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Voltage Compensation and Power Factor Correction in Distribution Networks with DVR

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Abstract—The stability analysis and voltage regulation in distribution systems, as well as power quality problems such as voltage sags, swells, due to connection and disconnection of large loads, short circuits and the presence of non-linear loads, require of the consideration of adequate technical solutions. In this paper, a Dynamic Voltage Restorer (*DVR*) model based on a power converter scheme for voltage compensation due to the presence of sags of amplitude since $0.1pu$ to $0.9pu$ and swells with amplitude from $1.1pu$ to $1.9pu$, and power factor correction in distribution networks is proposed. The results are verified through MATLAB & Simulink.

Keywords— *DVR*; power factor; sags; swells; distribution networks; power converter.

I. INTRODUCTION

It is clear that at present, the user that does usage of power is increasingly dependent on technology, for example in areas such as industry and medicine, where sensitive equipment to energy abrupt changes, damaged by poor voltage quality can cause large monetary losses, reduction of the devices lifespan, sensible harm to user's health or even death. To avoid such anomalies the power network operation under the proper voltage regulation and stability is required. Voltage sags in power networks are not always possible to prevent due to the finite time compensation of faults that cause voltage drops to spread to sensitive loads in distribution systems [1].

Dynamic Voltage Restorer (*DVR*) is a custom power device based on a power converter which is becoming increasingly popular in power system applications for voltage sags and swells compensation [2], to improve voltage stability, network failure recovery, to mitigate voltage flicker, security of load [3], damping of system oscillations and to improve generation system transient and dynamic stability in the system [4], [5]. The *DVR* is connected in series to the grid through a transformer; it is placed on the distribution system between the supply and the feeder critical load at the point of common coupling (*PCC*) [6]. Westinghouse for the Electric Power Research Institute (EPRI) built the first *DVR* in the U.S., and it was installed in 1996 on the Duke Power Company grid system

to protect an automated yarn manufacturing and weaving factory [7]. A *DVR* can be manipulated by different control strategies; for example, in [1] a *DVR* without energy storage elements is described. Thus, the overall size of the *DVR* is reduced. However, since it has no energy storage elements, it is not capable of compensating deep sags or pronounced swells. In [4] a *DVR* able to compensate for sags in a range of $0.16pu$ to $0.5pu$ is described, but it is not capable of correcting power factor. In [8] a *DVR* model for power factor correction based on an optimal control strategy is proposed.

This research work reports findings on the representation and results obtained from the *DVR* application for voltage compensation on sags of amplitude since $0.1pu$ to $0.9pu$ and swells with amplitude from $1.1pu$ to $1.9pu$, as well as power factor correction in power networks.

II. CHARACTERISTICS AND MODELING OF DVR IN THE DISTRIBUTION NETWORK

The *DVR* based on a Voltage Source Converter (*VSC*) operation generates AC voltages through the IGBTs switching [9]. A *DVR* produces a voltage, which can be continuously or gradually adjusted by the distribution line compensation. The 6-pulse three-phase is the most common arrangement. At DC converter terminals, a parallel capacitor is connected to simulate a voltage source; its purpose is to serve as energy storage for the power flow control. The phase current is flowing through the AC circuit, with respect to *VSC* voltage terminals. It determines if the *VSC* is operating as a rectifier or as an inverter, that is, by delivering or absorbing energy from the AC network. The *PCC* is the node where the *VSC* and the generating source are connected.

In this research, particular reference is made to the presence of voltage sags and swells. The case study to be described starts from initial conditions, with the system operating in steady state. Nominal operation data of *DVR* are $3MVA$ of base power with an input voltage $V_s = 2.5kV$ and a frequency of $60Hz$. *DVR* connection is made between two distribution lines;

of 25km and 1km, respectively, through a series load connection RL and a transformer with a turn ratio of 1:10, to regulate the voltage at the PCC, as shown by Figure 1.

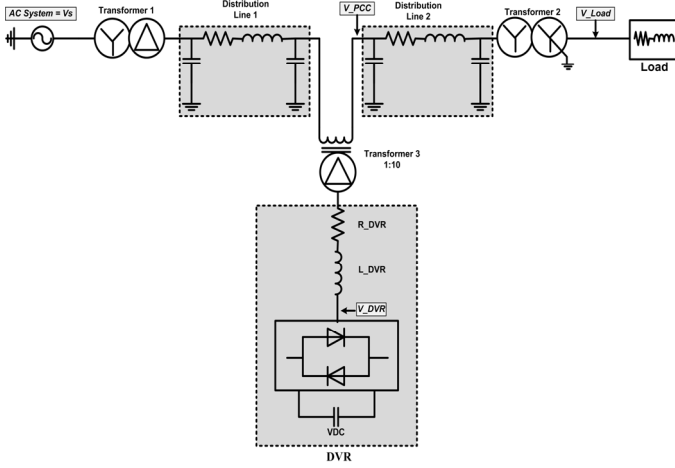


Figure 1 Distribution network with DVR

The DVR parameters are obtained from the base total power used and the input voltage as,

$$P_{PCC} = \frac{3}{2} V_{PCC} I_{PCC} \quad (1)$$

From (1) I is obtained as,

$$I_{PCC} = \left(\frac{2}{3} \right) \frac{P_{PCC}}{V_{PCC}} = \frac{2}{3} \left(\frac{3MVA}{2500V} \right) = 800A \quad (2)$$

The system base impedance is:

$$Z_{PCC} = \frac{V_{PCC}}{I_{PCC}} = \frac{2500V}{800A} = 3.125\Omega \quad (3)$$

The inductance value is calculated as,

$$L_{abc} = \frac{Z_{PCC}}{\omega_0} = \frac{3.125\Omega}{2\pi \cdot 60Hz} = \frac{3.125\Omega}{2\pi(60Hz)} = 8.3 \times 10^{-3} H \quad (4)$$

The resistance value is chosen in the range of 0.1Ω to 0.5Ω. For this case, the resistance value is 0.2Ω.

III. CONTROL AND MODELING: VOLTAGE COMPENSATION AND POWER FACTOR CORRECTION

Power factor correction is achieved by the line current through the i_d and i_q components, that is, feed-forward and feed backward signals are transformed to dq -frame reference, then processed by compensators, produced by control signals within the same framework. Finally, the control signals are transformed back to abc coordinates, which feeds the VSC. Reference commands i_{dref} and i_{qref} are limited by saturation blocks for the VSC protection.

The active power P and power factor θ are obtained from (5) and (6), which are controlled by the voltage amplitude, phase angle at the PCC and the VSC line current, respectively.

$$P_{PCCref}(t) = \frac{3}{2} [V_{PCCd}(t) i_d(t)] \quad (5)$$

$$\theta_{PCCref}(t) = -\frac{3}{2} [V_{PCCd}(t) i_q(t)] \quad (6)$$

Equations (7) and (8) are introduced in order to have independent control of P and θ , being the dq -frame reference used and assuming steady state operating conditions. P and θ can be manipulated through (9) and (10), that is:

$$i_{dref}(t) = \frac{2}{3} \left(\frac{P_{PCCref}(t)}{V_{PCCd}(t)} \right) \quad (7)$$

$$i_{qref}(t) = -\frac{2}{3} \left(\frac{\theta_{PCCref}(t)}{V_{PCCd}(t)} \right) \quad (8)$$

$$L \left(\frac{di_d}{dt} \right) = L\omega_0 i_q(t) - R i_d(t) + V_{id}(t) - V_{PCCd}(t) \quad (9)$$

$$L \left(\frac{di_q}{dt} \right) = -L\omega_0 i_d(t) - R i_q(t) + V_{iq}(t) - V_{PCCq}(t) \quad (10)$$

Figure 2 shows the VSC control diagram.

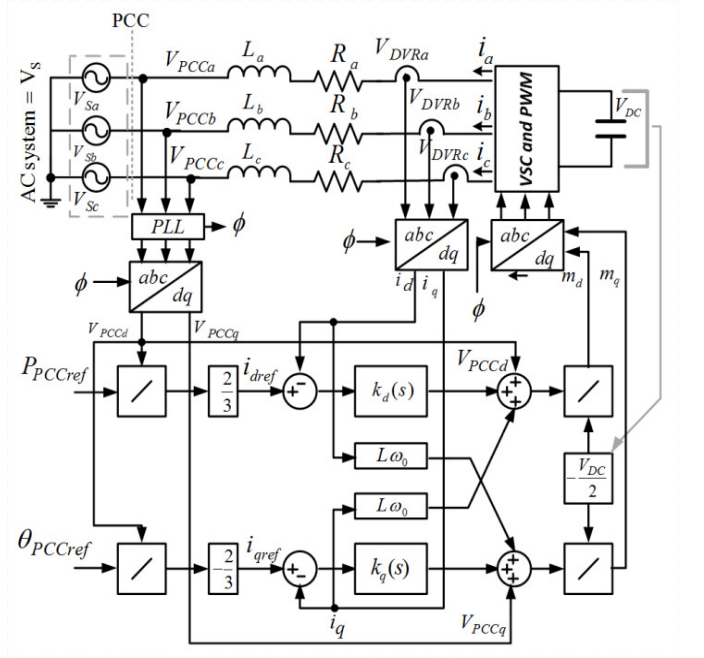


Figure 2 VSC control diagram

Finally, the dq compensating process is described by,

$$e_d(t) = i_{dref}(t) - i_d(t) \quad (11)$$

$$e_q(t) = i_{qref}(t) - i_q(t) \quad (12)$$

In Figure 2, $k_d(s)$ and $k_q(s)$ are replaced by a proportional integral compensator PI, given by,

$$k(s) = \frac{k_p(s) + k_i(s)}{s} \quad (13)$$

where k_p and k_i are the proportional and integral gains, respectively, obtained as,

$$k_p(s) = \frac{L}{\tau_i} \quad (14)$$

$$k_i(s) = \frac{R}{\tau_i} \quad (15)$$

where τ_i is the closed loop system time constant; usually it is in the range of $0.5-5ms$. A value of $5ms$ has been assumed.

The DVR is capable of providing the necessary reactance when a voltage variation occurs. This means that the DC bus voltage must be kept constant. Figure 3 shows the feedback model used.

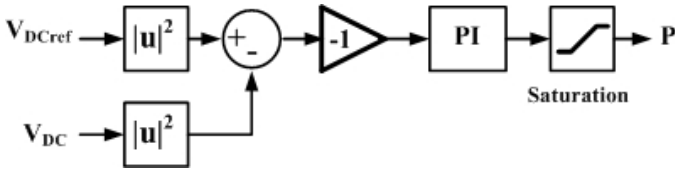


Figure 3 DC voltage feedback Diagram

The magnitude of the feedback DC voltage and reference DC voltage are squared, since the DC current increases to the square of the DC Voltage.

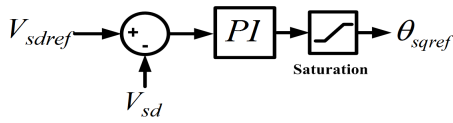


Figure 4 Schematic of the PCC Voltage Control [10].

Figure 4 shows the control diagram of the PCC voltage, the compensator PI is from $V_{PCCref} - V_{PCCd}$ generating θ_{PCCref} through a PI control.

IV. RESULTS: VOLTAGE SAGS AND SWELLS COMPENSATION AND POWER FACTOR CORRECTION

The DVR is able to perform voltage compensation on sags within a range of $0.1pu$ to $0.9pu$ and swells of amplitude from $1.1pu$ to $1.9pu$. In this research two events in a distribution system are thoroughly analyzed: a voltage sag of $0.5pu$ (Figure 5(a)) and a voltage swell of $1.5pu$ (Figure 5(b)) at source voltage V_s . The sag and swell operation conditions are due to power variations in the load.

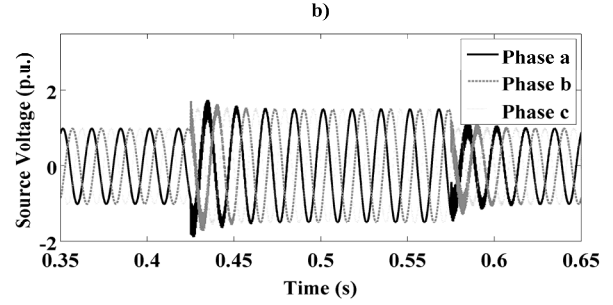
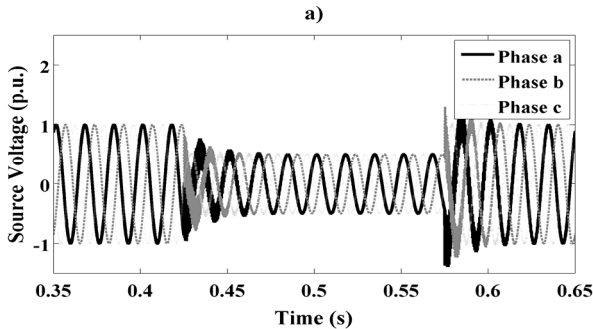


Figure 5 Voltage variations; a) Sag of $0.5pu$; b) Swell of $1.5pu$.

To verify the correct system operation, the capacitor DC voltage behavior is analyzed. Figure 6 shows the feedback voltage supplied by the DVR. For this operation condition, the DC voltage of DVR should be established; the DC voltage corresponding to a voltage sag of $0.5pu$ is shown in Figure 6(a) and in Figure 6(b) the DC voltage for a voltage swell of $1.5pu$, is presented. The behavior of the DC Voltage depends of the compensation voltage, that is, if a sag is present in the system, the DVR responds oppositely to inject the necessary compensation voltage at the PCC.

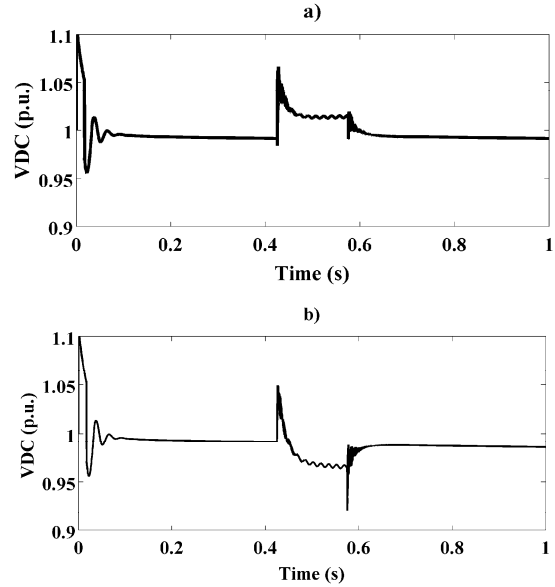
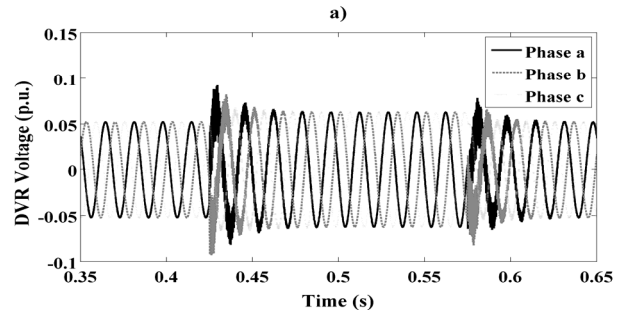


Figure 6 Feedback DC Voltage corresponding to; a) Voltage Sag; b) Voltage Swell

Figures 7(a) and 7(b) show the voltage generated by the DVR (V_{DVR}) to compensate the sag of $0.5pu$ (Figure 5(a)) and the swell of $1.5pu$ (Figure 5(b)), on V_s , respectively.



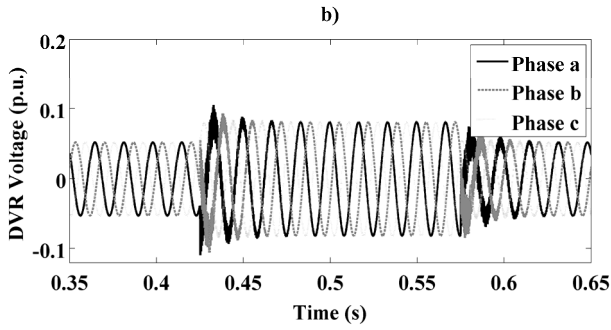


Figure 7 DVR Voltage; a) Sag; b) Swell

The purpose of connecting a DVR to the power network is to regulate the PCC voltage, as shown in Figure 8 for the assumed voltage sag (Figure 8(a)) and swell (Figure 8(b)).

Please observe that an effective correction has been achieved, being now the voltage waveforms at PCC of sinusoidal 1.0pu amplitude.

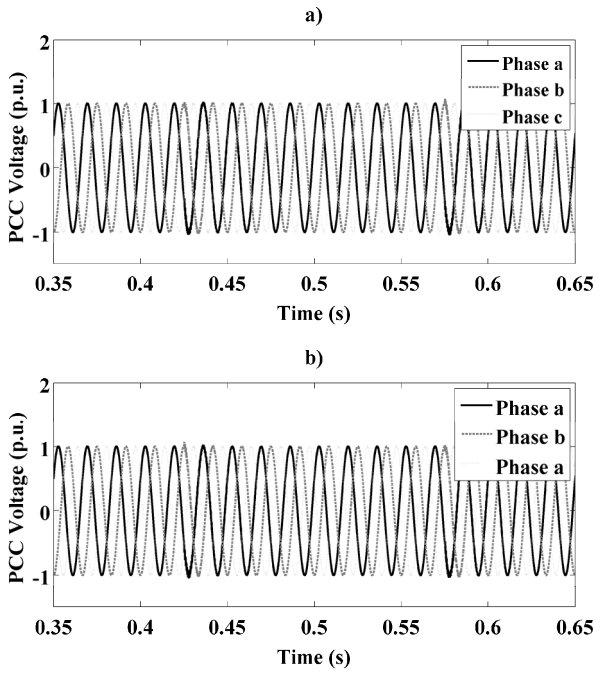


Figure 8 PCC Voltage; a) Sag; b) Swell

Please observe that the power network voltage profile is practically constant.

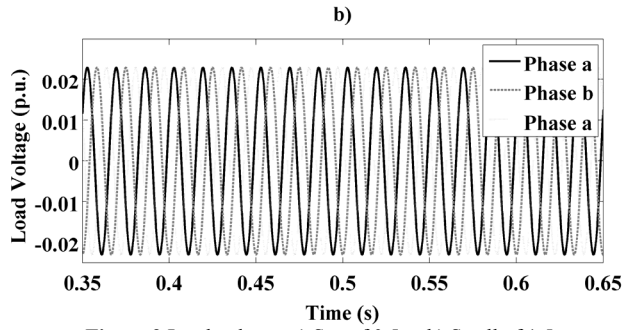
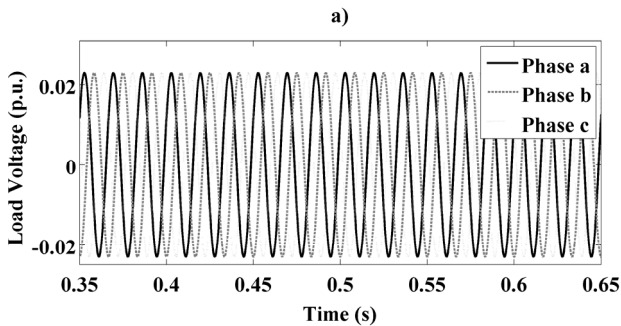


Figure 9 Load voltage; a) Sag of 0.5pu; b) Swell of 1.5pu

Figure 9 shows the voltage at the sensitive load. Results for the two operation conditions are shown for the presence of a sag (Figure 9(a)) and a swell (Figure 9(b)), respectively.

Figure 9 shows that the AC voltage is regulated when the VSC generates the necessary voltage in the system.

The DVR continuously generates the required voltage (V_{DVR}), for which the necessary reactive power is generated at the PCC. By maintaining unity power factor at the source V_s , the voltage and current in V_s are in phase, as shown in Figure 10(a) for a voltage sag of 0.5pu and 10(b) for a swell of 1.5pu.

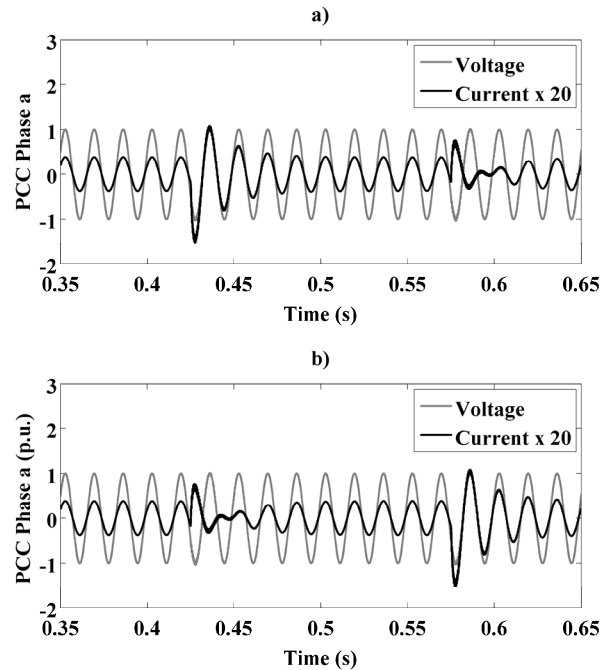


Figure 10 Voltage and current (phase a) in the PCC; a) sag of 0.5pu; b) swell of 1.5pu.

An extreme studio case study is resumed in Figure 11 and 12 with the waveforms most important. That is, the compensation of a sag voltage with amplitude of 0.9pu. Figure 11(a) shows the sag of 0.9pu on V_s ; the DVR Voltage is shown in Figure 11(b); the voltage compensations in the PCC and the sensitive load are shown in Figures 11(c) and 11(d), respectively, and the power factor correction at the PCC is shown in Figure 11(e), that is, the voltage and the current in the PCC are in phase, generating a unit power factor.

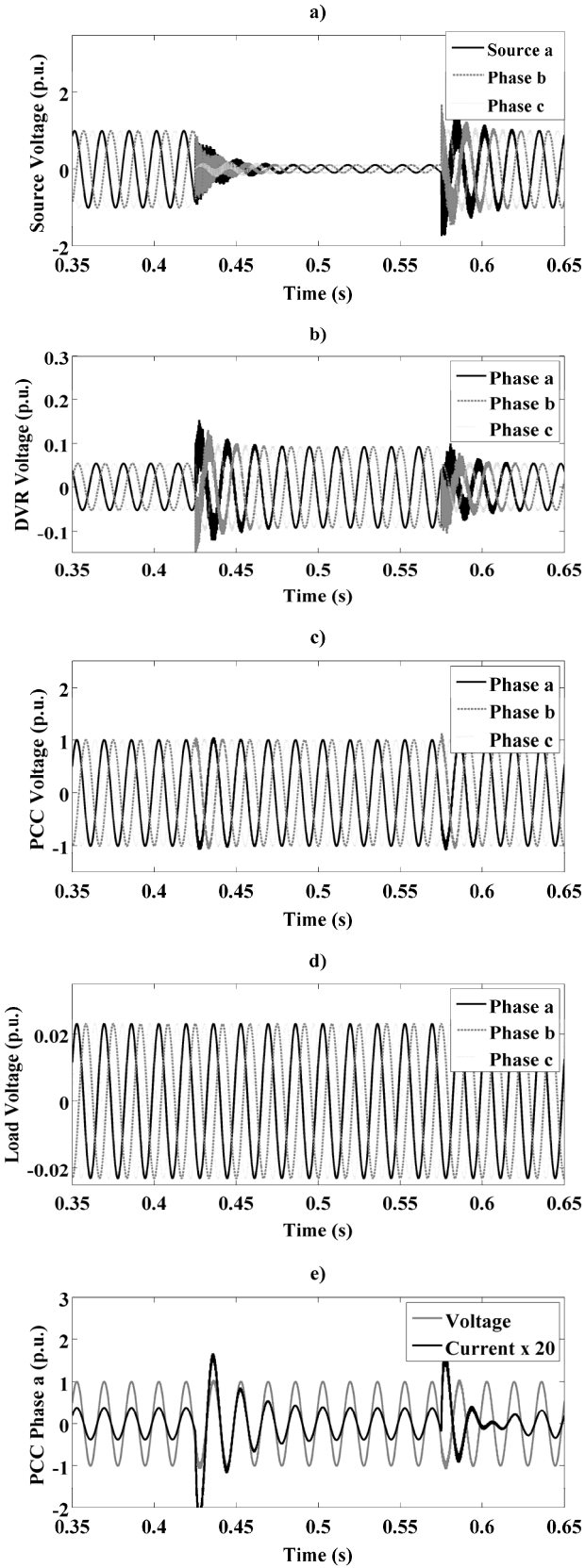


Figure 11 Waveforms for a sag of $0.9pu$; a) Source Voltage V_s ; b) DVR Voltage; c) PCC Voltage; d) Load Voltage; e) Voltage and current in the PCC (phase a) for sag of $0.9pu$.

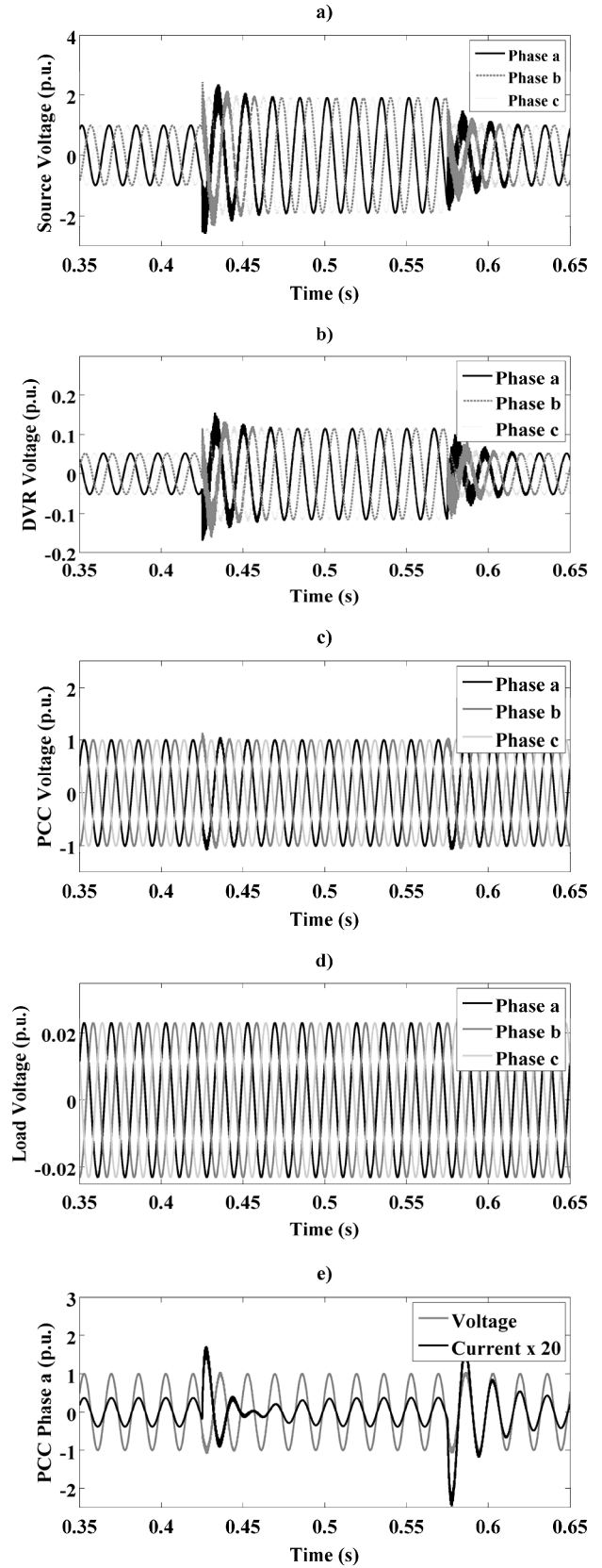


Figure 12 Waveforms for a swell of $1.9pu$; a) Source Voltage V_s ; b) DVR Voltage; c) PCC Voltage; d) Load Voltage; e) Voltage and current in the PCC (phase a) for swell of $1.9pu$.

Finally, in the Figure 12 the compensation of a swell voltage with amplitude of $1.9pu$ is presented. Figure 12(a) shows the swell occurs on V_s of $1.9pu$; the DVR Voltage is shown in Figure 12(b); the voltage compensations in the PCC in Figures 12(c), the sensitive load voltage are shown and 12(d) and the power factor correction at the PCC with unit power factor is shown in Figure 12(e).

V. CONCLUSIONS

In this contribution, an effective representation and modeling of the power system dynamic operation containing a DVR for sags/swells compensation and power factor correction has been presented.

It has been verified that it is viable and efficient to use a DVR in a distribution network, since it is able to inject the necessary voltage correction in the presence of unbalance and adverse power quality effects, thus improving its stability and power quality.

Simulation results in Matlab/Simulink® demonstrate that the control used in the DVR structure can effectively compensate voltage variations, that is, sags within a range of $0.1pu$ to $0.9pu$ and swells with amplitude from $1.1pu$ to $1.9pu$, achieve a load power factor equal to 1, that is, the load voltage and current are in phase.

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