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Full Length Research Paper

Three phase inverter control using DSP controller for dynamic voltage restorer (DVR) application

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This paper discusses the control technique improvement of a three-phase inverter using direct-quadrature-zero (d-q-0) controller based on DSP TMS320F2812 for dynamic voltage restorer (DVR) applications. The output of the inverter is then connected to a voltage grid via a second order filter and injection transformer. The control algorithms are developed using TMS320F 2812 DSP. The proposed technique achieves voltage regulation with low total harmonics distortion (THD) for both voltage and current. This paper also highlights a series of discussion, analysis and studies performed on the proposed control technique, including L-C filter design issue and the concept of DVR in the distribution system. An analysis and experimental results validate the effectiveness of the DSP controller in mitigating voltage sags and harmonics issues in the distribution system

Key words: TMS320F2812 DSP, inverters, dynamic voltage restorer (DVR), total harmonic distortion (THD), filter.

INTRODUCTION

With the rapid technology advancements in industrial control processes, electric utilities are experiencing more demanding requirements on the power quality from the large industrial power consumers. Such power quality problems have been better appreciated when the price paid, due to the economic losses caused by them, is large. These concerns are reflected in the newer versions of power quality standards, such as IEEE 1159-1995 (IEEE, 1995) and IEC6100-4-30 (IEC, 2003).

Among the various power quality problems, the voltage sag, usually resulting from the faults on parallel transmission/distribution feeders, is attracting quite a large amount of attention from researchers of both industry and academia (Nelson et al., 2004; Woodley, 2000). A definitive solution to this problem at large power levels has been commonly called dynamic voltage restorer (DVR), under the rubric of the custom power concept introduced by EPRI (Hingorani, 1999). The main function of DVR is to mitigate the voltage sag, although sometimes, additional functions such as harmonic compensation and reactive power compensation are also integrated to the device.

Power quality standards for connection of an inverter to the grid are still under development, since previously, there have been a few similar high power applications. In (IEEE, 1992) it is stated that the power quality is determined by the voltage quality, when the voltage is a controlled o variable.

Voltage sags in an electrical grid are well-known phenomenon due to the finite clearing time of the faults and the propagation of sags from the transmission and/or distribution system to the low voltage loads. The theory of

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voltage sags and interruptions for electrical networks is thoroughly described in the work of Bollen (1999). Dynamic voltage restorer (DVR) has been recognized as a cost effective solution for the protection of sensitive loads from voltage sags (Fitzer et al., 2004). DVR is primarily used for the distribution system by injecting compensating voltage in series with the supply network when an upstream fault is detected (Zhan et al., 2001; Kara et al., 1998; Nielsen et al., 2004). Loads connected downstream of the DVR are thus protected from any voltage sags caused by faults elsewhere on the network.

In order to deliver a good ac power, the controlled pulse width modulation (PWM) inverter and L-C output filter have to convert a dc voltage source (for example, batteries) to a sinusoidal ac voltage with low voltage THD and fast transient response under load disturbances. Another important aspect of power quality is harmonic distortion. General requirements for harmonic distortion can be found in standard as seen in the work of Casadei et al. (2005) and particularly for connection of distributed resources to grid in Iqbal et al. (2006).

PWM control is the most powerful technique that offers a simple method for control of analog systems with the processor's digital output (Grandi et al., 2006). With the availability of low cost, high performance DSP chips, characterized by the execution of most instructions in one instruction cycle, complicated control algorithms can be executed with fast speed, making very high sampling rate possible for digitally-controlled inverters (Hadiouche et al., 2006).

Recently, techniques to produce an output voltage with low total harmonic distortion (THD) in a three-phase pulse width modulation (PWM) inverter have been proposed (Maria et al., 2007).

In this paper, the implementation of a digital signal processor (DSP) using an improved d-q-0 based controller was done in order to control inverter pulses, and then the output of the inverter was injected through the injection transformer of the DVR.

The improvement of the controller is easy to design and does not depend much on circuit parameters. The dc value of the capacitor and harmonic ripple current due to input power circuit can be reduced. The controller can detect any disturbance in the network very fast.

THE CONCEPT OF THE DVR IN THE DISTRIBUTION SYSTEM

DVR operation and components

A power electronic converter based series compensator that can protect critical loads from all supply side disturbances other than outages is called a dynamic voltage restorer (Blaabjerg et al., 2004; Ojo et al., 2005). Figure 1 shows the configuration of the DVR consisting of an inverter, series or injection transformer, inverter control system and energy storage. The main function of a DVR is the protection of sensitive load from any disturbances coming from network. The main components of the DVR are summarized below;

Voltage injection transformers

In a three-phase system, either three single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose (Zhan et al., 2000).

Capacitor

DVR has a large DC capacitor to ensure stiff DC voltage input to inverter.

Inverter

An Inverter system is used to convert dc storage into ac form (Ravi et al., 2007). Voltage source inverter (VSI) of low voltage and high current with step up injection transformer is used for this purpose in the DVR compensation technique (Perera et al., 2006).

Passive filters

Filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This is achieved by eliminating the unwanted harmonic components generated VSI action. Higher orders harmonic components distort the compensated output voltage (Zhan et al., 2000).

Energy storage unit

It is responsible for energy storage in DC form. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used as energy storage devices. It supplies the real power requirements of the system when DVR is used for compensation (Banaei et al., 2006).

The basic idea of a DVR is to inject the missing voltage cycles into the system through series injection transformer whenever voltage sags are present in the system supply voltage. As a consequence, sag is unseen

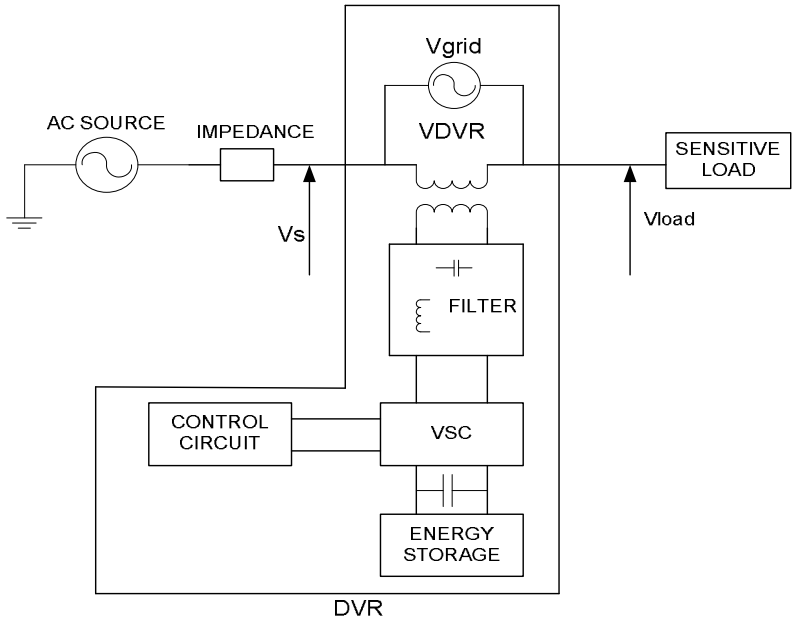


Figure 1. Conventional circuit configuration (Nielsen and Blaabjerg, 2005).

by the loads. During normal operation, the capacitor receives energy from the main supply source. When voltage dip or sags are detected, the capacitor delivers dc supply to the inverter. The inverter ensures that only the missing voltage is injected to the transformer. A relatively small capacitor is present on dc side of the PWM solid state inverter, and the voltage over this capacitor is kept constant by exchanging energy with the energy storage reservoir. The required output voltage is obtained by using pulse-width modulation switching pattern. As the controller will have to supply active, as well as reactive power, some kind of energy storage is needed. In the DVRs that are commercially available now, large capacitors are used as a source of energy (Chris et al., 2004). Other potential sources being considered are; battery banks, superconducting coils, and flywheels (Zhan et al., 2001; Mostafa et al., 2007). The concept of compensation techniques being used in DVR can be divided into two methods as discussed further (Monsef et al., 2006; Kasuni, 2007).

In-phase compensation method

The injection voltage is in phase with the source voltage. When the source voltage drops due to sagging problems in the network, the injection voltage produced by the Voltage Source Inverter (VSI) will inject the missing voltage based on the drop voltage magnitude. This method can be shown in Figure 2.

Pre-sag method

In this method, there is a difference between Vpre-sag and the sag voltage (Vsag). The injection voltage will inject the difference voltage between them as shown in Figure 3.

Inverter's output filter design dimensioning of a DVR

A general use of a filter is to perform some frequency-selective isolation between sources which is viewed as having a range of frequency components and a load to which it will pass only some of those frequency components and reject others.

A LC filter often works best in the dc mode if the load has switches, because a large L would face the dc supply and the large capacitor of high quality would provide low impedance for the switching frequency as shown in Figure 4. The transfer function *H(jω)* may relate the output and input voltages or current of the filter. In this case, the relationship between the output voltage and the input voltage is as follow:

$$H(jw) = \frac{V_o}{V_i}$$

Therefore, the transfer function of LC filter can be described as Equation (1)

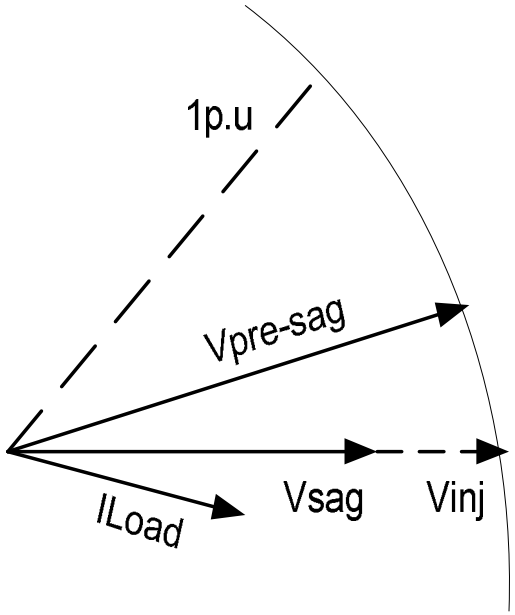


Figure 2. The diagram of in-phase compensation technique.

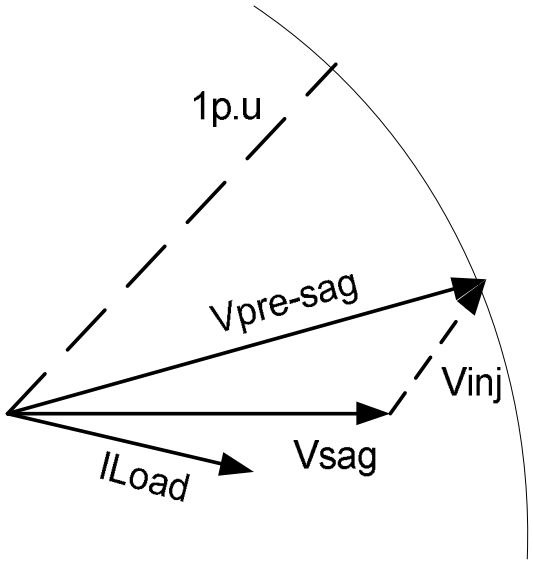


Figure 3. The diagram of pre-sag compensation technique.

$$H(jw)\frac{V_o}{V_i}=\frac{1}{j\omega L\left(\frac{1}{Z_L}+\frac{1}{j\omega c}\right)}=\frac{1}{1-\omega^2 LC+j\frac{\omega L}{Z_L}} \quad (1)$$

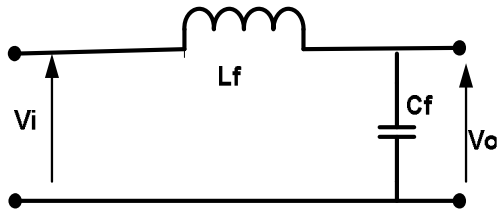


Figure 4. LC filter of a DVR system.

The values of L and C can be derived based on the following steps:

The first step is choose the suitable type of the filter that needs to be implemented in the circuit;

The second step is to calculate the designed impedance from the minimum value of the voltage (V_{min}) divided by the maximum current (I_{max}) which is $\frac{V_{(\min)}}{I_{(\min)}}=Z_L$;

The third step is to determine the cutoff frequency $f_{o;}$
Finally, compute the component values

$$L=\frac{Z_d}{2\pi f_o} \quad (2)$$

$$C=\frac{1}{2\pi f_o Z_d} \quad (3)$$

The frequency response curve of Equation (1) is shown in Figure 5. From the figure, it is recognized that the filter has desirable characteristics near fundamental frequency region.

CONTROL DEVELOPMENT OF THE DVR

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances. The control system only measures the r.m.s voltage at the load point, that is, no reactive power measurements are required. The VSI switching strategy is based on a space vector PWM technique which offers simplicity and good response. The control of DVR is very important and it involves detection of voltage sags (start, end and depth of the voltage sag) by appropriate detection algorithms which work in real time. The voltage sags can last from a few milliseconds to a few cycles, with typical depths

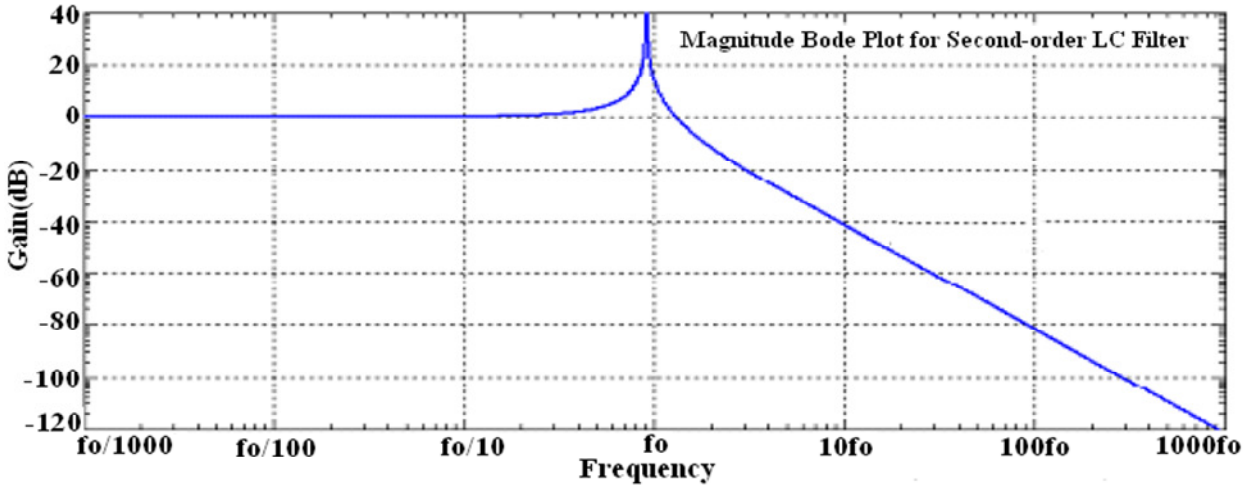


Figure 5. The frequency response curve of the LC filter.

ranging from 0.9 pu to 0.5 pu of a 1-pu nominal (Zhan et al., 2001; Monsef et al., 2006; Zhou and Wang, 2002; Rodriguez et al., 2007).

The proposed d-q-0 operated DVR system is implemented using DSP board. The general requirement of a control scheme is to obtain an ac waveform with minimum total harmonic distortion (THD) and best dynamic response against supply and load disturbance when the DVR is operated for voltage sag compensation (Mahinda et al., 2003). The main aspects of the control system are shown in Figures 6 and 7, and include the following blocks:

Block 1: used to convert the three phase load voltages (V_{La}, V_{Lb}, V_{Lc}) into the α-β-o coordinates as in Equation (4)

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_o \end{bmatrix} = Q \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} \quad (4)$$

Where $Q = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$

Block 1 is also used to convert the three phase load voltages (V_{La}, V_{Lb}, V_{Lc}) into the α-β-o coordinates as in Equation (1). The three phase load voltages reference components $V_{\alpha\text{-ref}}$, $V_{\alpha\text{-ref}}$ and Vo_{ref} can be converted to $V_{d\ ref}$ and $V_{q\ ref}$ as shown in Equation (5).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\ \theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (5)$$

Transformation to dqo to abc

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\ \theta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -0.5 & \frac{\sqrt{3}}{2} & 1 \\ -0.5 & \frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_o \end{bmatrix} \quad (7)$$

Block 2: is considered as source voltages (V_{sa}, V_{sb}, V_{sc}). The amplitude of AC voltage at the sources (V_{source}) can be calculated as follow;

$$V_{source} = \frac{2}{3}\left(\sqrt{(V_{sa})^2 + (V_{sb})^2 + (V_{sc})^2}\right) \quad (8)$$

Block 3: is a three phase PLL (Phase-locked loop). PLL comprises a Phase Detection (PD) scheme, a Loop Filter (LF), and a Voltage Controlled Oscillator (VCO). The

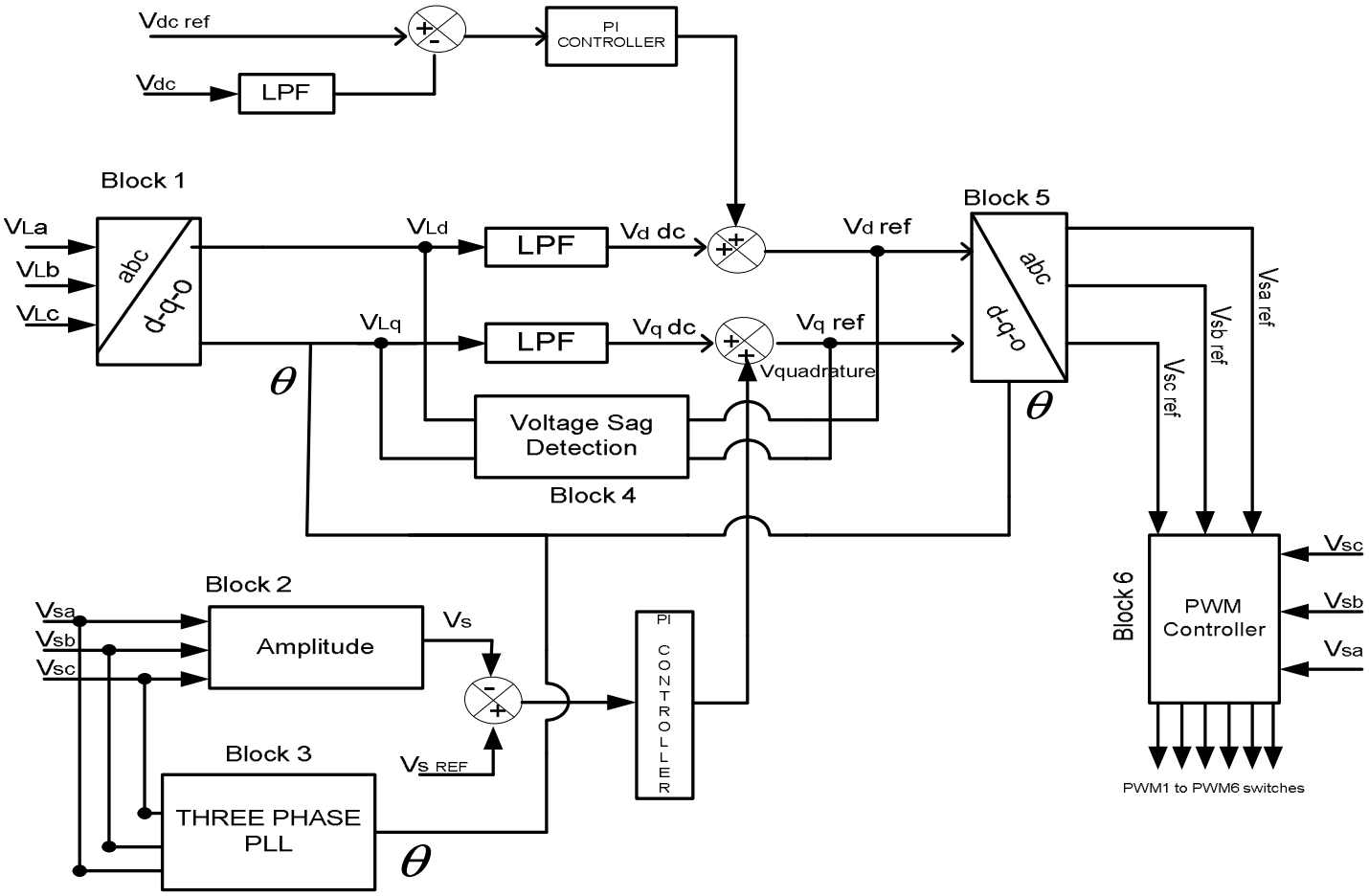


Figure 6. Block diagram control of the proposed scheme of DVR implemented in DSP.

phase difference between the input and the output signals is measured using a phase detection scheme and passed through a loop filter to generate an error signal driving a voltage-controlled oscillator (VCO) which generates the output signal.

Block 4: is the detection scheme for the voltage unbalanced compensator. From Figure 6, it shows that, the synchronous frame variables, V_d and V_q are used as inputs for low pass filters to generate voltage references in the synchronous frame.

Block 5: receives the components of the load voltage vectors V_d ref and V_q ref and transforms them to three phase coordinates using Equations (5) and (6). The generation voltages are used as the voltage reference. The DC link error in Figure 6 is used to get optimized controller output signal because the energy on the DC link will be changed during the voltage sag.

Block 6: is the PWM block which provides the firing for the Inverter switches (PWM1 to PWM6). The injection voltage is generated according to the difference between the reference load voltage and the supply voltage and is applied to the voltage source Inverter (VSI).

EXPERIMENTAL SET-UP

Experimental set-up can be divided into two sections. The first section is a power circuit design. The power circuit is composed of four parts; full bridge inverter circuit; DC power supply; LC filter and load. The prototype of the power circuit was built up as shown in Figure 8. The second part of the experimental set-up is integrated between inverter and the proposed DVR prototypes. A 5KVA prototype of DVR was built and tested. The prototype developed, based on schematic in Figure 9. All the system parameters for the

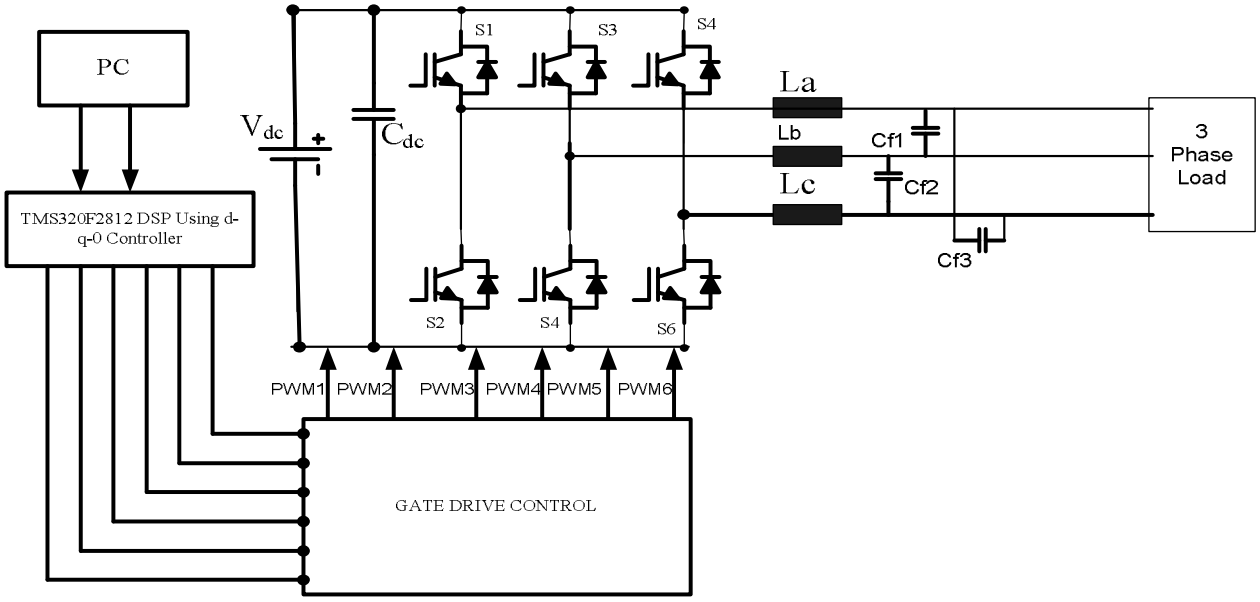


Figure 7. DSP controlled three -phase PWM inverter using d-q-0 controller.

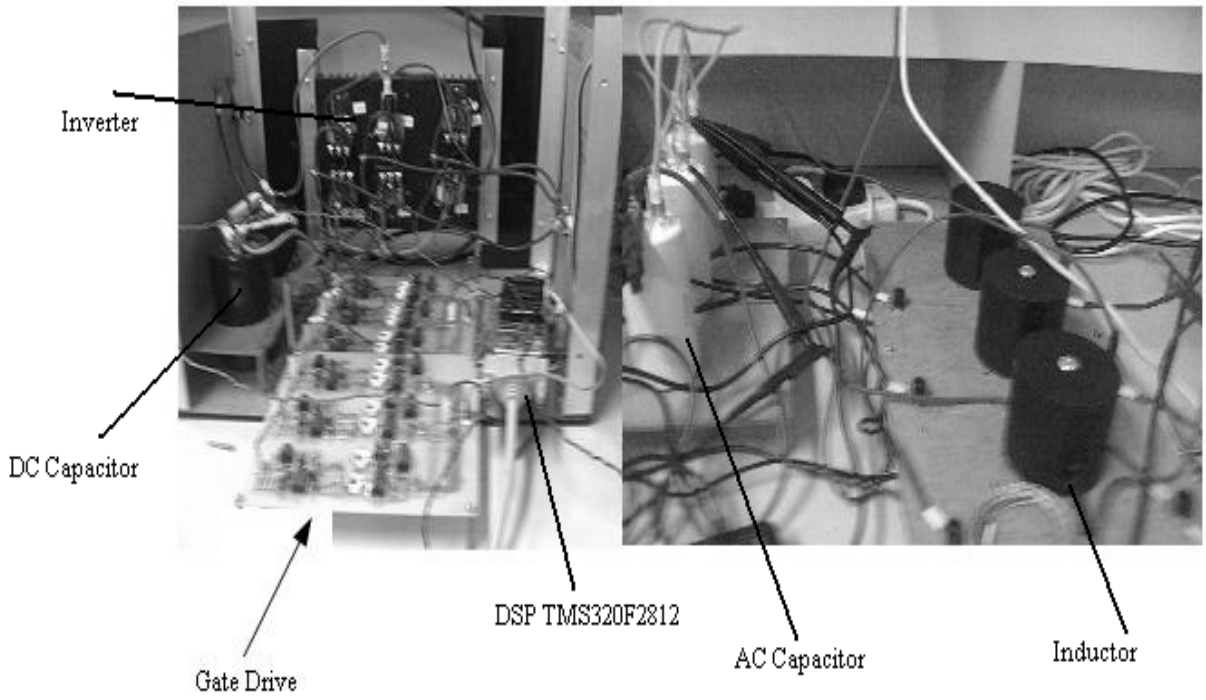


Figure 8. Experimental set-up of the power circuit consists of three phase inverter, DSP and filter scheme.

hardware designed is as shown in Table 1. The incoming three phase supply voltage is fed into the AC power source. The DVR injects active and reactive power into the system via three series injection transformers. The DVR obtains its active power from a lead acid battery bank.

The proposed control strategy is implemented digitally in DSP TMS320F2812. The DSP was selected as it has a 32-b CPU, operating at 150 MHz. The voltage and current sources were sent

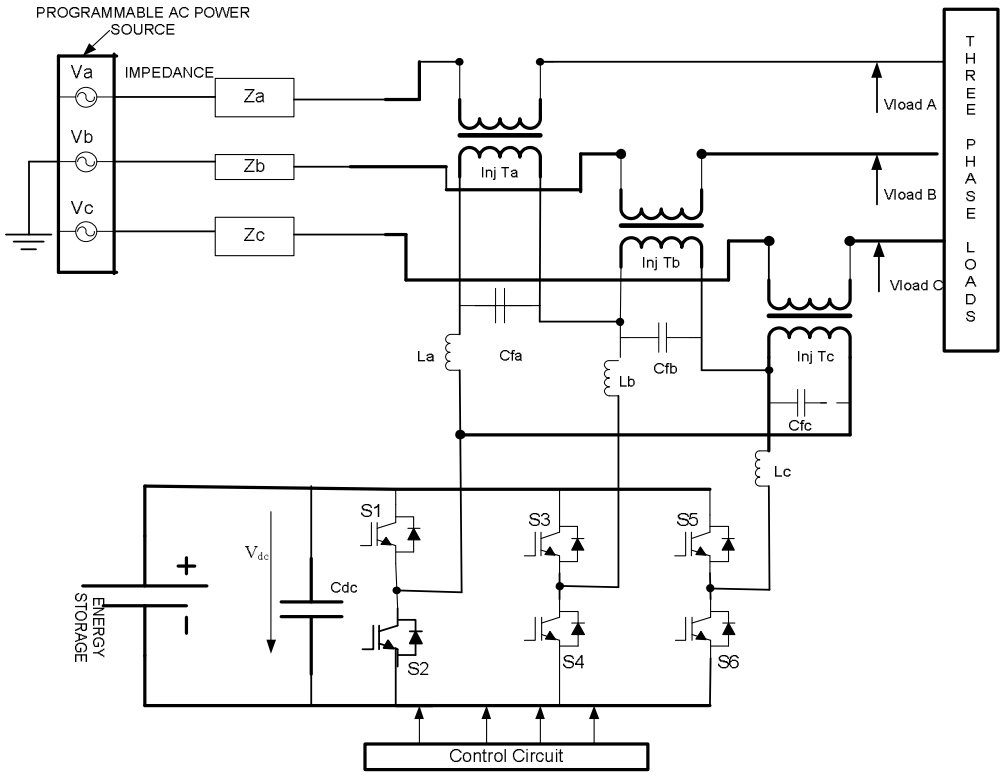


Figure 9. Configuration of the proposed DVR.

Table 1. Main specification of the DVR.

Nominal grid voltage	120 V (L-L)
Nominal load voltage	120 V(L-L)
Switching/sampling frequency	5 KHz
Max. inverter dc-bus voltage	120 V
Capacitor of dc- bus	26 uF
Filter inductance	3.947 mF
Filter capacitance	6.417 uF

to the analog digital converter of the DSP. The sampling times are governed by the DSP timer called a CpuTimer0 which generates periodic interrupt at each sampling times. The Interrupt Service Routine (ISR) will read the sampling value of the voltage and current source from the analog digital converter (ADC). The DSP controller offers a display function, which monitors the disturbances in the real time. The control algorithm which was proposed earlier is tested with a control using DSP TMS 320F 2812. The controller has its own ADC converters and PWM pulse outputs. The inputs of a 3-leg voltage source inverter (VSI) are the PWM pulses which are generated by the digital controller. The three phase supply voltage is measured continuously and is then compared with the reference voltage in order to regulate load voltage response. If any disturbances occur between the supply voltage and load voltage, the different voltage between them will be compensated. The amount of compensated voltage needed to be injected is calculated and the results of the supply, load and compensated voltages will be processed by the DSP and injected to the IGBT switching scheme (PWM1 to PWM 6).

RESULTS AND DISCUSSION

Output voltage waveforms of inverter of each phase without LC filter can be measured using the oscilloscope. The waveforms showed in the Figure 10(a, b, c) represent the unfiltered output of inverter of each phase voltages. When LC filter is connected to the inverter's output, a smooth sine waveform will be produced as

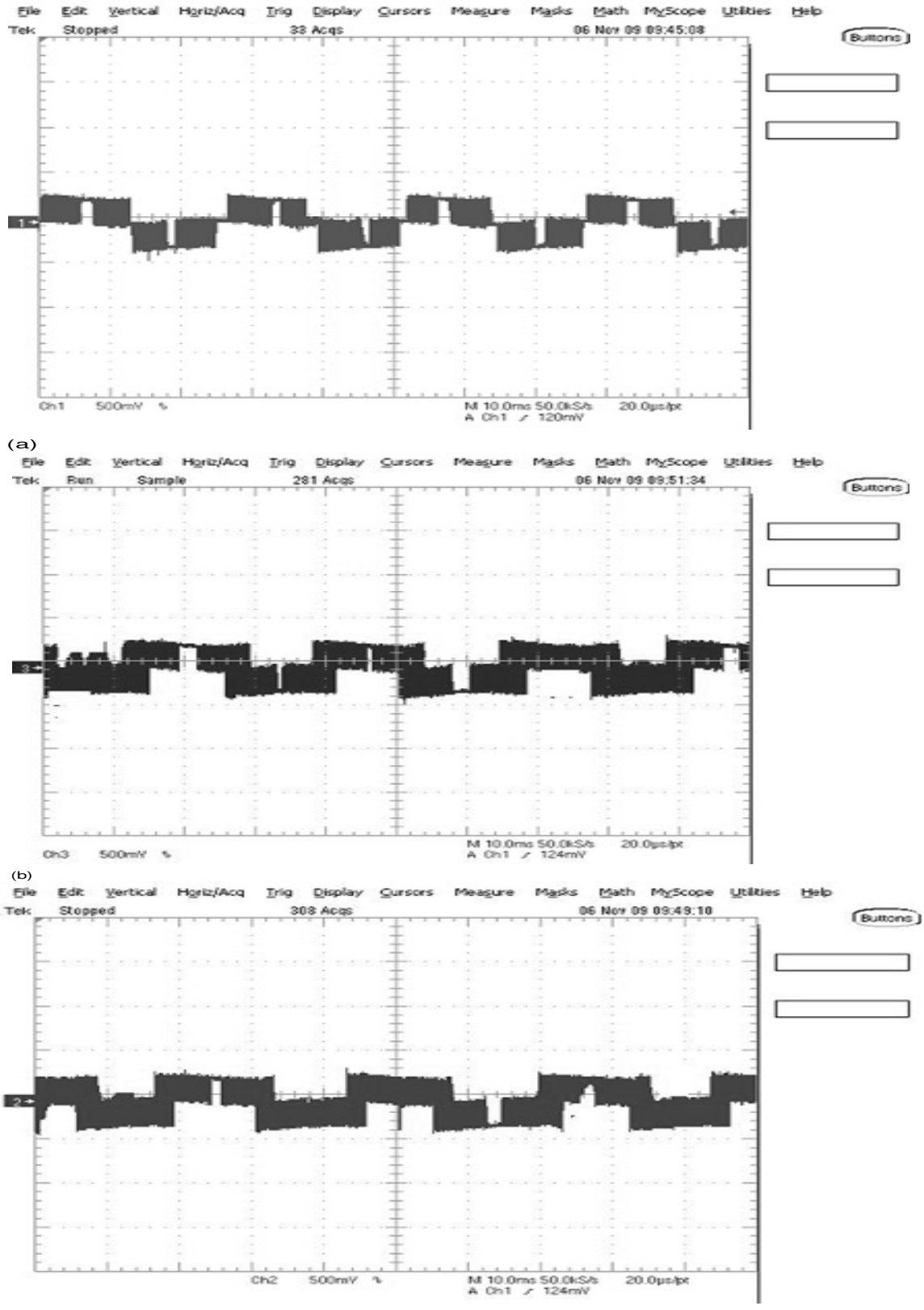


Figure 10 (a, b, c). The line voltages of phase A, B and C before connecting to the filter.

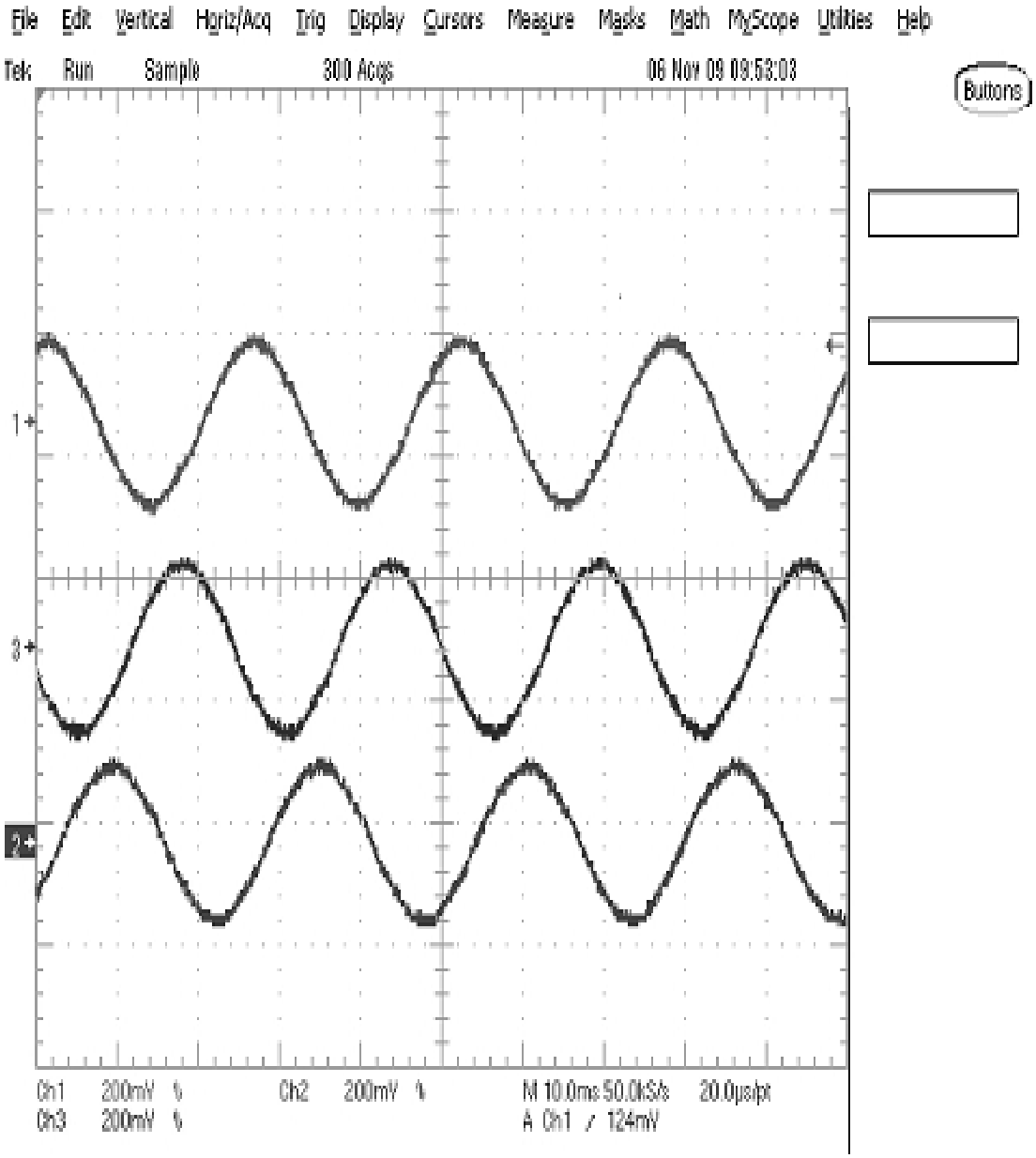


Figure 11. The line voltage of phase A ,B and C after connecting the filter.

shown in Figure 11(a, b, c). The three phases of the voltages of the inverter's output with LC filter were also measured. Figure 12 shows the results of the three phase waveform voltages with LC filter.

The phase voltage and phase current on the load side were also measured and it showed that the voltage and current are in phase and their waveforms are smoothed sinusoidal without any distortion. Figure 13 shows the results of phase voltage and current, which are in phase. Due to in phase voltage and current on the load side without any distortion there is stable power factor and the value is almost one.

Harmonics spectrum of the phase voltage at the load is shown in Figure 14. The value of total harmonics distortion (THD) for the voltage is around 1.22%. THD for the current at the load is reduced to 1.13% as shown in Figure 15. Both THD for the current and voltage are met to the IEEE standard; this shows the effectiveness of the proposed controller to decrease harmonics problems at the load side.

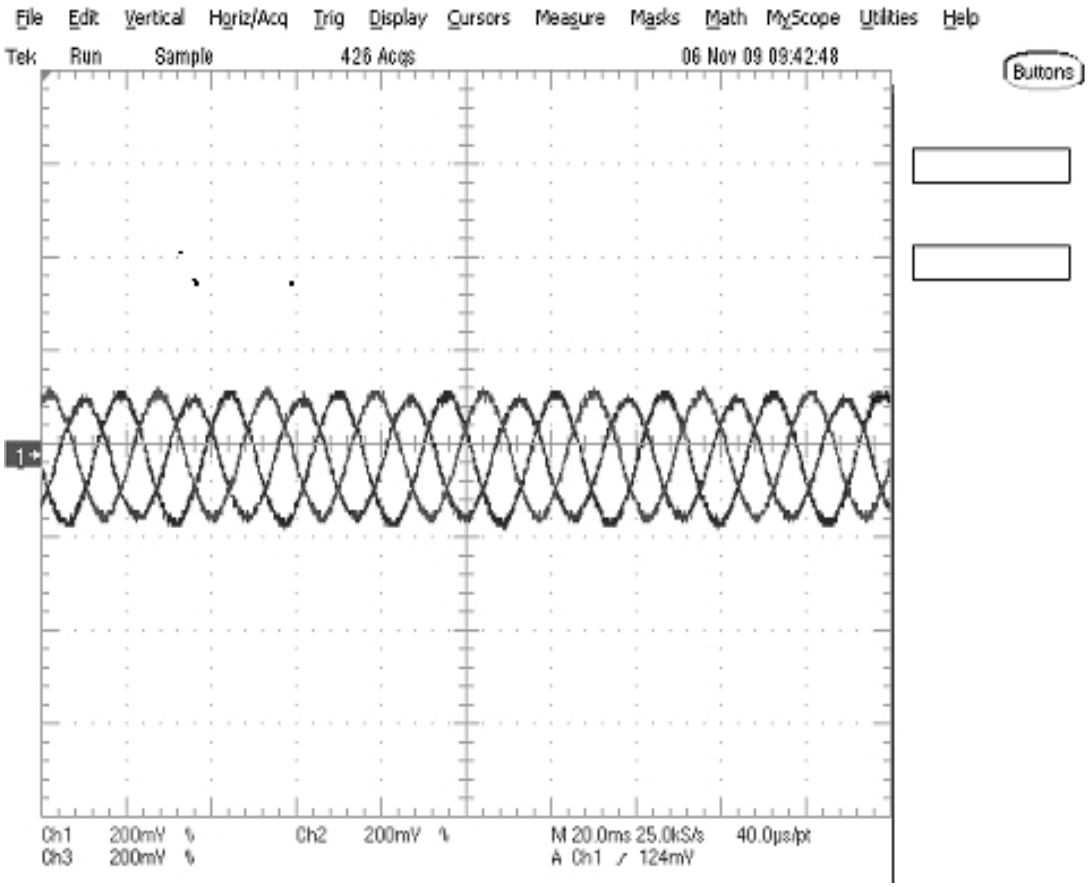


Figure 12. Three phase voltages at output of the inverter.

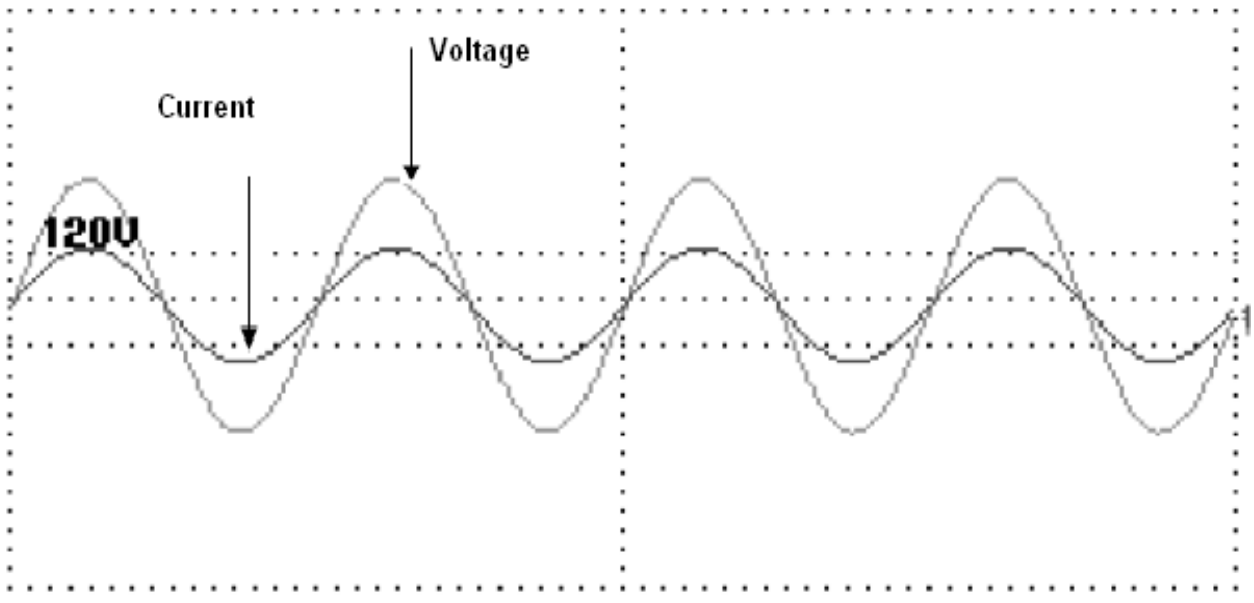


Figure 13. Phase voltage and current after voltage at the load.

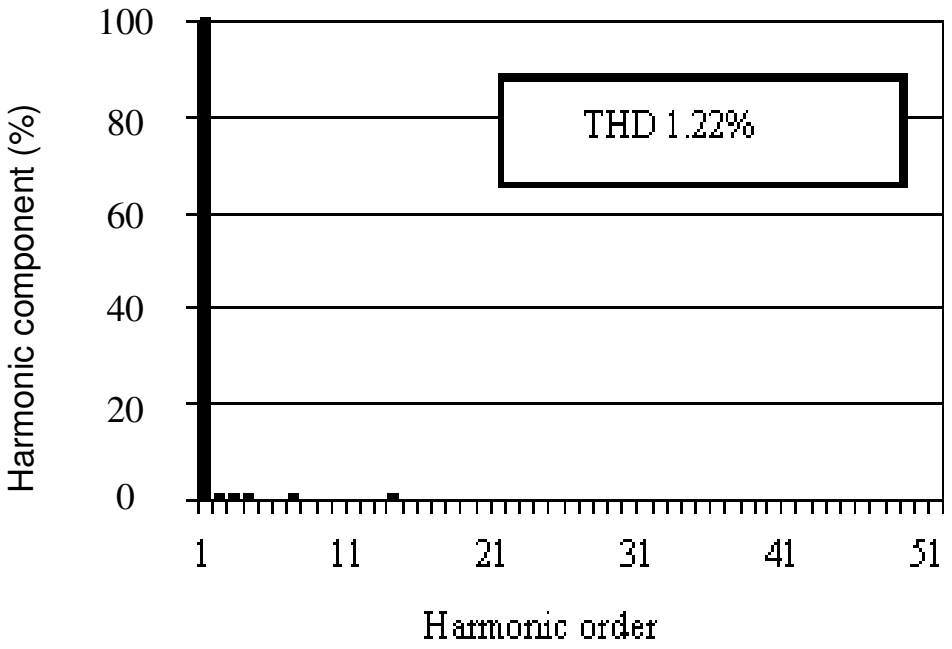


Figure 14. THD for the phase voltage.

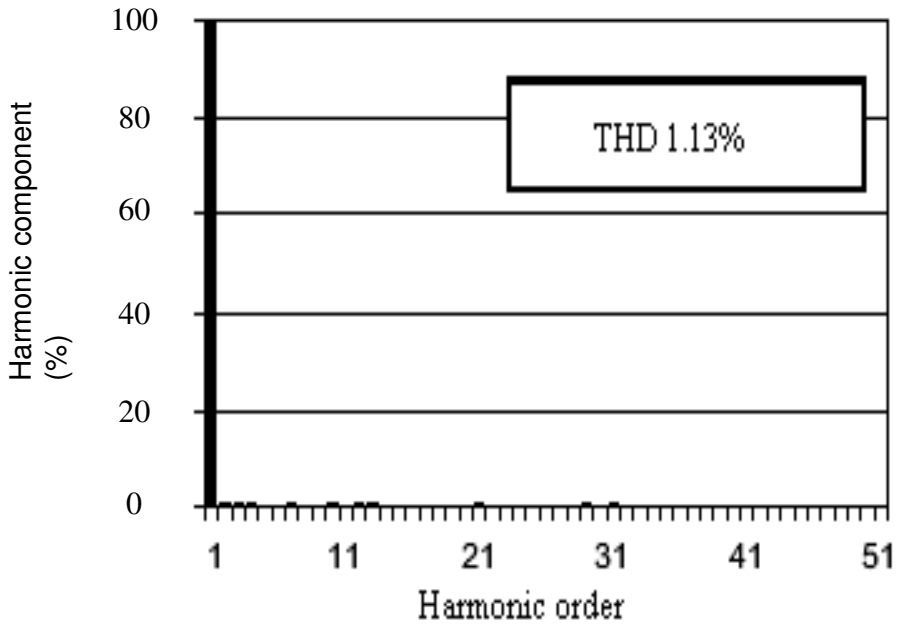


Figure 15. THD for the phase current.

Figure16 shows the currents of the output inverter with the balanced load connected. It can be seen from the figure the controller is able to stable the inverter current from distortion.

Figure 17 shows the single phase waveform which consists of the supply voltage, injection and load voltages. When there is sag, supply voltage will be decreased of its nominal value and the DVR is able to

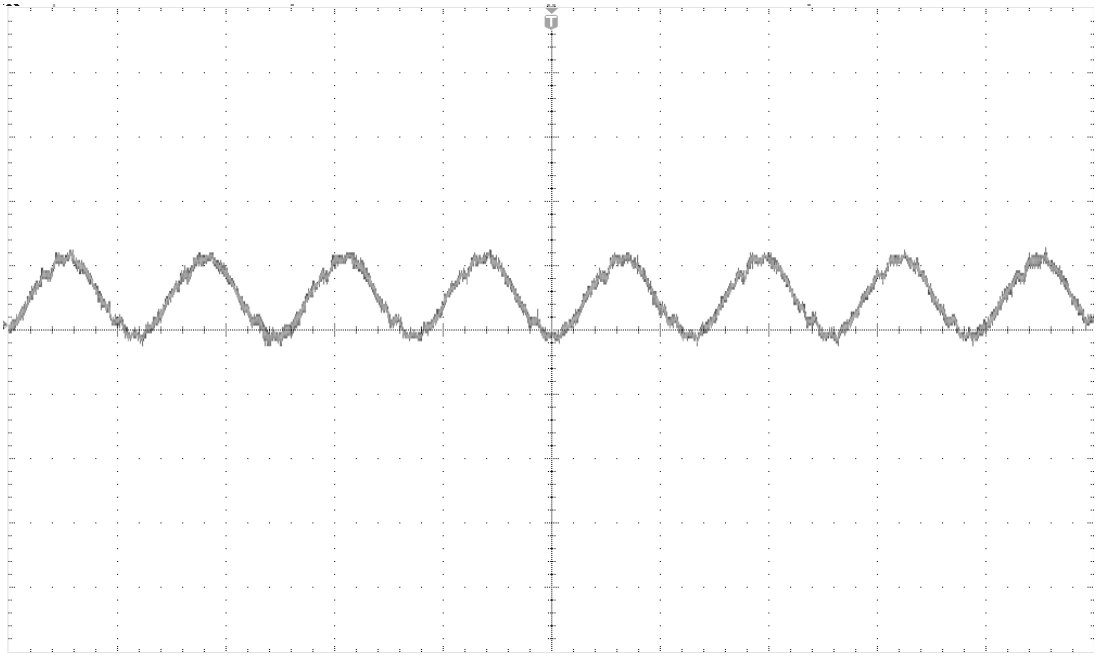


Figure 16. Current at the inverter output.

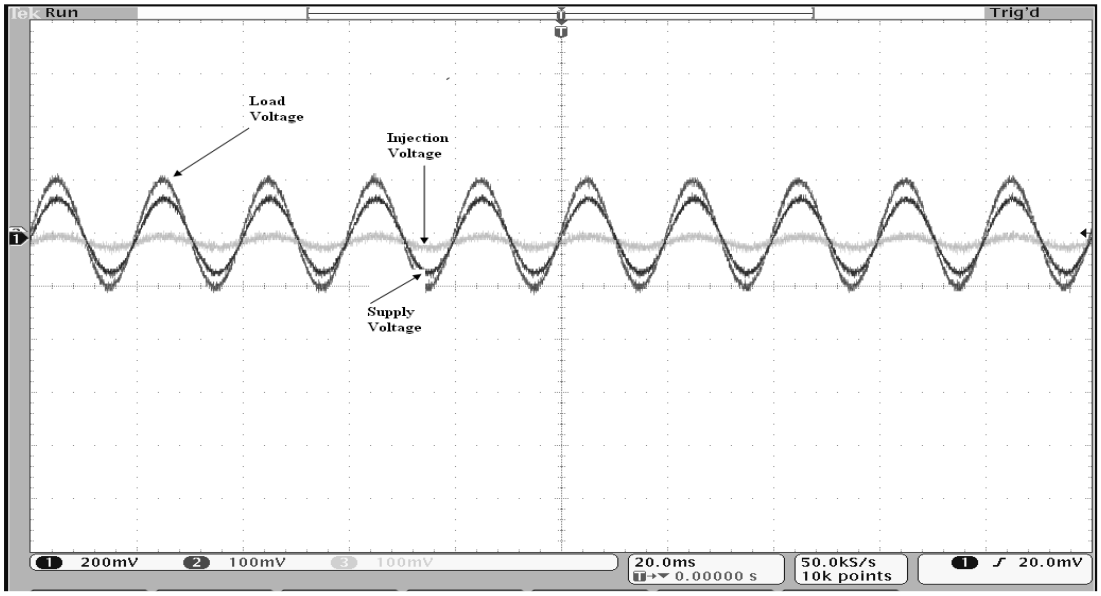


Figure 17. Waveform of supply voltage, injection voltage and load voltage.

inject the missing voltages in the distribution system. The capabilities of the DVR to inject the appropriate voltage caused the load voltage maintained constant.

The waveforms of the three phase balanced voltage sags, three phase injection and load voltages are shown in Figure 18 (a, b, c). The three phase balanced sags show the voltage will be decreased to 40% of its nominal value for duration of 100 m. The proposed DVR responds to the three phase balanced sags and injects the appropriate amount of missing voltage during the sag exit. The DVR injects the appropriate voltage to mitigate any deviation in the supply voltage in order to maintain

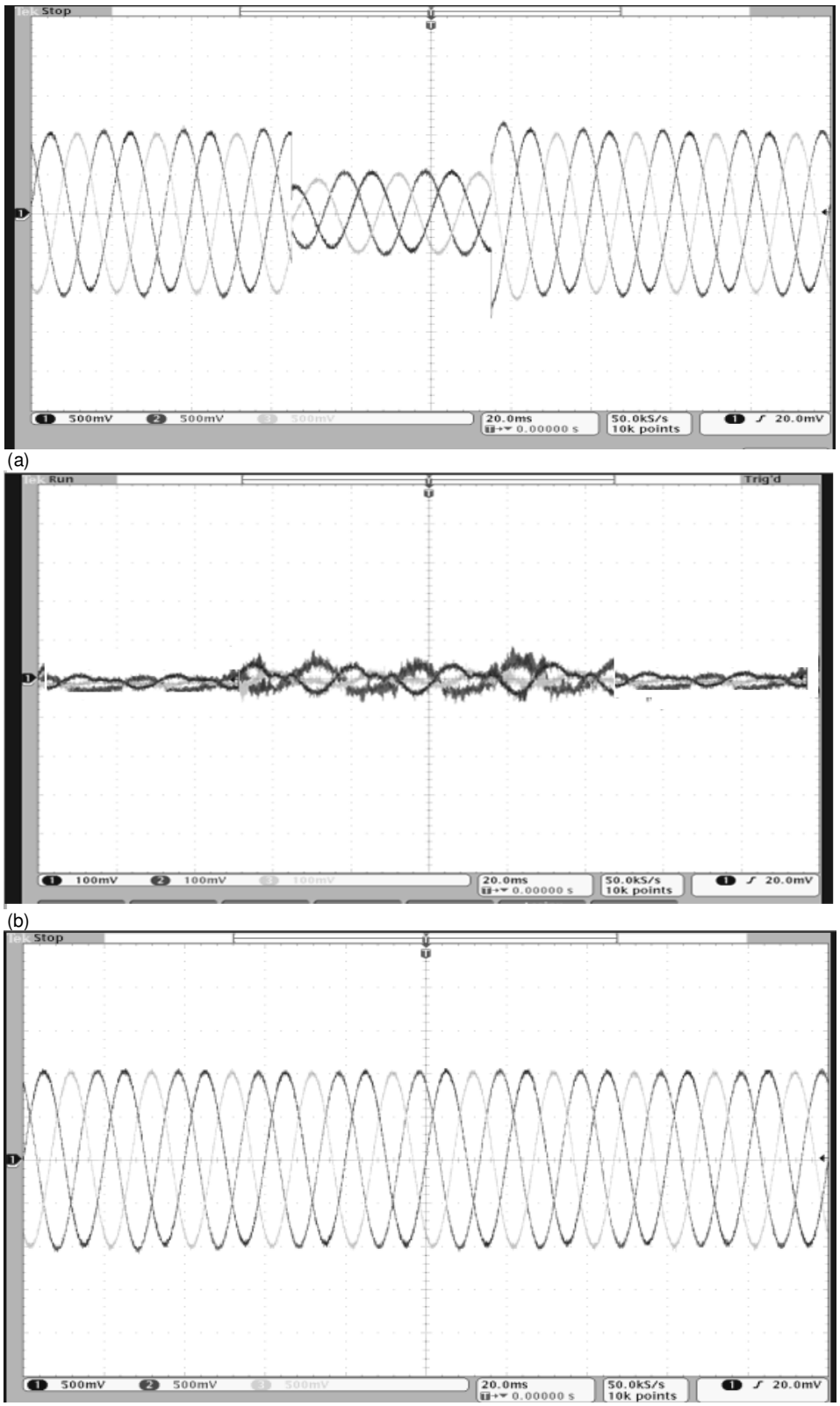
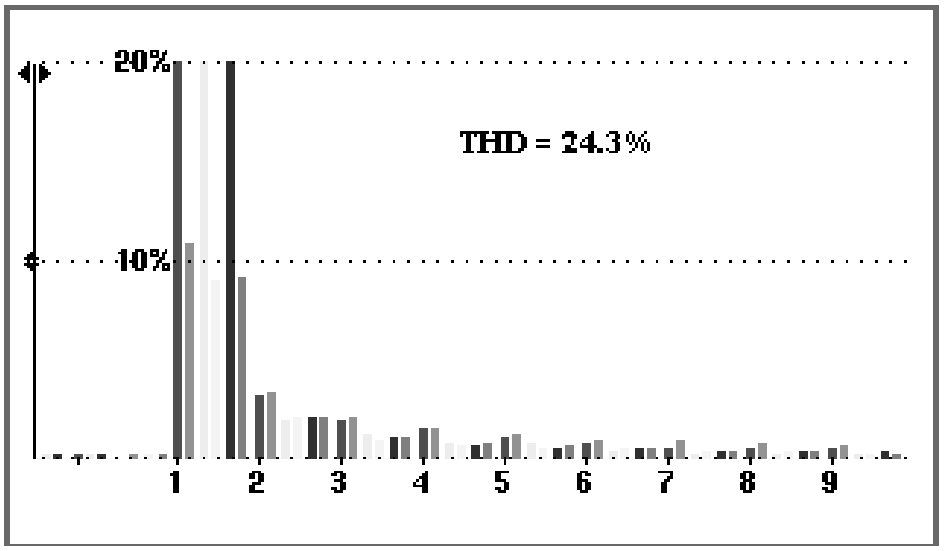
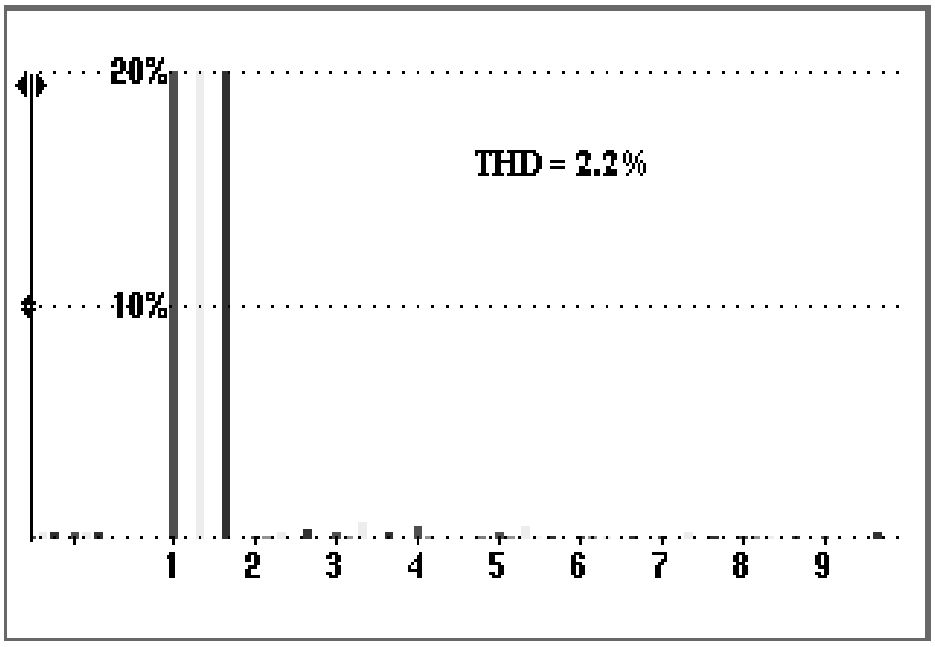


Figure 18. (a) Three phase balanced voltage sag; (b) injection voltages; (c) mitigation load voltages.



(a)



(b)

Figure 19. (a)Total harmonic distortion current (THD_I) under unstable dc-link; (b) total harmonic distortion current (THD_I) under stable dc-link.

the load voltage constant at the nominal value. The injection voltage by the DVR can be seen in Figure 18(b). The load recovery at its nominal value during the three phase sags is shown in Figure 18(c).

In the proposed system of the DVR configuration as shown in Figure 9, the DC link capacitor is used and it acts as an energy storage element of the DVR. In the calculation to determine the value of the DC link capacitor, the rating of IGBT must be considered. DC link capacitor must be large enough to absorb the ripple produced without distorting dc bus voltage. The harmonics current is totally dependent on the DC link voltage. When there is a disturbance in the dc voltage the inverter output causing distorts with third harmonics content is very high. The proposed controller is able to reduce third harmonics current due to disturbance for the case when there is sag. Figure 19(a, b) show the reduction of third harmonics current from 24.5 to 2.4%.

Conclusion

This paper presents the analysis and design of a digitally controlled three-phase PWM inverter based on DSP control application using d-q-0 controller in order to generate three-phase voltage for dynamic voltage restorer application. The basics of software optimization and hardware installation for proposed system have been presented in detail. The proposed technique achieves voltage regulation with low total harmonics distortion (THD) for both voltage and current at the connected load. The very close agreement of experimental results illustrates the efficiency, accuracy and dynamic response of DSP based PWM inverter design using d-q-0 controller. Three-phase voltages produced by inverter will be used to inject the missing voltage through injection transformer. The injection voltages through injection transformer are able to mitigate voltage sags and the load voltage is maintained at its nominal value. The experimental results also show that the capabilities of the proposed DVR along with the proposed controller DSP based in compensating voltage sags in low voltage distribution system.

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