Design & Simulation of novel Fuel Cell based High Efficiency 7-level Inverter

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Abstract- *Fuel cell inverters become more and more widespread within both private and commercial circles. These grid-connected inverters convert the available direct current supplied by the fuel cell and feed it into the utility grid. There is a strong trend in the photovoltaic inverter technology to use transformer less topologies in order to acquire higher efficiencies combining with very low ground leakage current. The goal of this paper is to reveal through simulation, some of the most effective and feasible power converters, already developed and large scale sold for different green energy sources, using new generation of semiconductors models. These high efficiency topologies are analyzed and discussed here in order to observe the advantages and the disadvantages between them. Also, it's almost mandatory to highlight the improvements of the last generation of SiC semiconductors in order to justify this work. The proposed concept is verified by using MATMAL/SIMULINK software and the corresponding results are presented.*

Keywords- Renewable Energy Sources, fuel cell (FC), Grid Connected System, DC/AC Converter Topologies

I. INTRODUCTION

Global energy consumption tends to grow continuously. To satisfy the demand for electric power against a background of the depletion of conventional, fossil resources the renewable energy sources are becoming more popular [1]. According to the researches [2] despite its fluctuating nature and weather dependency the capacity of renewable resources can satisfy overall global demand for energy. In recent years, the increasing demand for energy has stimulated the development of alternative power sources such as photovoltaic (PV) modules, fuel cells, and wind turbines. The PV modules are particularly attractive as renewable sources due to their relative small size, noiseless operation, simple installation, and to the possibility of installing them closer to the user. In PV modules, the output voltage has a low dc amplitude value. In order to be connected to the grid, the PV modules output voltage should be boosted and converted into an ac voltage. This task can be performed using one or more conversion stages (multi-stage).

The life cycle of the solar cell is more than 20 years, and it can minimize maintenance and management expenses. The output power of the solar cell is easily changed by the surrounding conditions such as irradiation and temperature, and also its efficiency is low. Thus high efficiency is required for the power conditioning system (PCS), which transmits power from the PV array to the load. In general, a single-phase PV PCS consists of single conversion stage (i.e., dc/dc conversion stage). The dc/dc converter is the optimal stage and it performs maximum power-point tracking (MPPT) and guarantees the dc-link voltage under low irradiance conditions. The power-electronic technology plays a vital role in distributed generation and in integration of renewable energy sources into the electrical grid/load. The increasing number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid/load in order to maintain or even to improve the power-supply reliability and quality.

Photovoltaic (PV) conversion approach is silent, modular, easily transportable and quickly installed. Power can be generated where it is required without the need of long transmission lines. Actually, terrestrial applications of photovoltaic panels provide auxiliary means of power generation. Also, there are installations in locations where other means of electricity supply would be as costly as photovoltaic panels. Moreover, this kind of installation provides important social benefits to rural communities throughout the world. Unfortunately, once there is a partial shadow on some panels, the system's energy yield becomes significantly reduced [2].

These grid-connected inverters convert the available direct current supplied by the PV panels and feed it into the utility grid. Transformer less PV inverters use different solutions to minimize the leakage ground current and improve the efficiency of the whole system, an issue that has previously been treated in many papers [1]–[3]. One of them is to connect the midpoint of the dc-link capacitors to the neutral of the grid, like the half-bridge, neutral point clamped (NPC), or three-phase full bridge with a split capacitor topology, thereby continuously clamping the PV array to the neutral connector of the utility grid. Half-bridge and NPC type of converters have very high efficiency, above 97%, as shown in [6]. Furthermore, the topology proposed in [6] reduces the dc current injection, which is an important issue in the case of transformer less topologies and is limited by different standards. This paper gives information about 5 converters structures, analyzing them regarding complexity and efficiency. It starts with simpler converters and ends with more comprehensive ones, but all of them have the main features: high efficiency, relative low number of semiconductors and the capability to inject energy into the grid without using transformers. Also, for conclusive results, each topology was designed at the same rated power, with the same active elements.

II. PROPOSED TRANSFORMERLESS CONVERTER TOPOLOGIES

The simulated converters presented and analyzed in this paper are: "Heric H5", "Coolcept Converter", "Cascade Boost-Switched-Capacitor Converter", "5 Level Converter" and "Soft switching Converter" [4].

A. Heric H5 Converter

This converter has one of the simplest topology and it is in the same time a very efficient one (Fig. 1). It has only five intelligently controlled transistors and by being transformer less, its efficiency is increased with about 3%, but instead of this, it has to solve all the issues related with the elimination of the transformer. That's why the fifth switch (S5) was introduced in the traditional H4 circuit. Its goal is to make the connection to the grid more efficient by eliminating the parasitical leakage currents. It also plays an important role in simplifying the command of the other four switches, using unipolar control strategy, resulting in decreased switching losses for two transistors.

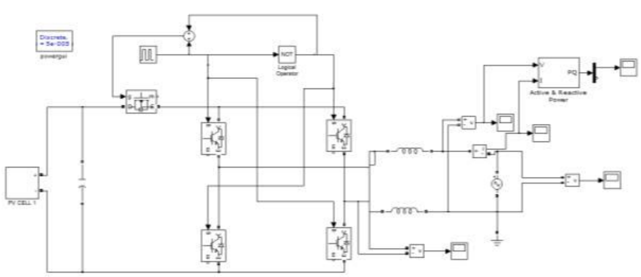
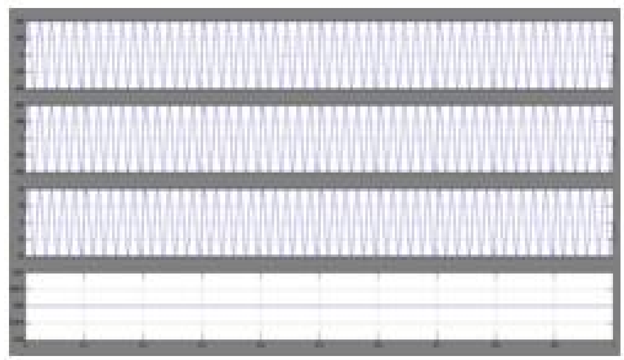


Fig 1. Heric H5 Converter

Related to the transistors and diodes, it's preferred to be chosen having the same parameters, because it's very important to obtain the voltage symmetrically distributed through the high frequency switched elements [4]. The simulation results are shown in Fig. 2 and were obtained using the elements converter & grid values. This value can be considered high enough to make it a competitive converter. The most important advantage is the fact that it realizes a separation between the grid and the power source, through the switch S5, eliminating this way the leakages currents from the grid into the photovoltaic panels, turbines etc. In the same time the switches S1-S4 of the inverter are intelligently switched. The unipolar strategy control removes the switching losses for two of the switches. The other two switches are PWM controlled and their losses depend by the transistors performance.

(a) PV Output Voltage & PV Power



(b) Converter Output Voltage, Grid Voltage, Grid Current, Total Power

Fig.2 Performance of Heric H-5 Converter (a) PV Output Voltage & PV Power (b) Converter Output Voltage, Grid Voltage, Grid Current, Total Power

Even though the topology is so simple, the biggest disadvantage of this converter is related to the fact that the energy source has to be much robust to supply the converter. Also the capacitors and the filters have to be larger and sometimes over dimensioned but still, because of the simplicity, its price makes this converter competitive. More than that, these characteristics make it very adaptive for Uninterruptible Power Supplies Applications. These kinds of systems are available on the market, ready to be sold. Most of them are readapted for the new tasks or even recycled and reconfigured.

B. Coolcept Converter

Coolcept" converter topology is presented in Fig. 3 and it comes with an innovative circuit design that achieves high efficiencies; it is now integrated into the Steca Grid inverters which are well sold for renewable energy applications. The Coolcept converter topology is based on a single-stage transformer less switching concept that uses proven standard components to implement symmetric step-down converters with downstream pole-reversing circuits. More than that, it is a multi-level topology and, because of the intelligent control, it can do all these tasks mainly with two of the all six transistors [6].

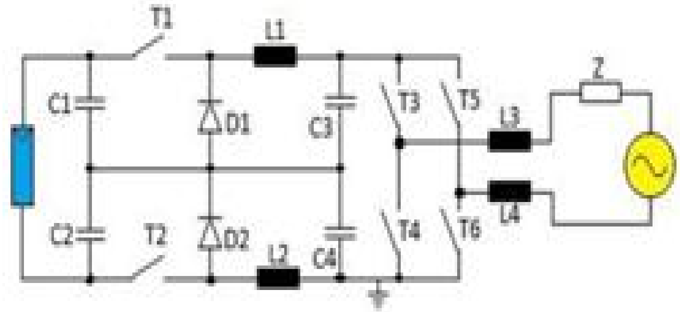


Fig.3 Schematic Diagram of Coolcept Converter topology

"Coolcept" converter, through its hybrid Buck stage on the DC Bus can operate on three levels. Its complexity is not so high and the most important, the losses are highly decreased by the number of transistors and the low frequency of the inverter. Previously, at its beginning, this topology was realized using IGBTs as switching elements, the most adequate technology available at that time. After a while, the development of MOSFETs has marked the existence of this topology, especially because of the improvements related to high frequency and less dependence by temperature. Nowadays, the SiC technology, which develops continuously, places this converter among the most effective structures [7].

By the way it works, this topology may be considered between the latest generations of high efficiency converters. For a better understanding is useful to split the system in two parts, the first part which acts as a two sided Buck converter and the second part which is a traditional inverter that works at very low frequency. It has to be mentioned that unlike the traditional Buck output, this time, the resulted shape of the output waveform consists in positive halves of a sinusoid, built on three levels. The inverter is the well-known traditional H Bridge with four transistors whose task is to let parts of the current to go through and alternate its sign. But this time it doesn't create the sinusoid by its own and only opens the opposite transistors of the two arms. This way a complete sinusoid with the frequency of 50 or 60 [Hz] is created by splitting the Buck output, letting one half of the sinusoid the way it is and inverting the other one.

The use of high performance semiconductors whose effects could be found in less lost power, improves our yields. More than that, if the losses are lower, imply that the temperature of the entire system is kept under control, which has positive repercussions over the life time of the converter. The results of the simulation are represented in Fig. 4.

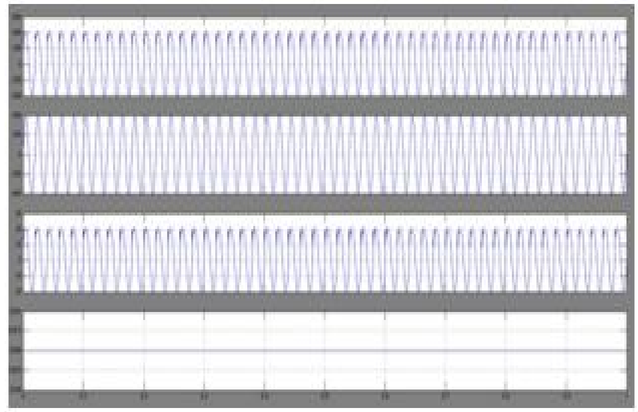


Fig.4 Converter Output Voltage, Grid Voltage, Grid Current, Total Power

Fig.4 Performance of Coolcept Converter, Output Voltage of Converter, Grid Voltage, Grid Current, Total Power of proposed topology. This is remarkable thinking to the fact that this converter offers the possibility of using lower filters because of its multi level operation mode. More than that, it can adapt itself to the power source acting like a Buck converter and offering the possibility of getting the maximum power point with a proper control and makes the efficiencies of these inverters only very slightly dependent on the module input voltage.

C. Cascade Boost-Switched-Capacitor Converter

In Fig. 5, a Cascade Boost-Switched-Capacitor Converter is presented. The efficiency of this converter is due to the low number of transistors chosen from the latest SiC technology and the type of commutation and control. Two structures, a switched-capacitor based boost converter and a two-level inverter, are connected in cascade. The DC multilevel output voltage which consists of series of positive halves of a sinusoid becomes the input voltage of the classical inverter, resulting in an alternating waveform for the inverter output voltage. Because the multilevel waveform is meant to be close to a sinusoid its harmonics can be reduced using multiple stages for the switched-capacitor converter. The output filter, very important for single stage converters, are now lower, resulting in a smaller size of the entire converter, as the switched-capacitor circuit dimensions can be reduced. Usually, both stages are operated at a high switching frequency, but in our case, only the DC stage is operated at high frequency, opposite to the inverter [8].

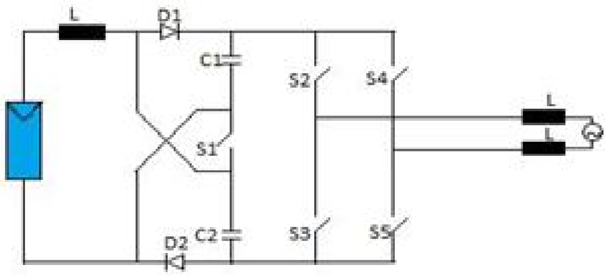


Fig.5 Cascade Boost-Switched-Capacitor Converter

For a better understanding, this converter also can be split in two: the DC part, respectively the inverting part. The DC part is a larger step-up ratio converter. Two identical capacitors are connected through the diodes to the output of a boost converter and this makes its step-up ratio to be much larger compared with the conventional boost converter. The explanation is that the capacitors are charged in parallel and discharged in series through the on-off transition of the main switching device S1. The circuit is simple and has some significant features of extended output voltage, less input current ripple and a lower output voltage ripple compared to the conventional boost converters.

The second part is a traditional one phase inverter. Considering this we can admit that the efficiency may be increased by using a more efficient topology for the inverter, but the main purpose of presenting this concept is that there are specific applications which can successfully use its particular features. The most relevant applications are the photo-voltaic ones, when the output voltage of the panels is under 50 volts [8,9].

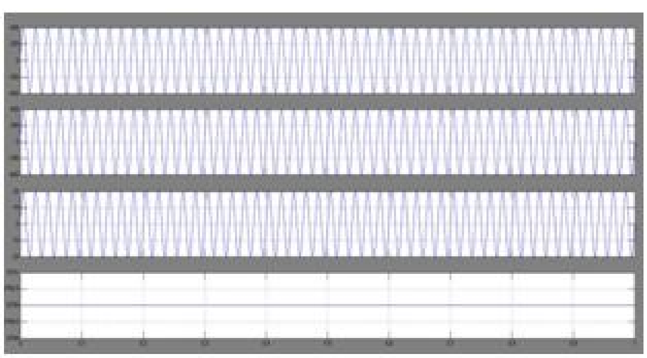


Fig.6 Converter Output Voltage, Grid Voltage, Grid Current, Total Power

Fig.6 shows the Performance of Cascade Boost-Switched-Capacitor Converter, Output Voltage of Converter, Grid Voltage, Grid Current, Total Power of proposed topology. The simulation was concentrated on the control of the main transistor S1 and the attention was focused on the DC component of the converter. The inverter was treated as a conventional bipolar inverter, just like the one used for the "Coolcept" topology. This solution doesn't affect pretty much the efficiency because the used components are models of high performance semiconductors; the needed control strategy of the inverter switches is allowed to be simple. Still it has to follow some conditions. In this case, this action forces a re-circulation of the leakage currents between the grid and inverter and does not push them to the power source. This is an important fact for all the transformer less topologies that does not have a galvanic isolation between the grid and the power source. The simulation results are represented in the Fig. 6.

The goal of this topology is to obtain multilevel inverters: a cascade of a boost-switched-capacitor converter which offers a larger step-up ratio and attached to this is a traditional full-bridge inverter. This circuit contains fewer elements than the other existent solutions for inverters with five-level output waveform. The multilevel output waveform can be improved, by simply adding more switched-capacitor circuits. Following to get a reduced harmonic distortion, the control procedures of the duty cycle used for the switches has been chosen to fluctuate between reasonable values. The presented converter may be considered an integrated cascade interconnection of two power stages. Having a simple and robust circuit, offering the possibility to get high voltage ratios with a transformer less configuration, the Cascade Boost-Switched-Capacitor Converter offers a good overall efficiency [10,11].

D. Soft Switching Converter

This is another topology whose number of switches is low enough to obtain lower switching and conduction losses. More than that, because of the way this converter works, the losses are even lower. At first sight, the converter which is illustrated in Fig. 9 looks like an incomplete "Coolcept" design. Actually it has the advantage of a lower number of elements.

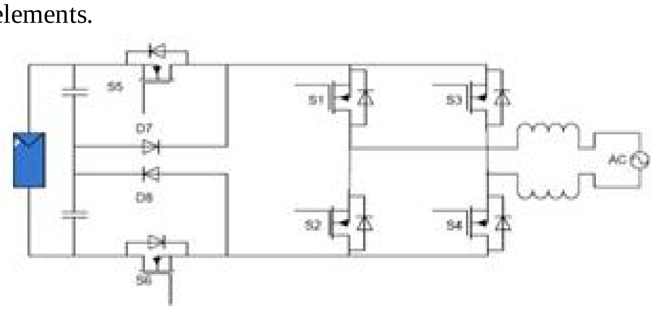


Fig 7 Soft switching Converter

To validate the characteristics of this converter, it was simulated in matlab, in order to obtain its efficiency and the certitude of working in specific conditions. In that SiC technology was introduced through the diodes and transistors, resulting in a proper efficiency, which makes this converter desirable in low power applications and smart grids, especially when the incoming energy is from a photovoltaic module. Also, by the way it works this converter pushes up the quality of the semiconductors to be so high, in order to decrease the conduction losses for the inverter and the switching losses, for the DC converter. Considering these facts, the designed simulation circuit achieved the results from Fig. 8 [15].

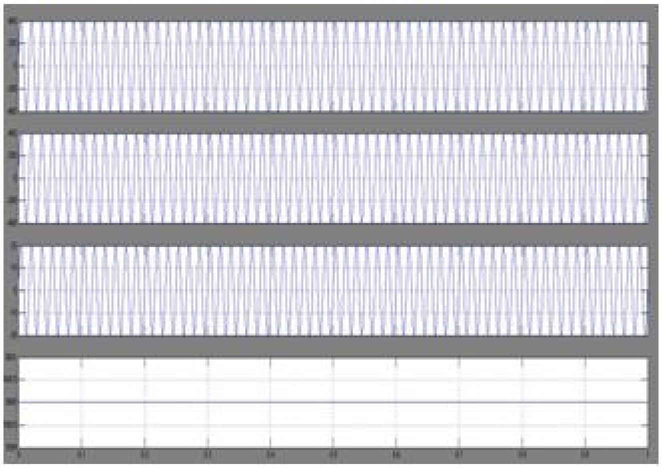


Fig.8 Converter Output Voltage, Grid Voltage, Grid Current, Total Power

As a conclusion, this is another topology that can be considered a convenient power-conversion stage for transformer less PV systems connected to the grid. Any improvement of its semiconductor, despite their higher price, has good repercussions for its efficiency and this will pay off later for the initial price of the converter [16].

E. 5-Level & 7-Level Converter Topologies

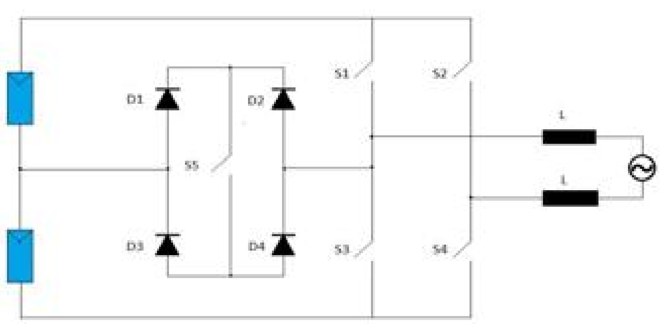


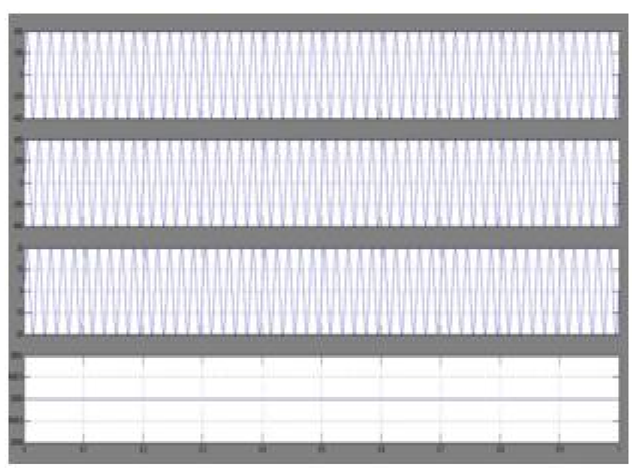
Fig. 9. 5 Level Converter.

This topology is illustrated in Fig. 9 and it is a single-phase multilevel converter that can decrease the harmonic components of the output voltage and load current. Operational principles and the switching functions are therefore analyzed. One switching element and four diodes are added to the conventional full bridge inverter. This additional module is connected between the middle points of the two sources and the two arms of inverter. With a proper switching control of the fifth transistor (S5), it generates a half level of the DC total supply voltage, and by alternating its sign, 5 levels of the final voltage are obtained (-Vin, -Vin/2, 0, Vin/2 and Vin). Just like the topologies presented before, the efficiency of this converter is mainly influenced by the switches performance. All transistors work at high frequency and it is very important to have very efficient diodes too.

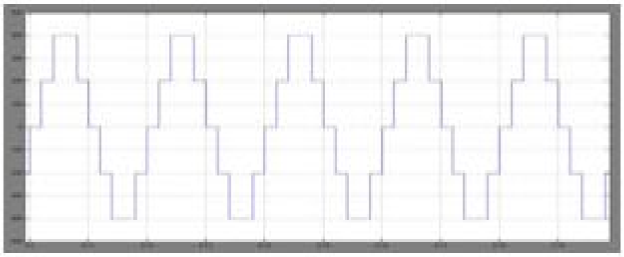
The topology of 5 & 7 Level converters has several promising advantages for the use as a single-phase, stand-alone photovoltaic system. One of these advantages is that this converter can be adapted to work with an additional DC-DC converter, influenced by the input source and power. Depending on the application where it’s used, the

5 Level converters can be configured differently. For example if it is used as a motor drive, it doesn’t require an output filter, because high order harmonics are effectively filtered directly by the reactance of the motor load; therefore, it can produce a high quality output alternative voltage and current with good harmonic characteristics. Also, it reduces stresses on power switching devices and the result is a lower Radio Frequency noise and Electromagnetic Interference.

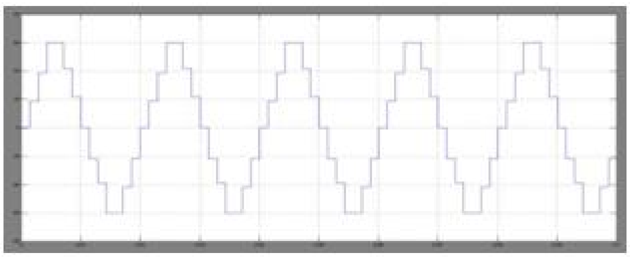
Also, this converter provides fewer Electromagnetic Compatibility problems, since multilevel inverters operate with a relative low switching frequency and voltage switching is done for lower voltage levels [14]. In the same time this converter offers good results when it is used in unconventional energy applications. The efficiency is high enough to be taken into account and more than that, the cost, complexity and performances are in balance.



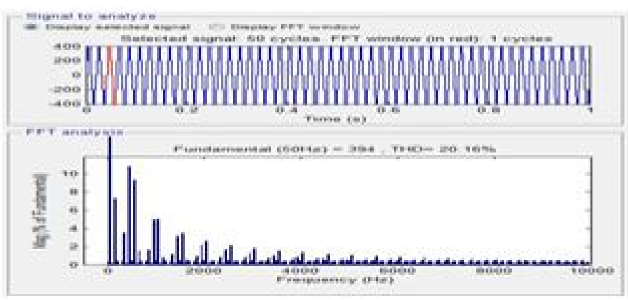
(a).5-Level Converter Output Voltage, Grid Voltage, Grid Current, Total Power



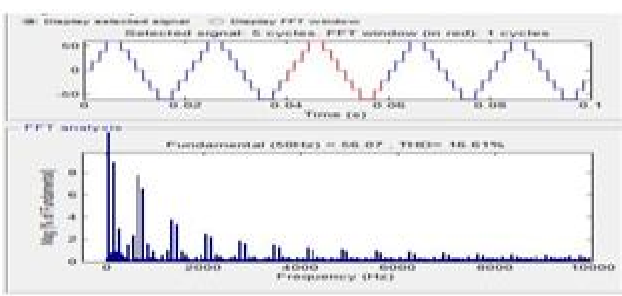
(b) Five Level Output Voltage



(c) Seven Level Output Voltage



(d) THD analysis of five level output voltage of proposed converter topology, here get 20.16%.



(e) THD analysis of seven level output voltage of proposed converter topology, here get 16.61%.

Fig.10 (a) 5-Level Converter Output Voltage, Grid Voltage, Grid Current, Total Power , (b) Five level Output Voltage, (c) Seven level Output Voltage, (d) THD analysis of five level output voltage of proposed converter topology, here get 20.16%., (e) THD analysis of seven level output voltage of proposed converter topology, here get 16.61% as levels increases get pure sinusoidal output waveform, then harmonic distortions goes to reduces no need of any large size filter to interact the grid.

VI. CONCLUSION

Renewable energy systems such as PV, solar thermal electricity such as dish-stirling systems, and WT are appropriate solar and wind technologies that can be considered for electric power generation. With the increase in load demand, the Renewable Energy Sources (RES) are increasingly connected in the distribution systems which utilizes power electronic Converters/Inverters. The most up to date topologies of grid-connected transformer less photovoltaic converters rely on the use of additional switches to fix the common mode voltage at the output of the power converter. Each of the five presented converters has a high efficiency, is suitable for unconventional energy applications and is integrated in systems that are already on the market. This paper is the result of trying to create realistic models of every topology, using the new technology of SiC semiconductors and analyze them and simulation results also presented as well as THD values well within IEEE standards.

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