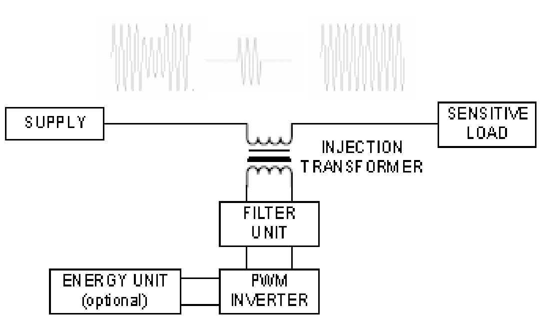

Figure 1. Typical application of DVR and its output

The basic operation principle is detecting the voltage sag and injecting the missing voltage in series to the bus as shown in Fig.1. DVR has become a cost effective solution for the protection of sensitive loads from voltage sags. Unlike UPS, the DVR is specifically designed for large loads ranging from a few MVA up to 50MVA or higher [16]. The DVR is fast, flexible and efficient solution to voltage sag problems. DVR consists of energy storage unit, PWM inverter, filter and, injection transformer.

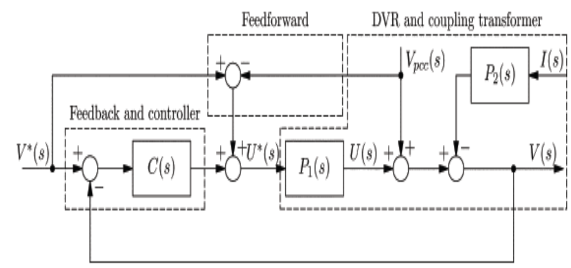

Figure 2. Closed loop control scheme

3. Design of control system

The controller is normally designed with some specific aims firmly in mind, such as the kind of disturbances it should ameliorate, the velocity of time response, error in steady-state, etc. the control structure implemented in this paper is based on use of feed forward term of the voltage at the PCC to obtain a fast transient response, and a feedback term of the load voltage to ensure zero error in steady state. The continuous time of the whole control system is depicted in Figure 2, where C(s) represents the controller, $P_1(s)$ represents DVR model and $P_2(s)$ is transfer function Ls + R, R and L are resistance and inductance of coupling transformer. Also V*(s) is the reference voltage for the load, U*(s) is the control output, whereas U(s) is the output voltage of the DVR and V(s) is the load voltage. The inputs $V_{pcc}(s)$ and I(s) stand for the grid voltage and the current through the load, respectively. Both inputs are assumed to be measurable.

Repetitive control is a contemporary control technique that may be used to cancel out, simultaneously, voltage sags, voltage harmonics, and voltage imbalances, characteristics rarely achieved with other control techniques, such as PI controllers. Since conventional repetitive controllers makes the closed loop system unstable, modified repetitive controller is used here.

$$C(s) = \frac{Q(s)e^{-(T-t_0)s}}{1 - Q(s)e^{-Ts}}$$

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Where Q(s) is the transfer function of a low-pass filter [17], $\hat{t}_0$ is the estimated value for the DVR delay [18], with $T=2\pi/\omega_1 - \beta$, and β is a design parameter which is smaller than the period of the grid voltage. A low-pass filter, which is approximated by a constant time delay within its pass band, can be designed with B_Q being the time delay of the filter. For continuous systems, Bessel filters can be used because they can be approximated by a constant time delay, while for discrete time systems, finite-impulse-response (FIR) filters with a linear phase in their pass-band can be used.

For detection of downstream fault, load current is measured and processed through a combinational logic circuit shown in figure 3. The output is one when downstream fault occurs. When fault is detected the phase of output of repetitive controller is changed to 90 degree leading to load current. This makes the output of DVR voltage exactly 90 degrees leading to current; this makes it to behave as pure inductor and controls the downstream fault.

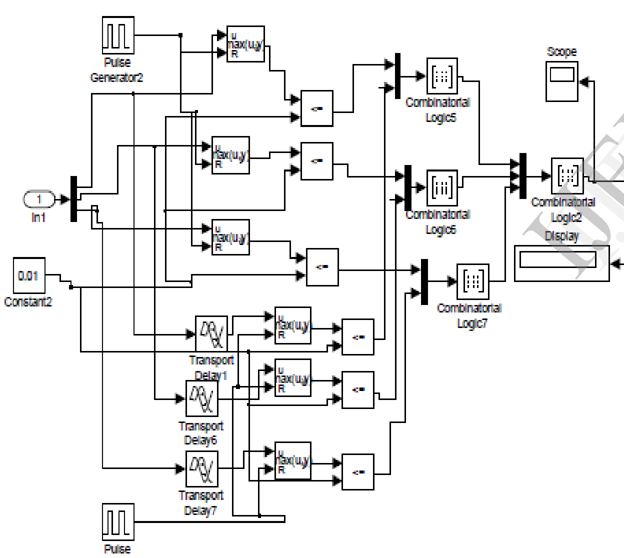

Figure 3. Downstream fault detection

4. Study case

The power system depicted in figure 1 and the controller shown in the figure 2 have been implemented in MATLAB/SIMULINK. The test system is composed by a 25 kV, 60 Hz generation system, feeding two transmission lines through a 3- winding transformer connected in Y/Y/Y, 735/315/315 kV. Such transmission lines feed two distribution networks through two transformers connected in Y/Y, 315/151 kV.

A two-level DVR is connected between the PCC and the sensitive load by means of a coupling transformer with a unity turns ratio and a star connected secondary winding. In this paper, a sinusoidal PWM scheme has been used to generate the switching signals for the power converter [19], which consists of a three-branch three-phase voltage-source inverter. A controller has been designed for each phase by using a three-phase a, b, c coordinate system. The reference frame a, b, c is perhaps the most popular alternative to control load voltages when operating under unbalanced conditions. The fundamental frequency was chosen as being equal to 60 Hz, while the switching frequency was set at 7.74 kHz in order to obtain a frequency-modulation (FM) index which was large enough.

4.1 Simulation result

The simulation result of test system show that dvr controlled through a repetitive controller is able to compensate all the three voltage quality disturbances namely, sag, unbalance and, harmonics as well as downstream fault current.

Voltage at PCC and across sensitive load is shown in fig. 4(a) and 4(b), when a 2-phase fault occurs at time t=0.067. This fault cause unbalance in voltage at PCC (as shown in fig. 4(a)). Figure 4(b) shows that voltage across sensitive load is compensated by the DVR.

Now considering the case when a highly inductive load is suddenly switched in the system at time t=0.067, the sag in the voltage at PCC is shown in figure 5(a) and voltage across sensitive load in figure 5(b). The results show that even though the voltage at PCC is dropped to about 65% but voltage at load is maintained by the DVR.

When a uncontrolled rectifier with resistive-inductive is switched in the system, it causes harmonics at supply side, measured by THD of about 12%, but at same time THD at sensitive load is measured to be around 2.5%. If a 2 phase fault is forced on the system during this period the THD at load side is increased to about 4.8%, but same time maintain the balance in the voltage disturbed by the fault. Thus two problems, fault as well as harmonics are taken care by the DVR simultaneously.

The results of the three phase fault in the system at time t=0.067, are shown in fig. 6(a) and 6(b). Three phase to ground fault causes the complete failure of voltage at PCC. The DVR again maintain that voltage through the repetitive controller.

Figure 7(a) shows the downstream current through DVR during downstream fault without any control scheme and figure 7(b) is same current controlled by making the output of DVR to behave as a pure inductor.

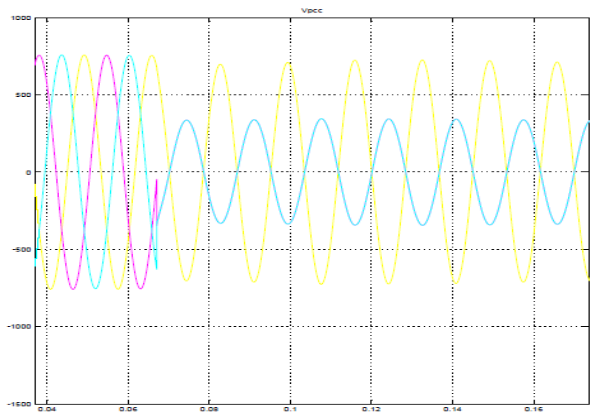

Figure 4(a). Voltage at PCC for 2 phase fault

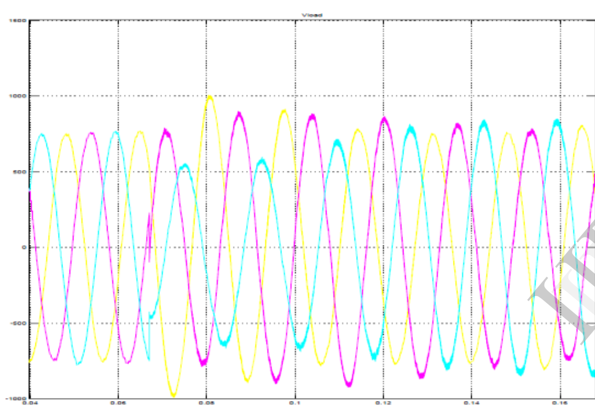

Figure 4(b). Voltage across sensitive load for 2 phase fault

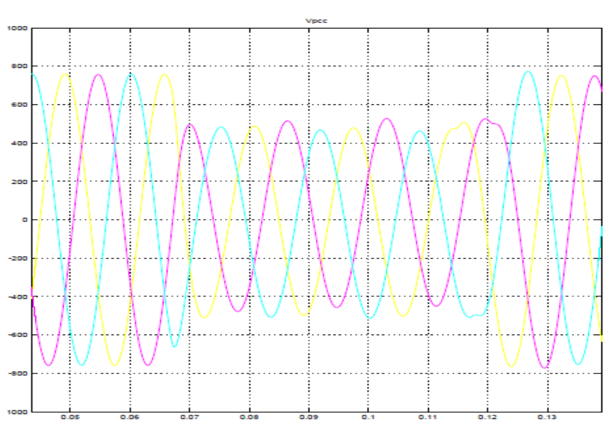

Figure 5(a). Voltage at PCC during sag

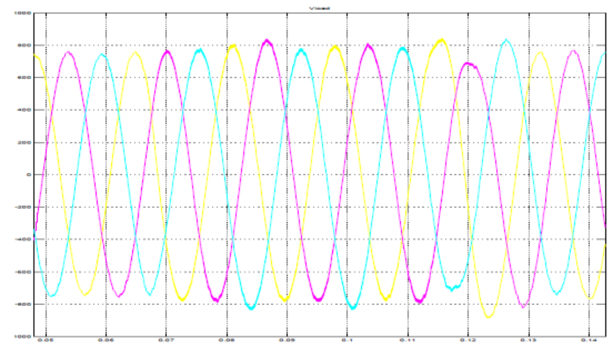

Figure 5(b). Voltage across sensitive load during sag

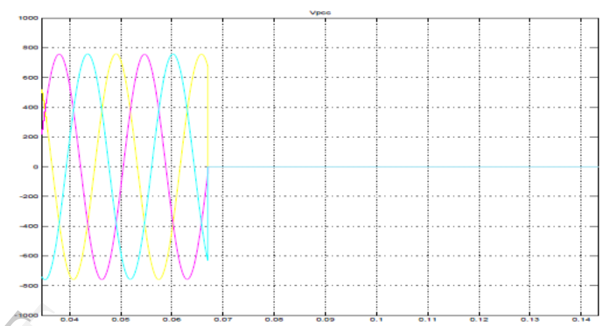

Figure 6(a). Voltage at PCC during 3 phase fault

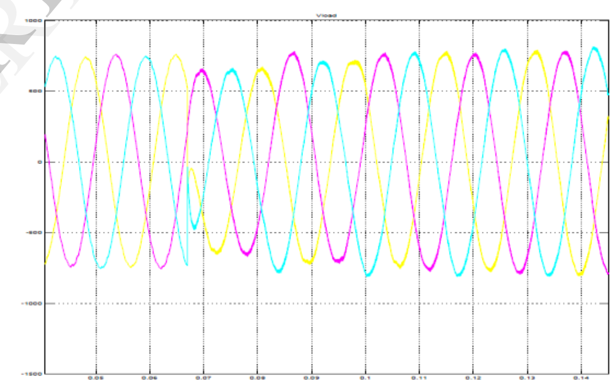

Figure 6(b). Voltage across load during 3 phase fault

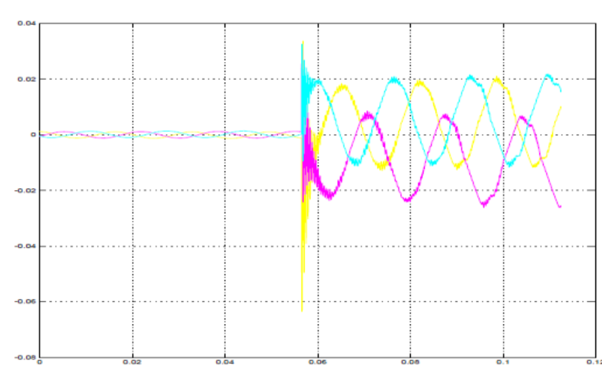

Figure 7(a). Uncontrolled downstream fault current

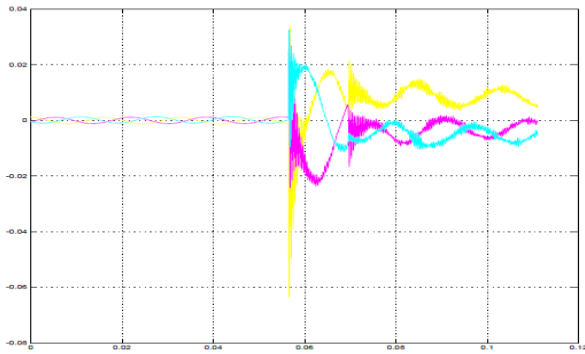

Figure 7(b). Downstream fault current

5. Conclusion

A key feature of this control scheme is its simplicity; only one controller is required to eliminate three PQ disturbances, namely, voltage sags, harmonic voltages, voltage imbalances without being affected by downstream fault. The controller can be implemented by using either a stationary reference frame or a rotating reference frame. In this paper, the highly developed graphical facilities available in MATLAB/SIMULINK have been used very effectively to carry out all aspects of the system implementation. Comprehensive simulation results using a simple test system show that the repetitive controller and the DVR yield excellent voltage regulation, thus screening a sensitive load point from upstream PQ disturbances.

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