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PROPORTIONAL REPETITIVE CONTROL OF A DYNAMIC VOLTAGE RESTORER (DVR) FOR POWER QUALITY IMPROVEMENT

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Abstract- This paper discusses a controller based on a proportional-repetitive control for a dynamic voltage restorer (DVR). Repetitive control can achieve zero steady-state error of tracking sinusoidal signal, but it doesn't make a quick response to the disturbance and needs at least one fundamental cycle to function properly. The control system based on proportional-repetitive controller, in stationary frame is proposed to achieve fast dynamic response and zero steady-state error at the same time. This controller can compensate power quality disturbances, such as voltage sag, harmonic voltages, and voltage imbalance, simultaneously. The control scheme is implemented in a test system with PSCAD/EMTDC software. Simulation results show that the output voltage of controller can track the reference signal quickly and accurately and therefore compensate disturbances.

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

I. INTRODUCTION

In recent years, there has been an increased emphasis on Power Quality (PQ) due to the widespread use of sensitive and nonlinear loads in electrical power systems, and the rapid growth of renewable energy sources [1]. The most common PQ disturbance in a power system is voltage sags, but other disturbances, such as harmonic voltages and voltage imbalances, can also negatively impact a facility's electric distribution system [2].

A voltage sag is normally caused by short-circuit faults in the power system [3] or inrush currents when large machines are switched on [4], or switching actions in the grid. Voltage sag occurs frequently, and therefore, sags form the leading power quality problem [5]. Lowering the voltage value increases transmission losses in lines, transformers and other devices.

Harmonics are produced by nonlinear equipments, such as arc furnaces, arc welders, high-pressure discharge lamps, magnetic core equipment, and loads which use power electronics. Non-linear loads represent a large percentage of the total loads. Under these conditions, total harmonic distortion (THD) may become very high and therefore dangerous for the system. Harmonics will intensify copper and iron losses in electrical equipment. In rotating machinery, they will produce pulsating torques and overheating [6].

The voltage imbalances are normally produced by unbalanced loads or unbalanced short-circuit faults. They cause overheating in synchronous machines and, in some extreme cases, leading to load shutdowns and equipment failure. Voltage imbalance can also result from different self and mutual impedances of individual phases of transmission system components.

DVR is one of the most common series device connected to the ac network via transformer, which was originally conceived to protect against voltage sag and swells during abnormal conditions in distribution systems. Its range of applicability can be extended with a suitable control scheme [7]. The basic operating principle of the DVR is voltage stabilization by connecting a series voltage source between the sensitive load and power supply source. The control scheme must be sufficient enough to restore the sensitive load voltage to its ideal state [8].

The performance analysis and control of the DVR, with different control strategies, have been studied and examined by researchers. Most of the published works on the DVR have used an ordinary proportional-integral (PI) controller in a synchronous frame. This basic approach is sufficient to enable voltage sag compensation, to warrant zero tracking error for the fundamental component, and to compensate certain kinds of unbalanced conditions but it cannot get zero steady-state error, when the reference is a sinusoidal signal superposed of different frequencies, because of its bandwidth limitation [9, 10].

Some of references add resonant control filters to the existing PI control scheme in order to eliminate specific harmonic voltages [11]. In this structure one filter is required for each harmonic to be eliminated. When a periodic disturbance has an infinite Fourier series, then an infinite number of resonant filters are required to reject it. In the repetitive control scheme, a simple delay in a proper feedback can be used to produce an infinite number of poles and thereby simulating a bank of an infinite number of resonant filters [12, 13]. But this controller does not make a quick response to load disturbance and needs at least one fundamental cycle.

This paper proposes a new control technique which combines repetitive controller scheme with a P controller. The simulation results verify the effectiveness of the combined control algorithm which can decrease response time, achieve fast dynamic response, and zero steady-state error at the same time.

II. DVR MODEL

A typical test system with a DVR is depicted in Figure 1. Test system contains two loads including a nonlinear load and a sensitive load. The DVR can make a sinusoidal voltage in any frequency, amplitude and phase angel. A transformer is used to connect output voltage to the sensitive load. An LC filter normally is used to obtain a DVR voltage without switching-ripple.

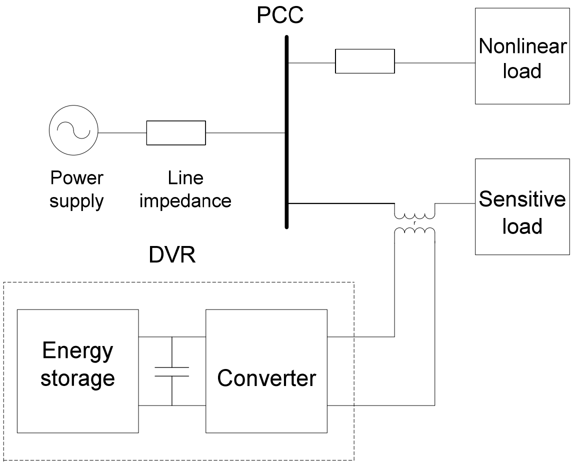

Figure 1. System configuration with a DVR

The equivalent circuit for the DVR is shown in Figure 2, where V_S is supply voltage, Z_S is line impedance, v_{PCC} is the voltage at the point of common coupling (PCC), U is the voltage of DVR, R and L are the resistance and inductance of the transformer respectively and v_L is the voltage at the sensitive load which is obtained with the following equation [13]:

$$v_L(t) = v_{PCC}(t) + u(t) - Ri(t) - L\frac{di}{dt} \tag{1}$$

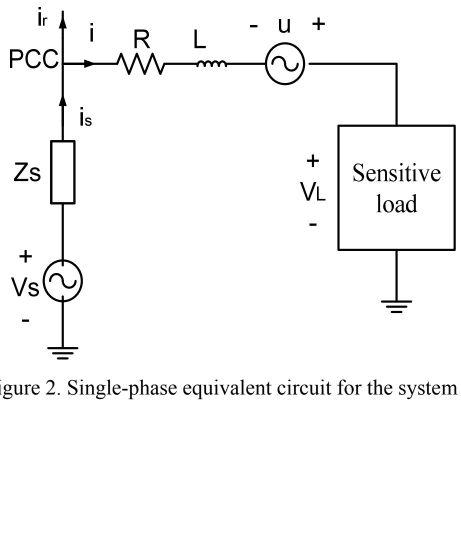

Figure 2. Single-phase equivalent circuit for the system

III. REPETITIVE CONTROL

The repetitive control is a control scheme for single-input single-output continuous system to achieve high accuracy for tracking periodic reference, which was proposed by Inoue etc. in the 1980's. If the sinusoidal signal is superposed of one harmonic frequency, one PR controller would be needed but if the signal is superposed of infinite harmonic frequencies, infinite PR controller would be needed. Repetitive controller is able to compensate all of harmonics only with a feedback of delay in its scheme. The negative-feedback repetitive control scheme with feedforward is depicted in figure 3 that has the following transfer function [14]:

$$R(s) = \frac{1 - e^{\frac{-\pi}{\omega_1}s}}{1 + e^{\frac{-\pi}{\omega_1}s}} \tag{2}$$

The transfer function has infinite poles on the imaginary axis. It should be noticed that with the presence of feedforward, infinite zeroes between any two consecutive poles will be appeared which allow peaks of higher gains and wider bandwidth. At the same time it will avoid excitation of even harmonics. Its Bode diagram is shown in Figure 4. In typical repetitive control maximum attainable gain is $\frac{1}{1-k}$ which is smaller than the one considering feedforward term. In modified repetitive control, there are simple valleys between peaks whose maximum achievable gain is $\frac{1+k}{1-k}$. So, performance and frequency response of the system is improved. Transfer function can be written as

$$R(s) = \frac{1 - e^{\frac{-\pi}{\omega_1}s}}{1 + e^{\frac{-\pi}{\omega_1}s}} = \frac{e^{\frac{\pi}{2\omega_1}s} - e^{\frac{-\pi}{2\omega_1}s}}{e^{\frac{\pi}{2\omega_1}s} + e^{\frac{-\pi}{2\omega_1}s}} =$$
$$= \frac{\sinh(\frac{\pi}{2\omega_1}s)}{\cosh(\frac{\pi}{2\omega_1}s)} = \frac{\frac{\pi}{2\omega_1}s\prod_{k=1}^{\infty}(\frac{s^2}{(2k)^2\omega_1^2}+1)}{\prod_{k=1}^{\infty}(\frac{s^2}{(2k-1)^2\omega_1^2}+1)} \tag{3}$$

However, above compensator is not ready to be used. To limit the infinite gain at the resonant frequencies and guarantee a safer operation, it is proposed to shift poles to the left side of the imaginary axis. The new transfer function will be changed to $\tilde{R}(s) = R(s+a)$. Using this shifting in the exponential term result $\mathrm{e}^{-(s+a)\frac{2\pi}{\omega_1}} = \mathrm{e}^{-s\frac{2\pi}{\omega_1}}\mathrm{e}^{-a\frac{2\pi}{\omega_1}}$ in which is like a gain $k = \mathrm{e}^{-a\frac{2\pi}{\omega_1}}$. If a gain $k>1$ be used, the poles will move to the right and if a gain $0<k<1$ be used, they will move to the left. So, using a simple low pass filter (LPF) is recommended in repetitive controllers. This would restrict the bandwidth of the controller, and at the same time improve the stability.

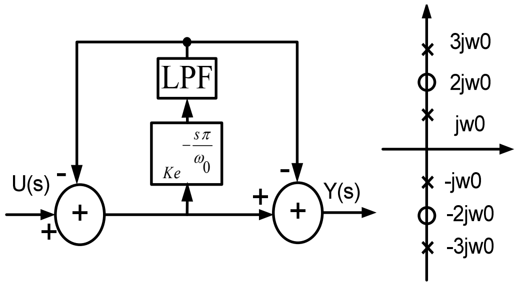

Figure 3. Continuous-time model and pole locations of negative feedback (odd harmonics) compensator with feedforward

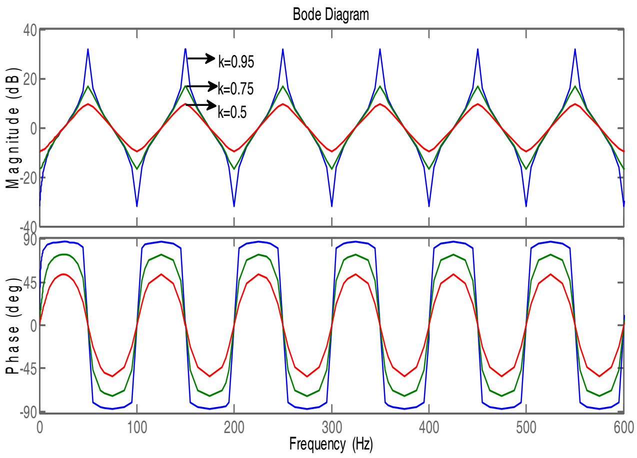

Figure 4. Bode plot of negative feedback repetitive controller with feedforward for different values of k (0.95, 0.75 and 0.5)

IV. PROPOSED CONTROL SCHEME

Proportional (P) controller improves the system dynamic performance and tracking speed but cannot achieve zero steady-state error of tracking signal which is a sinusoidal signal superposed of different frequencies. The traditional repetitive control can effectively reduce the static error and make output to follow the reference signal, but the controller does not make a quick suppression to disturbance and the output voltage needs at least one fundamental cycle to track the input voltage.

If the transient error is small, repetitive control will play a major role in the control, but if the disturbance error is large, P will respond immediately to reduce the tracking error. The bigger P is the faster error decreases, but P cannot be too large because it will make the system unsteadily. Improved repetitive control can decrease response time and eliminate the steady state error to keep system steady at same time. It should be noticed that P and repetitive control are used in stationary frame.

$$C(s) = k_p + \frac{1 - kQe^{\frac{-\pi}{\omega_1}s}}{1 + kQe^{\frac{-\pi}{\omega_1}s}} \qquad (4)$$

The continuous time of the whole control scheme is shown in Figure 5 where $C(s)$ is the proposed controller. Supposing $i(s)$ is load current, $P_1(s)=Ls+R$, $u(s)$ is the output voltage of DVR, $v^*(s)$ is the reference voltage for the load, $Gu(s)$ is the DVR modeled as a linear amplifier and $v(s)$ is the load voltage.

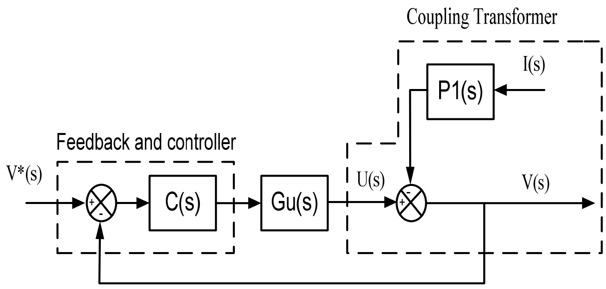

Figure 5. Modified control scheme

$$v(s) = F(s)v^*(s) + F_i(s)i(s) \qquad (5)$$

where

$$F(s) = \frac{C(s)Gu(s)}{1 + C(s)Gu(s)} \qquad (6)$$

$$F_i(s) = -\frac{P_1(s)}{1 + C(s)Gu(s)} \qquad (7)$$

The substitution of (4) into (6) and (7) and assuming $Gu(s)$=1 yields

$$F(s) = \frac{k_p(1 + kQe^{\frac{-\pi}{\omega_1}s}) + (1 - kQe^{\frac{-\pi}{\omega_1}s})}{(1 + k_p)(1 + kQe^{\frac{-\pi}{\omega_1}s}) + (1 - kQe^{\frac{-\pi}{\omega_1}s})} \qquad (8)$$

$$F_i(s) = -\frac{(1 + kQe^{\frac{-\pi}{\omega_1}s})P_1(s)}{(1 + k_P)(1 + kQe^{\frac{-\pi}{\omega_1}s}) + (1 - kQe^{\frac{-\pi}{\omega_1}s})} \qquad (9)$$

To calculate frequency response of (8) and (9), the variable s is substituted by $j\omega$. The term $1 + kQe^{\frac{-\pi}{\omega_1}s}$ is always zero because ω is an odd integer multiple of frequency ω_1, $k\approx1$, Q is a low-pass filter and the input signal is a sinusoidal signal composed of odd harmonics. So, $F(s)$=1 and $F_i(s)$=0 and if the closed-loop system be stable, the steady-state error will be zero. The characteristic equation of the closed-loop system is

$$1 + G(s) = (1 + k_p)(1 + kQe^{\frac{-\pi}{\omega_1}s}) + (1 - kQe^{\frac{-\pi}{\omega_1}s}) \qquad (10)$$

To guarantee stability, the term $G(s)$ in (10) must fulfill the Nyquist criterion: if the number of unstable poles of the open-loop system $G(s)$ is equal to zero (P=0), then the number of counterclockwise encirclements of the point (-1, 0) of the term $G(s)$ must be zero (N=0). It should be noticed that the low pass filter Q has been chosen so that its poles are stable (Q is a Bessel filter with cut-off frequency of 5 kHz).

V. SIMULATION ANALYSIS

The system shown in Figure 1 and the proposed controller are implemented in PSCAD/EMTDC. The AC power supply is a symmetric system with fundamental frequency 50Hz and load voltage 400V (rms line-to-line) which feeds two different loads: 1) a nonlinear load consists of a three phase uncontrolled rectifier and a RL load, 2) a three phase sensitive load. DVR is connected between the PCC and the sensitive load by means of a

20kVA coupling transformer with a unity turns. The voltage of the DC storage device is 650V. A sinusoidal PWM has been used to generate the switching signals for the converter. The main parameters are summarized in Table 1 [13].

Table 1. Parameters of the test system

Sensitive load	L_{sl}=50mH, R_{sl}=3Ω
Line impedance	L_s=500μH, R_s=7.5Ω
Nonlinear load	L_{DC}=0.4mH , R_{DC}=4Ω
Nonlinear load connection inductance	L_s=35μH
Transformer: inductance and resistance	L=6mH, R=0.3Ω
No load losses of transformer	P_0=0.02 p.u.

Figure 6 shows the Nyquist diagram of $G(s)$. It can be seen that the number of counterclockwise encirclements of the point (-1, 0) is zero (N=0) and because the number of unstable pole is zero (P=0), so the control system is stable. It should be noticed that the Nyquist diagram is depicted for k_p=0.5.

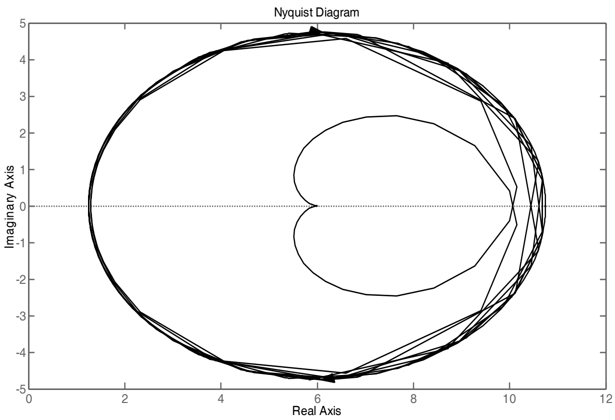

Figure 6. Nyquist diagram of $G(s)$ for stability analysis

Figure 7 shows the PCC voltage (rms) waveform. The PCC voltage is distorted because the nonlinear load is connected at t=0s. The Fourier analysis of the line-to-line voltage (V_{ab}) shows that the total harmonic voltage distortion is 13.21%. Figure 8 shows the harmonic spectrum of line-to-line voltage (V_{ab}). Sensitive load voltage (rms) is depicted in Figure 9 and the harmonic spectrum of line-to-line voltage is shown in Figure 10. According to the results, proposed controller not only compensated voltage drop but also can compensate harmonics efficiently and the total harmonic voltage distortion is decreased to 2.34% with a fast dynamic response (because of line impedance there is a little voltage drop).

A two-phase short-circuit fault (in the phases a and b) is happened at t=0.4s via a fault resistance of 0.2Ω. This short circuit fault results a 45% voltage sag in the two affected phases with respect to their nominal values and it causes a voltage drop until t=0.5s that the fault is removed. The nonlinear load is still connected. Figure 11 shows the three-phase voltage at PCC without DVR.

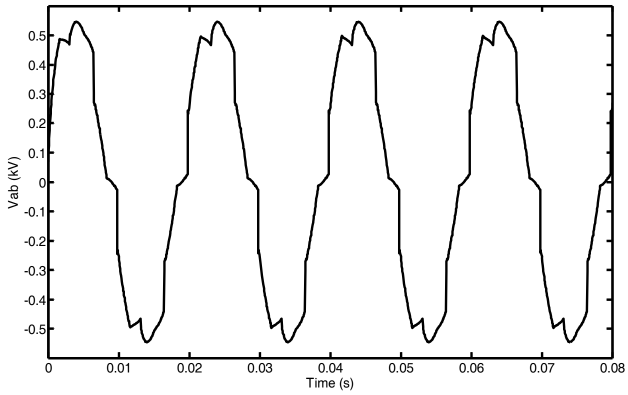

Figure 7. Line-to-line voltage at PCC

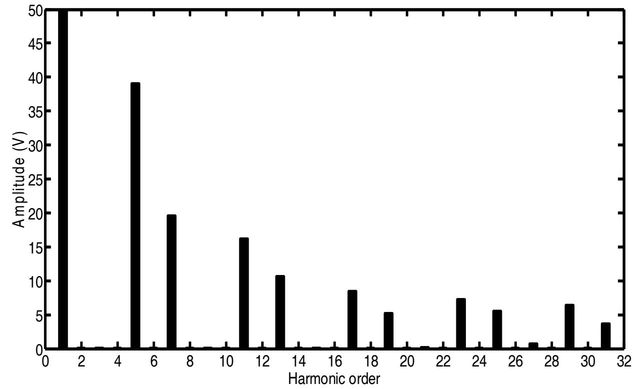

Figure 8. Harmonic spectrum of line-to-line voltage at PCC

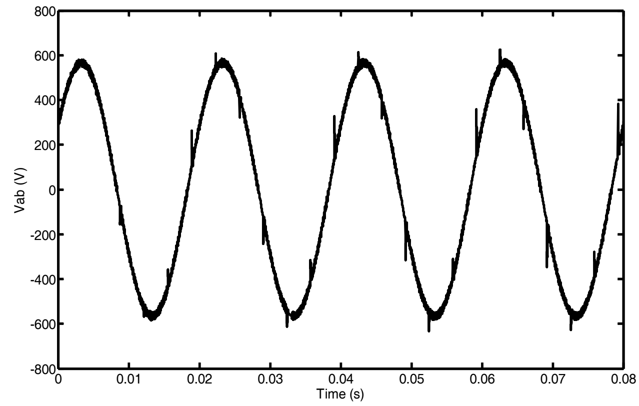

Figure 9. Line-to-line voltage at sensitive load

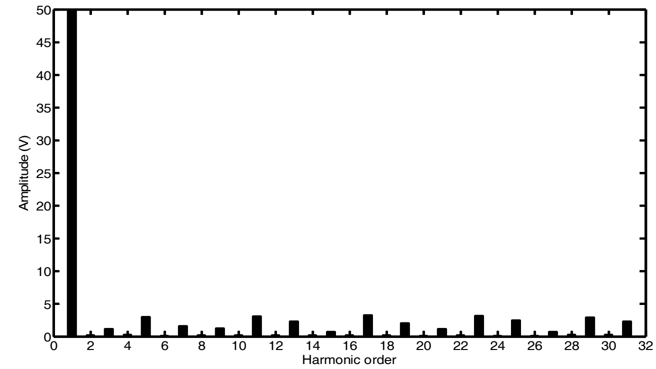

Figure 10. Harmonic spectrum of line-to-line voltage at sensitive load

The fault causes unbalanced voltage sag, while the nonlinear load continues to cause harmonic voltage distortion. The voltage waveform distortion is because of the harmonic currents drawn by the rectifier, while the total current provided to the sensitive load and the rectifier causes little voltage drop at the PCC but the two-phase short-circuit causes big voltage sag at PCC. The fundamental rms values of the line-to-line voltages at the PCC are $v^1_{PCC_{ab}}$=226.12, $v^1_{PCC_{bc}}$=365.75, $v^1_{PCC_{ca}}$=241.62 and the total harmonic distortions are THD_{ab}=12.63%, THD_{bc}=5.47%, THD_{ca}=2.93%.

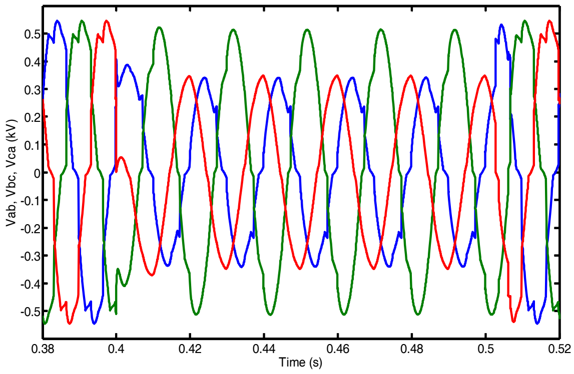

Figure 11. Line-to-line voltages at PCC during short circuit fault

Figure 12 shows three line-to-line voltages of the sensitive load. The two-phase short-circuit fault (the unbalanced voltage) is efficiently compensated. Furthermore, the proposed controller has the ability to cancel out harmonics and it guarantees zero-tracking error in steady state. The fundamental rms values of the line-to-line voltages at the sensitive load are $v^1_{PCC_{ab}}$=399.09, $v^1_{PCC_{bc}}$=399.36, $v^1_{PCC_{ca}}$=400.24 and the total harmonic distortions are THD_{ab}=2.23%, THD_{bc}=2.11%, THD_{ca}=1.76%.

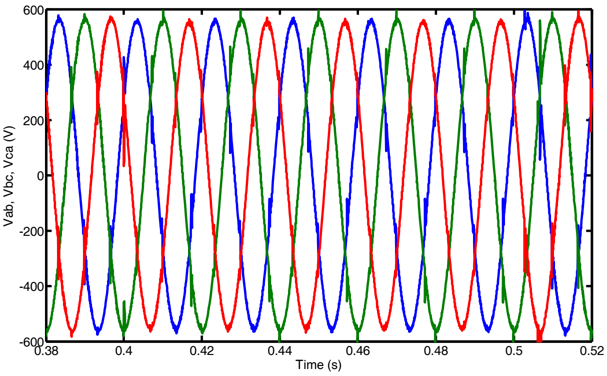

Figure 12. Line-to-line voltages at sensitive load during short circuit fault

So, Comparison of Figure 11 and 12 shows that the proposed control system and the DVR are able to cancel disturbances (the voltage sags, the unbalanced voltages, and the harmonic voltages) simultaneously. Figure 13 shows the three-phase rms voltage for the sensitive load (*a*) and the PCC (*b*). The rms voltage at PCC falls to 260V when the two-phase short circuit happened at t=0.4 s. It can be seen that the DVR and the proposed controller can maintaining the sensitive load voltage at 400 V.

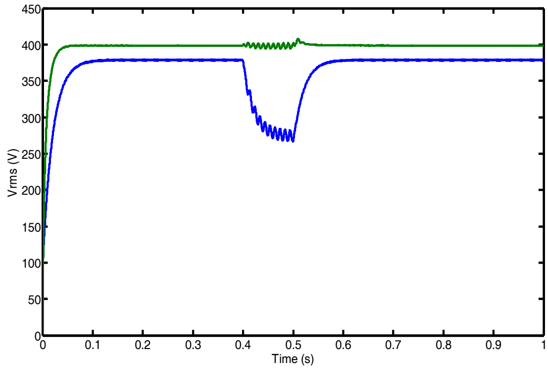

Figure 13. Three-phase rms voltage at sensitive load (*a*) and at PCC (*b*)

VI. CONCLUSIONS

A control scheme based on negative feedback repetitive control with feedforward and P control was proposed in this paper, in order to achieve fast dynamic response and zero steady-state error at the same time. The negative feedback repetitive control with feedforward, achieves zero steady state error and increases the system bandwidth without exciting even harmonics, but with a slow dynamic response. Adding the basic P controller improves dynamic performance of controller to track reference signal. The PSCAD/EMTDC software has been used to simulate all aspects of the test system. Comprehensive simulation results show superiority of the proposed controller to cancel all PQ disturbances at the same time. Adding repetitive controller to the system allows the output voltage amplitude close to the reference at steady state.

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BIOGRAPHIES

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