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Novel Multilevel Inverter using a Single H-Bridge

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Abstract- **A novel (N+1)-level multilevel inverter (MLI) using a modified solar panel (MSP) and newly proposed commutator coupled with slip rings, is presented in this paper. This multilevel inverter has only one H-bridge (HB) unit. The number of voltage levels of MLI depends on the number of the output terminal of MSP. The sinewave output is made possible by two-dimensional controls. The staircase sine wave has been converted into pure sinewave by using the filter capacitor at H-bridge. It is transformed to high voltage sinewave by using a step-up transformer. This proposed technique is verified by simulation and prototype**.

Index Terms— Commutator, H-Bridge, Modified Solar Panel, Multilevel Inverters, Speed Control.

I. INTRODUCTION

To cope up with uncompromising environmental challenges and the diminishing resources of fossil fuels as a result of large utilization of energy [1] it has become a global consensus to develop renewable, tenable and unending energy sources [2],[3]. Currently, renewable energy sources (RES) are

becoming more and more ample and influential due to environment friendly [4] and sustainable techniques for power generation [5]. This shifting of solar photovoltaic power generation technologies has been enhanced to a point where they are more affordable [6] then the fossil fuel bas power generation [7] Prices of PV modules and inverters are decreasing day by day [8]. So PV power generation is getting increasing shares in the market of electricity [9].

DC voltage is converted to AC voltage by a device which is called inverter [10]. Since most of the power systems use AC supplies [11], therefore, inverters are required for the purpose of ultimate usage from DC to AC supplies [12]. A continuous effort is made by the researchers for the development of in the inverter technology to make them feasible. These efforts are for the development of low price inverter, simplicity in construction and make them compatible at higher voltage levels.

An article named "The Inverter" was published by David Prince in 1925 [13]. After his invention, the H-bridge inverter evolved. The output of H-bridge inverter was similar to the square wave shape having two levels of voltage. The main disadvantages of the two levels H-bridge inverter were the large harmonics and high switching losses [14]. These were primarily used to drive lightening when the Grid was switched off [10]. These drawbacks of conventional two-level of multilevel inverter make it possible to use small size filters in place of conventional large size filters [15-17].

The introduction of multilevel enhanced the quality of sinusoidal wave and minimized harmonics [18]. In this way, two-level inverters were replaced by the inverters based on a new topology of multilevel switching and these modern inverters are now called as Multilevel Inverters [19]. Multilevel inverters were a breakthrough because these can provide higher voltage and high power ratio. This new topology is highly beneficial for medium to high voltage (range of 2-13 KV). Application of multilevel inverters is mainly in motor drive systems [20-22], power quality devices, i.e. Flexible AC transmission systems (FACTS) [23], Unified Power Flow Controllers (UPFC) [24], solid-state transformer [25], conveyors [26], industrial application, e.g. induction heating etc. Reduced harmonics of multilevel inverter make it possible to use small size filters in place of conventional large size filters [28],[29]. The problems addressed by these modern inverters are voltage stress reduction, and these provide lower switching losses as a result of lower switching frequency [30]. Furthermore, the fault-tolerant capability is also increased due to the usage of redundant switching states in the multilevel inverter. Revolution is brought when MLIs are integrated with renewable sources of energy Photovoltaic, fuel cells and wind) by improvement in energy harvesting and load sharing [30]. Reduced harmonics of DC input and number of levels gives the idea about the smoothness of output. By analyzing the previous work, different limitations of using multilevel inverter have been observed, e.g. cascaded H-bridge multilevel inverters need separate DC sources. As the number of levels increases, redundant switching states increases complexity, and complex switching control is required. Moreover, it is not possible to eliminate the low order harmonics. Attention towards improving inverters is getting more and more momentum. Inverters are electronic devices that contain many numbers of switching elements. The proper switching sequence makes it possible to get AC output of sinusoidal shape. The greater use of electronic components in these AC output inverters cause difficulty and problems in the form of losses and complexity of circuit and complexity of switching control. It also increases the implementation cost of the inverter.

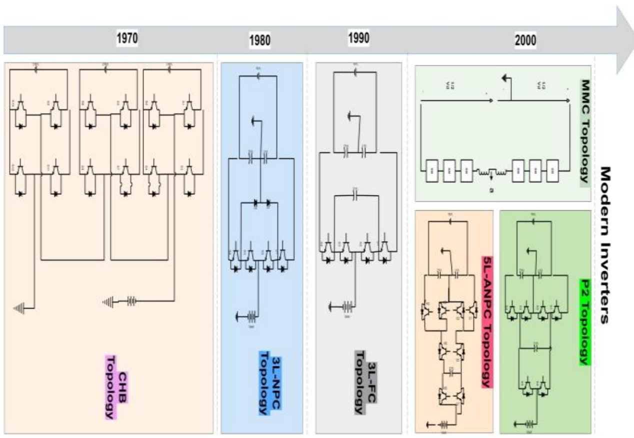


FIGURE 1. Perspective evolution of Multilevel inverters

The world is looking for economical and high-performance inverters regarding power rating. Moreover, these inverters should be pure sinewave inverters with minimum harmonics. In this paper, a novel idea of pure sinewave Inverter of high power rating is rendered. This novel proposed inverter is capable of meeting all of the above-mentioned demands of users of renewable energy for higher power conversion. A new methodology is proposed in which the need for cascading of H-bridges is eliminated and the switching of multilevel voltages is obtained by using a commutator along with a single H-Bridge. The authors contribution for designing of this novel sinewave Inverter is four fold, (1) the solid state switching is replace with the specially designed commutator switching. (2) the new design of solar-photo-voltaic panel for the proposed novel high power sinewave inverter, (3) the description of output frequency and phase control of proposed inverter (4) the designing of voltage step-up transformer for power distribution, utilization and grid connectivity. Moreover, voltage ripples and harmonics are removed by the use of filters.

This paper is arranged as given below. Section II presents the system description. Section III elaborates the design of all system components in detail. Section IV manifests the simulation and results for the proposed methodology. At the end of paper, a case study is rendered using a prototype in section V and section VI concludes the paper.

II. MATERIALS AND METHODS

The proposed novel inverter is composed of six components (1) modified solar panel, (2) Commutator coupled with sliprings (3) DC motor to rotate the commutator coupled with slip-rings (4) Controller to control the speed of DC motor (5) Single H-bridge composed of IJBTs (6) Step-up transformer. All of the above-mentioned components are presented in Fig. 2. To elaborate on the characteristics of all the components, we discuss one by one as follows. First of all, the construction of modified solar panel is somewhat different from the conventional solar panel. The conventional solar panel has only two output terminals with a single voltage level at the output.

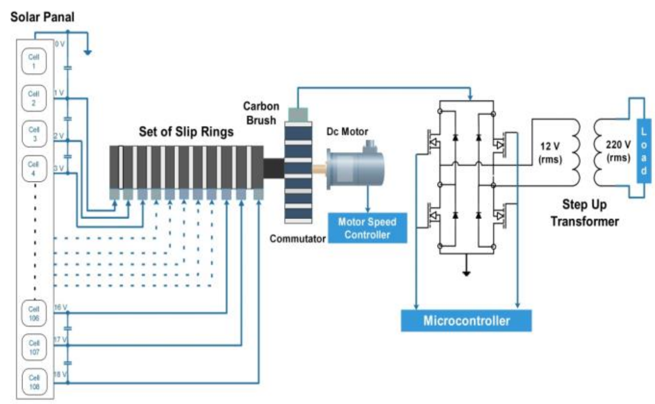


FIGURE 2. The complete layout of the setup of Novel Multilevel Inverter using Single H-bridge

While the modified solar panel has multiple output terminals with monotonically increasing voltage levels at the output, these multiple voltage levels are fed to the slip-rings. It is important to mention that one terminal of the modified solar panel is acting as a common terminal which has zero voltage level and common for all output terminal of a modified solar panel for completing the current path. As far as the description about the second important component of the system, i.e. commutator coupled with slip-rings is that commutator is specially designed, and it is somewhat different from the conventional commutator.

The commutator bars on the commutator wheel are placed at certain distances. The calculation of these distances is given in the design and implementation section. Moreover, slip-rings are Isolated from each other, and each slipring is connected to only one output terminal of the proposed solar panel. The sliprings and commutator wheel have the same axes of rotation and connected with each other with a rigid shaft. The third component of the system is acting as the rotating agent which rotates the common shaft of commutator and slip rings. This rotating agent is a DC motor. It is worth mentioning that as the frequency of inverter's output voltage is dependent on the speed of rotation of DC motor. So, a digital speed controller is used, which is the fourth important part of the system. The details about the controller are described in the next section. The fifth important component is the conventional H-bridge circuit which consists of four IJBTs as shown in Fig. 2. This H-bridge is used only for reversing the direction of current at its output terminals which make this system as an inverter, i.e. DC to AC inverter. The last important part of the system is the step-up transformer. The transformer is important as it changes the low voltage of sinewave to higher voltage, i.e. 220V sinewave for grid compatibility. Furthermore, the detailed design and working of each component are presented in the following section.

III. DESIGN OF MLI USING TWO DIMENSIONAL CONTROL

In this section, the design of the novel multilevel inverter is discussed. The detailed description is about the design of the above mentioned each major component of the system step by step.

A. DESIGN OF MODIFIED SOLAR PANEL

A solar cell or photovoltaic cell is an electrical device that is used to convert light energy into electricity by using the photovoltaic effect. PV cells are assembled in PV modules which are interconnected in series-parallel arrangement to produce arrays. The mathematical model of PV array is given by the following;

$$I_{PV}=N_P I_{ph}-N_p I_o\{e^{\frac{qV_{PV}}{HKTNs}}-1\} \quad (1)$$

where IP V is array output load current (A), VP V is PV array output voltage (V), Ns is the number of series PV cells and NP: the number of parallel PV cells, Io is the reverse saturation current of the diode (A), q is the electron charge that is 1.602 × 10-19 C, H is the diode ideality factor, K is the Boltzmann's constant which is 1.38×10-23 and T: ambient temperature (K). Electrical characteristics of photovoltaic cells such as resistance, voltage and current changes when light fall on it. When large numbers of solar cells are combined, they form modules or solar panels. Open circuit voltage of the single solar cell is 0.5 to 0.6 volts.

This solar panel has multiple output terminals with a specific voltage at each terminal. The numbers of output terminals are equal to the required number of levels of the multilevel inverter, i.e. "N". For a particular case in this paper, consider a modified solar panel with 18 output terminals. Individual solar cells are connected in series to obtain different voltage levels that range from 0 to 18 V. Each terminal of the modified solar panel with its output voltage is mentioned in Fig. 3. The power rating of this modified solar panel can be increased by increasing the number of solar cells in a parallel combination, which ultimately increases the current capacity.

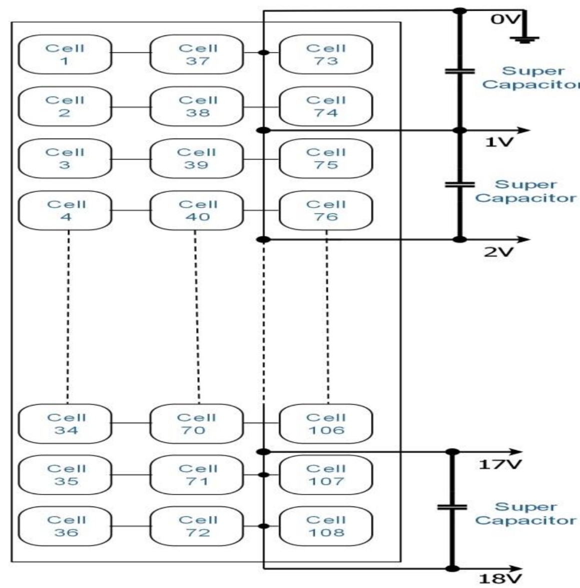


FIGURE 3. Schematic of modified solar panel

B. DESIGN OF COMMUTATOR COUPLED WITH SLIP-RINGS

The conventional multilevel inverters have complex circuitry of solid-state switches, i.e. FETs or BJTs. Complex switching control is also required for controlling the switching process. The proposed methodology provides the best alternative of the complex switch circuitry and complex control for novel multilevel inversion of DC voltage to AC voltage. A specially designed mechanical commutator is the best alternative. Instead of solid-state switching, a mechanical commutator is used for switching of different voltage levels. A set of slip rings is also coupled with the commutator wheel on the same shaft as shown in Fig.4. However, the DC motor is used to rotate this shaft. The number of slip rings depends on the number of voltage levels, i.e. "N" at the output terminal of modified solar panel.

REMARK1: It is important to mention that this commutator is different from the conventional commutator used in DC machines. The main difference between the conventional commutator and the modified commutator is that the distance between all the terminals of commutators is not the same. The distance between the commutator bars is intentionally planned to get the sine- wave shape voltage at the of H-bridge. These distances between the copper bars of the commutator are calculated as follows. It is a well established fact that the arc length can be calculated by (2)

REMARK 2: Note that the sinusoidal form of voltage repeats its values after a certain interval of time '*T'* known as the period of the sinewave. So, the value of instantaneous time '*t'* for analysis of the circular motion of commutator will range from 0 to *'T'*.

REMARK 3: The values of the voltage available at the output terminals of the modified solar panel will be the instant nous values of voltage at carbon brush arbitrarily attached to one of the commutator bars. Moreover, these instantaneous voltage values available to the carbon brush can form the sinewave shape, as shown in Fig.4(a). This can be done by two-dimensional control, (1) controlling the speed of rotation of commutator ω equal to the reference speed, (2) placing the commutator's bars at certain distances. These distances are calculated using (2)-(5). To calculate the position of commutator CBi bar connected with slip ring of given voltage levels $v(t) = vi$, first of all, calculate the value of ti by using Eq. 5. Afterwards, calculate the value of θi and value of arc length Si, i.e. the distance of CBi from $CB0$ by using Eq. 3 and 2, respectively.
Moreover, the f-number of rotations of commutator per second and f' *is* the frequency of inverted output sine wave. Furthermore, the sinusoidal waveform of voltage is mathematically represented by (4)

$$v(t) = VoSin\theta \quad (4)$$

Here, *'Vo'* is the peak value of voltage sinewave and *'v* (*t*)*'* is the instantaneous value of the voltage at the time 't'. Equations (4) witness the fact that voltage *'v* (*t*)*'* and θ are related to each other. Taking the advantage of this relationship, we can calculate the position of commutator bars on the circumference of the commutator by using (2)-(5).

$$v(t) = Vo\ Sin(\omega t)$$

$$t = \frac{\sin^{-1}\frac{v(t)}{V_o}}{\omega}, \quad (5)$$

$$S = r\theta \qquad (2)$$

Where *'r' is* the radius of the commutator and *'θ'* is the angular displacement (measured in rad) rotated in some time interval 't'. Also,

$$\theta = \omega t = 2\pi ft = 4\pi f't$$

Where 'ω' is the angular speed of commutator and f = 2f'.

The cross-section diagram of the commutator is shown in Fig.5.

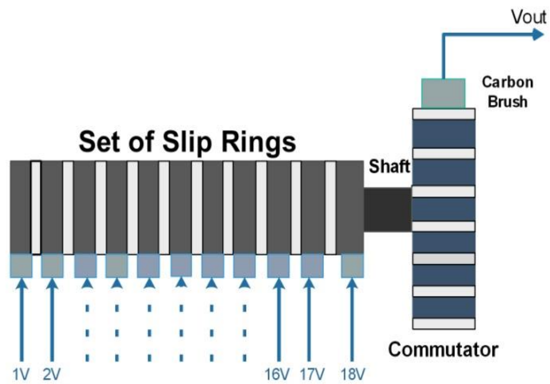


FIGURE 4. Slip rings and commutator on a common shaft

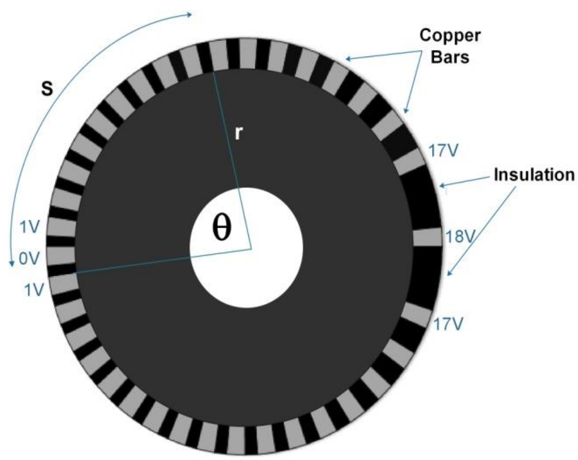


FIGURE 5. Commutator bars placement for generating staircase sinewave

C. DC MOTOR SPEED CONTROL

The frequency of the sinewave depends upon the speed of rotation of the commutator shaft run by DC shunt motor. In DC shunt motor, the field and armature circuits are connected to separate voltage source, as shown in Fig. 6.

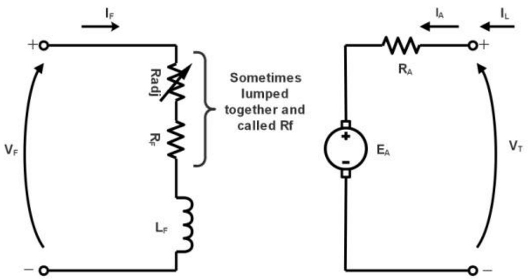


FIGURE 6. Electric circuit diagram of shunt DC motor

The mathematical model of DC motor is Chapman (2002):

Where

$$EA = K\,\Phi\omega, \quad (6)$$

$$L_F \frac{di_F}{dt} = V_T - i_F(R_F + R_{adj}), \quad (7)$$

$$L_A \frac{di_A}{dt} = V_T - i_A R_A - K\phi\omega, \quad (8)$$

$$J \frac{d\omega}{dt} = K\phi\omega - T_L, \quad (9)$$

From Eq.(6), it can be inferred that

$$\omega \propto \frac{E_A}{\Phi}, \quad (10)$$

where $EA = VT - IaRa$, so

$$\omega \propto \frac{V_T - R_a I_a}{\Phi}, \quad (11)$$

The voltage drop I_aR_a will be negligible as Ra is very small, also $VT >> I_aR_a$ therefore, the expression for the speed can be approximated as follows:

$$\omega \propto \frac{V_T}{\Phi}, \quad (12)$$

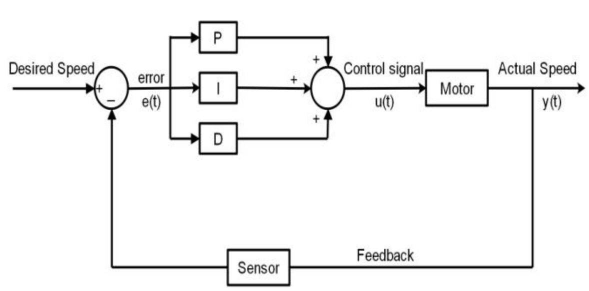


FIGURE 7. DC Motor speed control using PID Controller

This shows that the DC shunt motor speed is inversely proportional to flux φ and is directly proportional to applied voltage VT. In the proposed methodology, DC motor speed is controlled by Applied Voltage VT. In this method, the field winding of the motor is connected to a constant DC voltage. But armature voltage is controlled by using Pulse width modulation (PWM). The duty cycle of the PWM signal is calculated using PID control, as shown in Fig. 7. The flow chart for the speed control of DC motor is shown in Fig. 8.

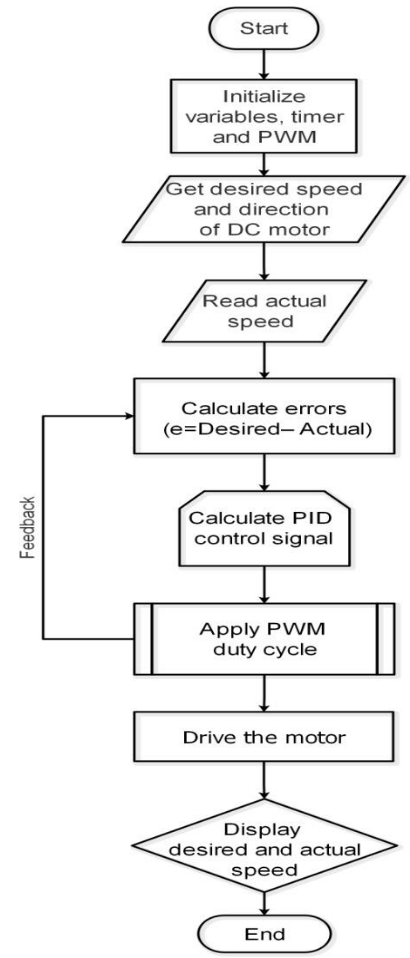


FIGURE 8. Flow chart for Speed control of DC motor

D. H-BRIDG FOR REVERSING THE CURRENT DIRECTION

An H-bridge is an electronic circuit that switches the polarity of a voltage at its output terminals. Most DC-to-AC converters (power inverters), AC/AC converters, the DC-to-DC push-pull converter, and many other kinds of power electronics use H-bridges. In this proposed methodology of the multilevel inverter, this H-bridge plays the crucial role for inversion of the polarity of the voltage applied at its input terminal, which is the half sinewave shape. At the output terminals of H-bridge, voltage wave will be a complete sinewave having both crust and trough. Moreover, the frequency of this complete sinewave *f* will be half of the rotation frequency of commutator, i.e. *f'*.

E. STEP-UP TRANSFORMER AS FILTER IN THE OUTPUT CURRENT

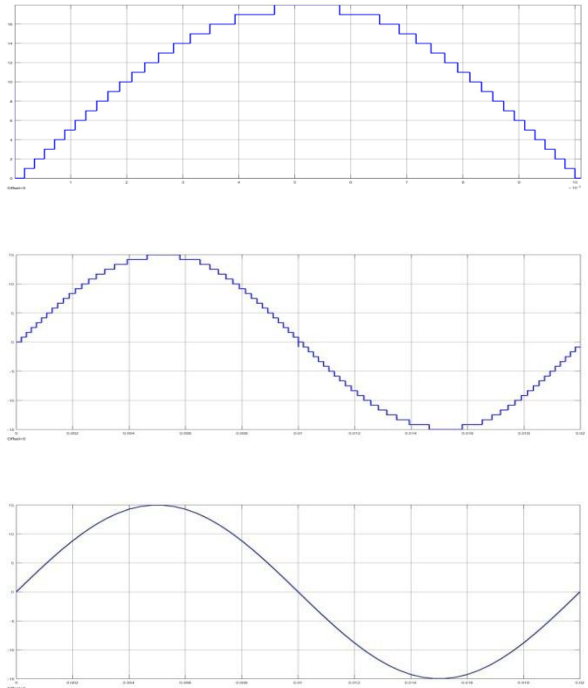
Step-up transformer is a conventional transformer for shifting the AC voltage to the upper level, i.e. 220 volts. An added advantage of this transformer is that it will also act as a filter for removing the ripples from output current. The primary and secondary coils of the transformer will resist the abrupt change in the load current because of the shifting of the voltage levels at commutator and brush connection and also because of switching of IJBTs of H-bridge. It is already mentioned that the number of output terminals of the solar panel will decide the number of levels. The larger the number levels will already decrease the large abrupt changes in the output voltage and the current. Moreover, the inductance of this transformer will further resist the variations in current, which will result in a sinusoidal current flow through the transformer. The output at the secondary of the transformer will have minimized ripples or harmonics. So, the output voltage wave will be almost pure sinewave of good quality.

IV. SIMULATION RESULTS AND DISCUSSION

The scheme for the multilevel inverter is tested through MATLAB simulation, and also it has been implemented on a prototype of 300-watt load driving capacity. The MATLAB simulation is implemented through a Simulink model, as shown in Fig. 9. This figure represents the three main parts of the proposed system model, i.e. voltage source, commutator equivalent circuit, and the H-bridge. The first two parts are further elaborated in Fig. 10.

REMARK 4: It is important to mention that the proposed commutator coupled slip-rings is not available in the MATLAB Simulink library. So, an equivalent circuit for the commutator representation is designed using the ideal switch block and the breaker control block, as shown in Fig. 10. Notice that the switch blocks are connected to the voltage source of different voltage levels. Moreover, only one switch will be in ON state at a time, out of all the switches. Furthermore, all the switches represent the commutator bars.

Also, note that total numbers of commutator bars will be equal to the voltage levels available at the output terminals of the specially designed solar panel. Similarly, in the Simulink model, the numbers of switches are as many as the commutator bars, and numbers of DC voltage sources are equal to the voltage levels of the proposed solar panels. The output of this equivalent commutator circuit is connected at the input of H-bridge. This output is similar to the crust of the staircase sinewave or in other words, the first half of the sinewave as shown in Fig. 4(a).
The simulation results measured at the output of the H-bridge is full multilevel staircase sinewave, as shown in Fig. 4(b). Pure sinewave can be obtained by using non-polar filter capacitor at the output of H-Bridge as shown in Fig.4(c)



(a)

(b)

(c)

Figure 11. Simulation Results: (a) Half sinewave generated by Simulink model of commutator (b) Full sinewave after H-Bridge (c) Pure-sine wave after using the filter capacitor.

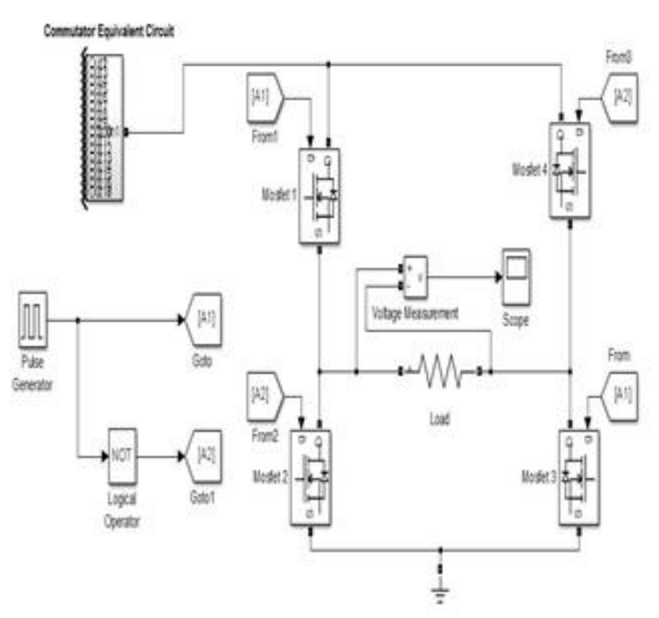


FIGURE 9. Simulink model to generate full sinewave from MSP

Comparison of cascaded h-bridge inverters and proposed novel multilevel inverter using single H-bridge is given in table 1.

	Advantages	Disadvantages
Diode Clamped Multilevel	1. Back to back inverters can be used. 2. Capacitors are pre charged. 3. Efficiency is high at fundamental frequency. 4. Capacitance is low.	1. Number of clamping diodes increases with the increase of each level 2. Dc level will discharge when control and monitoring are not precise
Flying Capacitors Multilevel Inverter	1. Static var. 2. For balancing capacitors' voltage levels, phase redundancies are available. 3. We can control reactive and real power flow.	1. Voltage control is difficult for all the capacitors 2. Complex startup 3. Poor Switching efficiency 4. Capacitors are expansive than diodes
Cascade H Bridge Multilevel	1. Output voltages levels are doubled the number of sources 2. Easy and quick Manufacturing 3. Packaging and layout is modularized. 4. We can control it Easily with a transformer	1. Every H Bridge needs a separate dc source 2. Due to large number of sources, Applications are Limited. 3. Complex 4. Power rating is limited 5. Costly
Novel Multilevel Inverter	1. Simple design. 2. High Power Rating 3. By using just one H-Bridge get N numbers of level of sinewave. 4. Minimum Cost. 5. Minimize Switching 6. Just four FETs are required. 7. Any no. of level can be achieved. 8. Frequency can be varying by controlling speed control. 9. Comparison of cascaded h-bridge inverters and proposed novel multilevel inverter using single H-bridge is given in table 1.	1. Need wear and tear due to mechanical components

Table 1: Comparison between Conventional Inverter Proposed Novel Multilevel Inverter.

V. CONCLUSION

This paper has proposed a novel multilevel inverter that minimizes the complexity and cost of the conventional multilevel inverter by using lightweight commutator coupled slip-rings. The power rating of the proposed multilevel inverter can be high as compared to conventional inverters. By using a modified solar panel, 37 voltage levels are achieved. Proposed commutator coupled slip rings generate a half-sine wave in the staircase. Single H-bridge is used at the end of commutator coupled slip-rings, and a full sine wave is generated in the staircase. The pure sine wave is obtained by using a suitable capacitor at the output of H-Bridge.

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