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CURRENT-SOURCE INVERTER WITH PERFECT SINUSOIDAL OUTPUT FOR ENERGIZING CRITICAL EQUIPMENT IN NUCLEAR FACILITIES

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ABSTRACT

The present work proposes an AC current-source inverter to energize critical equipment used in the nuclear facilities. The basic switching circuit of the proposed current-source inverter is based on an H-bridge four MOSFETs with gate drivers and optocoupler isolators. A well-designed LC filter is used for sinusoidal shaping of the H-bridge output voltage/current to get the inverter operating as an AC current source that satisfies the objectives of current regulation, frequency stabilization, and minimization of the total harmonic distortion (THD), a control system based on a fast DSP unit and a microcontroller is designed for cancelation of the higher-order harmonics to produce a pure sinusoidal output with almost zero total harmonic distortion (THD). For experimental evaluation, a prototype is fabricated for the complete system of the proposed current-source inverter including the MOSFET Bridge, LC filter, the feedback circuit, and the DSP unit. It is shown by simulation as well as experimental measurement that the proposed current-source inverter provides current regulation, frequency stabilization with THD $< 6 \times 10^{-4}\%$ (It is nearly nonexistent).

KEYWORDS: Current-source inverter, Total harmonic distortion (THD), Solar photovoltaic.

عاكس مصدر تيار مع إخراج جيبى مثالى لإمداد الطاقة للمعدات الحيوية في المرافق النووية

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الملخص

يقترح العمل الحالي عاكسًا لمصدر التيار المتردد لإمداد الطاقة للمعدات الحيوية المستخدمة في المرافق النووية. تعتمد دائرة التبديل الأساسية لعاكس مصدر التيار المقترح على جسر H-bridge وأربع وحدات MOSFET مع برامج تشغيل البوابة وعوازل (optocoupler) يتم استخدام مرشح LC مصمم جيدًا للتشكيل الجيبي للجهد/تيار الخارج من الجسر H-bridge للحصول على تشغيل العاكس كمصدر تيار متردد يلبي أهداف تنظيم التيار، وتثبيت التردد، وتقليل التشوه التوافقي الإجمالي

(THD)، تم تصميم نظام تحكم يعتمد على وحدة DSP سريعة ووحدة تحكم دقيقة لإلغاء التوافقيات ذات الترتيب الأعلى لإنتاج مخرجات جيبية نقية مع تشويه توافقي (THD) إجمالي صفر تقريبًا. للتقييم التجريبي، تم تصنيع نموذج أولي للنظام الكامل لعاكس مصدر التيار المقترح بما في ذلك جسر MOSFET ومرشح LC ودائرة التغذية المرتدة ووحدة (DSP) . يتضح من خلال المحاكاة وكذلك القياس التجريبي أن عاكس مصدر التيار المقترح يوفر منظم للتيار وتردد ثابت مع تشوه توافقى (THD) حوالي THD <6×10^(-4)%(يكاد يكون منعدم).

الكلمات المفتاحية : عاكس مصدر التيار، التشوه التوافقي الإجمالي (THD)، الطاقة الشمسية.

1. INTRODUCTION

The neutron transmutation doping (NTD) method is widely used in various fields, such as solar cells that can provide direct commercial income for nuclear research reactors using the silicon doping process [1]. Egypt second research reactor (ETRR-2) has two irradiation positions for silicon doping using NTD that are used in production of doped Silicon Wafers for Solar Panels and Basic Electronics [2]. Solar cell is an electrical device that converts light into electricity at the atomic level.

These devices use inorganic or organic semiconductor materials that absorb photons with energy greater than their band-gap to promote energy carriers into their conduction band. Smart grid refers to the conversion of the traditional grid into a new power system that has been designed with two-way power and communication signal transfer. Integration of dispersed generation sources, enhancement of micro-grid structures, and development of power electronics devices with greater communication capabilities are the primary catalysts for the smart grid evaluation.

Solar energy sources and other comparable micro-sources are used to build micro-grids, which are distributed power systems. In order to meet the requirements of smart grid architecture, communication technologies integrated into power electronic devices. The advancement of micro-grid and distributed generation brought individual generation and accelerated the improvements observed in power inverters [3-5].

Power inverters play an important role in the solar energy system and are considered to be the brains of the system. Its basic function is to convert the direct current (DC) output into the alternating current (AC) [6]. Total harmonic distortion, or THD for brief, is a measurement of how much harmonic distortion there is in a signal relative to its original frequency. Any type of periodic signal, particularly power and audio signals, can have its value computed. The type of inverter and the load it is driving can have an impact on the THD of the output signal in an inverter. An inverter's output waveform is often a sequence of low- and high-voltage pulses within the inverter's frequency range, or a pulse width modulated (PWM) signal [7].

In 2011, Mohamed Azab presented accurate solutions for nonlinear transcendental equations of the selective harmonic elimination technique used in three-phase PWM inverters feeding the induction motor by particle swarm optimization (PSO) [8].

In Beginning of 2013, T.R.Sumithira et al. designed and implemented a multilevel inverter to operate a stand-alone solar photovoltaic system. The proposed system uses pulse-width modulation (PWM) in the multilevel inverter to convert DC voltage from battery storage to supply AC loads [9].

In April 2013, P. S. Aravind et al. presented the selective harmonic elimination problem in multilevel inverter using Artificial Neural Networks (ANN) to generate the switching angles for an eleven-level full-bridge cascaded H-bridge multilevel inverter powered by five varying DC input sources (solar panels) [10].

In 2014, S. A. Alexander et al. proposed an optimal harmonic stepped waveform (OHSW) method to reduce the voltage harmonics available at the output of solar photovoltaic (SPV) fed fifteen level cascaded multilevel inverter (CMLI) [11].

In 2016, S. S. Letha et al. proposed a novel method to eliminate harmonics in a solar powered CHMLI (cascaded H-bridge multilevel inverter). The problem uses Newton Raphson and PSO (Particle Swarm Optimization) based SHE (Selective Harmonic Elimination) techniques for solving the non-linear transcendental equations and to obtain the optimal switching angles [12].

In 2019, M. R. Miranda et al. investigated a hybrid control scheme to grant multiple functions to a grid-connected PV inverter and presented additional functions that decreased the total harmonic distortion and improved the power factor of the active power demanded from and supplied to the grid [13].

In 2021, N. Ahmed et al. presented the design of a microcontroller based pure sine wave single phase inverter. The inverter had fewer harmonics, was simpler to design compared to the traditional inverter technology [14].

In 2023, G. LI et al. realized the random pulse width modulation (RPWM) selective harmonic elimination in one basic cell, and the coordinated control among the cells is realized by using the carrier stacking strategy [15].

2. COMPLETE DESIGN OF THE PROPOSED CURRENT-SOURCE INVERTER

The design of the proposed current-source inverter includes the basic MOSFET circuit, the MOSFET gate driver, the optocoupler isolator and ccontrol of the H-Bridge Output.

2.1. Design of the Proposed Current -Source Inverter

The complete design of the proposed current-source inverter including the basic MOSFET circuit, the MOSFET gate driver and the optocoupler isolator is presented in **Fig. 1**.

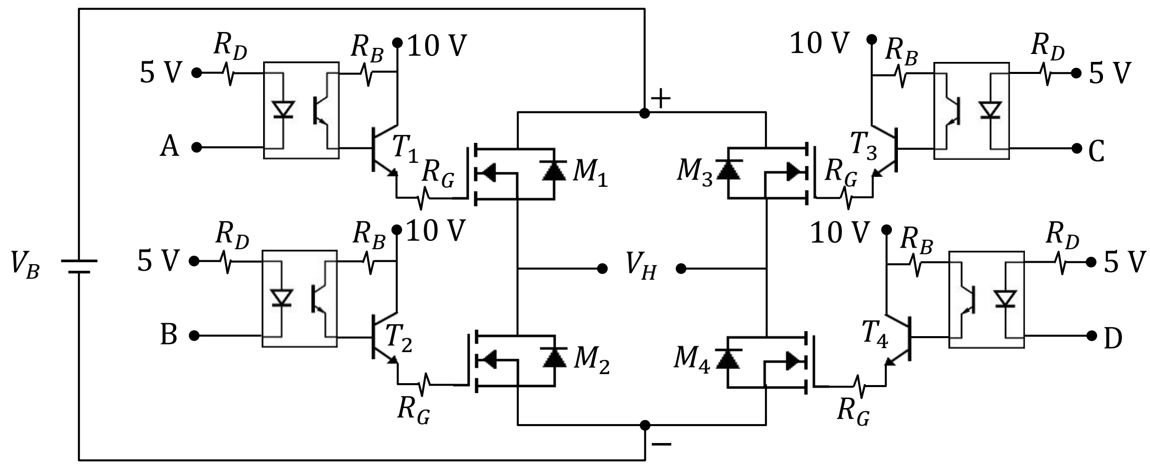


Fig. 1. Complete design of the proposed current-source inverter (Without the control system for minimizing the THD).

2.2. Control of the H-Bridge Output through Pulse Width Modulation

The time waveforms of the MOSFET H-bridge input control signals A, B ,C , D (see **Fig. 1**) and the inverter output voltage, V_H, at no-load are presented in **Fig.2**. The frequency of the H-bridge output signal, f, can be determined as follows.

$$f = \frac{1}{T_L + T_H} \tag{1}$$

Let us define the following ratio.

$$R_r = \frac{T_H}{T_L} \tag{2}$$

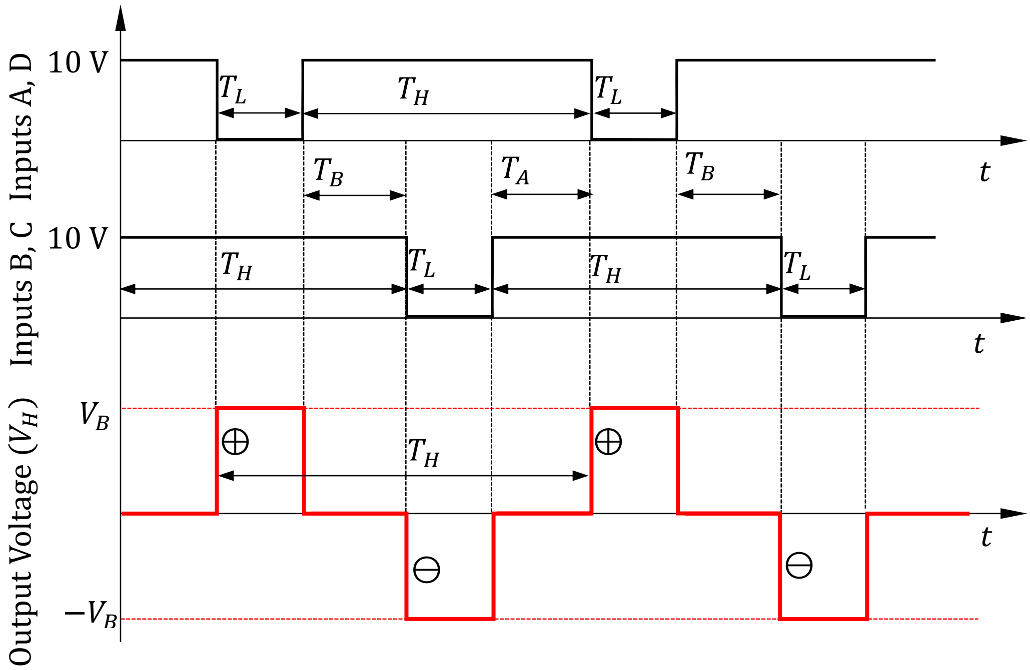


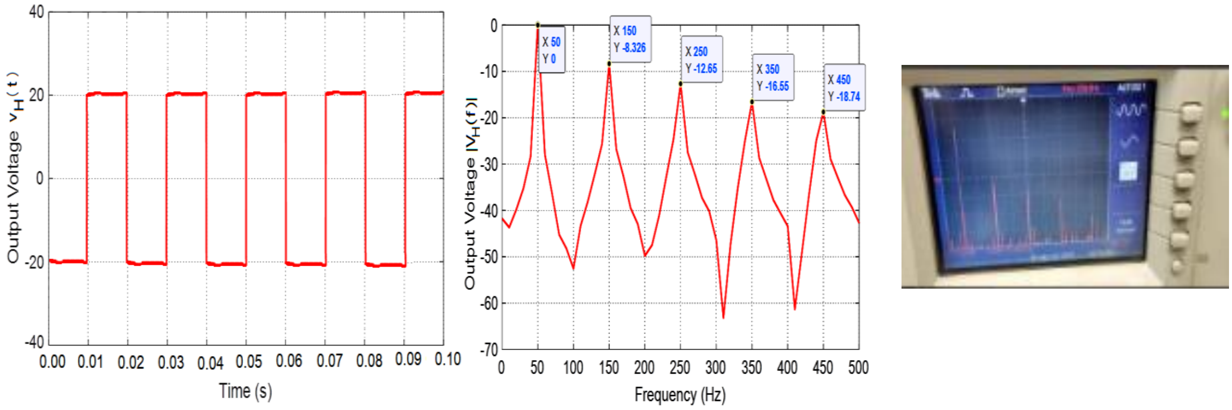
Fig. 2. Time waveforms of the MOSFET H-bridge input control signals (A, B, C, D) and the inverter output voltage, V_H, at no-load.

3. TOTAL HARMONIC DISTORTION ANALYSIS

The time waveform of the output voltage, $v_H(t)$, of the H-bridge is presented in **Fig. 3a** and the spectrum (magnitude of the Fourier transform) is presented in **Fig. 3b,3c.** It is shown that the principal (dominant) harmonic is exactly at 50 Hz. However, many higher-order harmonics of significant magnitude exist at the higher frequencies. Due to the odd symmetry of the time waveform $v_H(t)$ the frequency harmonics of its spectrum are odd-multiples of 50 Hz such as 150 Hz, 250 Hz, ..,$50(2m-1)$ Hz ,.. etc. where m is an integer. The output voltage can be expressed in a Fourier series as follows [16].

$$v_H(t) = \sum_{n=1}^{\infty} a_{Hn} \cos(\omega_n t) = \sum_{n=1}^{\infty} a_{Hn} \cos(n\omega_1 t), \quad n = 1,3,5,.. \tag{3}$$

a_{Hn} is the magnitude of the n^{th}-order harmonic of the Fourier expansion of $v_H(t)$.
where,$\omega_1 = 2\pi f_1$ and $f_1 = 50$ Hz.



(a) **(b)** **(c)**

Fig. 3. Output voltage of the MOSFET H-bridge (without applying the sinusoidal shaping filter), as measured by Tektronix oscilloscope model TDS2012B for PWMR, $R = 1$. **(a)** Time waveform, $v_H(t)$. **(b), (c)** Spectrum, $|V_H(f)|$.

The total harmonic distortion (THD) is defined as the ratio of the square root of the total power of the unwanted harmonics to the square root of the power of the principle (desired) harmonic. Let H_H be the THD of the square wave $v_H(t)$ at the H-bridge output; this can be expressed as follows [17].

$$H_H = \frac{1}{a_{H_1}} \sqrt{\sum_{n \geq 2} a_{Hn}^2} \tag{4}$$

As the frequency of the square wave is 50 Hz, the magnitude of the 1st-order harmonic, a_{H1}, will be much greater than the higher-order harmonics ($a_{H1} \gg a_{Hn}, n \geq 2$). However, the Fourier series of the square wave is slowly convergent as it has very slowly decaying magnitudes and, hence, large number of terms is required for accurate calculation of the series in (3). The rms value of the H-bridge output voltage, $V_{H\,rms}$, can be expressed in terms of the principal harmonic magnitude, a_{H1}, and the THD as follows.

$$V_{H\,rms} = a_{H_1} \sqrt{\frac{1 + {H_H}^2}{2}} \tag{5}$$

Comparing the expression (5) to (4), it can be shown that,

$$a_{H\,1} = \frac{2V_B}{\sqrt{(1 + R)(1 + {H_H}^2)}} \tag{6}$$

By application of expression (4) the THD is shown to be about -8 dB (i.e. about 10%) which needs much improvement.

4. SINUSOIDAL SHAPING OF THE INVERTER OUTPUT

The time waveform of $v_H(t)$ can be processed by a sinusoidal shaping filter that acts as a narrow band pass filter to remove the harmonics other than the principle harmonic at $\omega_1 = 2\pi \times 50$ rad/s. Thus, the sinusoidal waveform of the output voltage can be achieved by an LC filter as shown in **Fig. 4**. The proposed LC filter has its resonance at the desired frequency (50 Hz), a coil of inductance L_F and a capacitor of capacitance C_F. This coil has unavoidable internal resistance r_F that is usually small for a high quality wire-wrapped copper coil. It is required that the transfer function, $G_F(\omega)$, of the sinusoidal shaping filter has a sharp maximum at 50 Hz. This can be achieved if $\omega^2 L_F C_F = 1$ at 50 Hz, which requires C_F to be expressed in terms of L_F as follows.

$$C_F = \frac{1}{\omega_1^2 L_F} \tag{7}$$

where $\omega_1 = 100\pi$ rad/s.

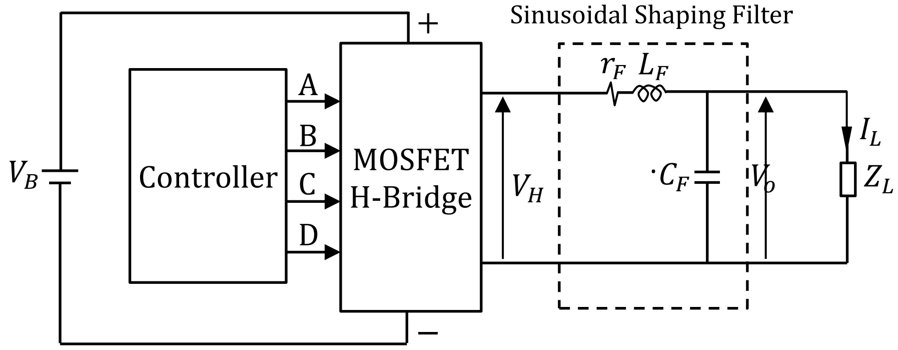


Fig. 4. Sinusoidal shaping of the inverter output voltage/current waveform using smoothing LC filter.

For a given value of L_F, the best value of the capacitance C_F that results in the minimum THD depends on the coil internal resistance, r_F as shown in **Fig. 5**.

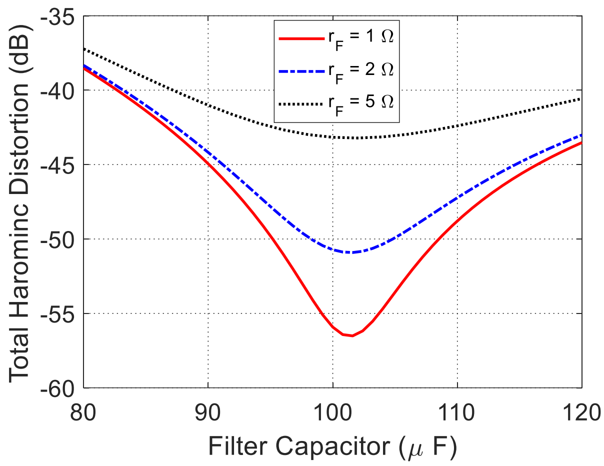
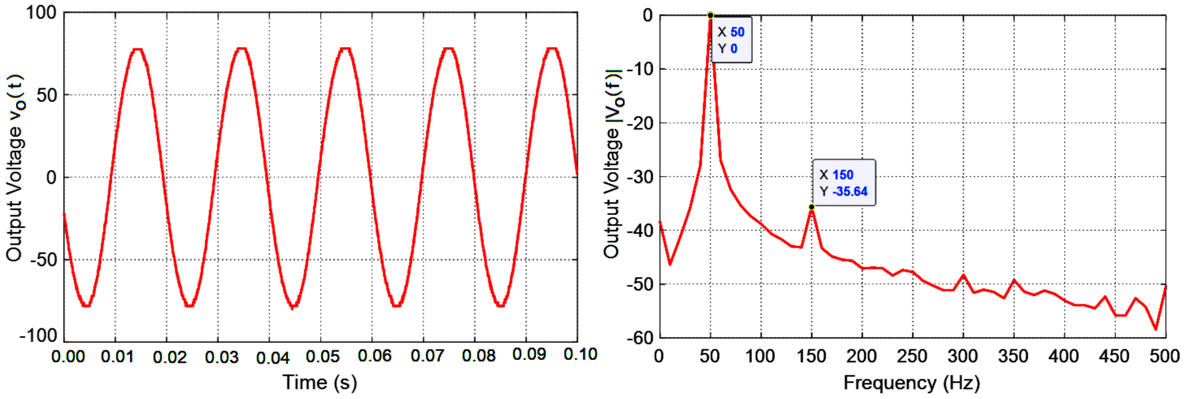


Fig. 5. Dependence of the THD of the inverter output voltage/current on the filter capacitance, C_F, for $L_F = 0.1\ H$ and varying values of the coil resistance, r_F, at $|Z_L| = 1$ kΩ and $R_r = 1$.

The insertion of the sinusoidal shaping LC filter at the inverter output results in a perfect sinusoidal shape of the output voltage, $v_o(t)$, as shown in **Fig. 6a**. The magnitude of its spectrum, $|V_o(f)|$, is plotted with the frequency as shown in **Fig. 6b**. By comparing the spectrum presented in **Fig. 6b** to that presented in **Fig. 3b**, it becomes clear that the THD is considerably improved due to the LC filter. By application of expression (4) the THD is shown to be about -35 dB (i.e. less than 0.05%). Thus, the THD is improved from -8 dB to -35 dB due to the insertion of the sinusoidal shaping LC filter at the inverter output.



(a) (b)

Fig. 6. Output voltage of the sinusoidal shaping filter (see **Fig. 4**), as measured by the Tektronix oscilloscope model TDS2012B for at $|Z_L| = 1\ \text{k}\Omega$ and $R_r = 1$. (a) Time waveform, $v_o(t)$. (b) Spectrum, $|V_o(f)|$.

5. DEPENDENCE OF THE TOTAL HARMONIC DISTORTION ON THE PWMR

The dependence of the higher-order harmonic level of the time waveform voltage, $v_o(t)$, at the output of the LC filter on the PWM Ratio, R_r, for different values of the load impedance magnitude, $|Z_L|$, is presented in **Fig. 7**. Making use of these curves, the control system described in Section 6 is used to improve the THD by selecting the value of R_r to the value that gives the minimum THD.

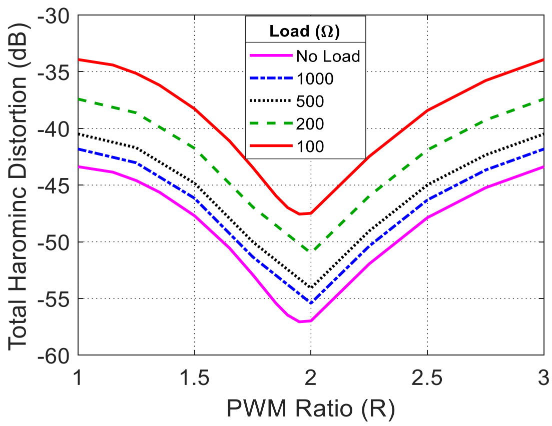


Fig. 7. Dependence of the THD of the inverter output voltage on the PWMR for different magnitudes of the load impedance for $C_F = 100\ \mu\text{F}$, for $L_F = 0.1\ H$, $r_F = 1\ \Omega$, $|Z_L| = 1\ \text{k}\Omega$.

6. CONTROL SYSTEM FOR CURRENT REGULATION, FREQUENCY STABILIZATION, AND MINIMIZATION OF THD

To get the inverter functioning as an AC current source, the control system with the feedback circuit shown in **Fig. 8** is used for stabilizing (regulating) the load current at the desired value irrespective of the load impedance. The method proposed for load current regulation depends on a feedback system for stabilization of the amplitude of I_L. A small resistance (r) is placed in series with the load impedance, Z_L. The voltage V_r is proportional to the load current. A non-inverting differential amplifier is used to get the feedback voltage signal, V_D, that is proportional to the load current I_L.

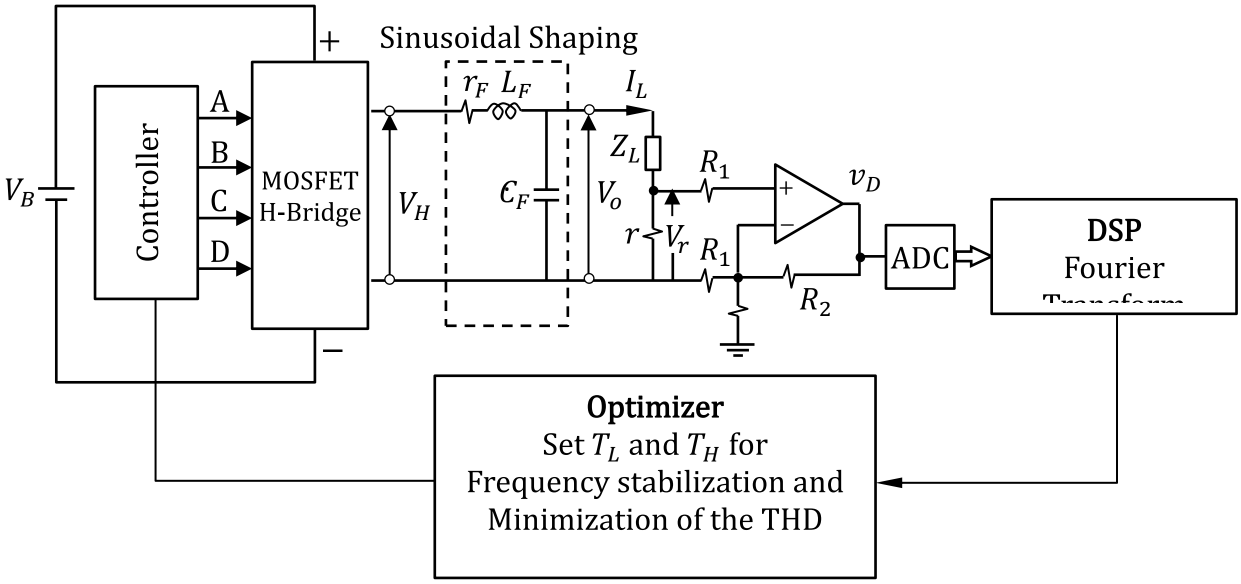


Fig. 8: Control system with feedback for current regulation, frequency stabilization and minimization of THD.

The voltage drop, V_r, across the feedback resistance, r, can be expressed as follows,

$$V_r = I_L \ r \tag{8}$$

The feedback voltage (v_D) at the output of the differential amplifier can be expressed as follows;

$$v_D = \left(1 + \frac{R_2}{R_1}\right) r I_L \tag{9}$$

The last expression (9) shows that the output voltage v_0 of the rectifier is proportional to I_L.

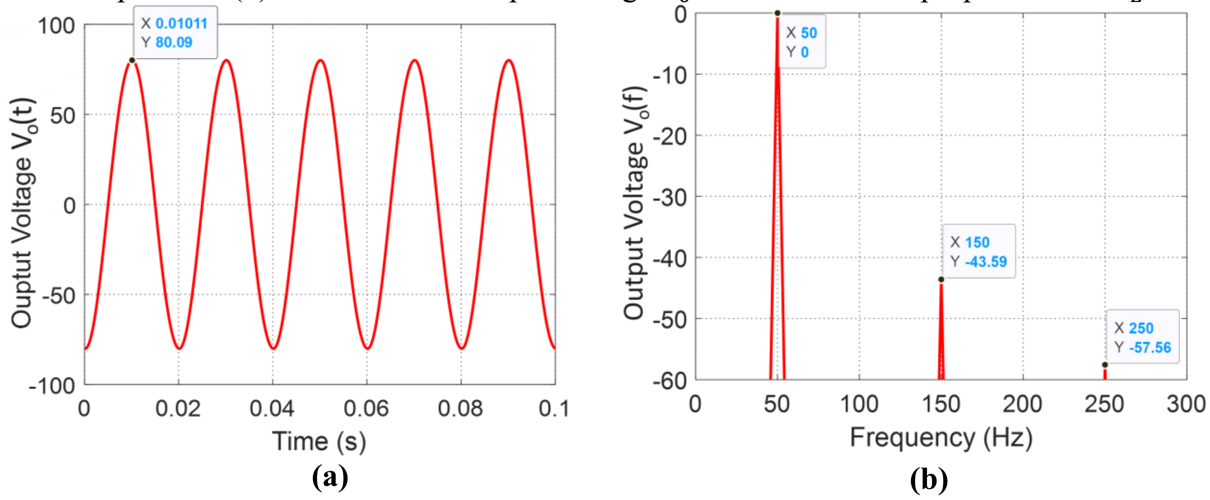


Fig. 9. The sinusoidal voltage at the output of the LC filter of the proposed current source inverter as measured by Tektronix oscilloscope model TDS2012B for $Z_L = 1\ k\Omega$ and PWM ratio, R_r= 2, the LC filter parameters are $C_F = 100\mu$F, $L_F = 0.1\ H$, and $r_F = 5\ \Omega$. **(a)** Time-waveform of the LC filter output voltage. **(b)** The corresponding normalized spectrum magnitude showing the first significant three harmonics.

By comparing the sinusoidal time waveform of the inverter output voltage, $V_o(t)$, shown in **Fig.9a** to that shown in **Fig. 6**, it becomes clear that the control system plays a significant role for further improvement of the sinusoidal shape of time waveform of output voltage/current of the proposed current-source inverter. Moreover, as shown in **Fig. 9b**, the higher-order harmonics are more suppressed. By applying expression (4), the THD is found to be -43 dB

(6×10^{-4} %). The progressive improvements with the successive stages of the proposed current-source inverter of the THD are listed in **Table 1**.

Table 1. Progressive improvements of the THD of the output voltage/current of the proposed current-source inverter with the successive design stages.

Stage	H-Bridge	Sinusoidal Shaping Filter	Control System
THD	-8dB (10%)	-35dB (0.05%)	-43dB (0.0006%)

A prototype of the complete current-source inverter is fabricated for experimental evaluation of fulfillment of the design objectives including current regulation, frequency stabilization, and minimization of THD. The fabricated prototype and the measurement setup using the Tektronix oscilloscope model TDS2012B are shown in **Fig. 10**.

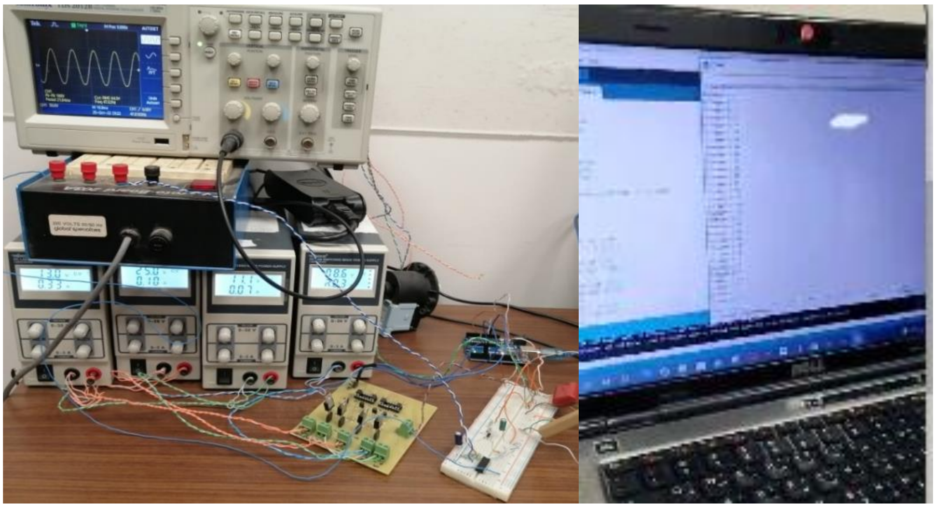


Fig. 10: Fabrication of the complete prototype of the proposed current-source inverter for experimental evaluation.

It is shown experimentally that the output current has constant amplitude irrespective of the load impedance and have a pure sinusoidal shape with almost zero THD as measured by Tektronix oscilloscope model TDS2012B. The Tektronix oscilloscope model TDS2012B displays the pure sinusoidal shape of the current-source inverter output.

7. CONCLUSION

This study investigates an AC current-source inverter to energize critical equipment used in the nuclear facilities. The basic switching circuit of the proposed current-source inverter is an H-bridge based on four MOSFETs. LC filter is used for sinusoidal shaping of the H-bridge output voltage/current. To get the inverter operating as an AC current source that satisfies the objectives of current regulation, frequency stabilization, and minimization of the total harmonic distortion (THD), a control system with current feedback and DSP unit is designed and implemented. For experimental evaluation, a prototype is fabricated; a prototype is fabricated for the complete system of the proposed current-source inverter including the MOSFET Bridge, the feedback circuit, and the DSP unit. It is shown by simulation as well as experimental measurement that the proposed current-source inverter provides current regulation, frequency stabilization with very low THD.

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