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Two-Stage Inverter Based on Combination of High Gain DC-DC Converter and Five-Level Inverter for PV-Battery Energy Conversion

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Abstract- *This paper proposes a new two-stage inverter based on transformer-less high gain DC-DC converter for energy conversion of a photovoltaic system. The designed system consists of a high gain DC-DC converter cascaded with a three-phase inverter. The proposed DC-DC converter has a simple structure, and it has one switch in its structure. The output voltage of the DC-DC converter supplies DC source for the inverter part of the multi-stage inverter. The advanced two-stage inverter sample was fabricated, then the findings of the acquired simulation and hardware warranted the configuration applicability. Finally, the MATLAB/SIMULINK is employed for the simulation of PV-battery system. The obtained results revel that the proposed power conversion system effectively chases the load and generation fluctuations and also properly handles the power mismatches in PV-battery system.*

Keyword: Renewable energy, Two-stage inverter, DC-DC converter, Multilevel inverter.

1. INTRODUCTION

Nowadays, the use of renewable power and green sources are gaining attention. Photovoltaic (PV) systems and fuel cell (FC) are new sources of energy that generate DC voltage [1, 2] among which photovoltaic energy systems are well developed and frequently applied. These energy systems may be operated as an isolated system (standalone) or grid connected. DC-AC inverters are power electronic devices used to produce mains voltage AC power from DC sources (from an output of the rectifier, battery, PV or FC). The inverters may be categorized as single or multi-stages inverter [3-5]. For the energy conversion, the typical converter is according to the multi-stage converter and specially two-stage one. The two-stage arrangement is chiefly employed since of its interests of comfortable control as current injection and maximum power point tracking (MPPT) control [4-7]. For example, in the PV system the first level is a DC–DC boost chopper responsible for taking out the MPPT and enhancing the PV voltage to a special amount (larger than the grid voltage top).

The second step is an inverter that injects current into the grid or generates a voltage to supply charges. The DC voltage is produced by photovoltaic modules which includes a low value. These low DC values are not proper to be employed only to generate the required AC voltage. Rising the DC-AC conversion gain rate by raising the DC-DC conversion gain rate is one solution to overcome the challenge. Various topologies have been proposed to describe this solution. The direct solution is to utilize a transformer [7, 8]. This transformer may be a low or high-frequency transformer. The transformers may be having the regarding problems [9]: High cost, high losses, large volume and high failure rate in comparison to converters. On the other side, transformer fewer topologies introduce topologies regarding maximum weight, volume, and efficiency. Transformer-less DC–DC structures are more effective, low weight , being lighter, and lower cost compared to utilized transformer configurations [5, 10, 11]. In [12], the voltage gain recorded is five times the input DC one by combining boost converter and extensive bridge inverter. In [13], multi-stage boost converter proposed as a resolution for enormous conversion ratio. This circuit requires many components resulting in less reliability, overall system complexity, and high expense, particularly for small energy demands.

Multilevel inverters are one of the power electronic devices which can be considered as voltage synthesizers that can be used in multi-stage inverter. There are several types of multilevel inverters. One of the important problems in multilevel inverters is the number of components that plays important roles on the cost and realization of the inverter. In recent years, many topologies are suggested to multilevel converter with a low number of switches, gate driver circuits and DC voltage sources. Recently cascaded transformer multilevel topology is proposed [14]. This has the advantage of having single storage capacitor or DC

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voltage source. This topology has transformers in its structure. The transformers in its structure can be used to isolation and voltage transformation.

In this paper, the analyzed hybrid system is a combination of battery and photovoltaic subsystems. The important issue of this study is to ensure the safe energy supply of the ac loads during transient load and variable air/irradiation conditions. In one respect, dc-link of inverter can be fed by Photovoltaic (PV) and battery with variable DC voltage at their output terminals. Hence, a boost converter must be connected at the output of these PVs so that the required DC voltage for feeding the inverter part. In this research, a multi-stage inverter configuration is developed according to latest transformer less peak gain DC-DC converter. This paper introduces a novel DC-DC converter that can provide high step-up voltage gain and low input current ripple. This converter has single controllable semiconductor switch. This switched has acted so that converter has operated in the continuous mode, and accordingly that its output is connected to the Multi-Level Inverter (MLI) part. In the DC-AC part of the multi-stage converter, one five-level multilevel inverter is used. Multilevel inverters have functionally operated to synthesize an appropriate output voltage through a number of DC voltage levels as inputs. As a result, high number of voltage levels let the multilevel inverter to render a high quality voltage. Aside from the beneficial advantages of multilevel inverters, the most important disadvantage of them is entailing the great number of semiconductor switches that consequently will bring such repercussions: complexity of circuit along with its relevant control strategy, increase of cost price, decrease of reliability, and maintenance of structure. In this paper, a neoteric cascaded transformer multilevel inverter is suggested so that a quasi-sinusoidal voltage with fewer harmonics against the reduced number components to be acquired. According to this fact, an energy conditioner model, made by a DC-DC and a DC-AC energy converter, has been created and a simple control procedure has been executed to approve the operation.

2. TWO-STAGE DC/AC CONVERTER

The proposed two-stage inverter is illustrated in Fig. 1. The developed system contains novel DC-DC converter cascaded with a 5-level multilevel inverter. The proposed DC-DC converter is called double inductor double boost converter (DIDB). The DIDB has high-voltage gain benefits. The DIDB includes two coils, two capacitors, five diodes and one switch with the shown arrangement in Fig. 1. The second stage of proposed converter is one five-level multilevel inverter. The five-level inverter not just picks benefits of both initial flying capacitor and cascade H-bridge, additionally reduces the number of DC sources, capacitors, and switching devices in comparison with conventional multilevel converters. Fig. 1 shows single phase converter. The common dc bus technique is used to collect the total energy from the battery and photovoltaic subsystems and uses to supply the loads via a single phase or three phase inverter and to charge the battery bank sometime with the energy in excess.

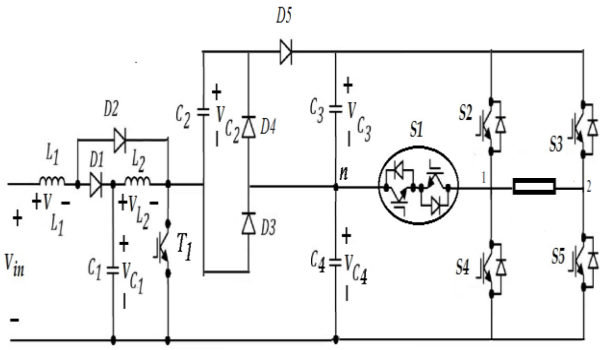


Fig. 1. Proposed multi-stage inverter.

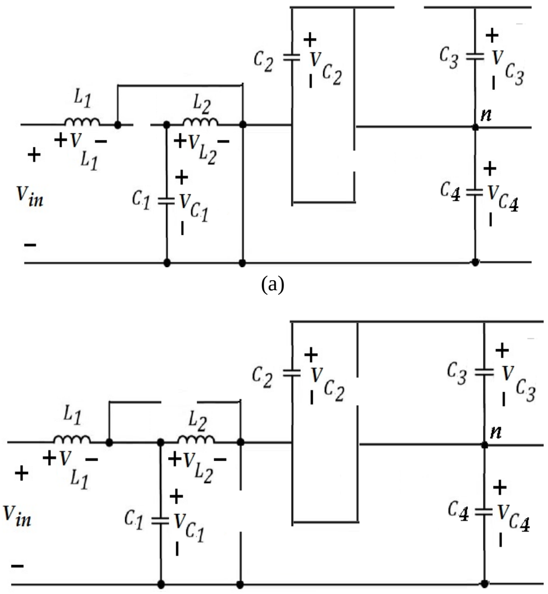
2.1. Operation and Investigation of the DC-DC Converter

Operation of the presented DC–DC converter is the same as conventional DC–DC boost converter. The presented converter is called DIDB. This converter has two operation status because it has one controllable switch. In the DIDB the deduced voltage is controlled by duty cycle of T_1 switch. T_1 switch has two states and by notice to switching state of T_1 switch, DIDB modes of operations are described as two modes. Fig. 2 shows two modes of DC–DC boost converter.
Further, to clarify this investigation, the DIDB will be examined considering a purely resistive load R is connected to its terminus alternatively and the resistance of semiconductors, inductors, and capacitors are neglected.

If t_{on}, T, and f_S are the on switch time, switching period and frequency respectively. The duty cycle is:

$$K = \frac{t_{0n}}{T} = t_{0n}.f_S \quad (1)$$

First mode: Happens while the switch T1 is ON, this results in diode D2 and D4 to be shifted to ON status and diodes D1 and D3 to be changed to OFF status. Thus the L2 inductor and C1 capacitor are parallel, and the L1 inductor and DC voltage source are parallel. In this mode inductors are charged. Fig. 2(a) shows the mode 1 DIDB circuit.



(a)

(b)

Fig. 2. Modes of DC-DC boost converter (a) mode 1 and (b) mode 2.

Over the mode 1, the voltages across the inductors are:

$$V_{L1} = V_{in} \quad (2)$$

$$V_{L2} = V_{C1} \quad (3)$$

$$V_{C2} = V_{C4} \quad (4)$$

Second mode: Happens while the switch T_1 is OFF, this results in diode D_1, D_3 and D_5 to be shifted to ON status and diodes D_2 and D_4 to be changed to OFF status. Fig. 2(b) represents the mode 2 DIDB circuit. Through mode 2, the voltages across the inductors are:

$$V_{L1} = V_{in} - V_{C1} \quad (5)$$

$$V_{L2} = V_{C1} - V_{C4} \quad (6)$$

By notice the Eqs. (1) - (5), the zero average inductors voltages over one carrier cycle are:

$$\overline{V_{L1}} = 0 = KV_{in} + (1-K)(V_{in} - V_{C1}) \Rightarrow \\ V_{in} = (1-K)V_{C1} \quad (7)$$

$$\overline{V_{L2}} = 0 = KV_{C1} + (1-K)(V_{C1} - V_{C4}) \Rightarrow \\ V_{C1} = (1-K)V_{C4} \quad (8)$$

By replacing Eq. (7) in Eq. (8):

$$V_{C4} = \frac{1}{(1-K)^2} V_{in} \quad (9)$$

In steady state, the voltages of output capacitors are equal ($V_{C3}=V_{C4}$) then the output voltage of DIDB is given as:

$$V_O = V_{C3} + V_{C4} = 2V_{C4} \quad (10)$$

$$V_O = \frac{2}{(1-K)^2} V_{in} \quad (11)$$

Fig. 3 shows the voltage gain for different duty ratio. As shown in Fig. 3, DIDB has high gain and can be used in photovoltaic systems to step up the voltage of PV panels. It is one of the advantages of DIDB.

Using semiconductors with low voltage stress is other advantage of DIDB. A main issue in power electronic converters is the ratings of semiconductors. On the other hand, voltage rating of the semiconductors in a converter play a critical role on the expense and achievement. The voltage stresses on semiconductor are given as:

$$VS_{T1} = VS_{D3} = VS_{D4} = \frac{V_O}{2} \quad (12)$$

$$VS_{D1} = \frac{(1-K)V_O}{2} \quad (13)$$

$$VS_{D2} = \frac{KV_O}{2} \quad (14)$$

Having input current with low ripple is one advantage in classic boost DC-DC converter. The ripple of input current in DIDB is the same as classic boost DC-DC converter.

The voltages across L1 and L2 in mode one have been given in Eq. (2) and Eq. (3). Thus, L1, L2, and ripple of currents can be calculated by

$$V_{L1} = V_{in} = \frac{\Delta I_{L1}}{\Delta t} L_1 = \frac{\Delta I_{L1} f_S}{K} L_1 \Rightarrow \\ \Delta I_{L1} = \frac{K}{f_S L_1} V_{in} \quad (15)$$

$$V_{L2} = V_{C1} = \frac{\Delta I_{L2}}{\Delta t} L_2 = \frac{1}{(1-K)} V_{in} \Rightarrow \\ \Delta I_{L2} = \frac{K}{f_S (1-K) L_2} V_{in} \quad (16)$$

To confirm the above mentioned accuracy of analyses, it would be ideal to generate a simulation model. The circuit parameters are given in Table 1. Signal duty cycle of 50% is applied over power switch T1. The output voltage is approximately 400 V. Fig. 4 shows operation of DIDB converter.

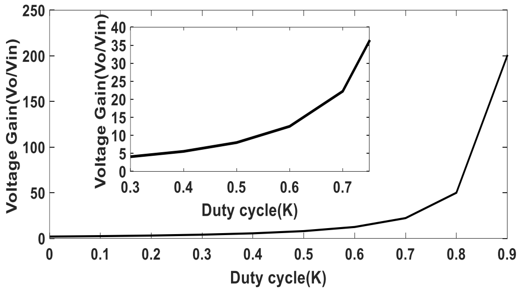


Fig. 3. Voltage gain for different duty ratio.

Table 1: Parameters.

DC source	50 V
L_1 and L_2	500 µH
C_1, C_2 , C_3 and C_4	100 µF
Switching frequency	25 KHz
K	0.5
Load	1200 W

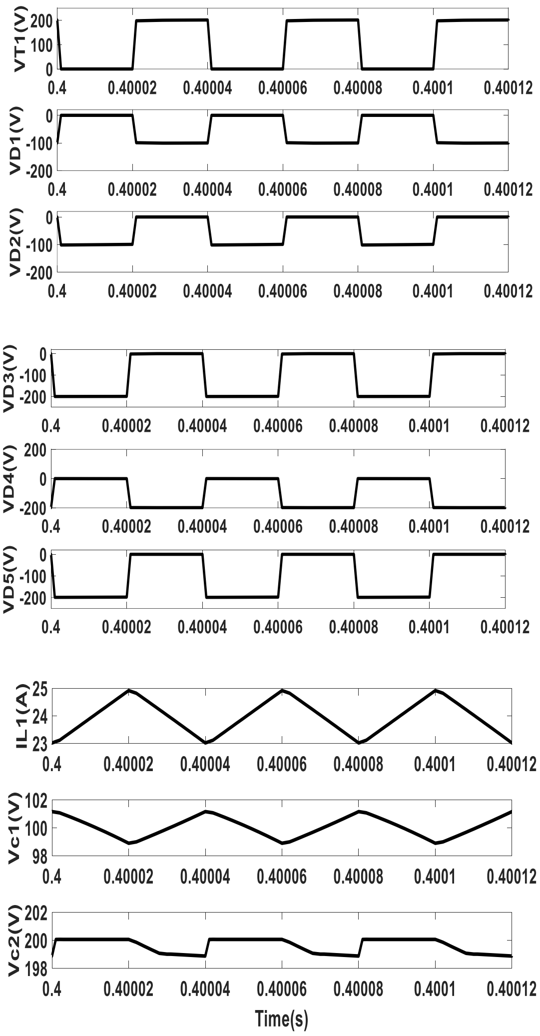


Fig. 4: Operation of DIDB converter.

The voltage of semiconductors (V_{T1}, V_{D1}, V_{D2}, V_{D3}, V_{D4} and V_{D5}) is depicted in Fig. 4 that proves Eqs. (12) - (14). Also, Fig. 4 shows the voltage of C_1 and current of L_1.

The charge and discharge of capacitor and inductor have been visible.

$$V_o = \frac{2*50}{(1-0.5)^2} = 400 \tag{17}$$

As can be seen in Fig. 5 comparison has been performed among the gain of the proposed converter, conventional cascaded boost converter and novel converter of [32] in ideal case. It is obvious that the gain of the proposed converter is higher than the conventional boost converter by a factor of two.

The control of DIDB converter depends on MPPT technique. According to load matching theory, maximum power is being conveyed from PV module to load when PV source impedance is equal to the load impedance. The MPPT can be done by adapting the duty cycle (K) of the DIDB. With varying air and sun conditions, the duty cycle has to be adjusted to obtain the highest energy from PV module. In this paper, the conventional incremental conductance method (INC) is adopted for MPPT procedure. This technique is extensively employed in the MPPT controllers since their simplicity and simple implementation.

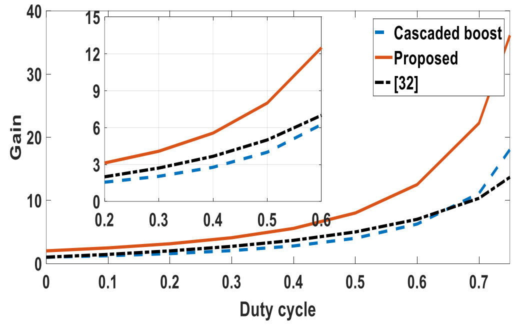


Fig. 5. gain comparison of the proposed converter, conventional cascaded boost converter and novel converter of [32].

2.2. Operation and analysis of five-level inverter

Multilevel converters have some distinct drawbacks. They require a lot of semiconductor switches, and each one needs a compatible gate driver and security circuit. Some of them require various separate capacitors or DC sources. These provisions raise the price and complexity and lead to decrease safety and security. Different topologies with decreased number of switches, DC voltage sources and capacitors have been suggested in recent years to overcome limitations above [14-17]. In this research, the 5-level inverter is used as second part of the two-stage converter. Using cascaded transformer technique is presented in this part to eliminate needing to different DC sources in different phases. The circuit diagram of the five-level inverter is illustrated in Fig. 6.

It involves two level capacitor voltage divider, five switches in each phase, and one DC voltage source. The required five voltage output levels are produced as Table 2. The performance of this five-level inverter can be classified into five states. Figure 7 shows modulation waveforms. As shown in Fig. 7, the triangular waveforms are carriers and the reference waveform is sin wave. Triangular waveforms have the same amplitude and frequency but the positive triangular waveforms have 180degree phase difference with negative triangular waveforms. This aids us to generate symmetric output voltage. The sin reference wave defines output voltage frequency. At each instant, the result of the comparison is used to generate the proper switching function to give suitable output voltage level. The power electronic switches of the inverter are turned in low frequency.

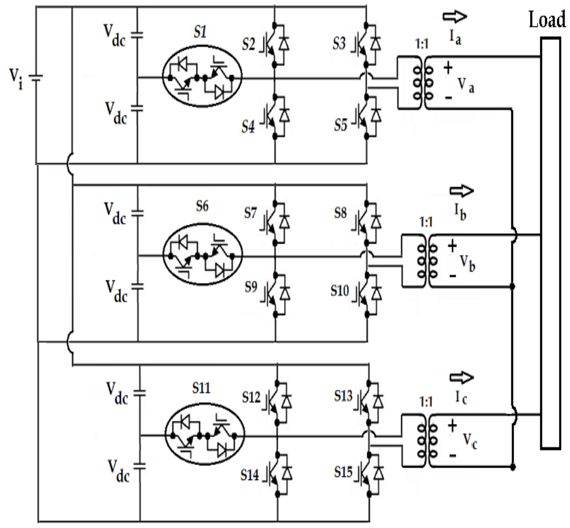


Fig. 6: Five-level inverter.

As the dc capacitor voltages are adjusted by regulating the five-level inverter, the DC capacitor voltages can be designated as follows:

$$V_{C3} = V_{C4} = \frac{V_O}{2} = V_{dc} \tag{18}$$

The five-level topology provides a meaningful decrease of semiconductor tools and capacitors needed to perform a multilevel inverter.

Table 2: Look-up table for the five-level inverter.

On Switches	V_a
S_2, S_3 or S_4, S_5	0
S_1, S_5	V_{dc}
S_2, S_5	$2V_{dc}$
S_1, S_3	$-V_{dc}$
S_3, S_4	$-2V_{dc}$

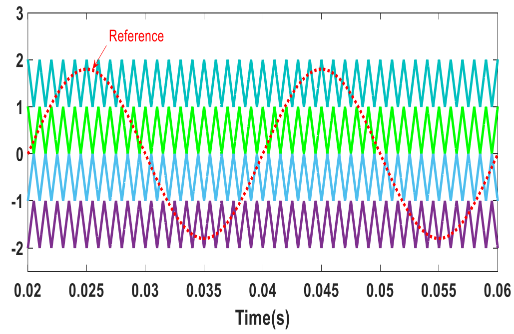


Fig. 7. Modulation waveforms.

3. APPLICATION IN PV SYSTEM

The distributed generation (DG) methods can be attached to the energy grid, or they can likewise be run separated from the central grid [15-20]. The proposed structure can be used in DG systems. At isolated from the main grid mode, voltage control method is used. To enhance reliability, the battery storage system is employed parallel with the PV system.

In DIDB, MPPT controller controls converter and obtained the highest energy from PV systems. The voltage control approach for DIDB and five-level converters are shown in Fig. 8 in isolated from the main grid mode [13,15]. The output voltage from the solar panel varies in different range. In order to obtain a stable output voltage, we have to design a closed-loop control. The battery charge controller creates constant DC-link. In the five-level inverter, inverter output voltage (Vabc) is measured and converted to d-q structure utilizing Park transformation [29-31]. Results are examined with evidence values (Vdref=1, Vqref=0), the error signal is transferred within controllers and repeatedly converted to abc structure by Park inverse-transformation. The voltage at set point (load voltage) has been sensed and transformed into d-q component with respect to the Park transformations. As for these transformations, the zero-sequence component to be pulled apart of the abc references. Provided absence of the zero-sequence component, the d–q components have been appropriately controlled. Because of the probability of various disturbances in the power system, it is presumed that three-phase input voltage of the PLL is unbalanced and harmonically contorted. The multilevel sinusoidal pulse width modulation (MSPWM) technique is a popular method to implement DC/AC inversion technology. Ultimately, the reference voltage is employed to modulation unit to generate switching signals. In order to produce the three-phase AC voltage to synchronize to the main grid voltage, we take the grid signals as the control signal. Battery creates constant DC-link almost. When the power of PV is bigger than the power of load, the battery absorbs exceed the power, and when the power of PV is lower than the power of load, the battery injects required power. In order to survey the performance of the controller, the main outputs of case study are illustrated in simulation part.

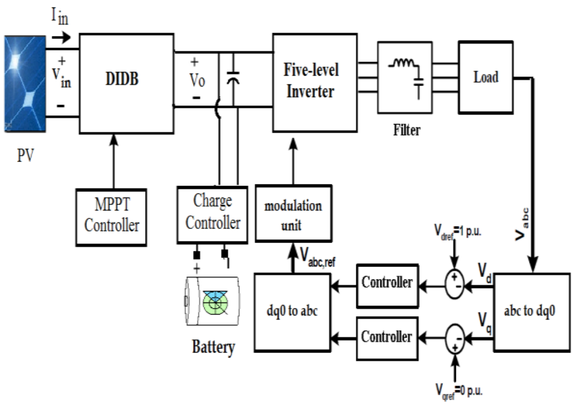


Fig. 7. Presented topology with additional switched inductor cells.

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1. Simulation findings

Some cases simulated by using MATLAB/SIMULINK software to reveal the operation of the developed converter. The PV used in this study consists of 6 module configured as one string of six modules each. The SUNPOWER SPR-305-WHT photovoltaic modules are used as PV source in the case study in these simulation. The I-V characteristic curve of the SUNPOWER SPR-305-WHT module is shown in Fig. 9. Its main electrical specifications data of PV module are illustrated in Table 3. Table 4 presents the parameters of a simulation study. The hybrid energy (PV-Battery) system is supposed to provide fixed 1200W power for the connected AC load at unity power factor despite photovoltaic and weather variations. Some elected simulation outcomes have been determined to prove the performance of the advanced system. Fig. 10(a) shows temperature and irradiance. The PV array power (P_{PV}) is changed by changing of irradiance and temperature.

The PV array outputs; power and voltage are illustrated in Fig. 10(b) and (c). The PV array voltage is less than DC bus, so the DIDB boosts PV voltage.

The DIDB boosts PV voltage and extracts maximum power from PV array. According to PV array character and electrical data in Fig. 9, the maximum power of PV array in 1000 and 500 (W/m2) irradiance are 1830 and 900 W in STC condition. Fig. 10(b) verifies extracting maximum power from PV array.

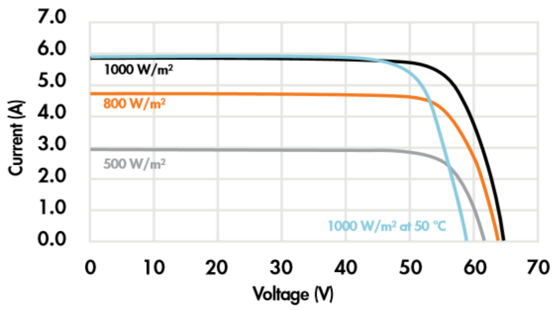


Fig. 9: IV curve specification of PV module (Current/voltage characteristics with dependence on irradiance and module temperature).

Table 3: Electrical data(Measured at Standard Test Conditions (STC): irradiance of 1000/m2, air mass 1.5 g, and cell temperature 25° C).

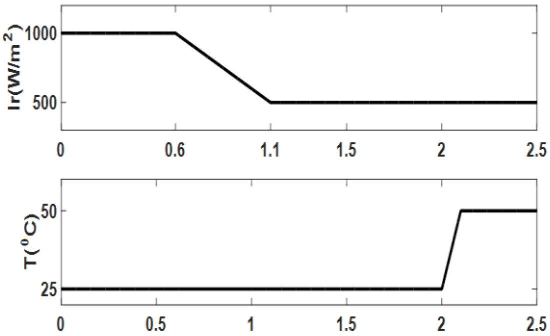
Parameters		values
Peak Power (+/-5%)	Pmax	305 W
Rated Voltage	Vmp	54.7 V
Open Circuit Voltage	Voc	64.2 V
Rated Current	Imp	5.58 A
Short Circuit Current	Isc	5.96 A
Maximum System Voltage	IEC, UL	1000 V, 600 V
Temperature Coefficients		
	Power	–0.38% / °C
	Voltage (Voc)	–176.6 mV/°C
	Current (Isc)	3.5 mA/°C
Series Fuse Rating		15 A
Peak Power per Unit Area		187 W/m², 17.4 W/ft²
CEC PTC Rating		282.1 W

Figure 11 shows power exchange of proposed system. When the power of PV is bigger than the power of load, the remaining power is injected to the battery. When the power of PV is smaller than power of load, the required power is provided from the battery. The current and voltage of load are depicted in Fig. 12.

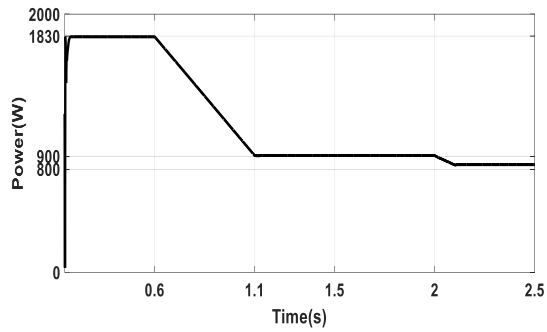
Table 4: Simulation parameters.

Parameters	values
DC bus voltage	400 V
Battery voltage	96 V
L_1, L_2	500 µH
DIDB switching frequency	25 KHz
C_1, C_2, C_3, C_4	100 µF
Inverter switching frequency	1000 Hz
Filter(L_f, C_f)	1 mH,100 µF
Load	380 V, 50 Hz,1200 W

Figure 13 illustrates the load voltage without a filter for one phase. As depicted in Fig. 13, the voltage of load has five levels. There are various modulation procedures for multilevel inverters. In this research, the SPWM switching approach is employed.



(a)



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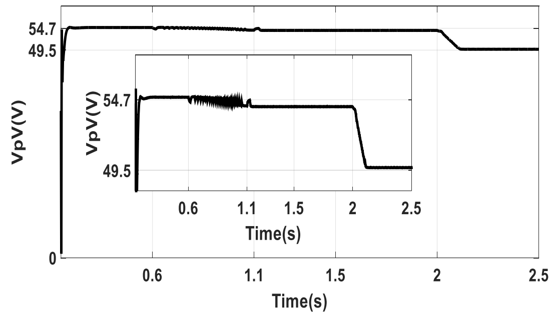


(c)

Fig. 10: Some selected simulation results (a) irradiance and temperature (b) power of PV (c) PV array voltage.

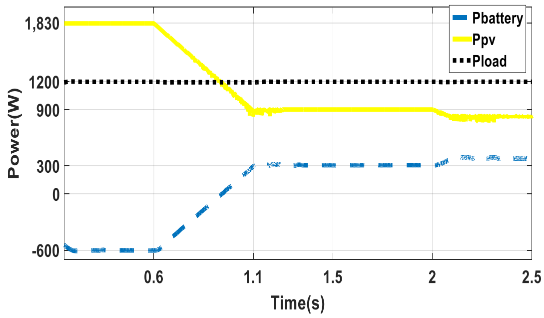


Fig. 11: Power exchange of proposed system.

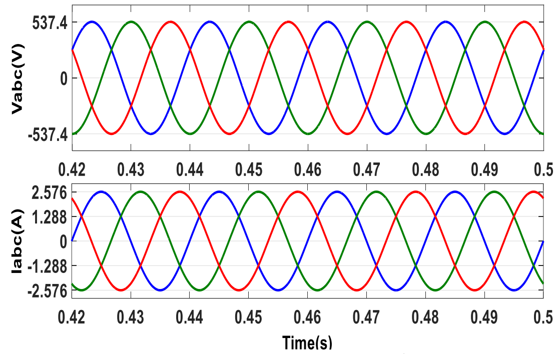


Fig. 12: The voltage and current of the load.

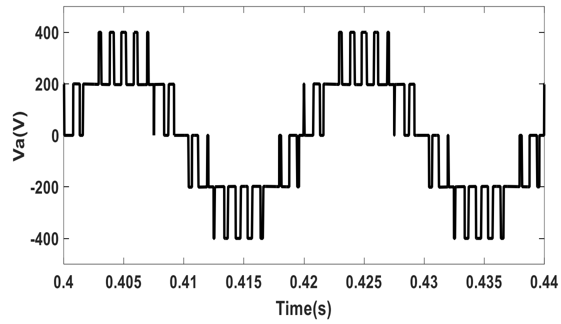


Fig. 13: Load voltage without a filter.

4.2. Experimental results

A model is executed according to the suggested topology based on what is shown in Fig. 1, to evaluate the operation of the suggested converter in the production of an intended output voltage waveform. The DIDB generate DC voltage that is required for the inverter. The specifications of the DIDB circuit are given in Table 5. The load is resistive with a value of 400 Ω. In this study, the input voltage of the inverter is 240 V. In this part, the main frequency switching approach has been employed [24, 25]. The data acquisition ATMEGA32 is utilized to execute inverter controller, and the opt-coupler TLP250 is applied to drive switches. Each unidirectional switch in the recommended topology is formed of one IGBT H25R1202. Fig. 15 represents a prototype circuit.

Figure 15(b) shows output voltage of DIDB. Figure 16 depicts the voltage of semiconductors in DIDB. The voltage of main switches (T1) is shown in Fig. 16(a). The voltage of D3 is the same as T1. Comparison between Fig. 15(b) and Fig. 16(a) results that the voltage stress of T1 and D3 is half of output voltage and verifies Eq. (12). The voltage stress of D4 and D5 are the same as T1. Fig. 16(b) shows the voltage of D1 that verifies Eq. (13). The inverter is shown in Fig. 1 is a 5-level multilevel inverter and can produce staircase waveform with the peak 240 V on-phase output. Fig. 17 depicts the measured output voltage waveform. In this study, fundamental switching strategy was used [25-30].

Here $\theta_1 = 18$ and $\theta_2 = 45$. As it can be observed, the consequences prove the efficacy of suggested inverter in the production of intended output voltage waveform.

Table 5. DIDB parameters

Parameters	values
V_{in}	30 V
L_1, L_2	500 µH
DIDB switching frequency	20 KHz
C_1, C_2, C_3, C_4	100 µF
switch	IGBT H25R1202
Diode	UF5404

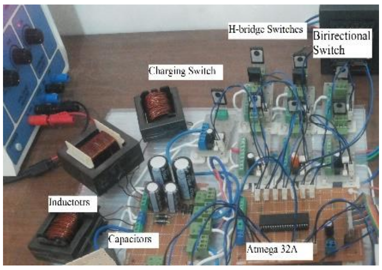
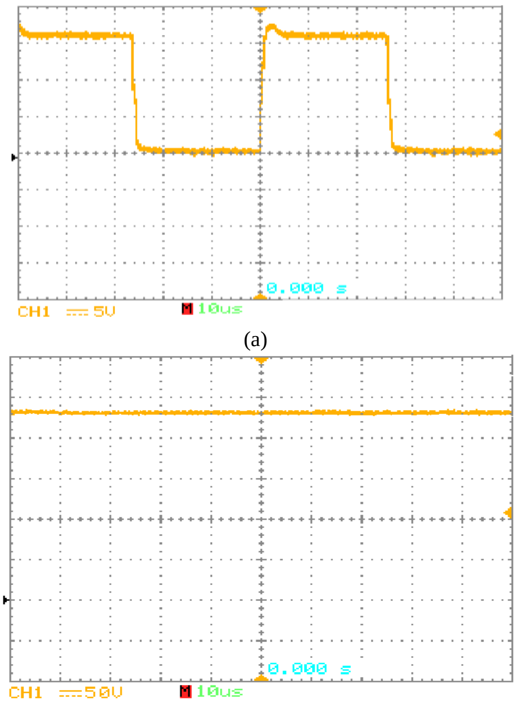


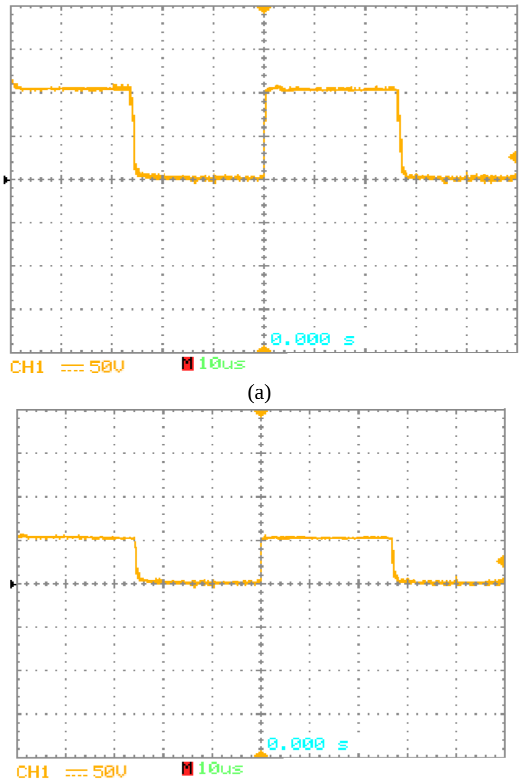
Fig. 14. Circuit of prototype.



(a)

(b)

Fig. 15. Measured output waveform of DIDB (a) gate pulse (b) output voltage.



(a)

(b)

Fig. 16. The voltage of semiconductors in DIDB (a) voltage of T1 (b) voltage of D1.

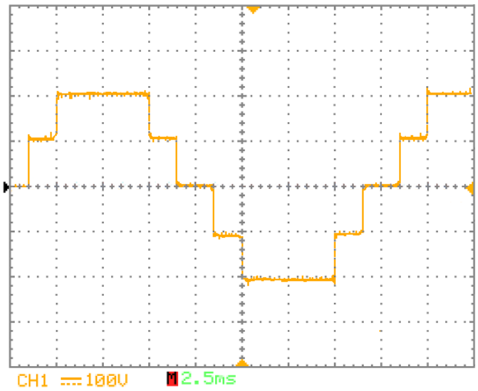


Fig. 17. Measured output phase voltage.

5. Conclusions

A two-stage inverter is developed in this research. The operation of proposed inverter is analyzed properly. This converter has two parts. The first part is a boost DC-DC converter. The DC-DC converter with step-up voltage gain is widely employed for various uses, like PV energy conversion systems. The second part of the two-stage inverter is the multilevel inverter that generates high-quality voltage by using few numbers of switches. In fact, the paper proposed two-stage inverter according to high gain DC-DC converter and multilevel inverter for energy conversion in DG systems. The multi-stage inverter has some advantages as improving the output voltage and current quality, using high gain DC-DC converter, using a multilevel inverter. Simulation and experimental results demonstrate the proper execution and feasibility of the developed topology. Photovoltaic energy is clean and renewable. In recent years, its applications have attracted much worldwide attention. Therefore, the design of solar panel energy systems is a very popular research area.

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