Design and Simulation of a High Performance Standalone Photovoltaic System

Hussain A. Attia, Yousif I. Al-Mashhadany, Beza N. Getu

***Abstract*— This paper proposes a full design with all included stages of a high performance standalone photovoltaic system based on discrete electronic components. The design proposes a solution to reduce or eliminate the fluctuation of the supplied DC voltage of solar panel due to weather variations. The proposed internal stages include DC-DC boost converter that controls directly the duty cycle of the drive switching pulse by sensing the level of solar output voltage. The next stage proposes a modified unipolar Sinusoidal Pulse Width Modulation inverter with Zero Crossing Detector circuit that is designed with a modified higher power reference wave compared with traditional SPWM. The modified SPWM controls the Modulation Index to stabilize the fluctuation in the output AC voltage. The selected filter type LCL-Filter is designed to minimize the effect of harmonics on the load voltage. On the other hand, an accurate DC power supply is designed to provide the required stable DC voltages for all included electronic circuits; the solar panel voltage is an input to the designed DC power supply. Total Harmonic Distribution measurements, the stable output voltage levels of the DC-DC converter, DC power supply, and the stabilization of the load voltage reflect the effectiveness of the proposed photovoltaic system. The satisfactory simulation results indicate that there is a promise to implement the proposed electronic design using discrete components as practical module.**

Index Terms*—*PV System, DC-DC Converter, Duty Cycle, SPWM, Sensing Circuit, Close Loop, LCL Filter, DC Supply

I. INTRODUCTION

THE abundance and wide spread availability of solar energy, make it the most attractive among other energies that can be feasibly extracted. It can be converted into electricity through photovoltaic (PV) energy system for portable applications or use in rural areas [1]. The first component in the PV system is solar cell, which is an electronic component manufactured from a certain layers of semiconductor materials that transfer the incident light energy to direct current (DC) with a certain value of voltage, that means, the solar cell works as a voltage source [2]. Solar panel is a matrix of solar cells connected in a specified serial and/or parallel connection to have a desired output voltage and power levels [3]. The instantaneous levels of output DC voltage of solar panels suffer from the fluctuation between low and high levels according to the instantaneous values of the solar radiation, in other words, the output of the solar panel is unregulated DC supply due to change in weather conditions [4]. A standalone photovoltaic system is suitable for portable low power applications and as a power source in rural areas that are is far from electric networks. For standalone system characterized by optimal load, it is important to include DC-DC converter as a second part after solar panel in the system to have more stable DC voltage level and then supply it to the inverter stage to produce desired AC power [5]. At first stage, The proposed photovoltaic system has a solar panel with nominal voltage 24 V, and the voltage 38 V at Maximum Power Point (MPP) of 200W. The next stage is DC-DC boost converter with constant output voltage during Maximum Power Point Tracking (MPPT). The DC-DC converter is followed by a closed loop modified Sinusoidal Pulse Width Modulation (SPWM) inverter, LCL filter, and finally a Step Up Transformer to deliver higher AC voltage to a connected load. On the other hand, the proposed standalone system uses a DC power supply that is designed to work with solar power input voltage in the range of (Vin = +15 V to +50 V). The designed power supply manipulates the low voltage levels or the voltage fluctuations that may occur in the case of low solar radiation, and produces an output voltage (Vout = +12 V, 0 V, -12V). Additional power cut protection part is added to the power supply circuit in order to work in the cases where the solar panel voltage is less than the limited lower level. The Multisim software was used to simulate all the stages included in the proposed standalone photovoltaic system, and all related simulation results are presented.

II. PROPOSED PHOTOVOLTAIC SYSTEM

The proposed system focuses on reducing or eliminating the fluctuation disadvantages in the DC output voltage level of connected solar panel. The design and simulation process takes into account the selected solar panel type photovoltaic module 4200J with the data of voltage and current at maximum power, open circuit, short circuit, and

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normal conditions. The proposed system is represented by four major parts, which are DC-DC converter, modified SPWM inverter, LCL filter, and DC power supply. The simulation results are recorded for a range of voltage variations that emulate the variation of the supplied voltage from the selected solar panel. Figure 1 shows the block diagram of the proposed system

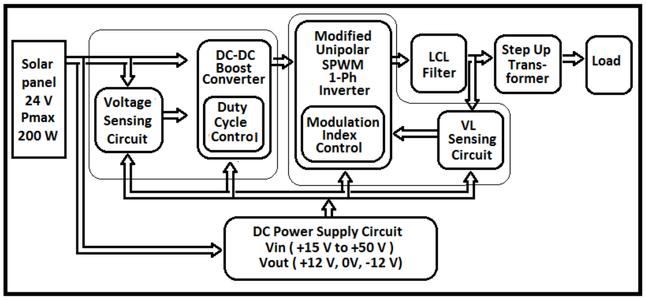


Fig. 1. Block diagram of the proposed standalone PV system

The design takes the variation of the solar radiation into account and finds suitable solution in order to produce a regulated and stable DC voltage using a DC-DC boost converter and MPPT algorithm. After DC-DC converter, the modified unipolar SPWM inverter regulates the variation in the load voltage and then delivers fixed voltage with higher power compared with traditional unipolar SPWM inverter. The LCL filter is selected to produce a load waveform which is very close to a pure sine wave after removing the higher order harmonics and reducing Total Harmonic Distribution (THD). The qualities of the DC-DC converter, PWM inverter, as well as the LCL filter are tested and proved through simulations. On the other side, it is advantages in standalone photovoltaic system to have a stable DC power supply. The regulated DC power supply uses unregulated DC supply such as solar panel and able to produce fixed required DC voltages to deliver all related electronic circuits without the need to battery in the photovoltaic system.

III. DC-DC BOOST CONVERTER

There are many types of DC-DC converters that are used to convert the unregulated input DC voltage to other desired regulated level, and the work in [6] shows a comparison of the converter types. Boost converter type is selected because of simple control during MPPT control technique. The basic DC-DC boost converter is shown in Fig. 2.

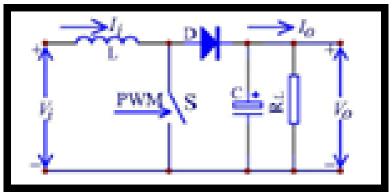


Fig. 2. Basic boost dc-dc converter

There two operating modes of boost converter: Continuous Conduction Mode (CCM) and Discontinuous Continuous Mode (DCM). If the converter works in CCM, the rate of on time to the total cycle time of drive pulse called Duty (D) cycle has relationship with input and output voltages of converter as explained in [9], [11] and given as:

$$V_o = \frac{1}{1-D}\, Vin \qquad (1)$$

where V_o is the output voltage of the boost converter, V_{in} is the input voltage, that assumes the case of standalone PV system. The input voltage here is the output voltage of solar PV panel, which will be represented as input voltage to the proposed converter, while D is the duty cycle or conducting ratio of the power electronic switch that is included in the converter.

The boundary condition for the converter to work in CCM is the connected inductance in the converter (L) which should be more than the condition value ($L > L_C$) [10] and given as :

$$L_C = \frac{R_L\, D\, (1-D)^2}{2f} \qquad (2)$$

where f is the switching frequency, R_L is the load resistance. If the converter is in CCM and L within large enough value, the output ripple voltage (V_{PP}) will be:

$$V_{PP} = \frac{Vo - Vin}{R_L\, Cf} \qquad (3)$$

The minimum value of the capacitor (C_{min}) can be determined by the desired output ripple voltage V_{PP} ,

$$C_{min} = \frac{Vo - Vin_{min}}{R_{Lmax}\, V_{pp} f} \qquad (4)$$

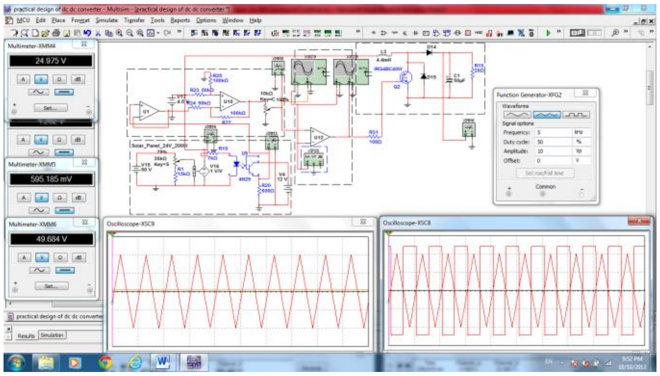
The designed values of the included inductor and capacitor in the boost dc-dc converter are calculated from (2) and (4) according to other desired related values, which are V_{in} = +15 to +50V, V_o = 50V, the output ripple voltage V_{pp} = 2% V_o , R_L = 10 Ω to 150 Ω, f = 5KHz. The minimum value of capacitance is 46.7 µF, the minimum condition inductance at R_L = 10 Ω and R_L = 150 Ω is 0.125 mH and 1.875 mH respectively. The selected values in the multisim simulation program are C = 50 µF, L = 4.4 mH.

On the other side, the MPPT controlling technique used with the converter is adopted after doing literature review for MPPT fundamental algorithms or methods as described in [7]. The selected MPPT method is the Constant Voltage (CV) method, which depends on the fact that MPP voltage at different irradiance is approximately equal to a common value 76% of the open circuit voltage of the PV panel [8].

$$V_{MPP} = k * V_{oc} \qquad (5)$$

where k ⊐ 0.76. The major advantage of this method is that the MPP may be located very quickly. From this point of view, the proposed DC-DC converter adopts tracking function during CV method to produce drive pulses for a connected power electronic switch in the boost converter. the process of controlling function is started by continuous sensing the output terminal voltage of solar panel to produce low level of DC voltage proportional to the actual voltage of the panel. Next the duty cycle controller represented by suitable differential operational amplifier is designed to produce suitable PWM drive pulses by comparing a certain range of DC level with a triangular carrier waveform. The PWM pulses will have variable pulse width or different on / off time periods inversely proportional with the instantaneous value of the terminal voltage of solar panel.

Fig. 3. shows the simulation of proposed design with simulated results at V_{in} = 24.975 V, R_L = 20 Ω, in this condition, V_0 = 49.684 V.



Multimeter-XMM4: 24.975 V

Multimeter-XMM5: 595.185 mV

Multimeter-XMM6: 49.684 V

Frequency: 5 kHz

Duty cycle: 50 %

Amplitude: 10 Vp

Offset: 0 V

Fig. 3. Simulation results of proposed converter by Multisim program

Figure 4. shows the response for two values of R_L = 20Ω, and full load R_L 10Ω. Fig. 5. explains the behavior of duty controller in the proposed boost converter to produce an instantaneous controlled duty cycle percent with respect to the unregulated DC level of solar PV panel.

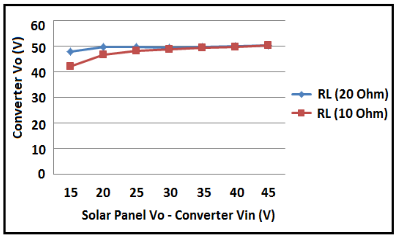


Fig. 4. Simulation results for two load values

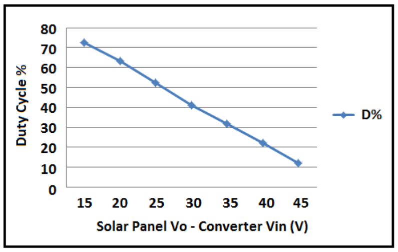


Fig. 5. Simulation results of duty cycle percent with respect to Solar Panel DC level

The above results indicate and prove the accuracy of design and simulation process with respect to the related theoretical relations. Fig. 4. Reflects the stability in the output voltage of the converter between full load and lower load values, while Fig. 5. shows linearity in the changing of duty cycle to produce PWM drive pulses with controlled conducting time.

IV. MODIFIED SPWM INVERTER & LCL FILTER

The inverter is a power electronic equipment used to invert the type of input direct current power (DC) to output alternating current power (AC). There are a different types of inverters used to produce AC waveforms with a different specifications according to the applied technique of switching pulses that will be used to drive the power electronic switches in the power stage of inverter. Fig. 6. shows the full H-Bridge configuration represented by four power transistor switches type Insulated Gate Bipolar Transistor (IGBT). [12], [13].

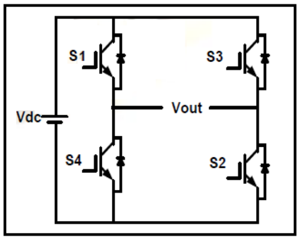


Fig. 6. Full H-Bridge

The output voltage levels can be obtained from full H-bridge that one of these levels , (+Vdc) when switched on S1 & S2, or (-Vdc) when switched on S3 &S4, while the level of Vout will be equal zero if all switches are switched off or when S2 & S4 switched on.

The output waveform is pure square wave if the applied switching between +Vdc and –Vdc, this means the output signal will have high levels of harmonics which lead to more losses in applied power as well as unexpected response with negative effect on the applied AC connected loads [14].

Pulse Width Modulation (PWM) is a type of modulation with different switching techniques developed to have many interests explained in [15] especially in minimizing the levels of harmonics distributions and linear modulation control range, Fig. 7. Explains how the PWM pulses produced by comparing fundamental reference waveform r(t) which have lower frequency while other waveform is a carrier signal (triangular or saw tooth) c(t) with high frequency, the resultant pulse have carrier signal frequency with width or duty cycle related to the instantaneous value of fundamental signal.

The binary PWM output $b_{pwm}(t)$ is explained in (6)

$$b_{pwm}(t) = \mathrm{sgn}\,[r(t) - c(t)] \qquad (6)$$

where "sgn" is the sign function [16], the reference signal r(t) can include DC and a single frequency sinusoidal component that is to maximize the AC voltage that can be produced from the available DC voltage source [17], r(t) can be represented by (7)

$$r(t) = R_0 + R_1 \cos(2\pi f_1 t + \theta_1) \quad (7)$$

where R_0 is a DC component in r(t), R_1 is an amplitude of r(t), f_1 is a reference frequency, and θ_1 is a phase shift of fundamental signal r(t).

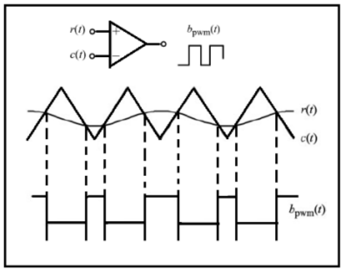


Fig. 7. PWM pluses implementation

There are multi levels of PWM starting from two levels that in which the type name is bipolar PWM, while in three level the name is unipolar PWM , and the other levels are higher from three. In case of unipolar PWM switching the pulses will have twice carrier frequency value compared with bipolar PWM, in other meaning unipolar type have less harmonics distribution and this will lead to the output filter can be smaller in values and size of filter components because the main factor in filter design or function are included components (inductors and capacitors) values [18], [19].

In unipolar PWM, carrier signal c(t) changes between 0 and positive peak, the reference is always positive [16]. There are two important factors that have direct effect on the shape and duty cycle of the produced PWM pulses. These factors are Modulation Index (MI) and Frequency Ratio (FR). MI is the ratio of reference signal amplitude to the carrier signal amplitude, while FR is the ratio of carrier frequency (f_c) to the reference frequency (f_1) as given in (8), FR is a fixed value in the SPWM.

$$FR = f_c / f_1 \quad (8)$$

The proposed modified SPWM single phase Voltage Source Inverter (VSI) adopts unipolar PWM technique and takes into account more interests by focusing on three important points in the design and simulation compared with traditional SPWM. Firstly, the inverter works to stabilize the AC load voltage after LCL filter a closed loop control system. The control starts by sensing the load voltage and then control the instantaneous value of MI inversely with measured AC load voltage which in turn affected by the value of connected load and the value of DC level of voltage supplied to the inverter H-bridge. Secondly, the shape of the reference sine wave is modified by addition of a certain DC level to increase the output power [17]. Thirdly, the design presents protection “switch off pulses” that are produced by full wave rectifier and zero crossing detection circuit, these circuits produce controlled width zero crossing pulses which used to protect the four connected switches in H-bridge. Figure 8. shows the block diagram of proposed unipolar single phase modified SPWM Voltage Source Inverter.

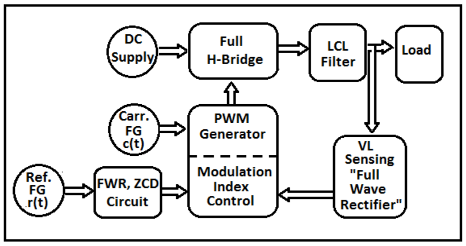


Fig. 8. Block diagram of the proposed SPWM inverter

Fig. 9. Shows the simulation resultant waveforms of FWR signal, and small and big widths of ZCD pulses.

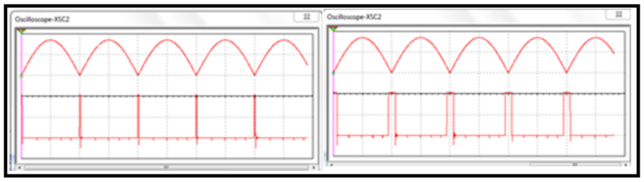


Fig. 9. Simulation results of FWR and ZCD circuits

The simulation below shows the steps of traditional SPWM for comparing with the modified SPWM, Fig. 10. show the steps of PWM pulses generation at triangular wave carrier frequency of 1KHz. The generated PWM pulses are used to drive the power electronic switches of the H-bridge circuit supplied by 50V DC supply. The AC load signal is generated by traditional SPWM technique at modulation index MI =0.85 and frequency ratio FR=20, whereas the FR in the proposed SPWM inverter is FR= 40, and the modulation index is variable with controlled range from MI=0.7 to MI=1.

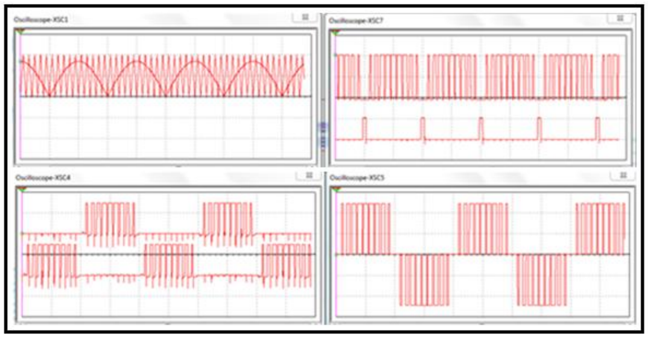


Fig. 10. Simulation steps of traditional SPWM inverter at carrier 1KHz

The output filter is necessary between the output of inverter and the AC load in order to reduce or eliminate the negative effects of unwanted higher order harmonics. The basic filter topologies are discussed in [20], [21].

In our work, the LCL filter is design for a resonant frequency of f_{res} = 800Hz taking into account the attenuation of the LCL filter is 60dB/decade for the frequencies above resonant frequency. The cut-off frequency of the filter must be minimally 10 times greater than reference frequency (50 Hz)and simultaneously maximally one half of the switching frequency (2 KHz) [20]. Based on the resonant frequency f_{res} = 800Hz, the used values of the LCL filter components are L_1 = 12 mH, L_2 = 6 mH, and C = 10 µF.

The conventional calculation relationship of Total Harmonics Distribution (THD) is defined as [22]:

$$\mathrm{THD} = \frac{\sqrt{V2^2 + V3^2 + \ldots\ldots + Vn^2}}{V1} \qquad (9)$$

where V_1 is the fundamental frequency content and V_2, V_3, …., V_n are the harmonics contents. Fig. 11. shows the simulation results of traditional SPWM output AC waveforms before and after LCL filter at FR =40, MI =0.85, Vdc input =50V the AC output voltage after filter =24.489V, THD =6.839%, Vcontrol =0V.

The proposed SPWM inverter adopts closed loop controlled function for fixed load to inversely control the value of MI starting from 0.7 at input dc voltage 70V while MI reach to 1 when input dc voltage 40V to have AC output voltage with stability and value around 27.5V ±1%. from other side the controller add a suitable dc level to the fundamental FWR wave. Fig. 12. show the results of the output AC load voltage of the inverter at Vdc =50V.

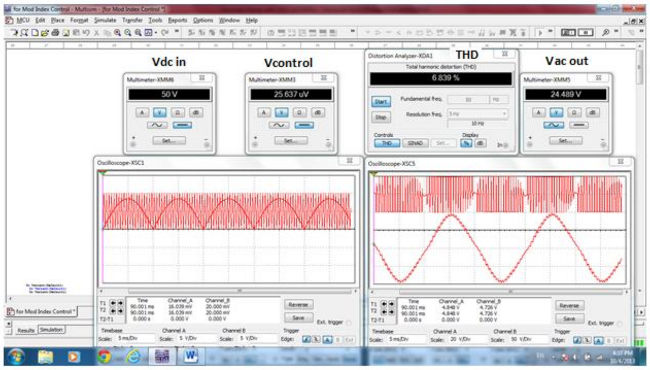


Fig. 11. Results of traditional SPWM inverter and LCL filter out at Vdc= 50 V, MI= 0.85, FR =40, Vac= 24.5V, THD =6.84%, Vcontrol= (0V)

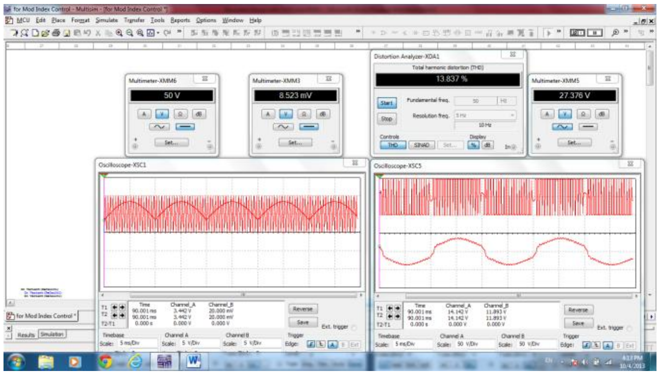


Fig. 12. Results of proposed SPWM inverter and LCL filter out at Vdc= 50V, MI =0.85, FR= 40, Vac= 27.376V, THD= 13.837, Vcontrol 8.5mV

Figure 13. shows comparison between behavior of the proposed SPWM inverter and behavior of the traditional SPWM for range of input DC supply voltage when the load resistance R_L = 50 Ω.

Figure 14. show the instantaneous values of closed loop controlled voltage level of the proposed MI controller compare with 0V or no control voltage in traditional SPWM.

The simulation results of Fig. 13. to Fig. 14. indicate the high level of stability in the output voltage of AC load connected to the proposed inverter compared with the low level of stability in the traditional inverter.

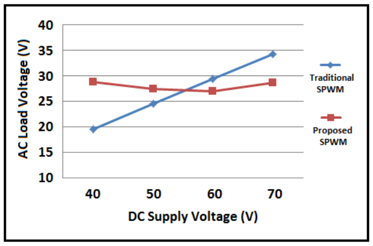


Fig. 13. Comparison between output voltages of traditional SPWM inverter and proposed SPWM inverter

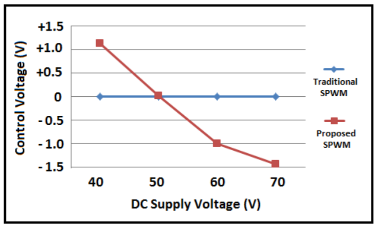


Fig. 14. Comparison between traditional SPWM inverter and proposed SPWM inverter during the value of control voltage.

V. DC POWER SUPPLY

The design considers high importance to include power supply depend on the connected solar panel to produce all required DC voltages. Chopper circuit, voltage regulators types 7812, and 7912, and Zener diodes with V_Z = 7.5V, and V_Z = 15V are play a main role in the design . Reference [23] works with the same field. The supply works with input voltage +15V to +50V. The comparator circuit activate the relay to conduct the supply to all PV system circuits during this voltage range and reset the relay at input voltage less than +15V. Fig. 15. shows the block diagram of the power supply. Fig. 16. shows the measurements inside supply circuit at input voltages Vin = 25V, 15.3V, 14.7V. Fig. 17. indicate the stability during input range.

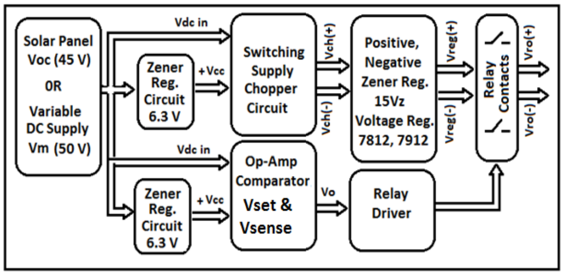
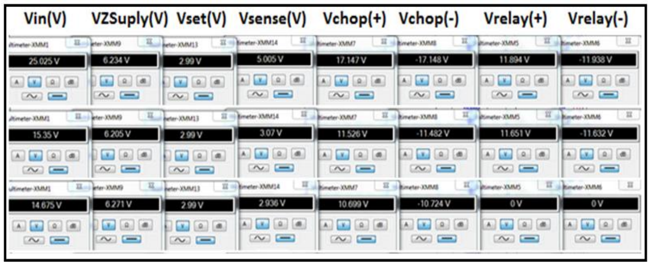


Fig. 15. Block diagram of the proposed power supply



Vin(V)	VZSuply(V)	Vset(V)	Vsense(V)	Vchop(+)	Vchop(-)	Vrelay(+)	Vrelay(-)
25.025 V	6.234 V	2.99 V	5.005 V	17.147 V	-17.148 V	11.894 V	-11.938 V
15.35 V	6.205 V	2.99 V	3.07 V	11.526 V	-11.482 V	11.651 V	-11.632 V
14.675 V	6.271 V	2.99 V	2.936 V	10.699 V	-10.724 V	0 V	0 V

Fig. 16. Simulation results of the proposed power supply

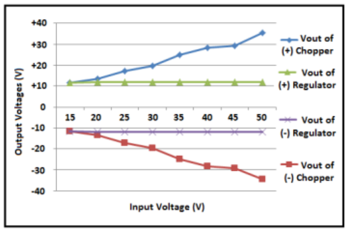


Fig. 17. The behavior of the DC supply

VI. CONCLUSION

This work investigated a standalone photovoltaic system based on discrete components and special design for boost DC-DC converter with suitable MPPT algorithm, modified SPWM inverter and DC-power supply. There is high degree of stability in various stages of the system and more importantly in the output of the AC load voltage with respect to the wide variation of the input DC supply voltage compared with the traditional SPWM technique. The value of the output voltage of the LCL filter to be delivered to the AC load is around 27.3V±1% while the variation of the input DC supply voltage of the inverter is between Vdc =40 V to Vdc=70V by modulation index controlling in the range of MI=0.7 to MI=1. In the same condition of input DC supply variation to the traditional inverter, the output voltage of the LCL filter changes between 19 to 35V showing a high degree of instability. The simulation result of the DC-DC boost converter reflect high stability in the values of its dc power with respect to the variation in its input, which is emulated as the output of PV module (4200J). The results of the proposed DC power supply electronic circuit show a high satisfactory output voltage levels (+12V, 0V, -12V) for wide range variations of input Vin=+15V to +50V.

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