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Improvement of Power Quality Using Repetitive Controller for Dynamic Voltage Restorer

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Abstract: ***Quality of the output power delivered from the utilities has become a major concern of the modern industries for the last decade. These power quality associated problems are voltage sag, surge, flicker, voltage imbalance, interruptions and harmonic problems. This paper discusses a controller based on repetitive control for a dynamic voltage restorer (DVR) to compensate voltage sag, harmonic voltages and voltage imbalances. Repetitive control can achieve zero steady-state error. The simulation is carried out in the MATLAB/SIMULINK environment which shows reliable results.***

Keywords: Dynamic Voltage Restorer (DVR), Harmonic Distortion, Repetitive Control, Voltage Sag, Voltage swell.

1. Introduction

The importance of power quality (PQ) has risen very considerably over the last two decades due to a marked increase in the number of equipment which is sensitive to adverse PQ environments, the disturbances introduced by nonlinear loads, and the proliferation of renewable energy sources, among others. At least 50% of all PQ disturbances are of the voltage quality type, where the interest is the study of any deviation of the voltage waveform from its ideal form. The best well-known disturbances are voltage sags and swells, harmonic and inter-harmonic voltages, and, for three-phase systems, voltage imbalances. A voltage sag is normally caused by short-circuit faults in the power network or by the starting up of induction motors of large rating. The ensuing adverse consequences are a reduction in the energy transfers of electric motors and the disconnection of sensitive equipment and industrial processes brought to a standstill.

Harmonics are produced by nonlinear equipment, such as electric arc furnaces, variable speed drives, large concentrations of arc discharge lamps, and loads which use power electronics. Harmonic currents generated by a nonlinear device or created as a result of existing harmonic voltages will exacerbate copper and iron losses in electrical equipment. In rotating machinery, they will produce pulsating torques and overheating. Voltage imbalances are normally brought about by unbalanced loads or unbalanced short-circuit faults, thus producing overheating in synchronous machines and, in some extreme cases, leading to load shutdowns and equipment failure.

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. 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 reestablish the voltage to its presag state. Its rate of success in combating voltage sags in actual installations is well documented, this being one of the reasons why it continues to attract a great deal of interest in industry and in academic circles. Research work has been reported on DVR two-level and multilevel topologies as well as on control and operation. The latter may be divided into several topics.

1) The configuration, whether two-level or multilevel, relates to the availability, or otherwise, of energy storage , the output filter, and the capacity to cancel out unbalanced voltages in three-phase four-wire systems.
2) The voltage-sag detection. Several techniques have been used to detect the instant of sag appearance, such as measurement of the peak value of the grid voltage.
3) The DVR may be operated to inject the series voltage according to several criteria, such as minimum energy exchange with the grid.

The three most popular strategies to compensate voltage sags are:

1) Presag compensation. The injected DVR voltage is calculated to simply compensate the load voltage to its presag condition;
2) Inphase compensation. The DVR voltage is always in phase with the grid voltage; and
3) Optimal energy compensation. This strategy minimizes the energy transfer between the energy storage and the grid during steady-state operation. Although these are the best well-known control strategies, many efforts are being made to develop new ones to enable better DVR utilization.

The repetitive controller presented in this paper has a wider range of applicability; it is used in a DVR system to ameliorate voltage sags, harmonic voltages, and voltage imbalances within a bandwidth. Unlike other schemes, which also have a comparable range of applicability, only one controller is needed to cancel all three disturbances simultaneously. The control structure contains a grid voltage feed forward term to improve the system transient response, and a closed-loop control which comprises a feedback of the load voltage with the repetitive controller in order to warrant zero tracking error in steady state.

2. Circuit Model

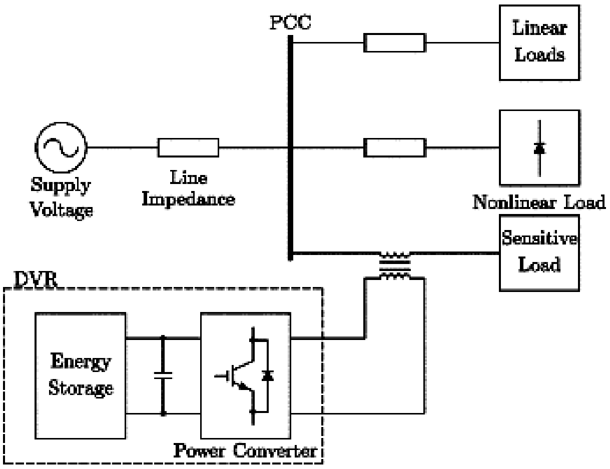

Figure 1: System Configuration with DVR

A typical test system, incorporating a DVR, is depicted in Fig. 1. Various kinds of loads are connected at the point of common coupling (PCC), including a linear load, a nonlinear load, and a sensitive load. The series connection of the voltage-source converter (VSC) making up the DVR with the ac system is achieved by means of a coupling transformer whose primary is connected in series between the mains and the load. Although a passive LC filter is normally used to obtain a switching-ripple-free DVR voltage, in this paper, this filter is not considered in order to fully assess the harmonic cancelling properties of the repetitive controller.

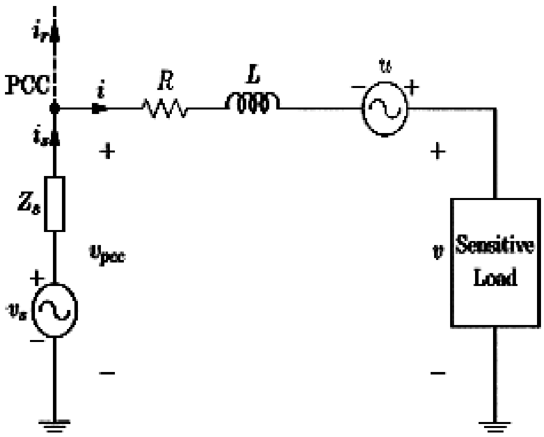

Figure 2: Equivalent circuit of a DVR

Fig. 2 shows the equivalent circuit for the DVR, where Vs is the supply voltage, Z_s is the line impedance, i_s is the current supplied by the source, which splits at the PCC into a current injected into the sensitive load i and a current injected into other loads i_r . The voltage V_{PCC} is the measured voltage at the PCC; u is the voltage representing the DVR, which is modeled as an ideal voltage source. Also, R and L are the resistance and inductance of the coupling transformer, respectively, and v is the measured voltage across the sensitive load.

3. Problem Formulation

The sensitive-load voltage from Fig.2 can be obtained as

$$V(t) = V_{pcc} + u(t) - R\,i(t) - L\frac{di}{dt}$$

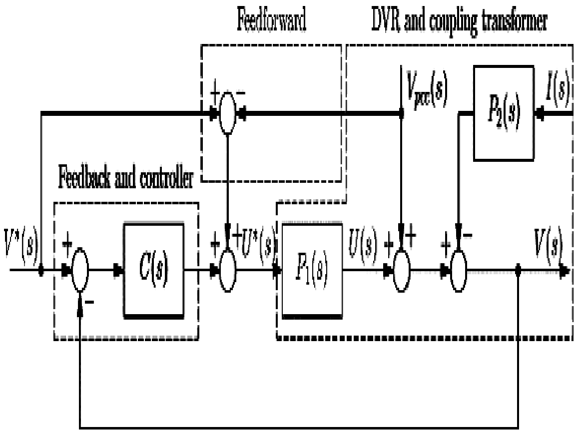

Figure 3: Closed loop control scheme

The aim of the control system is to regulate the load voltage in the presence of various kinds of disturbances. The control structure proposed in this paper is based on the use of a 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 Fig.3 where C(s) represents the controller. If the switching frequency is high enough, the DVR can be modeled as a linear amplifier with a pure delay $P_1(S) = e^{-t_0 S}$.

This delay is the sum of one-sample-period plus the time delay of the inverter due to PWM switching. The former applies in cases of microprocessor-based implementations and the latter can be taken to be half the switching period. The transfer function P_2(s) is equal to Ls+R, 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. The model may be extended with ease to three-phase applications.

The load voltage is

$$V(s) = F(s)\,V^*(s) + F_w(s)\,V_{pcc}(s) + F_i(s)\,I(s)$$

Where

$$F(s) = \frac{[1+C(s)]P_1(s)}{1+C(s)P_1(s)}$$

$$F_w(S) = \frac{1-P_1(S)}{1+C(s)P_1(S)}$$

$$F_i(S) = -\frac{P_2(S)}{1+C(S)P_1(S)}$$

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. As a first approximation, as described in conventional repetitive-control theory, the controller C(s) can be written as

$$C(S) = \frac{M(S)}{1-e^{-\frac{2\pi}{w_1}S}}$$

Where M(s) is a transfer function chosen so that the closed-loop stability is always fulfilled and ω1 is the fundamental frequency at the mains.

$$F(S) \;=\; \frac{\left[1 - e^{-\frac{2\pi}{w_1}S} + M(S)\right] P_1\,(S)}{[1 - e^{-\frac{2\pi}{w_1}S} + M(S)P_1(S)}$$

$$F_W(S) \;=\; \frac{[1 - P_1(S)][1 - e^{-\frac{2\pi}{w_1}S}]}{1 - e^{-\frac{2\pi}{W_1}S} + M(S)P_1(S)}$$

$$F_i(S) \;=\; -\,\frac{\left[1-e^{-\frac{2\pi}{w_1}S}\right]P_2(S)}{1-e^{-\frac{2\pi}{w_1}S}+M(S)P_1\,(S)}.$$

In order to calculate the frequency response, the variable S is substituted by jω. It should be noticed that the term (1-e$^{(-2\pi)/(\omega 1)j\omega}$) is always zero whenever ω is an integer multiple of the frequency ω1 (e.g., ω= 3ω1 , then (1-e$^{-j6\pi}$)=0). Hence, the frequency response shows that F(j ω_h)=1, Fω(jω_h)=0and F$_i$(jω_h)=0 for frequencies ω_h=hω1 with h=0, 1, 2, ……∞ . Therefore, if the closed-loop system is stable, the error in steady state is zero for sinusoidal reference inputs or sinusoidal disturbance inputs of frequency ω_h. Since the delay t_0 is smaller than the grid-voltage period (t_0<(2π)/ω_1)), the transfer function M(s) can be chosen as

$$M(S) = e^{-\left(\frac{2\pi}{w_1} - t_0\right)S}$$

With the substitution and rearranging the terms yields

$$\text{V(S)}= e^{-\frac{2\pi}{w_1}S}\,V^*(S) + \left[1 - e^{-\frac{2\pi}{w_1}S}\right]e^{-t_0\,s}\,V^*(S)$$
$$+\left[1 - e^{-\frac{2\pi}{w_1}S}\right][(1\text{-}e^{-t_0 S})V_{PCC}(S)$$
$$-P_2(S)\,I(S)$$

Unfortunately, the delay t_0 is not exactly known and the closed loop system will not be stable if a controller is designed for an estimated $\hat{t}_0 \neq t_0$

To tackle this problem, a modified controller C(s) is proposed as

$$C(S) = \frac{Q(S)e^{-(T-t^{\wedge}{}_0)S}}{1 - Q(S)e^{-TS}}$$

Where Q(s) is the transfer function of a low-pass filter, $\hat{t}_0$ is the estimated value for the DVR delay, with T=(2π/ω_1)-β and β is a design parameter which is smaller than the period of the grid voltage (β<(2π)/(ω_1)). The corresponding transfer functions are given as

$$F(S) = \frac{e^{-t_0 S} + Q(S)e^{-Ts}[e^{-\delta S} - e^{-t_0 S}]}{1 + Q(S)e^{-TS}(e^{-\delta s} - 1)}$$

$$F_W(S) = \frac{[1 - e^{-t_0 S}][1 - Q(S)e^{-TS}]}{1 + Q(S)e^{-TS}(e^{-\delta S} - 1)}$$

$$F_i(s) = -\frac{[1 - Q(S)e^{-TS}]P_2(S)}{1 + Q(S)e^{-TS}(e^{-\delta S} - 1)}$$

Where δ=(t_0- $\hat{t}_0$)

4. Repetitive Controller

Repetitive Control is a Control technique based on the Internal Model Principle (IMP) used when you need to follow or reject periodic signals. According to The IMP the generator of the signal to be tracked/ rejected must be introduced inside the control loop. It can be proven that the generator of a generic periodical signal has the following the shape.

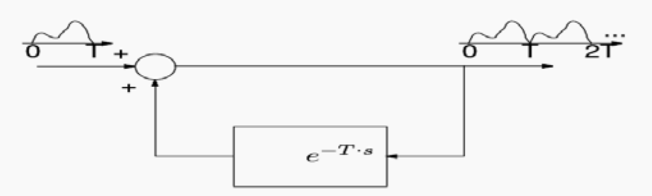

Figure 4: Basic circuit of repetitive controller

One of the key issues is to assure stability once the basic cell has been introduced inside decontrol loop. Repetitive Control has been extensively used in different areas as such as CD and disk arm actuators, robotics, machining, electro-hydraulics, torque vibration suppression in motor control, electronic rectifiers, PWM Inverters, UPS systems, Harmonic active filters and electronic Converters.

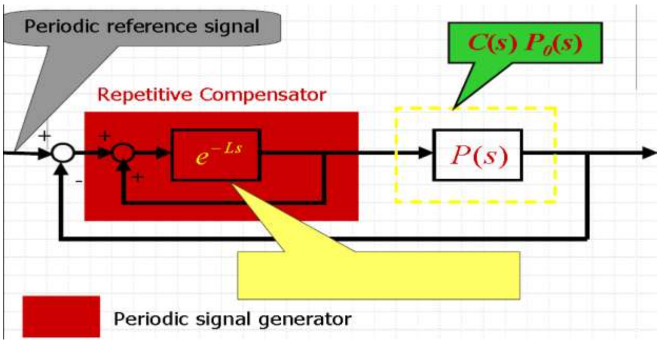

Figure 5: General construction

5. Control Philosophy

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.6. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (*Vref*). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A proportional-integral (PI) controller (shown in Fig. 6) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is V_{ref} - V_{in} V_{ref} equal to 1 p. u. voltage and V_{in} voltage in p. u. at the load terminals.

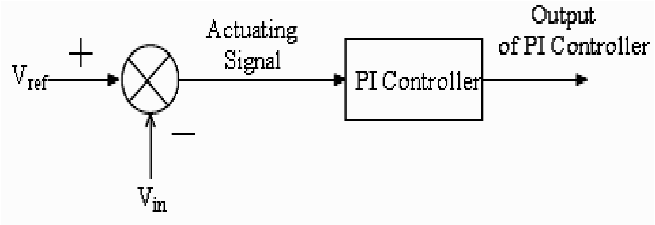

Figure 6: Schematic of a typical PI Controller

In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme shown in figure 7.

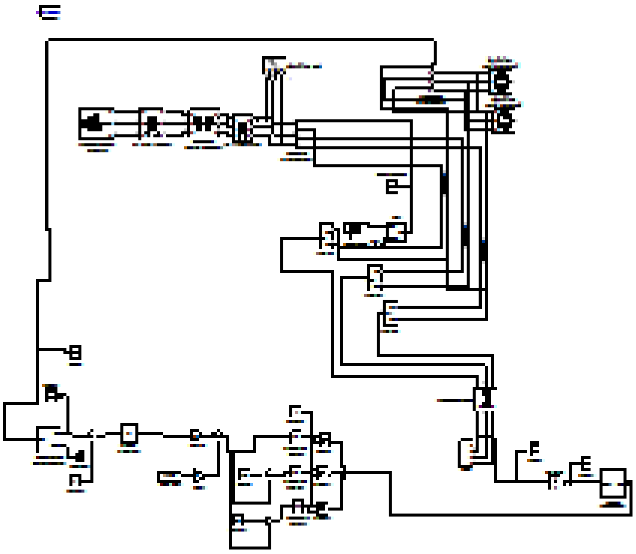

Figure 7: Circuit model of a DVR test System using PI Control

The proposed DVR sets the operating frequency automatically by checking the source voltage when the system starts up.

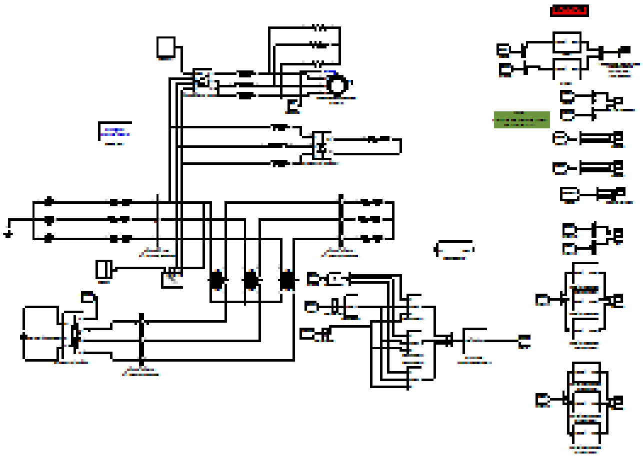

Figure 8: Circuit model of a DVR test System with repetitive Controller

6. Simulation Results

A typical test system, incorporating a DVR, is depicted in Fig. 7 and Fig 8. Various kinds of loads are connected at the point of common coupling (PCC), including a linear load, a nonlinear load, and a sensitive load. The series connection of the voltage-source converter (VSC) making up the DVR with the ac system is achieved by means of a coupling transformer whose primary is connected in series between the mains and the load. Although a passive LC filter is normally used to obtain a switching-ripple-free DVR voltage, in this paper, this filter is not considered in order to fully assess the harmonic cancelling properties of the repetitive controller.

6.1 Voltage Sag Mitigation

A case of Three-phase voltage sag is simulated and the results are shown in Fig. 8. In this case, we assume that there is a 30% three-phase voltage sag with +30° phase. Fig.10 shows the result of voltage sag compensation. Fig.10 also shows the serial injected voltage components. Moreover, the compensated load voltage is shown. As it can be seen from the results, the DVR is able to produce the required voltage components for different phases rapidly and help to maintain a balanced and constant load voltage at the nominal value.

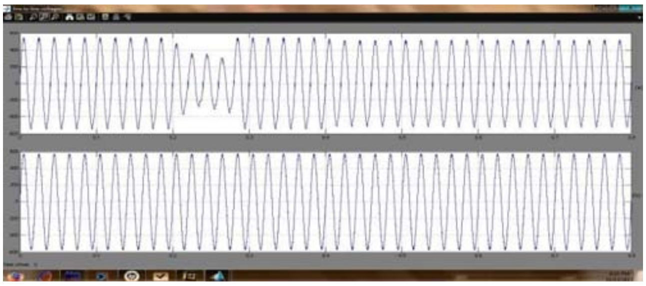

Figure 9: Voltage Sag and Mitigation

Figure 10: 3-Φ rms voltage across (a) The sensitive load and (b) at PCC

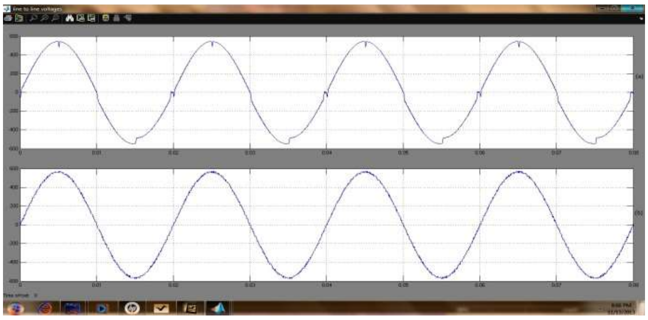

Figure 11: 3-Φ rms voltage across (a) The sensitive load and (b) at PCC

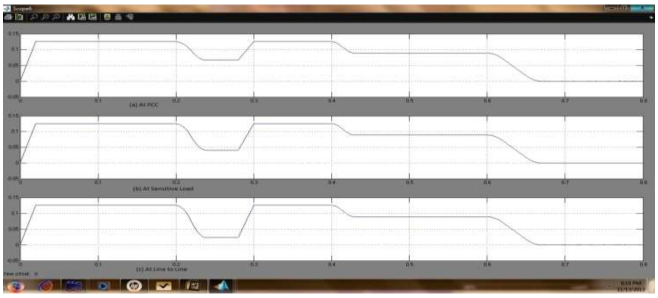

Figure 12: THD values of source voltage (a) at PCC and (b) sensitive load

Fundamental Ha Rmonic Rms Value And Voltage Total Harmonic Distortion Of The Line-To-Line Voltage At Thepcc And Across The Sensitive Load For Different Instants

	Vrms(v)	THDv(%)
Time Interval 0<t<0.2(balanced conditions)		
PCC(ab)	385	12.52
Sensitive Load(ab)	399.63	3.07
Time Interval(s): 0.2<t<0.28(unbalanced conditions)		
PCC(ab)	225.37	6.71
PCC(bc)	363.23	4.07
PCC(ca)	242.07	2.30
Sensitive Load(ab)	399.33	6.88
Sensitive Load(bc)	400.19	6.56
Sensitive Load(ca)	399.77	7.12
Time Interval(s): 0.4<t<0.65(balanced conditions)		
PCC(ab)	365	8.91
Sensitive Load(ab)	400.17	3.77
Time Interval(s): 0.65<t<0.8(balanced conditions)		
PCC(ab)	369	0.00
Sensitive Load(ab)	399.78	3.17

The use of dynamic voltage restorers in PQ-related applications is increasing. The most popular application has been on voltage sags amelioration but other voltage-quality phenomena may also benefit from its use, provided that more robust control schemes than the basic PI controller become available. A case in point is the so called repetitive controller proposed in this paper, which has a fast transient response and ensures zero error in steady state for any sinusoidal reference input and for any sinusoidal disturbance whose frequencies are an integer multiple of the fundamental frequency. To achieve this, the controller has been provided with a feed forward term and feedback term. The design has been carried out by studying the stability of the closed-loop system including possible modeling errors, resulting in a controller which possesses very good transient and steady-state performances for various kinds of disturbances. 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, and voltage imbalances. The controller can be implemented by using either a stationary reference frame or a rotating reference frame. Comprehensive simulation results using a simple but realistic test system show that the repetitive controller and the DVR yield excellent voltage regulation, thus screening a sensitive load point from upstream PQ disturbances.

7. Acknowledgement

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