

An Advanced 21-Level Single-Phase Inverter with Minimized Switches and Sources for Renewable Energy Applications

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Abstract—The focus of this paper lies on the designing of a sophisticated multilevel single-phase inverter which comprises 21-levels. The proposed configuration makes use of just a single power source and yields a voltage gain up to ten times the input voltage. It is important to mention here that this configuration needs minimum number of switches compared to other multilevel inverter configurations and, therefore, helps minimize the switching loss. As far as capacitors are concerned, they possess a natural capability to balance themselves. Therefore, there is no need for any extra circuit to maintain their balancing in the proposed inverter system. Moreover, NLM technique is employed to generate high quality stepped waveform having low THD. The entire inverter has been simulated in MATLAB/Simulink.

Index Terms—Multilevel Inverter, Switched Capacitor, Voltage Gain, THD, NLM, Power Electronics

I. INTRODUCTION

The proposed design is related to the designing of advanced multi-level (21 level) single phase inverter through the implementation of switching capacitor structure. In the given design, only one DC voltage source is used to produce multiple level AC output voltage. As against the traditional designs where the design of multiple level inverters is done through the use of multiple DC sources and more number of switching devices, in the current inverter design, switching capacitor approach is used to attain more gain in voltage through the reduction in component count. The inverter design consists of switching devices such as MOSFET, capacitors for attaining multiple voltages and associated switching circuits. Voltage across capacitors is modulated in specific sequence in order to produce different voltages at the output end. Output voltage waveform is produced based on the summation of DC source voltage and capacitor voltages. It is very noteworthy that, without using other electronic components like DC-DC boost converter, it is possible to increase the voltage gain in the inverter circuitry. This is made possible because of the use of capacitor voltage boosting method in the inverter. Therefore, the inverter is more applicable for low-voltage renewable energy sources such as solar PV energy generation. It is very important to highlight that switching pulses can be generated with the help of any modulation algorithm. For example, nearest level modulation (NLM). Multilevel inverters have many power electronic applications owing to their capability to decrease harmonics and improve the quality of the output. It is a known fact that conventional two-level inverters generate square waveforms with harmonic contents. As a result, it is necessary to have bulky filter circuits. In contrast to two-level inverters, multilevel inverters generate step waveforms with less harmonic content. Consequently, it is quite obvious that multilevel inverters require fewer filter circuits than two-level inverters. It is also important to note that one of the interesting features about the switched capacitor inverter is that it features self-balancing capacitors. These capacitors balance themselves depending on the switching process. Therefore, there is no need for designing a special circuitry to balance these capacitors. Another feature of this type of inverter is that it can boost voltage.

Simulation tests were conducted using the software package of MATLAB/Simulink. Some of the simulation outputs include the output voltage waveform, output current waveform, capacitor voltage balancing, and total harmonic distortion values. When a smoother current delivery is needed, the cuk converter uses capacitance to minimize the ripple effect in both the input and output circuits. This will be determined based on whether the operation of the converter falls within Continuous Conduction Mode, where the inductor current is not zero, or the Discontinuous Conduction Mode, which is used in low load conditions. In Continuous Conduction Mode, there is a direct relationship between the switching period and the voltage; however, in Discontinuous Conduction Mode, there are complex relationships involving frequency and inductance. An inverter is basically a power electronics circuit which transforms DC input supply to an output AC signal of desired frequency and voltage. Though in theory, ideally the inverter should generate a sinusoidal signal but, in reality, because of reduced harmonic content, non-sinusoidal waveforms are preferred which can be achieved by high speed switching. In some industrial systems, the device works on the principle of "DC link converter" whereby first rectification of the input signal is achieved and then the AC signal generated is again converted to variable frequency AC. In practical application, the switching losses and voltage stress across semiconductors are two important factors influencing the performance of any power electronic system. The novel inverter topology proposed here reduces the voltage stress across the switches by sharing it among different switch states. As a result, lower rated semiconductors can be employed thus making the inverter system economical. Besides, due to reduced switching frequency in certain operating modes, the switching losses are minimized. Harmonic analysis is another method that can be used in the assessment of the quality of the output waveform. The more voltage levels used in the design of the inverter, the lower is the total harmonic distortion (THD), thus, increasing the power quality. Since the output waveform from the inverter is stepped waveform, it resembles sinusoidal waveform, which means that there is no need for any additional filter circuit in order to make sure that the waveforms are filtered and pure sinusoids. It makes the designed inverter quite efficient and small in size. It is also necessary to mention the ability of the proposed inverter to work under various load conditions. The main advantage of the inverter is that it generates sinusoidal voltages under the resistive loads, while the sinusoidal current is

observed under the inductive load. The ability of the inverter to generate sinusoidal voltages and currents proves that it is capable of being used in real applications (for example, as a drive motor).

II. LITERATURE REVIEW

J. Rodriguez, J. S. Lai, and F. Z. Peng (2002) This paper presents a comprehensive survey of multilevel inverter topologies, highlighting their advantages in reducing harmonic distortion and improving power quality. It also discusses challenges such as complexity and control strategies.[1]

E. Babaei (2008) This study introduces a new cascaded multilevel inverter topology with a reduced number of DC sources and switches. It focuses on improving efficiency while maintaining output waveform quality.[2]

K. Gupta and A. Jain (2014) This paper reviews various multilevel inverter topologies and compares their performance in terms of THD, switching losses, and cost. It emphasizes the need for reduced component designs.[3]

S. Mekhilef, M. N. Kadir, and N. A. Rahim (2011) This research focuses on multilevel inverter applications in renewable energy systems and highlights their ability to enhance efficiency and reduce harmonic distortion.[4]

J. S. Lai and F. Z. Peng (1996) This paper introduces multilevel converters as an effective solution for high-power applications, emphasizing reduced voltage stress and improved waveform quality.[5]

M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Pérez (2010) This study provides a detailed analysis of cascaded multilevel inverters, including their control techniques and industrial applications.[6]

P. Lezana, J. Rodriguez, and D. A. Oyarzun (2008) This research discusses hybrid multilevel inverter topologies and their advantages in reducing switching losses and improving efficiency.[7]

S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, and L. G. Franquelo (2010) This paper reviews recent advances in multilevel converter technologies and highlights their growing importance in modern power systems.[8]

Y. Hinago and H. Koizumi (2012) This study proposes a switched-capacitor multilevel inverter topology that achieves voltage boosting without additional DC sources and discusses its efficiency advantages.[9]

M. Saedifard and R. Iravani (2010) This paper analyzes capacitor voltage balancing methods in multilevel converters and highlights challenges in maintaining stability.[10]

A. Ajami, H. Ardi, and A. Farakhor (2010) This research introduces a new switched-capacitor-based multilevel inverter with reduced switch count and improved voltage gain.[11]

N. Sandeep and U. R. Yaragatti (2016) This study presents a novel multilevel inverter topology with fewer components and improved THD performance for power applications.[12]

III. METHODOLOGY

The new topology of the proposed 21-level inverter depends upon the switched capacitor principle wherein a single source of DC power is employed in order to derive various levels of voltages. Unlike the existing multilevel inverters where various independent DC sources have to be used, in this case, capacitors will act as energy storing devices to step up the voltage levels. Capacitors can be charged and discharged through controlled switching operations to get different levels of voltages at the output terminals. With only a single DC source being used, there is a considerable reduction in the overall complexity of the system design and also in costs. As the inverter now has only one input voltage source, it is ideally suited for use in solar photovoltaic applications. Also, due to the proper arrangement of the switches, only minimal number of conducting switches is required per current path. Thus, this leads to reduced conduction losses and increased efficiency. The inverter that is proposed herein works under two different modes, which are known as positive half cycle and negative half cycle of operation. Under the positive half cycle mode of operation, the DC supply and the capacitors are connected in series by switching to produce increasing voltage levels. In the negative half cycle of operation, the polarity of the output voltage is switched in order to produce symmetrical negative voltage levels.

In the proposed inverter, the process of charging and discharging the capacitors is very important. Under certain switch-on switching states, the capacitors get charged using the DC supply, while under others, they discharge to help in producing the required output voltage level. With the switch-on sequence chosen in the inverter design, the average voltage across each capacitor becomes balanced throughout the entire cycle. This self-balancing process makes an extra balancing circuit unnecessary. Inverter modulation is achieved through Nearest Level Modulation (NLM). This requires comparison between the reference sinusoidal waveform and the levels of voltage present, followed by selection of the nearest voltage level for switching operations. The resultant waveform takes a shape resembling that of a sine wave. NLM is quite effective since the switching takes place where necessary, thereby minimizing switching losses. Output of the inverter can be generated from the load connected to the circuit;

the load can either be resistive or inductive. With the resistive load, there is an in-phase relationship between the voltage and the current waves, thereby ensuring efficiency in the system. On the other hand, the current waves are always lagging behind the voltage waves in the inductive load. The stepped wave output from the inverter reduces harmonics. The proposed model is analyzed using MATLAB/Simulink simulation tool. The simulation of this model is performed and analysis is carried out. In this case study, DC source, switching circuit, capacitor array, and load are considered in the system. Various parameters such as output voltage, output current, voltage balance across the capacitor array, and THD are measured for this model.

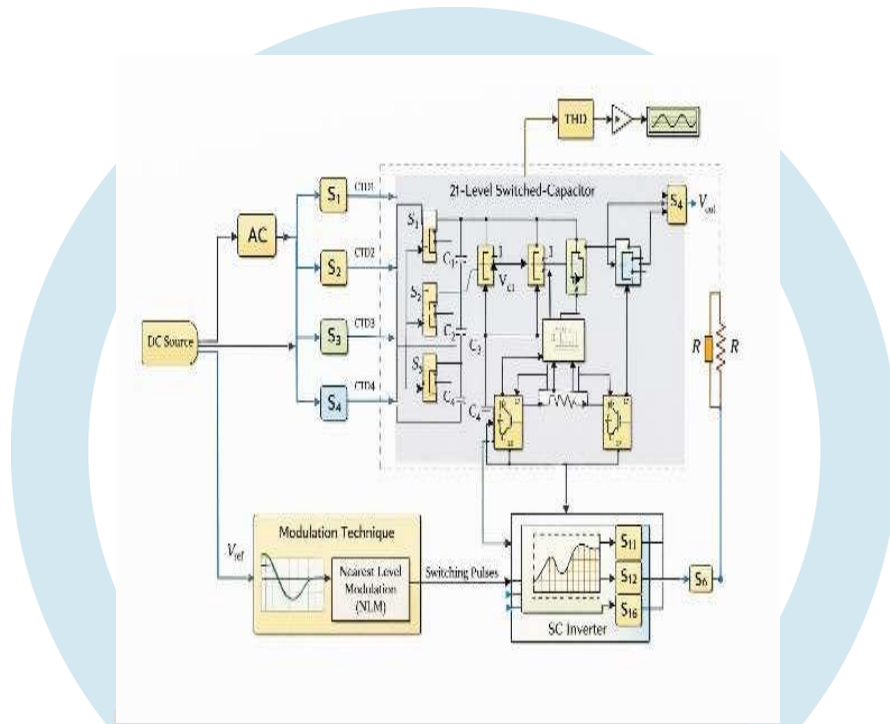


Fig.1. Circuit diagram for An Advanced 21-Level Single-Phase Inverter with Minimized Switches and Sources for Renewable Energy Applications .

IV. ANALYTICAL STUDY AND SIMULATION DIAGRAM

The initial phase of the new design involves a DC voltage source at the input side, which acts as the main power supply for the inverter. Unlike the traditional architecture, where multiple isolated DC voltage sources are used for the generation of various levels of voltage, the presented architecture requires one DC voltage source and uses switched capacitors to increase voltage gain. In other words, the suggested inverter offers an efficient solution for the simplification of the circuit architecture, as well as significant cost savings on the hardware, which does not affect its performance and voltage gain. The DC source is linked to a set of semiconductor switches, capacitors, and diodes, forming the main components of the switched-capacitor inverter. Multiple voltage levels are achieved through the application of semiconductor switches under the principle of Nearest Level Modulation (NLM). Under this method, a sinusoidal reference waveform is compared with the existing voltage levels, and the nearest value is chosen to generate required switching pulses. When the switches turn ON, the capacitors are charged by the DC source directly or in a cascade manner.

If the switches turn OFF, the energy accumulated in the capacitor is discharged together with the voltage from the DC source, producing higher voltages. In its operation, the proposed inverter operates in two stages, which are positive half cycle and negative half cycle. During the positive half cycle, the DC supply along with capacitors are arranged in series depending on the switching arrangements in order to generate increasing voltages. The lowest output voltage is generated using only the DC supply, but more voltage levels are produced by combining capacitors in series with the DC supply. Maximum voltage output level can be produced by arranging all the capacitors in combination with the DC supply. During the negative half cycle, the output voltage is inverted due to the change in switching state arrangement. The negative voltage levels produced are symmetric about the zero point without the need of a separate H-bridge circuit.

One important aspect of the proposed inverter is that capacitors are simultaneously charged and discharged at a particular instant. Some capacitors produce the output voltage, while other capacitors are being charged. The output voltage level is sustained in this manner without fail. Current regulation is performed using auxiliary diodes so that switching devices are not stressed. Switching devices also benefit from the use of redundant switching states. In this case, the output of the inverter is taken out from the load side, and an output signal consisting of twenty-one level step waves is produced to represent the output in the form of a sine wave. Designing a multilevel inverter plays a significant role in minimizing harmonics in the output signal, thus improving the quality of the power. The simulation of the proposed multilevel inverter is done using the MATLAB/Simulink software.

V.EXPERIMENT RESULTS

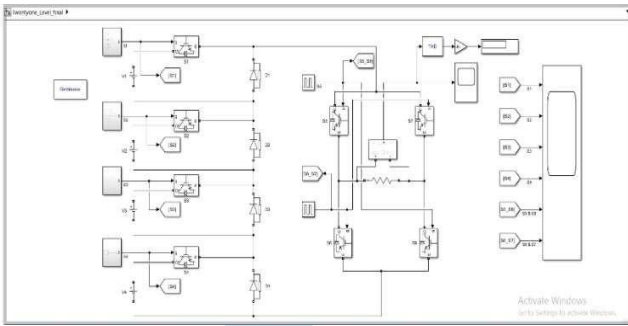


Fig.2. Simulation Diagram

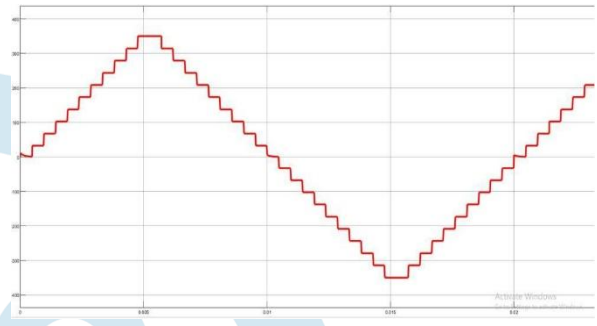


Fig.3. Output Voltage Waveform

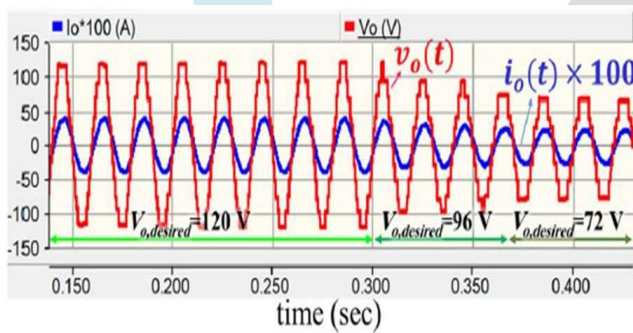


Fig.4. Phase Lock Loop Voltage and Current.

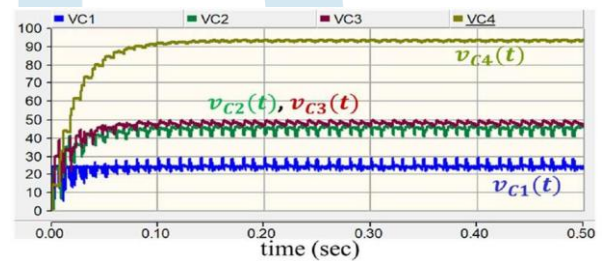


Fig.5Capacitor Voltage Balancing

The wave form of the output voltage of the developed 21-level inverter proves the efficient implementation of the switched capacitor method and the proposed modulation strategy. It is obvious that there are several levels, which leads to the formation of a stepped sine wave. The equidistant spacing of steps indicates proper switching operation and accurate voltage levels generation..Moreover, the symmetrical positive and negative halves prove balanced performance of the inverter. Because of its multilevel structure, harmonic content is greatly minimized, and as a result, the output waveform is very close to the ideal sine wave.Apart from the output voltage waveform, the output current waveform also proves that the inverter has the ability to generate power effectively for the load. It is obvious that the output current waveform follows the sinusoidal curve even though the output voltage waveform is a stepped waveform. Therefore, it shows that the inverter has the ability to provide stable and continuous current. It also proves the efficient and stable operation of the multilevel inverter through the output current and voltage waveforms.The waveform behavior of capacitor voltages serves to illustrate that the proposed switched-capacitor inverter self-balances by its nature. It is evident that the voltage values of the capacitors are increasing initially due to the transient states until they reach steady state voltages. In this state, the voltages of the capacitors are going to remain nearly constant, with only minor variations as a result of the switching action. Various voltage values of different capacitors serve as an example of how these elements enable voltage amplification and creation of various voltage values. The self-balancing feature allows achieving voltage stabilization without the help of other control circuits.Variation changes in the voltage output values under different operational modes serve as a confirmation of the controllability of the inverter. It can be stated that there are different values of voltage such as 120V, 96V, and 72V, illustrating that the inverter is able to respond to various modulation needs. Voltage values in the inverter output can be controlled as they differ according to needs.

Finally, the whole performance of the inverter is tested using the waveform analysis technique, which proves that the performance of the inverter is steady, having lesser harmonics, and efficient energy conversion. Due to the multilevel architecture of the inverter, there is low switching voltage, leading to increased efficiency in the inverter. The smooth output waves, stable capacitor voltages, and steady current output prove that the proposed inverter can be used for renewable energy systems.

VI. HARDWARE RESULTS

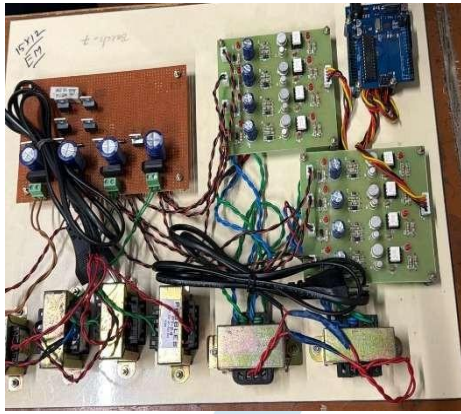


Fig. 6. Hardware Kit

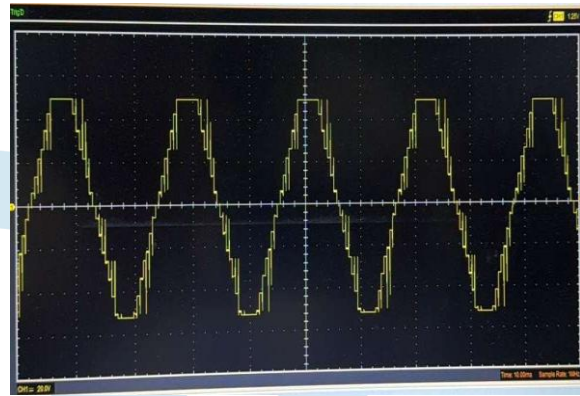


Fig. 7. Voltage waveform

VII. CONCLUSION

A high performance power converter system using a 21-level switched capacitor based single phase inverter has been developed and analyzed. The proposed converter offers an effective solution by employing a single DC supply with fewer switches in order to simplify the structure of the circuit and reduce its cost. The converter can produce several voltage levels having a high voltage gain, which greatly improves the output waveform with respect to low harmonic distortion. It is clear from the simulation results that the output waveform consists of several steps of voltage that approximate a sinusoidal waveform. In addition, the performance analysis of the inverter proves that the proposed method for modulation and control works properly. The employment of the Nearest Level Modulation (NLM) method guarantees accurate voltage level selection, which leads to reduced switching losses. The stable voltage waveforms of the capacitors prove the capability of the proposed scheme to achieve self-balancing without the need for any additional control circuit. Consequently, the complexity of the system and controller have been reduced. Moreover, it is evident that the output current waveform has followed the shape of a perfect sinusoid. In addition, the performance analysis of the inverter proves that the proposed method for modulation and control works properly. The employment of the Nearest Level Modulation (NLM) method guarantees accurate voltage level selection, which leads to reduced switching losses. The stable voltage waveforms of the capacitors prove the capability of the proposed scheme to achieve self-balancing without the need for any additional control circuit. Consequently, the complexity of the system and controller have been reduced. Moreover, it is evident that the output current waveform has followed the shape of a perfect sinusoid.

Also, the inverter is designed to provide maximum voltage gain up to ten times the magnitude of the voltage applied at the input terminal, thereby making it very useful as an inverter for low-voltage energy sources like the photovoltaics systems. Lowering the Total Harmonic Distortion (THD) in the output voltage is another indication of the effectiveness of the multilevel circuitry used. Reduction of voltage stresses across the switches and reduced switching losses increase the efficiency and lifespan of the power electronics used in the system. Thus, the inverter exhibits satisfactory performance, making it a viable device for use in the power electronics industry. Finally, this project can be concluded as having designed a high gain, low component number multilevel inverter system that meets the desired criteria for performance. The low number of switches used in the system, self-balancing of the capacitors, and improved output waveform are some of the features that make the inverter very efficient.

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