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A streamlined 17-level cascaded H-bridge multilevel converter with solar PV integration

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ABSTRACT

The quest for a green electrical power system has increased the use of renewable energy resources and power electronic converters in the existing power system. These power electronic converters, however, are a major cause of harmonics and result in the degradation of power quality. In the last two decades, researchers have proposed various designs of multilevel converters to minimize these harmonic distortions, however, a comprehensive solution for stand-alone solar photovoltaic (PV) systems with low total harmonic distortion (THD) is still missing in the present body of knowledge. This paper proposes a single-phase 17-level cascaded H-bridge multilevel converter (CHMC) model for a stand-alone system using solar PV arrays. The proposed model employs eight different flexible PV arrays that can be replaced with DC voltage sources when required to meet the load demand. The proposed model does not include any capacitor and filter thus saving a lot of cost in the overall system. The model has been implemented in the Simulink environment using a model-based design approach. The simulation results show that the proposed model has reduced the THD to almost 7% as compared to the existing models. The cost comparison of the proposed converter also proved its economic benefit over other types.

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1. INTRODUCTION

The multilevel converter is an electronic device that can provide various levels of voltage at the output for more similarity with a pure sine wave. In such converters, various lower-level DC voltages are used at the input side. Multilevel converter applications have been mostly used in renewable energy systems. For instance, fuel cells, solar, hydroelectric energy, wind energy, biomass, and geothermal power. The new semiconductor technologies, power switches having lower prices, and the demand for current for inverters having high performance have increased the multilevel converters applications in renewable energy systems [1]. The technical specifications of the system are summarised in Table 1.

The multilevel converters have gained interest among PV systems due to their attractive features, e.g., high-quality waveform, and high nominal power. That is why the researchers have introduced many converters such as cascade H-bridge converters, neutral point clamped converters, and hybrid multilevel converters. These converters can be applicable in medium and high-power applications.

Table 1. Technical Specifications of the components

Components	Specifications
Solar PV (single panel)	TSM-250PA05.08 Maximum output power=250W Voltages at mpp (V_{mmp})=31V Current at mpp (I_{mpp})=8.01A Cells per module=60 cells
IGBT switches	Internal resistance R_{on}=1e-3 ohms Snubber resistance R_s=1e5 ohms

In the PV systems, the multilevel converters give a proper solution for quality renewable energy generation [2]. The classical PV converters include a feature named grid frequency transformer, and this component is hefty and costly between the electrical grid and converter [3]. We always need improved efficiency, less weight, and less cost. By neglecting the transformer frequency, we get many advantages, as mentioned earlier, but the quality of output power goes down. It also gives DC injection to the grid [4, 5], and creates the problem related to ground leakage current [6, 7]. While PV module active parts are electrically insulated from the frame, which is ground connected but there becomes an AC ground leakage current path, this path is because of parasitic capacitance between frame and module. Ground leakage current is mostly because of variations of standard mode voltage due to high frequency at the output of the power converter [7]. For the reduction of the harmonic content of universal mode voltage, many solutions have been proposed in [8, 9]. The goal of multilevel converters is to improve efficiency and reduce the cost and size, and all this can be achieved if we reduce the filter size.

The first reported use of multilevel converters was in the power train and high voltage industrial applications. In the renewable energy domain, these converters were used in utility-scale plants for the first time, and still, they are used on a large scale in utility-scale plants these days [10, 11]. Recently they are going on the way of single-phase PV converters on the residential level, and this is an important topic for research these days [12]. If we roughly divide the single-phase multilevel converters, then main types of these converters are neutral point clamped (NPC), and cascaded full bridge (CFB).

The diode-clamped converter is also called the NPC converter because when it is used in a three-level converter, the mid-voltage level is defined as the neutral point level [13]. The electric potential between the ground and the PV cells in NPC topology is kept fixed by providing a constant potential to the grid through the neutral wire and is shown in Figure 1. The primary benefit of single-phase NPC is that it resists ground leakage current, but on the other hand, three-phase NPC is not much better against leakage current [14].

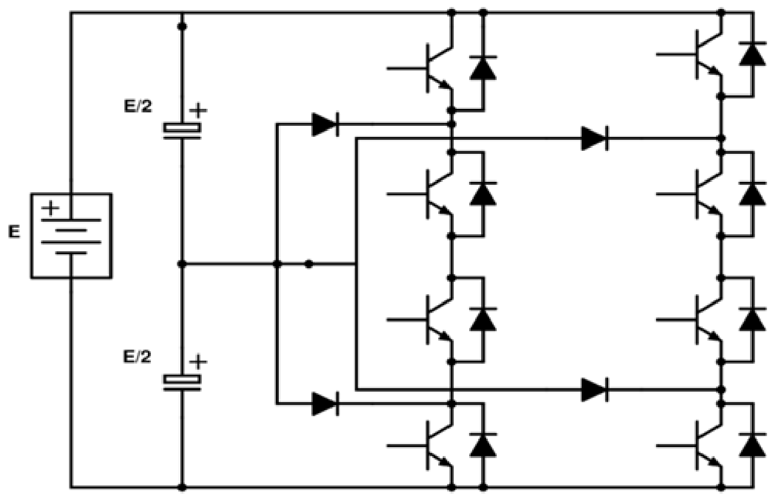


Figure 1. Neutral point clamped

The primary deficiency of NPC converters regarding the full bridge is that they require dual DC-link voltage [15]. For highly computable designs, we use the CFB converters. The combination of capacitors and switches pair is called an H-bridge and gives the separate input DC voltage for each H-bridge. It consists of H-bridge cells, and each cell can provide three different voltages like zero, positive DC, and negative DC voltages [16]. Inside the CFB converter, almost every full-bridge requires a power supply that should be insulated, and it should be matching with the field of multi-string PV [17]. CFB converters also have some other applications [18]. PV voltage changes always in PV applications due to maximum power point tracking (MPPT) and the variation of the radiation of solar. The voltage ratio can control output voltages [19].

The renewable energy systems (RESs) used with a grid has been considered a significant and critical task in the last decade, and it is due to a large number of usages of new power plants containing solar PV and wind energy [19]. The PV systems follow wind energy. In 2013, the total power of solar PV was almost 136 GW, which was globally installed, but in 2000 this power was just around 1.5 GW. From 2008-2013 the annual growth rate of solar has become nearly 40%. In 2013 Germany was the king of PV energy because 26% of the total PV energy was installed in Germany. Some other countries were also producing a vast amount of PV energy like the US, China, Italy, Spain, and Japan. [20]. There was a solar farm in the USA named a topaz solar farm, which was producing 550 MW of energy in 2015.

In the PV installation, the most crucial technique is grid-connected inverter configuration. The arrangement of PV cells falls into the main four groups, i.e., AC module and AC cell technology, centralized technology, string technology, multi-string technology. These approaches have some advantages and disadvantages [21, 22]. These approaches will accommodate many aspects like cost, harmonic generation, modularity, complexity, reliability, efficiency, safety, and flexibility.

For residential installations of PV, the string and multi-string configurations are considered as best. By using such a setting, losses that are related to the string diodes become minimal in comparison to other technologies. However, MPPT is achievable for all these strings, and it can be installed in various locations and sizes. There are multiple strategies for the implementation of string and multi-string technologies. Such techniques contain DC to DC converter and solar array, which are controlled by the MPPT algorithm. Then the output of these converters makes a DC voltage, which is converted into AC with the help of an inverter. A stand-alone renewable energy system (SARES) should provide the AC at its output for the consumer. Most of the SARES contain an energy storage device, which is mostly in the form of lead-acid battery banks. Both AC and DC bus modulators provide AC at the output for the consumer. Figure 2 shows a DC bus modulator.

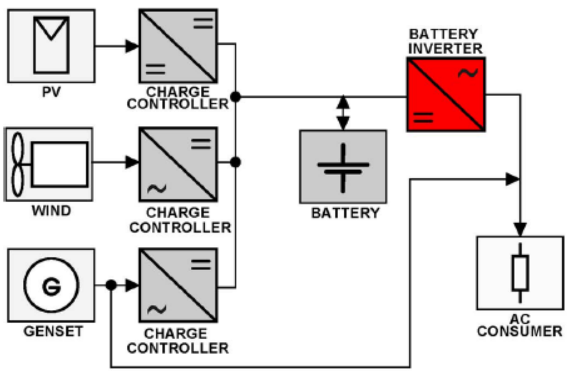


Figure 2. DC bus modulator [18]

Both the AC and DC modulator contain wind, the PV system, and the battery storage bank. Figure 3 shows an AC modulator. The main element in PV hybrid systems is the device, which converts the DC voltages of the battery into AC voltages. These DC to AC converters are mostly named inverters. From the last decade, these converters are widely used in industry and uninterruptible power supplies. The RES battery inverter has surge power capacity, reliability, efficiency, and no-load consumption. The most common multilevel converters are diode clamped multilevel converter (DCMC), also called neutral-point clamped as I discuss earlier, FCMC, cascaded multilevel converters (CMC). All these topologies are using a $2^{(n-1)}$ switching states to get 'n' voltage levels. Hence, one or more different switching state combinations are required for each level [23, 24].

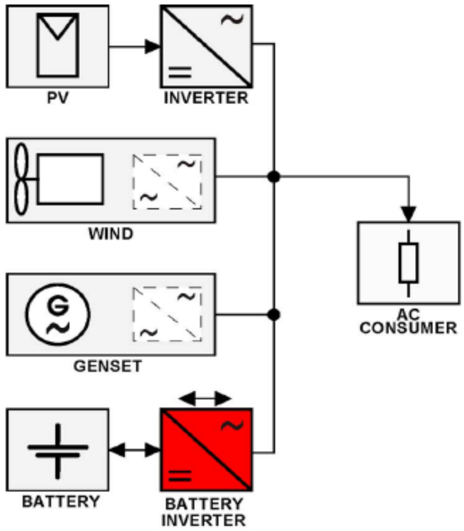


Figure 3. AC bus modulator [18]

To design such a combination, which has fewer power electronics switches but produces multilevel output is an important research area [25]. Hybrid multilevel converters (HMC) are used as an alternative for obtaining more voltage levels [26-28]. A five-level (ANPC5L) clamped active neutral point converter with the reduced component number was proposed by González *et al.* [29]. A related topology has been analyzed by Mohideen *et al.* [30]. Two distinct topologies are cascaded with a hybrid modulation strategy that constitutes a multilevel asymmetric cascade (CAMC) converter. On the contrary, the other five-level symmetric topologies, such as Flying capacitors multilevel converters (FCMC), DCMC, or cascaded multilevel converters (CMC), the CAMC uses almost half switching states, half diodes, and capacitors. The symmetric topology is limited to less number of voltage levels. For industrial applications, we are already using three-level DCMC (NPC). Producing more output levels with fewer switches is currently missing in the present body of knowledge.

By using the proposed converter (CHMC), these disadvantages of a lesser number of output levels with the less possible amount of power electronic switches are resolved. It has 17 different voltage levels, but the right voltage balance is maintained. It has eight H-bridges, which are connected in cascaded circuits. CHMC can be better for renewable energy systems because it does not require any clamping diodes and capacitors. The proposed 17 level CHMC will increase the system efficiency with less total harmonic distortion (THD) and improved modified sinusoidal output and has not been implemented in literature work so far. In this paper, our contribution is to achieve 17-level (8 positives, 8 negative, and zero levels) output voltage using CHMC. We also integrated our model with parallel PV-arrays rather than old DC supplies to get better efficiency due to the MPPT algorithm.

The following is the structure of this paper. Section 2 comprises of research method of a 17 level cascaded H-bridge multilevel converter. In section 3, all the results are discussed. In sections 4 and 5, the comparison of the proposed converter model with the classical model and industrial converters is presented respectively. Finally, the paper's conclusion is provided in the last section.

2. RESEARCH METHOD

The proposed model is derived from the literature on multilevel converters. Xue *et al.* [9] proposed a topology with 5 level converters using DC supplies, which we also use as a reference model. This proposed model contains a 17-level cascaded H-bridge multilevel converter, which is also integrated with eight separate solar PV arrays. The seventeen-level CHMC is used to convert the DC voltages into AC to drive the loads. The proposed converter is sinusoidal PWM controlled, which consists of a reference sinusoidal signal and sixteen triangular waves to achieve the desired 17 levels. Due to variation in environmental factors of temperature and irradiance, the output voltages of the solar module are also changed, but constant voltages are required to drive the loads. PV arrays are operated at a continuous irradiance and temperature to avoid the buck-boost converter for fixed DC voltages. Figure 4 presents the block diagram of the proposed system. To explain the working of our experimental model, a detailed flow chart is presented in Figure 5. The technical specifications of the components are presented in Table 1.

This flow chart is revealing that the temperature and irradiance are provided to the solar PV arrays, which produce DC voltages, and these varying DC voltages are stabilized using capacitor banks. Then these fixed DC voltages are fed to the CHMC to convert these into AC voltages, as shown in Figure 5. Fixed atmospheric temperature (i.e., 25ºC) and constant solar irradiance are the assumptions of this experimental work, but practically, temperature values change during the whole twenty-four hours. Moreover, solar irradiance is also assumed to be constant i.e., 1000 $Wm^{-2,}$ but almost solar irradiance is maximum during the day and is zero at night. These constant environmental factors are used to get a fixed DC output, which helped to avoid the use of buck-boost converters.

The power electronics switches are assumed to be ideal switches with almost negligible leakage current in block condition, and it's expected that switches have very little reverse recovery time. The sinusoidal PWM control technique is used in this paper, which has limitations of fixed PWM. So, practically we need to use buck-boost converters to obtain fix DC voltages at the input side of the converter to get a fixed output.

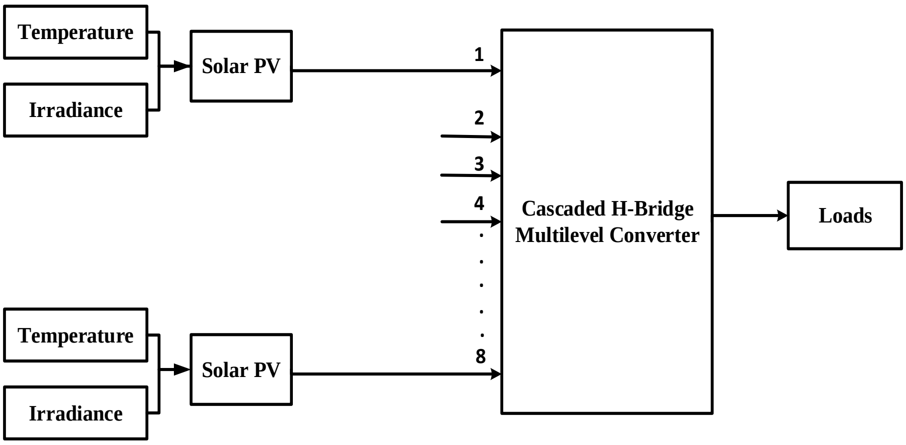


Figure 4. Block diagram of cascaded H-bridge multilevel converter implemented in solar grid

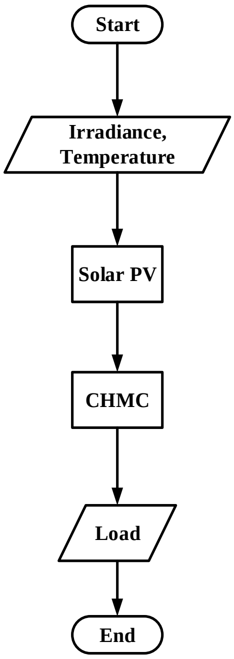


Figure 5. Flow chart of cascaded H-bridge multilevel converter implemented in solar grid

3. RESULTS AND DISCUSSION

The proposed converter is designed using eight cascaded H-bridges to achieve the desired seventeen level output. Each bridge constitutes four different MOSFET switches, and a total of eight bridges are used to complete the design model. Overall, thirty-two MOSFETs are used as power electronic switches to shift the converter output into sixteen levels, and an extra zero level is also added to achieve the total 17 levels. Figure 6 depicts the complete circuit of the design model. It is intended to design a flexible model for the PV array requirement. This proposed model is currently using eight isolated PV arrays, but all of these arrays can be replaced with constant DC voltage sources as per provisions in the circuit. Now, constant solar irradiance and temperature are applied to all the solar PV arrays used in the converter to make the model comparable with fixed DC voltage sources.

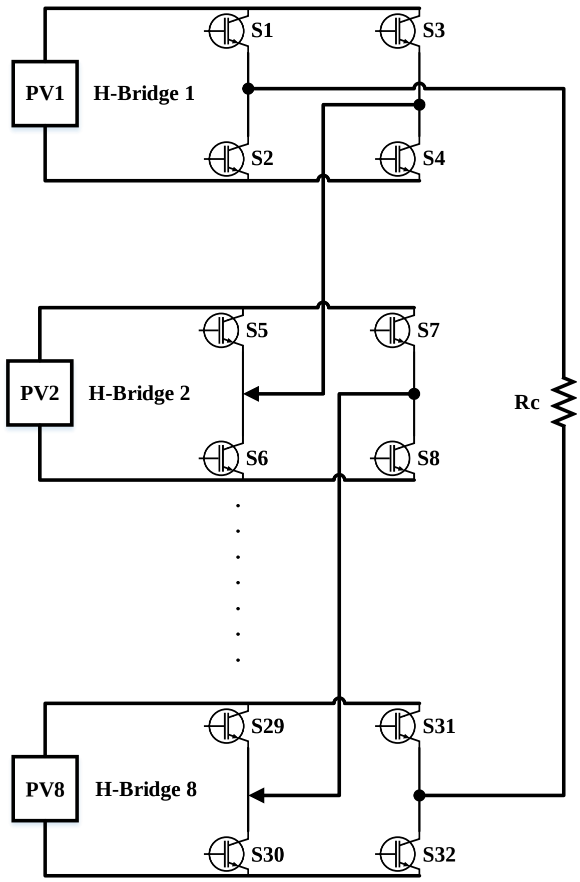
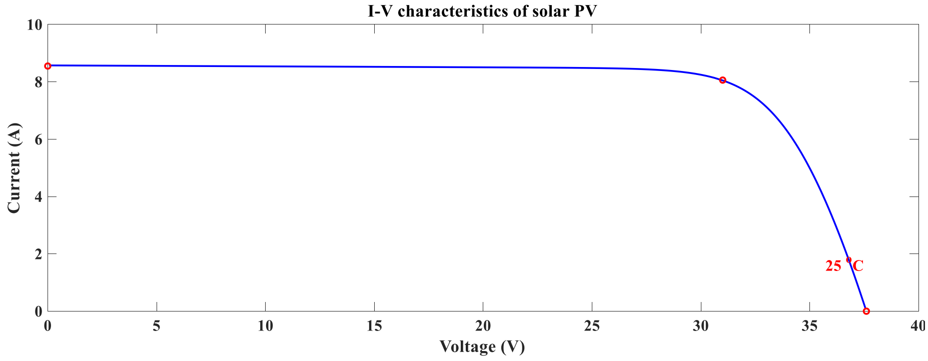
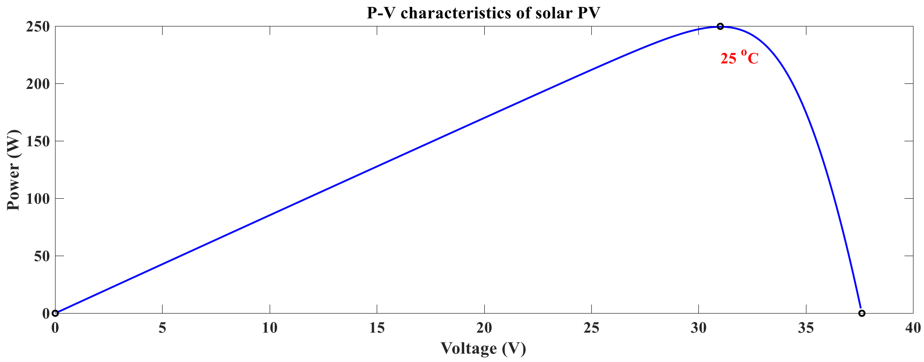


Figure 6. Circuit diagram of 17-level cascaded H-bridge multilevel converter

All the eight PV arrays are fed with 25ºC temperature and 1000 Wm^{-2} irradiance, and they are producing 31 V and 8.5 A at the output of each array, which can be changed by increasing or decreasing the PV modules. The overall power rating of the circuit is flexible and can be changed as per requirement. Simultaneously, the present I-V and P-V characteristics of a single PV array are shown in Figures 7(a) and 7(b), respectively, and the output characteristics of all other arrays are also identical. The I-V characteristic of the solar cell changes with the sunshine intensity (SW/m^2) and cell temperature t (ºC). The actual equivalent circuit of the PV array with an H-bridge is shown in Figure 6. Figure 7(a) and 7(b) illustrates the I-V and P-V characteristics at the constant illumination when the temperature changes. Temperature effects are the result of an inherent characteristic of crystalline silicon cell-based modules. They tend to produce a higher voltage as the temperature drops and, conversely, to lose voltage in high temperatures. Any PV array or system derating calculation must include the adjustment for this temperature effect.



(a)



(b)

Figure 7. Characteristics of a single PV array, (a) I-V, (b) P-V

Sinusoidal pulse width modulation (SPWM) is used to control the switching of MOSFETs. A sinusoidal signal of 50Hz is used as a reference signal, and sixteen different triangular signs are used as carrier signals to produce the required PWM. Although this PWM technique has a limitation of fixed output and changing DC input will provide changing AC output voltages, so fixed DC input is applied to the CHMC input side. The first eight carrier waves are used to the first four H-bridges, which are producing positive eight levels, and the next eight carrier waves are applied to the following four H-bridges to get the negative eight levels of the output. The control signal is shown below in Figure 8. The output of traditional inverters is three-level, which means they are full of harmonics and their THD level is high. However, loads require pure sinusoidal waveforms, and conventionally, bigger filters are needed to convert that three-level waveform into the sinusoidal wave. The addition of filters causes an increase in the cost of the system and makes it complicated. Filters also have power losses, so overall system loss has also been increased due to the addition of filters.

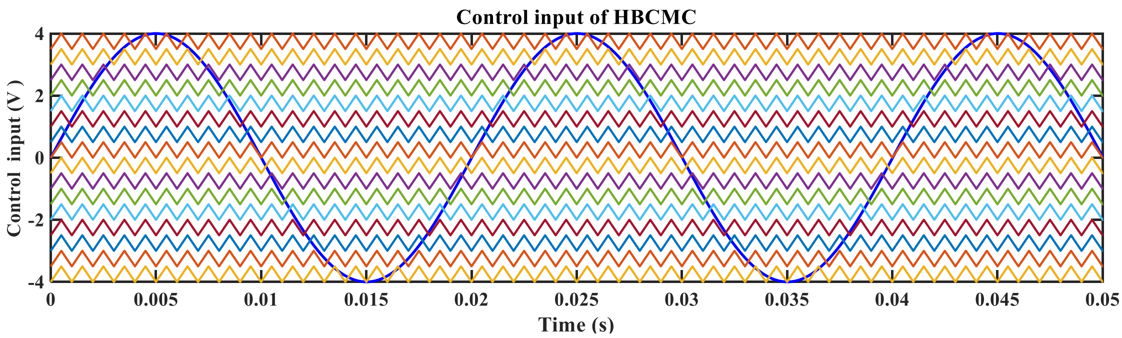


Figure 8. The control signal of the 17-level cascaded H-bridge multilevel converter

The proposed model consists of 32 switches, 8 H-bridges integrated with 8 PV arrays. These 32 switches, along with eight PV arrays, provide 17 levels (8 positives, 8 negatives, and zero levels) output voltage, as shown below in Figure 9. To achieve more levels of output voltage was to increase the system efficiency by minimizing the THD level. By making 17 levels of output, the presented model has significantly reduced the harmonic distortion, while the essential component is not lost. The THD level is shown in Figure 10 which demonstrates that the THD level is reduced to 6.9%.

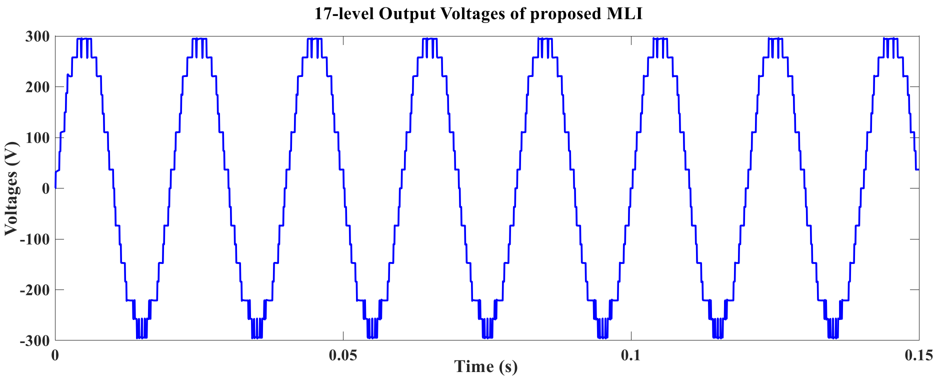


Figure 9. Seventeen level output graph of the proposed cascaded H-bridge multi-level converter

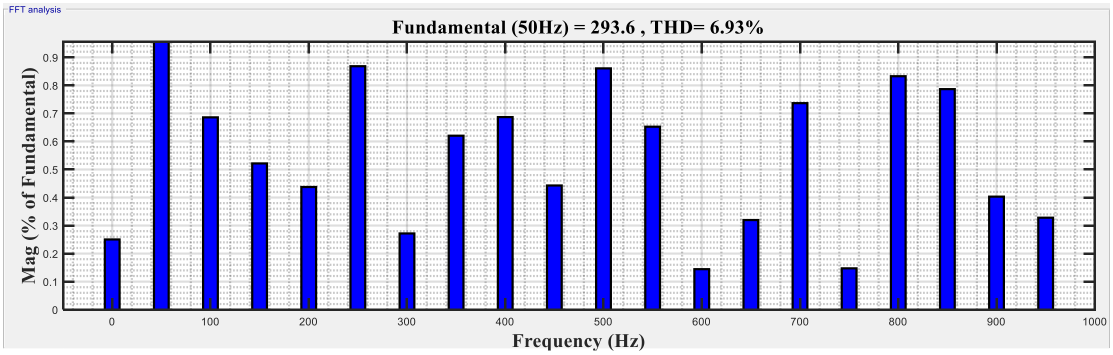


Figure 10. Total harmonic distortion level at the output of cascaded H-bridge multi-level converter

4. COMPARISON WITH REFERENCE MODEL

Xue *et al*. [9] proposed topology with a five-level converter using DC supplies. The reference model was including capacitors, while the proposed model does not need capacitors, and it has achieved a stable output that is stable without capacitors. Moreover, the reference model was using six power electronic switches in a single bridge, while the proposed model is using four switches in each bridge. The reference model also included diodes, while the presented circuit does not need any diodes. Hence, this paper has achieved state of the art and highly significant results, which are missing in the current body of knowledge. A detailed comparison is presented below in Table 2.

Table 2. Comparative analysis with a reference model

Parameters	Reference model	Proposed model
Number of output levels	5	17
Number of H-bridges used	1	8
Number of switches used	6	32
Number of diodes used	2	0
Number of capacitors used	2	0
Number of PV arrays used	0	8
Total harmonic distortion	21%	6.9%

Our main contribution is to achieve 17-level voltage output using a cascaded H-bridge multilevel converter, and we have integrated this CHMC with a PV array instead of DC supplies. In the classical model, only 5 levels achieved which has high THD and low reliability as compared to the proposed model. The proposed model is very much significant in comparison with the reference model because of more output levels, higher efficiency, and less THD. Table 3 demonstrates the THD for different multilevel converter topologies. Among these three converter topologies, the CHMC converter topology has the best harmonic performance. The harmonic performance of the NPC topology is not as good as that of the CHMC converter topology. The harmonic content decreases rapidly with an increasing number of levels. The CHMC converter is more economical than the others. The 17 level CHMC converter is a low-cost high-performance converter and it is suitable for the connection of an 11 kV system directly. Table 3 also shows the estimated cost of different converter topologies. Because of the lower voltage and current requirements, the total semiconductor cost of the 17 level CHMC converter is lower than all other topologies. The cost comparison of the proposed converter also proved its economic benefit over other types.

Table 3. Cost and performance of different multilevel converters [9]

Variable	NPC	FC	Proposed CHMC
IGBTs	60	60	32
Diodes	54	-	-
Capacitors	-	135	-
Total comp.	114	195	60
THD%	7.07	7.28	6.9
Complexity	41	55	55
Total cost (AU$)	115663	109545	82159

5. COMPARISON WITH INDUSTRIAL CONVERTER

Before the introduction of multilevel converters, the area of medium-voltage high-energy applications was dominated by current topology sources such as the PWM current source inverter (CSI) and the load commutated inverter (LCI). The major downside of the current source topologies lies in the limited dynamic output due to the use of large DC-chokes as DC-link. This is where multilevel voltage source converters come in as an interesting solution because they can achieve better dynamic efficiency, but without the dv/dt problems and voltage limit of the classic 2-level voltage source inverter.

6. CONCLUSION

This paper proposed a single-phase 17-level cascaded H-bridge multilevel converter (CHMC) model for a stand-alone system using solar photovoltaic (PV) arrays. The proposed model employed eight different flexible PV arrays that can be replaced with DC voltage sources when required to meet the load demand. The proposed model did not include any capacitor and filter thus saving a lot of cost in the overall system. The model was implemented in the Simulink environment using a model-based design approach. The simulation results showed that the proposed model has reduced the THD to almost 7% as compared to the existing models. The further direction of this study is to optimize the H-bridges to reduce the THD level as per the IEEE standard. Hardware implementation of this proposed Simulink model and comparison with the simulation results is also part of the future plan of authors.

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