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Dynamic Voltage Restorer Based on High-Frequency Isolated DC-DC Converter

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ABSTRACT

The increased utilization of voltage-sensitive loads is clearly visible in the distribution systems. If power quality problems are expected, a dynamic voltage restorer (DVR) can be employed for the protection of sensitive appliances against voltage problems. The main factors considering the voltage quality are the voltage sags and voltage swells. This paper proposes a DVR that uses of a high-frequency isolated DC-DC converter. A variety of energy storage devices are used in DVR power circuit. In this paper DC energy storage system (DC link capacitor) charged by main power supply (or grid) via three phase rectifier. The presented system is able to restore the voltage and compensate voltage sag, voltage swell and other problems as DVR functions and in the same time acts as ordinary active power filter (APF). The operation and performance of the suggested case study has been verified by the simulation results using SIMULINK /MATLAB.

Key Words: *Power electronic converters, voltage sag, dynamic voltage restorer, high frequency transformer.*

1. INTRODUCTION

Power Quality problems encompass a wide range of disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions [1-3]. In the recent decades, the power quality problem is becoming worse in the power system. So many devices such as active power filter, dynamic voltage restorer, FACTS and etc are introduced to improve power quality.

Voltage sags and swells are considered to be the frequent type of power quality problems. Voltage sag and swell can cause sensitive equipments to fail, or shut down and miss-operation of adjusTable speed drive systems. These effects can be very expensive for customer, so different solutions have been developed to relieve these power quality problems. Among those, dynamic voltage restorer (DVR) has become popular as a cost effective and efficient solution. The dynamic voltage restorer (DVR) is a well-known custom power device that is available for protection of critical and sensitive loads from disturbances occurring in the power system [3-7]. A DVR is basically a controlled voltage source converter installed between the supply and a critical and sensitive load. Figure 1 shows components of a generic DVR. The DVR injects a voltage to the distribution system in order to keep constant the load voltage magnitude and phase when disturbances occurring in the system. The energy storage

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element provides the required active power to compensate the voltage disturbances. Energy storage devices, such as batteries or Super-conducting Magnetic Energy Storage Systems (SMES) are required to provide this active power. When AC voltage is already available, DC source can be generated using rectifier [8].

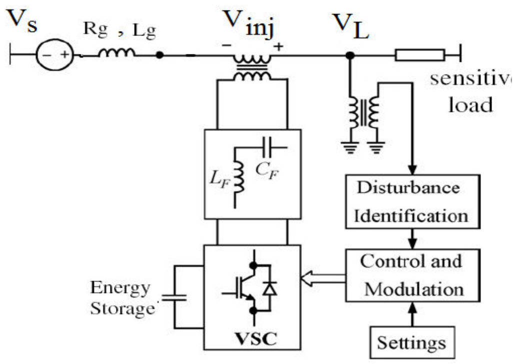


Figure 1. Components of a generic DVR.

Transformers are important equipment in DVR structure system. They can step down or step up voltages to the needed level of end-users. Additionally, many functions, for instance, isolation, noise decoupling or phase-shifting can be achieved through transformers. A transformer is a static device consisting of a winding, or two or more coupled windings, with different number of turns on a magnetic core, for inducing mutual coupling between circuits. A low frequency (60/50 Hz) transformer is one the most bulky and expensive components in electrical power system. There have been inclusive studies to reduce size and weight of the transformer [9-14].

This paper presents a dynamic voltage restorer (DVR) that is characterized by the use of a high-frequency unidirectional isolated DC-DC converter. This paper discusses the control and performance of a DVR using a high-frequency isolated DC-DC converter. The high-frequency transformer in the DC-DC converter is smaller in volume than the line-frequency transformer. A traditional DVR has a large and bulky series transformer. The energy storage element (DC source) is generated using shunt three-phase rectifier. Moreover, connecting the shunt three-phase rectifier to AC source (or grid) can be used for elimination harmonic and unbalances of load currents. The presented system is able to restore the voltage and compensate voltage sag, voltage swell and other problems as DVR functions and in the same time acts as ordinary active power filter (APF). Power quality improvement with proposed converter has been verified by the simulation results. The simulations perform using MATLAB/ SIMULINK.

2. SYSTEM OF CASE STUDY

Figure 2 shows the basic configuration of case study. Two type of connection exist in the case study, shunt connection and series connection. The shunt connection is used to create DC source for the energy storage element that provides the required active power to compensate the voltage disturbances. The series connection is used to inject required voltage.

Figure 3 shows a typical actual circuit diagram of the proposed DVR with DC-link creator, which is used as case study. As can be seen from Figure 3, circuit of proposed DVR has three types of converters that include an AC/DC converter (Rectifier), a DC/DC converter and a DC/AC converter (Inverter).

2.1. AC/DC Converter

The AC/DC converter is directly connected with the voltage source (or grid). The AC/DC converter is a three phase rectifier, which is used to convert the primary low frequency voltage into the DC voltage and to keep the grid from harmonics and reactive power components. This converter acts as a controllable current source. The current drawn from the voltage source is forced purely sinusoidal and in phase with the phase voltage at unity power factor by AC/DC converter. Several control techniques have been proposed for the APF or three phase rectifier [15-18].

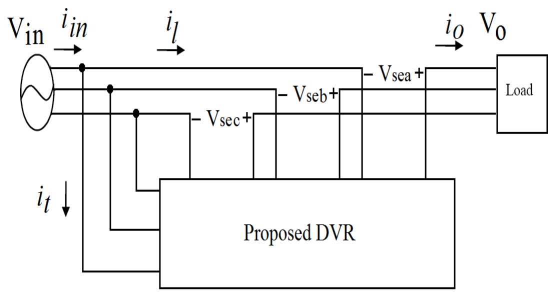


Figure 2. Basic configuration of the case study.

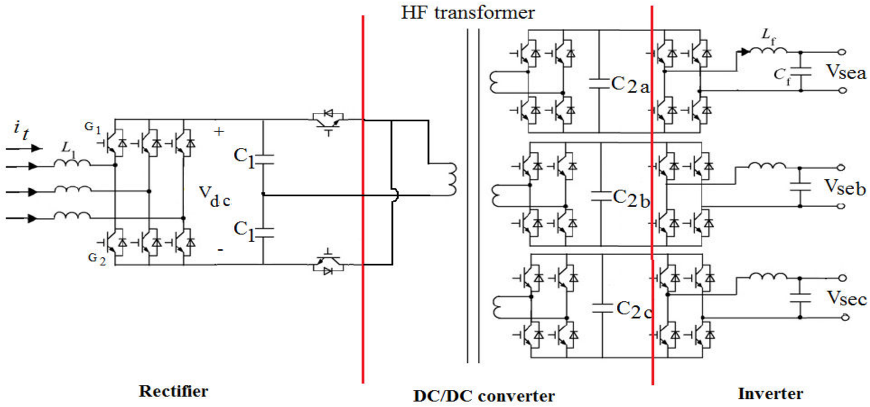


Figure 3. Circuit diagram of proposed DVR in the case study.

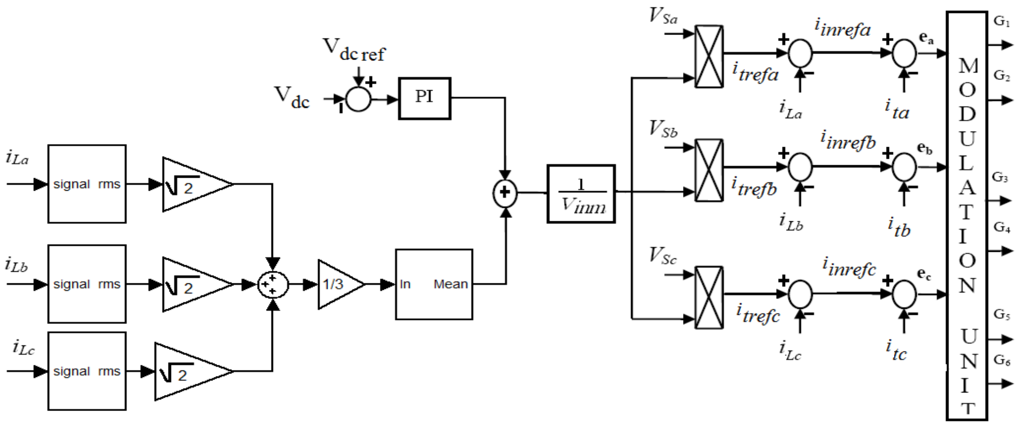


Figure 4. Three phase rectifier control diagram.

Three phase rectifier control diagram is shown in Figure 4. To keep constant DC-link voltage and keep input current sinusoidal and in phase with the phase voltage, one PI controller is used. The control unit generates the current references. The current references are the inputs to the modulation unit to generate the modulating signals for the converter switches.

The compensating currents of rectifier are calculated by sensing the load currents, DC-link voltage (V_{dc}), peak voltage of AC source (V_{inm}) and zero crossing point of source voltage. The last two parameters are used for calculation of instantaneous voltages of AC source as below:

$$V_{ina} = V_{inm} \sin(\omega t)$$
$$V_{inb} = V_{inm} \sin(\omega t - 2\pi / 3) \quad (1)$$
$$V_{inc} = V_{inm} \sin(\omega t + 2\pi / 3)$$

The peak of source reference current has two components. The first component is corresponding to the average load current and the second component is corresponding to the DC capacitor voltage regulator. The AC source currents must be sinusoidal and in phase with source voltages. Therefore the desired currents of AC source (i_{inref}) can be calculated with multiplying peak source current to a unity sinusoidal signal. The reference currents of rectifier (i_{tref}) can be obtained by comparison between the desired currents of AC source and currents of load. The reference signals (e_a, e_b and e_c) for converter switching are obtained from comparison between reference currents of rectifier and currents of rectifier. The hysteresis band current controller decides the switching pattern of input stage. The switching logic is formulated as follows:

If ea>0.001 then upper switch is OFF and lower switch is ON for leg “a” (G2=1).

If ea<-0.001 then upper switch is ON and lower switch is OFF for leg “a” (G1=1).

The switching functions for phases B and C are determined similarly.

2.2. DC/DC Converter

The second converter is a DC/DC converter, which is used to convert the DC voltage coming from input rectifier to multiple DC voltage sources. Figure 5 shows the circuit of the DC/DC converter. In this part, the DC voltage is converted to a high-frequency square-wave voltage, coupled to the secondary of the multi winding high frequency (HF) transformer then high frequency voltages are rectified to form the DC link voltages. The galvanic isolation between the DC voltage coming from input rectifier and the load is obtained with a HF transformer of reduced size and weight [9-14]. The size of the transformer and its volt–ampere (VA) rating has the following relationship [14]:

$$VA = 2.22.K.f.A_C.A_e.J.B_m \tag{2}$$

where VA= VA rating of the transformer [VA], K=copper fill factor, f=frequency of excitation [Hz], A_C=core area [m], A_e=winding area [m], J=current density of the conductor [A/m], and B_m= peak flux density [T]. The size of the transformer can be expressed as a function of frequency and peak flux density:

$$A_C.A_e = \frac{VA}{2.22.K.f.J.B_m} \tag{3}$$

Eq. (3) shows that the transformer size is inversely proportional to the frequency and flux density. Therefore, transformer size can be reduced by increasing the operating frequency.

In the DC/DC converter, there is a single-phase high frequency Half-bridge cell voltage source converter, which converts the input DC voltage to AC square voltage with high (or medium) frequency. To simplify the design of the control system, open loop control is applied for this converter. Control diagram of Half-bridge cell voltage source converter is shown in Figure 6(a). The principle of modulation is based on a comparison of a sinusoidal reference waveform with zero carrier waveform. If sine reference wave has a frequency f_r and an amplitude A_r then output voltage of H-bridge cell has a frequency f_r.

The main functions of the multi winding HF transformer are voltage transformation and isolation. By neglecting the losses of HF transformer, the transformer can be treated as a proportional amplifier. Various square voltage sources can be generated using multi winding HF transformer. H-bridge cell voltage source converters are used to convert the AC square voltage to DC voltage. Control diagram of H-bridge cell rectifiers is shown in Figure 6(b). To simplify the design of the circuit, diode rectifiers can be used instance of H-bridge cell rectifiers.

2.3. DC/AC Converter

The output part is a voltage source inverter which regenerates the desired AC waveforms. There are three single-phase inverters in the output part of the proposed DVR. The circuit diagram of the DC/AC converters compensated distribution system is shown in Figure 7.

It contains three H-bridge inverters. Note that each switch represents a power semiconductor device and an anti-parallel diode combination. The DC bus of all the three inverters is supplied through common DC energy storage capacitors that have been provided DC/DC converter. In the basic configuration of the classic DVR for voltage compensation, the voltage source converter is installed in series with supply voltage through a transformer. In the other words single-phase transformers are used to perform the series connection.

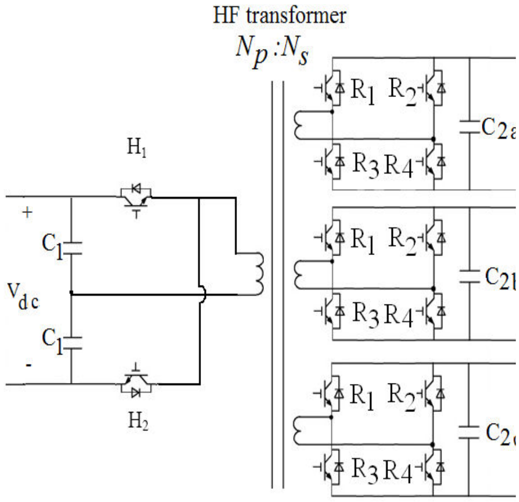
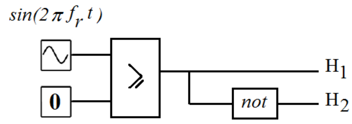
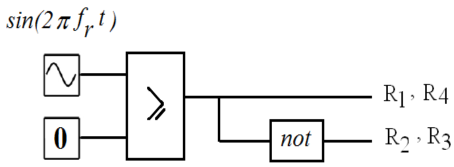


Figure 5. DC/DC converter.



(a)



(a)

Figure 6. Control diagram of DC/DC converter (a) Control diagram of Half-bridge cell (b) Control diagram of H-bridge cell rectifiers.

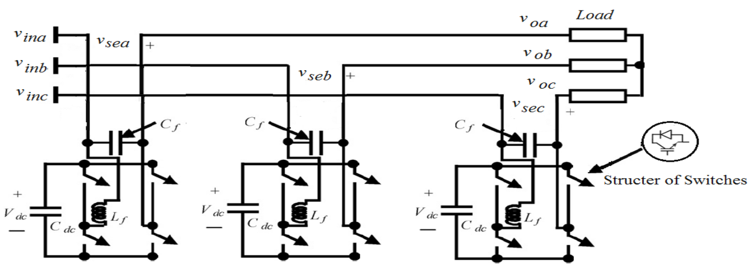


Figure 7. Circuit diagram of the DC/AC converters compensated distribution system.

Although the transformers provide voltage transformation and isolation between the inverters and the AC system but these transformers have the many disadvantages such as high price, losses, large volume, higher failure rate than power electronic converters and etc [18]. In the suggested DVR, the low frequency transformers have been eliminated.

The supply voltage, the DC/AC converters injection voltage and the load voltage are denoted by v_i, v_{se} *and* v_o, respectively. Using KVL the load voltage is:

$$v_o = v_i + v_{se} \tag{4}$$

If the supply voltage has voltage disturbances, the injected voltage by the DC/AC converters should be controlled. When the DC/AC converter is operated in voltage regulation mode, it injects a voltage, v_{se} in the distribution system such that it regulates the load voltage, v_o to a reference v_o^* having a pre-specified magnitude and angle at system nominal frequency. The reference voltage of the DC/AC converter (v_{se}^*) is then given by

$$v_{se}^* = v_o^* - v_o \tag{5}$$

Control diagram of the DC/AC converter is shown in Figure 8. The synchronous d–q reference frame algorithm is applied to extract the reference voltage for the DVR. . In this paper, the three phase voltage source inverter is controlled by SPWM method. In this case, the direct axis, quadratic axis, and zero sequence quantities for three-phase sinusoidal signal is computed by Park transformation. Then the dq voltage terms are compared by reference signals $V_{dref}=1$ and $V_{qref}=0$ and error signals enter to PI controllers. Then the PI outputs transformed to three-phase sinusoidal abc voltage terms and are used to generate appropriate inverter gate pulses.

3. SIMULATION RESULTS

The case study operation using above structure and control has been discussed here.

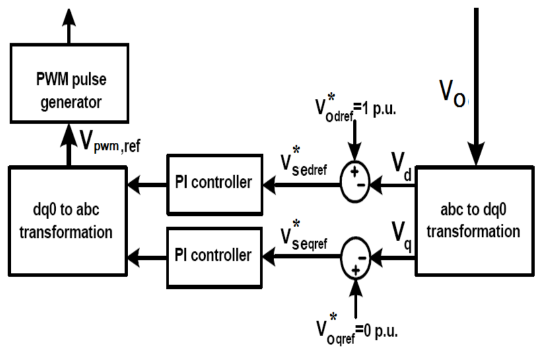


Figure 8. Control diagram of the DC/AC converter.

A detailed simulation has been carried out using MATLAB/SIMULINK software to verify the efficacy of the case study system. Let us assume that the source frequency is constant at the distribution system nominal frequency, i.e., at 50 Hz. The case study parameters used for the simulation studies are given in Table 1. A number of simulation results with different operating conditions were developed. The capability of the DVR to compensate the different voltage and current problems such as voltage sag and swell and power factor correction for the balanced and unbalanced sensitive load are shown. The simulation results in steady state operation are presented.

3.1. Balanced Sensitive Load

3.1.1. Balanced Voltage Sag

In the first simulation, it is assumed that during the period of 0.2 s≤*t*≤0.4 s 30 percent voltage sag of the supply voltage is occurred. Figure 9 shows the the DC-link voltage of input rectifier. As it can be seen in the Figure 9, the DC-link voltage of input stage is 800 V. The voltage controller in Figure 4 acts so that the DC-link voltage is regulated in reference value. Figure 10 shows the the supply voltage and the load voltage. The load, the supply and the DVR injected (V_{se}) voltages in one phase are presented in Figure 11. In the first time, the system is in steady state and the voltage magnitude of the supply is nominal value (326.59 V). At *t* = 0.2 s, the supply voltage decreases to 70 percent nominal voltage and the fault duration is 0.2 s then the fault is cleared at *t* = 0.4 s . In case of normal operation conditions, the load voltage is equal to the supply voltage and the DVR injected voltage is zero. During the voltage sag, the DVR output voltage increases to keep the load voltage at the normal operation conditions.

Table 1. The case study parameters.

Parameters	Value
Input voltage	400 V
Power frequency	50 Hz
HF transformer	1:1, 1000 Hz, 50 kVA
Output voltage	400 V
L, C_1 =C_2	1.5 mH, 1650 μF
LC filter(L_f, C_f)	1.5 mH, 330 μF
Sensitive load	40 kW+j30 kVAR (R=2.56 Ω, L=6.1155 mH)

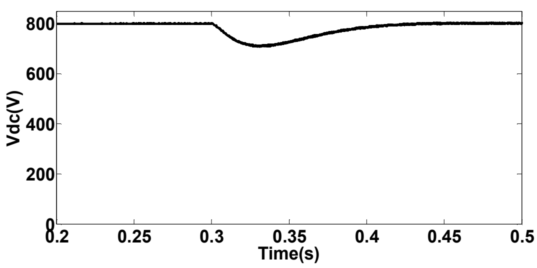
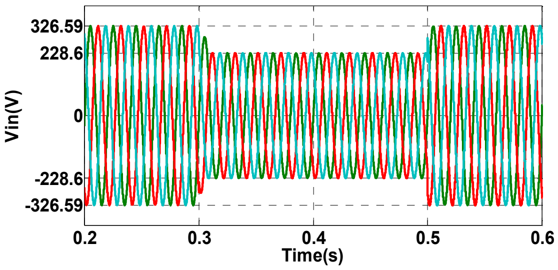
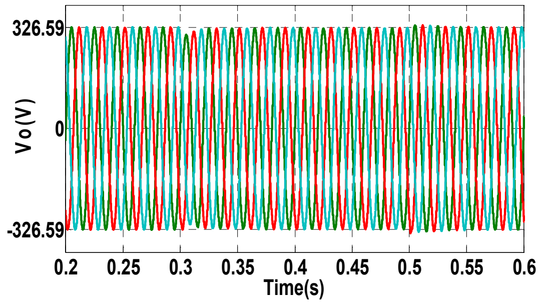


Figure 9. The DC-link voltage of input rectifier.



(a)



(b)

Figure 10. (a) supply voltage, (b) the load voltage for three-phase balanced voltage sag.

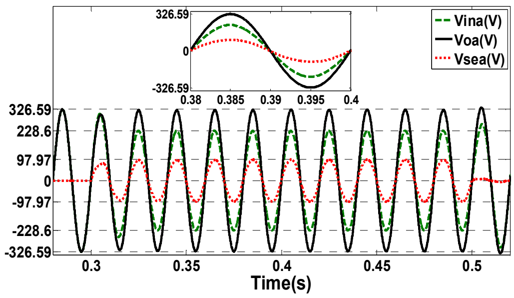


Figure 11. Supply voltage, the DVR injection voltage and the load voltage for single-phase.

3.1.2. Balanced Voltage Swell

Figure 12 and Figure 13 show how the system handles the voltage swell conditions. Figure 12 shows the DC-link voltage of input rectifier. Figure 13 shows the supply and the load voltages. The load, the supply and the DVR injected (V_{se}) voltages in one phase are presented in Figure 14. In Figure 14, the power supply voltage is increased 30 percent for 10 time cycles. As it can be seen, the DVR manages these situations properly and adjusts the output voltage to desired level without any swell in output signal.

3.2. Unbalanced Sensitive Load

In the second part of simulations, it is assumed that during the period of 0.2 s≤*t*≤0.4 s 30 percent voltage sag of the supply voltage is occurred while the load is unbalanced sensitive load. The unbalanced load configuration is described in Figure 15. Figure 16 shows the the DC-link voltage of input rectifier. As it can be seen in the Figure 16, the DC-link voltage of input stage is 800 V and its voltage ripple is bigger than state that load is balanced. Despite of the voltage ripple on the DC-link, the DVR will operate properly because the voltage source inverters will eliminate the voltage ripple by proper variation of modulation index. Figure 17 shows the supply voltage and the load voltage.

Figure 18 shows the simulation waveforms of the current, the output current and the supply current. Figure 18(a) shows the unbalanced load current. The input rectifier injects current to balance supply current. Figure 18(b) shows the balanced supply current. These results show that supply currents always remain sinusoidal and balanced.

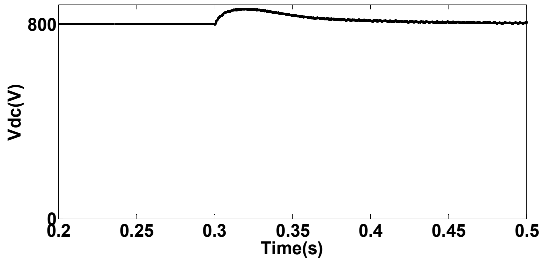
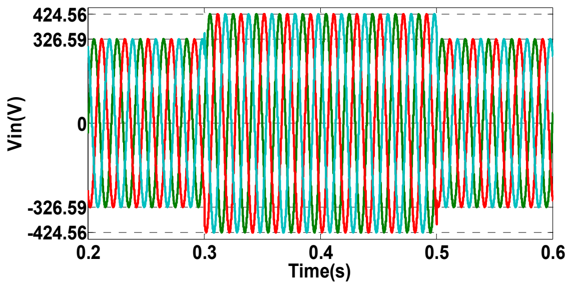
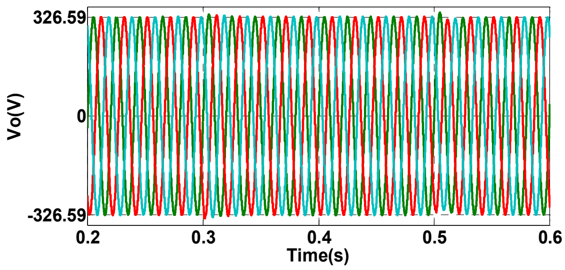


Figure 12. The DC-link voltage of input rectifier.



(a)



(b)

Figure 13. (a) supply voltage, (b) the load voltage for three-phase balanced voltage swell.

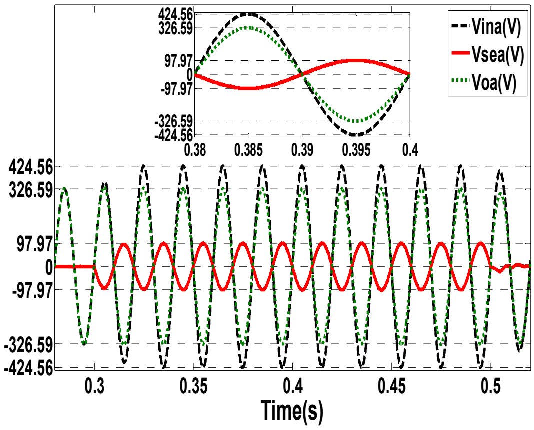


Figure 14. supply voltage, (b) the DVR injection voltage and (c) the load voltage for single-phase.

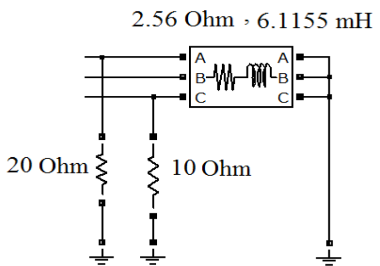


Figure 15. The unbalanced load configuration.

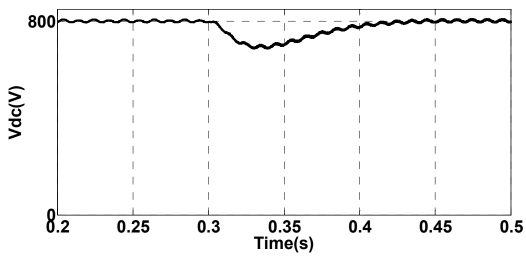
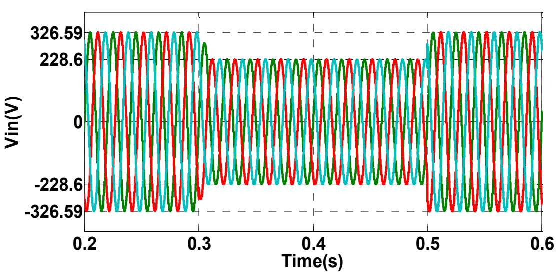
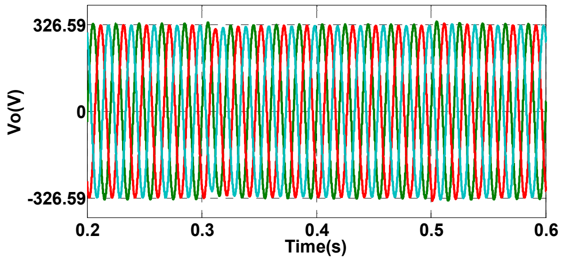


Figure 16. The DC-link voltage of input rectifier.

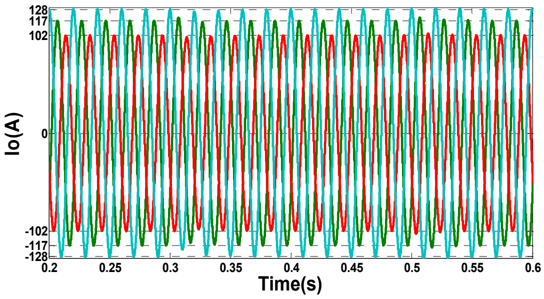


(a)

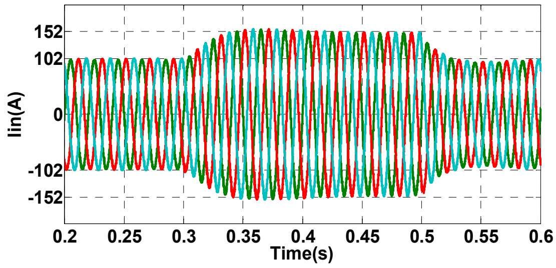


(b)

Figure 17. (a) supply voltage, (b) the load voltage for three-phase balanced voltage sag.



(a)

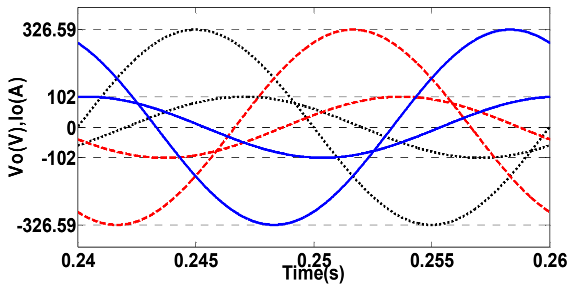


(b)

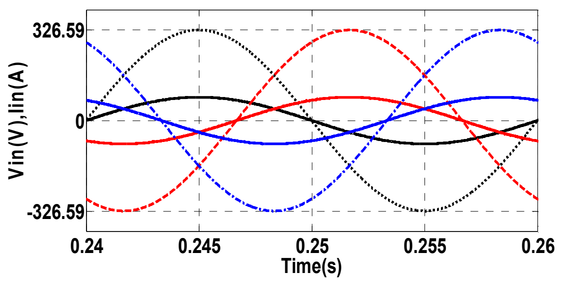
Figure 18. (a) load current (b) supply current.

3.3. Power Factor Correction

In the case study the load is lag. Figure 19 shows power factor correction ability when the load is balanced. The output voltage and current is shown in Figure 19(a). Figure 19(b) shows supply voltage and current. As it can be seen, in this Figure, the input current and the input voltage are in phase and have sinusoidal wave shapes despite the load currents are lag. Figure 20 shows power factor correction ability when the load is unbalanced. Figure 21 shows the DVR input power factor correction ability in fault duration when load is balanced and voltage sag state has occurred. This Figure is given for one phase.

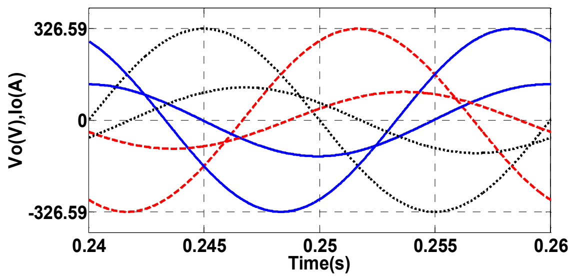


(a)

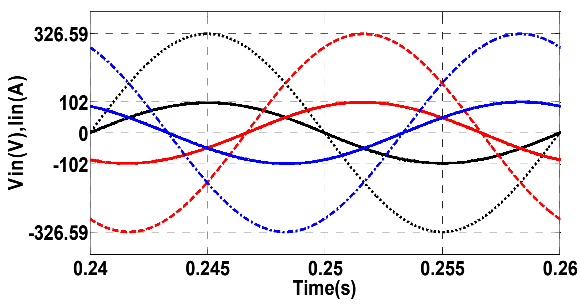


(b)

Figure 19. Power factor correction ability when the load is balanced (a) output voltage and current (b) supply voltage and current.



(a)



(b)

Figure 20. Power factor correction ability when the load is unbalanced (a) output voltage and current (b) supply voltage and current.

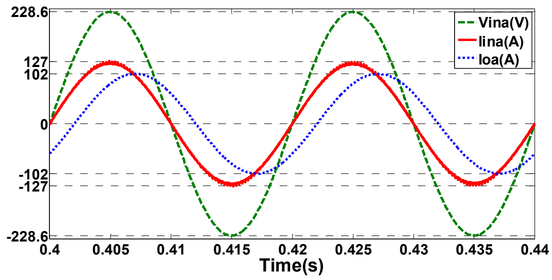


Figure 21. Power factor correction ability in sag conditions.

CONCLUSION

In this paper, the DVR that uses of a three power electronic converter is proposed. Due to using the high frequency transformer, the proposed DVR does not need any coupling low frequency transformer. In this paper DC energy storage system (DC link capacitor) charged by main power supply (or grid) via three phase rectifier. The operation of the proposed DVR has been demonstrated through computer simulation under voltage sag and swell condition when the load is balanced and unbalanced. Simulation results show the validity and effectiveness of presented DVR for compensation of power factor and unbalance currents, too.

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