



A Photovoltaic Cell based DG system using Interleaved Boost converter and Diode clamped multi-level inverter

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Abstract-With addition of DGs or Micro grids to the distribution system complexity increases substantially. Installing high performing DGs have many advantages. However if not implemented properly DGs can be become more harmful than beneficial. If these DGs are not properly controlled they may lead to grid instability. Implementation of renewable energy like Photo voltaic or Wind turbine based DGs usually requires implementation of both DC-DC converter and DC-AC voltage source Inverter (VSI). In our work we have specifically focused on DGs based on solar energy. In our proposed work we are using a PV Cell based power source, DC DC boost converter to convert low voltage DC to high voltage DC and finally a multi-level inverter to convert DC to AC. By using multi-level inverter we are able to produce better quality power and filters required to filter AC output will need low cost components. In order to simulate the results for different cases we created a SIMULINK model in MATLAB to generate our results. To generate all desired results we created two Models in MATLAB. First Model is based on conventional boost converter and conventional three phase inverter. While the second one is based on interleaved boost converter and five level diode clamped multilevel inverter. Simulation results confirm that proposed method performs better than conventional method.

Keywords: Distributed generation (DG); Interleaved boost converter; Diode clamped multilevel inverter

I INTRODUCTION

A power distribution system can be broadly be divided into two parts. Generation sources form the upstream parts

while distribution system forms the downstream part. Radial or loop or meshed arrangements are three popular configuration arrangements for a distribution system. Due to simplicity of implementation and lesser cost, still makes radial distribution a popular option. In order to increase the reliability of a radial distribution system, Load transfer technique is popularly used. The major limitation of load transfer is that thermal limits are not exceeded by the currents flowing in the health distribution feeders [1].

Fossil fuel still constitute as the major energy supplier across the world. Environmental concerns coupled with demand to produce more energy closer to consumption loads to increase stability of distribution system has created a lot of interest in clean technologies. This has led to the rapid development of renewable energy based power distribution system [2]. Other than environmental concerns, power quality improvements, safety and commercial incentives also increasing interest in the use of alternative energy sources. Alternative energy sources may include Solar, Wind turbine, fuel cells, micro-turbines, etc. [3]. Distributed power generation systems (DPGSs) based on renewable energy sources experience a large development worldwide, with USA, Japan, Denmark and Germany as leaders in the development in this field [2]. "It has been estimated that all of the world's electricity demands could be met several times over if 20% of the energy that could be harvested from wind farms across the globe were used." [4]

Microgrids are a part of a power distribution network and are located downstream of the distribution substation. Micro grids are usually Low voltage networks or at times medium voltage networks. An important feature of a micro-grid is that they can operate both in grid connected

mode or islanded mode or hybrid mode. Including Micro-grids in distribution system greatly enhances efficiency, stability, increased network scalability and resilience to outages [5] [6].

Introduction of distributed generation to power system distribution has become a trend in the world. DGs with the capacity up to 10 MW such as hydro generators, photovoltaic array, wind turbines and cogeneration systems are being connected to the power distribution systems [1]. The reasons behind increasing use of DG includes high cost of energy, environmental concerns and latest advancements in the DG technology [7].

Installing high performing DGs have many advantages. DGs can help in reducing the size of the power plants. DGs can also be installed in a modular way. DGs based on renewable energy sources such as hydropower, Wind turbines, PV cells, Fuel Cells, etc. can help in addressing environmental concerns. DGs have many technical advantages like improvements in voltage levels and reduction in power losses in radial lines. DG also promotes cogeneration as well as improves overall system efficiency.

However if not implemented properly DGs can become more harmful than beneficial. Location of DG installation has to be done carefully by assessing load type and its power consumption characteristics. Switching operations in DGs may cause transient effects. Short circuit level may be altered with the insertion of a DG. Stability margin may get reduced. Most protection schemes do not consider bi-directional power flow, causing unexpected operations of protection devices both in fault and healthy conditions. Distribution systems with DGs should also meet International standards for harmonic distortion, voltage imbalance, voltage fluctuations and fast transients irrespective of load type [8].

Power electronics based technologies are critical and are commonly used in DG power flow control. Voltage source converter (VSC) is employed by all DGs. Power control including real power P and reactive power Q controls of inverter based DG is of great importance and interest. The main challenge is to maintain or even enhance the system stability in grid connected mode, as well as providing quality power to local loads in islanded mode. Hence it is essential to employ power flow control techniques which results in stable system, fast response to transients and reduced coupling between active and reactive power [9].

Other than VSC some DG implementation also use DC DC boost converter to boost the lower voltages of some energy sources like PV Cell and provide acceptable high voltages for voltage inversion. Recent technology improvements in power electronics has led to development of Converters which can meet strict requirements for DG operation as mentioned before [10].

II Problem Description

Implementation of DGs require use of complex power electronics based devices. They also need to meet international parameters and technical constraints like grid frequency synchronization, low harmonic distortion, voltage imbalance, fast transients response etc. In a distributed generation, electrical power generation as well as electrical load both are installed in a distributed manner instead of a lumped generation or consumption. Unlike in traditional radial distribution system, Energy sources are closer to loads. This both improves the quality and reliability of the energy provided. However it makes the system more complex since both power and magnitude of power can change and mostly unpredictable. Moreover traditional protection devices cannot be used in distributed generation. Hence a robust control strategy is required. Relay and other safety devices need to be coordinated well, multi-control area are involved, for which a well-established and fast acting policy is required.

Implementation of renewable energy like Photo voltaic or Wind turbine based DGs usually requires implementation of both DC-DC converter and DC-AC voltage source Inverter (VSI). In our work we have specifically focused on DGs based on solar energy. Single solar cells do not produce sufficient power which can be directly converted to AC using inverter. Also voltage levels of these solar cells do not meet the voltage level requirements of distribution grids. Voltage levels of Solar Cells range in few tens of volts while of grid is of few kilo volts range. Lastly maximum power point tracking (MPPT) is essential to implement to draw maximum power from the solar cells. Because of all these reasons, it is very essential to implement a DC – DC converter to boost voltage level of Solar cells to acceptable level before inverting it to AC. Due to low power and low voltage levels of Solar cells, they are mostly connected in series parallel combinations. Here also DC DC converter plays a critical role to both manage the power flow and draw maximum possible power from solar cells using MPPT algorithms. Another important role of DC-DC converter to maintain constant DC Bus voltage which is then fed to inverter circuits to convert DC power to AC power. The introduction of DC Bus helps to significantly reduce transients during DC AC inversion. When there is sudden connection and disconnection of loads happens to AC grid, without Bus DC or DC-DC converters, transients will be significantly higher and at times it may altogether fail to adjust to sudden electrical condition.

DC-AC inverter on the other hand is essential to supply AC power to the grid. The inverter main task is to produce AC power with same voltage and frequency levels. It is also essential that when connecting to grid, frequency of power generated by inverter and grid frequency must be synchronized. This is also task of DC-AC inverter to

match grid frequency synchronization. Other than that DGs have one more advantage. Along with active power, they can both produce or consume reactive power. This feature is of great importance since it enhances the stability of the grid. However proper implementation of DGs is essential otherwise rather than stabilizing DGs can even de-stabilize the Grid. There are many topologies developed for inverters. However multi-level inverters have seen less use in DGs. Multi-level inverters can enhance the harmonic performance of the inverter circuits. They also reduce the stress on power electronics devices thereby reducing cost and enhancing life of power electronics used.

Power flow control is a steady state condition which aims to meet constraints of voltage levels, currents, real and reactive power under a given load conditions. Energy produced by the renewable energy sources can be transferred to the grid by controlling the amplitude of the voltage produced by DG, and the angle (β angle) between the grid voltage and the DG voltage through a coupling inductor (LS). VSI used in a DG unit provides a real and reactive power as expressed in the equations below:

$$P = \frac{V_s V_{cf}}{X} \sin \delta$$

Where, V_s is equivalent main voltage, X is equivalent line reactance, V_{cf} is equivalent receiving main voltage and δ is phase angle.

To control power flow from DG to grid the voltage angle DG should be ahead of voltage angle of grid. In this condition DG will deliver active power to the grid. In case it is less than grid voltage angle, then DG absorbs active power from the grid. On similar lines, if voltage amplitude of DG is more than Voltage amplitude of Grid, DG delivers reactive power to the grid. While in opposite case DG will absorb reactive power from the grid. The β angle is determined by the average power flowing to the grid. The relationship between V_A and V_{source} and I_{source} can be expressed as:

$$V_A \cos \beta = V_{source}$$

$$\frac{V_A \sin \beta}{X_q} = I_{Asource}$$

[A] DC-DC converter

A DC-DC converter is used as an interface between energy source and DC voltage bus. This DC voltage bus is fed to inverter which converts it to AC power. A step up converter is used to boost the voltage generated by energy sources. It also provides required energy during fast transients required by local loads. As a result disturbances are minimized in feeder current. For an inverter, a DC-DC

converter simply acts as a DC energy source. But to deliver maximum power, Maximum power point tracking (MPPT) is required. This algorithm is also implemented by DC-DC converter. For stable operation of converters, proportional integral (PI) controllers are popularly used. PI constants can be calculated using phase-margin method and cutoff frequency. Equations to calculate the constants are as under:

$$k_{prop} \frac{G_{OL}}{\omega_{FCL}} = 1$$

$$k_{int} = k_{prop} \frac{\omega_{FCL}}{\tan(mf)}$$

Where, G_{OL} is open loop gain, ω_{FCL} is angular frequency and mf is phase margin. Because of wide variation in input voltage and variation in ambient conditions (such as temperature, irradiation), we require the feedback controller to stabilize and augment the output voltage of the entire system through the PI controller. A typical dc-dc converter have two stages of PI controllers, one each for voltage and current references. The respective gains are generally designated as P_v and P_i . More details about it are discussed in proposed work section.

[B] DC-AC Inverter

PI controllers can again be used for DC-AC inverters. Here also closed loop control can be implemented both for voltage and current. It will guarantee the power quality. The design method for PI controllers is same as DC-DC converters. In order to achieve good compensation, closed loop cut off frequency is chosen one decade below the switching frequency. This may still result in residual error for lower frequencies. To remove them we can use feed-forward of reference voltage. The power requirement of the proposed topology is very high, which requires a lower switching frequency. This will increase the harmonic components in the AC power generated by inverter. In order to minimize these harmonics, a resonant controller is used in parallel with conventional PI controller. Using a multi-level inverter can also help in minimizing harmonics and reducing stress on power electronics devices. More is discussed in proposed work section.

[C] Grid use case

In order to implement the proposed algorithm which is discussed in subsequent sections, we chose a grid used case which includes 13.8KV feeders connected with 69 KV radial line through a 69/13.8-kv substation transformer. A DG is inserted to the distribution system by using 13.8/0.38 KV transformer. Breakers were also added to isolate DG from distribution system, in case DG works in islanded mode. Since power levels of both voltage and currents are very high, PWM switching frequency is

chosen as 12 KHz. Another parameter that of concern while connecting to grid is grid frequency synchronization. For this purpose Phase lock loop (PLL) algorithm can be used. PLL also calculates the average of internal product between V_{source} and V_{grid} . If the product is equal to zero in steady state both sources are perpendicular to each other.

Connecting DG to a grid is a two-step process. First we need to produce AC source whose frequency is synchronized with the grid. Once frequencies are synchronized then zero crossing point has to be identified. When both frequencies crosses zero, switches are closed to connect DG to grid. Closing switches at zero crossing minimizes the transient effects. After that a soft power transfer is initiated and slowly it is increased to required levels. Overall this process helps to minimize the disturbances to minimal level.

III Proposed Work

In our proposed work we are using a PV Cell based power source, DC-DC boost converter to convert low voltage DC to high voltage DC and finally a multi-level inverter to convert DC to AC. By using multi-level inverter we are able to produce better quality power and filters required to filter AC output will need low cost components. Detailed description and construction of all three components are discussed below:

[A] PV CELL modeling and construction

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic (PV) cell. The photovoltaic module is the result of associating a group of PV cells in series and parallel and it represents the conversion unit in this generation system. An array is the result of associating a group of photovoltaic modules in series and parallel. [11]

In our work we have modelled PV array as a simple ideal voltage source with an internal resistance in series as shown in figure below:

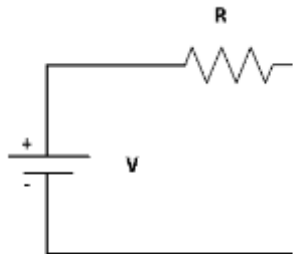


Fig 1. PV array modelling as a simple ideal voltage source

Also it is assumed that panel is comprised of N_s cells in series and N_p cells in parallel to achieve required voltage

current and power levels. The value of V and R are derived as function of irradiance E and temperature T . The equations for the same are as mentioned below:

$$V = N_s \times V_{oc}$$

$$V_{oc} = R_p \cdot [I_{ph} - I_{s1} [e^{\frac{V_{th}}{V_T}} - 1] - I_{s2} [e^{\frac{V_{th}}{A V_T}}]]$$

While for resistance the values are as under:

$$R = [(V_{oc} - V_{pm}) / I_{pm}] \times (N_s / N_p)$$

Where V_{pm} and I_{pm} are voltage and currents values when array maximum powers. These values are calculated from V-I characteristics of PV cell.

[B] DC-DC Boost converter

DC converters are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklifts trucks, and mine haulers. They provide high efficiency, good acceleration control and fast dynamic response [12]. The DC/DC converters are widely used in regulated switch mode DC power supplies. The input of these converters is an unregulated DC voltage, which is obtained by PV array and therefore it will be fluctuated due to changes in radiation and temperature [13].

There are many topologies popular for boost converter. Conventional topology being the simplest one, has one voltage source, one inductor on switching device, one diode and at least two capacitors both at input end and output end. Conventional topology is simple hence of lower cost. However it has high ripple current on passive and active components, large voltage stress on power switches and requires large capacitor values for keeping output voltage steady [14].

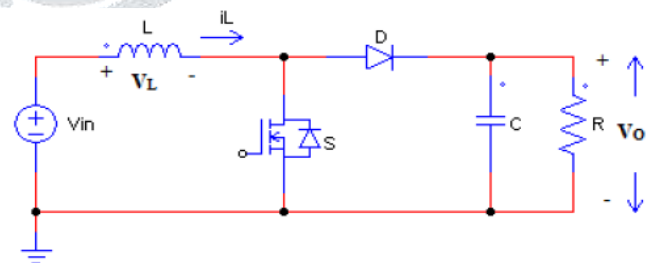


Fig 2. Conventional boost converter

Interleaved boost converter is another topology which is based on binary branches operating 180 degree out of phase from each other. Generally each phase operates in the same way as conventional boost converter. Due to binary branches there is effective doubling effect on operating frequency which has many advantages. Output ripples are halved hence lower capacity capacitors are required both at input side and output side. Since the current is also divided across the two branches, over all power losses (I^2R) are also reduced. Due to lower current

in each branch stress on power electronic switches is also reduced. However on negative side, due to two branches cost may increase. But this cost may be compensated by the fact that now much lower rating components are required [14][15].

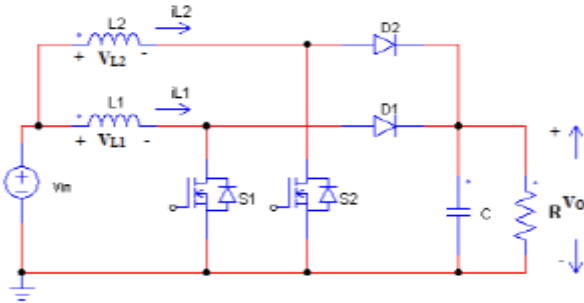


Fig 3. Two stage Interleaved boost converter

[C] DC-AC Inverter

Inverters are power electronics based circuits which can convert a DC power to AC power. Conventional inverters have two levels and they can generate AC power from a DC source. Pulse width modulation switching scheme is used in conventional inverters to generate AC power. Shown below is the topology of a conventional inverter:

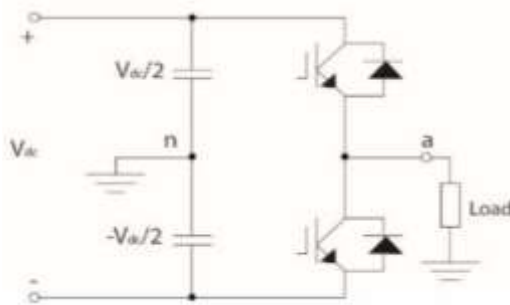


Fig 4. Topology of a conventional inverter

Based on DC source there are two categories of multilevel inverters. First one is Single DC source based inverters which has two variants. The first variant is diode clamped multilevel inverter. The second variant is Flying capacitor inverter. Second category is based on multiple DC sources. In such case Cascaded multilevel inverter is used. In our proposed work we have used diode clamped multilevel inverter as shown below:

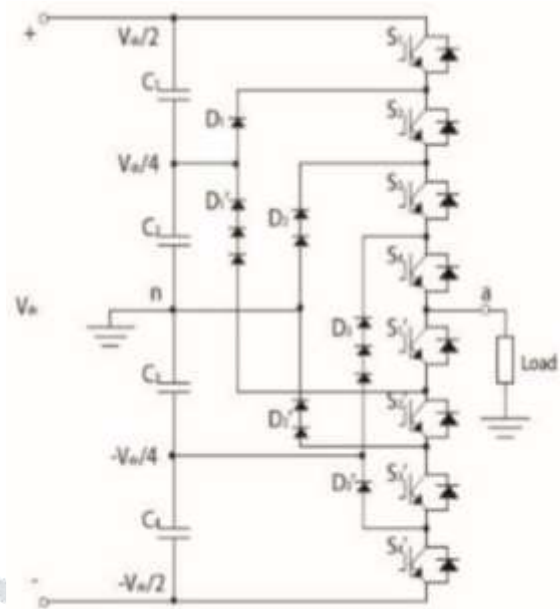


Fig 5. Topology of a diode clamped multilevel inverter

IV Simulation and Results

In order to simulate the results for different cases we created a SIMULINK model in MATLAB to generate our results. In this section we are discussing the implementation of different Models that we used in our thesis to generate desired simulation results. To generate all desired results we created two Models in MATLAB. First Model is based on conventional boost converter and conventional three phase inverter shown below:

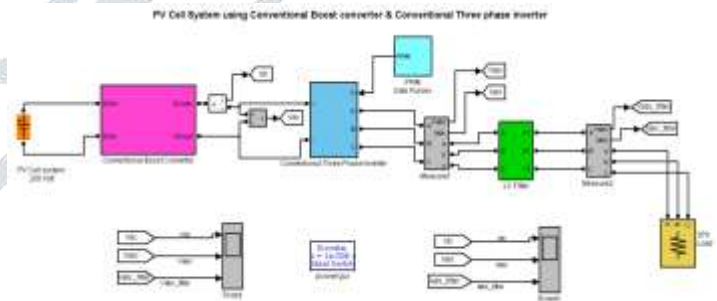


Fig 6. Matlab Model based on conventional boost converter and conventional three phase inverter

This model consists of a PV Cell system which act as a power source and voltage of this PV Cell system is chosen as 200 volt. Next block is conventional boost converter which boost 200 volt to approximately 400 volt. This 400 volt is then fed to a conventional three phase inverter which converts it into three phase AC. To control the three phase inverter a PWM input has to be given, hence a

PWM block is used. To measure the output of Inverter we have used a three phase measurement block. After that we have used a LC filter to filter the harmonics in the AC output. Then again to measure the voltages and currents after filtering the harmonics, we used another three phase measurement block and finally a three phase 5KW load is used. The simulation results of boost converter are as shown below:

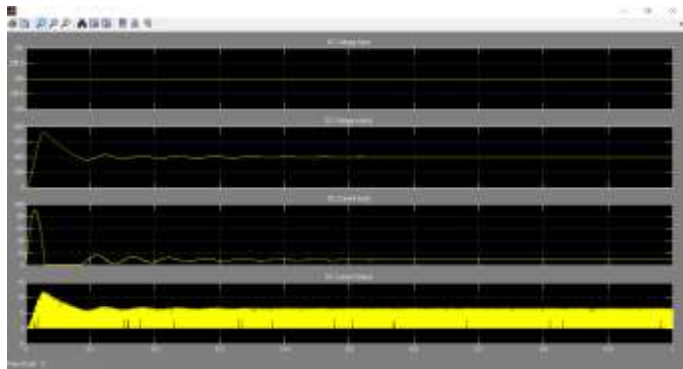


Fig 7.Voltage and current waveforms of conventional boost converter

The first two graphs from the top are input and output voltages of boost converter. Since Input DC voltage is constant, hence we are seeing a straight line in the first graph. In the second graph we are seeing the output of Boost converter. Initially when boost start operating, we are seeing some voltage spike, which stabilizes after some time to 400 volts. In the third graph we are seeing the current drawn from the input source while in the fourth graph we are seeing the output current waveform of Boost converter. The simulation results of conventional H-Bridge Inverter are as shown below:

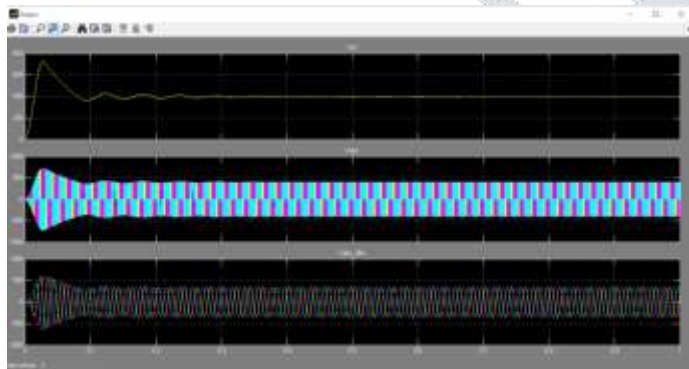


Fig 8.Voltage waveforms of conventional H-Bridge Inverter

In the first graph we are seeing is the DC input voltage to inverter circuit, second graph is three phase AC voltage output of inverter while the third graph is three phase AC output voltage after filter. Similarly Current waveforms are shown below:

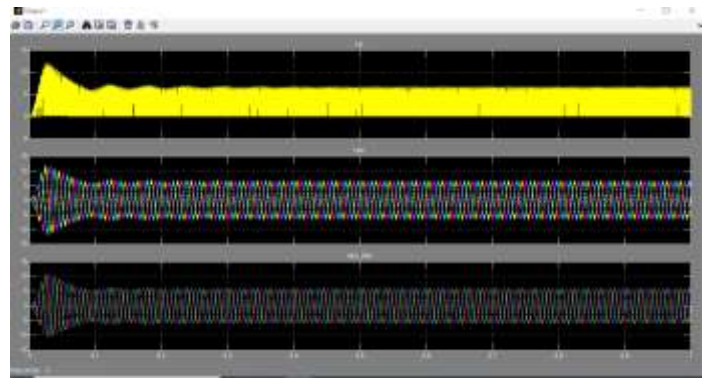


Fig 9.Current waveforms of conventional H-Bridge Inverter

If we take a zoomed in view of the Voltage output of conventional boost converter after it reaches steady state (after 0.8 seconds), we can measure ripples in output voltage. The zoomed in DC waveform is shown below:

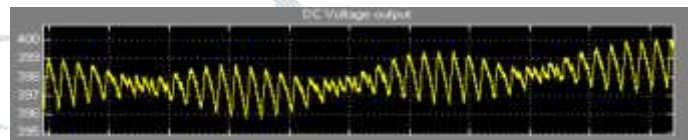


Fig 10. Zoomed in view of the Voltage output of conventional boost converter

As it is clearly seen in the figure above, DC voltage varies between 395.5 volts to 400 volts. Hence voltage ripple is of 4.5 volts peak to peak. Total Harmonic distortion in case of conventional system is measures as 68.96% as shown below:

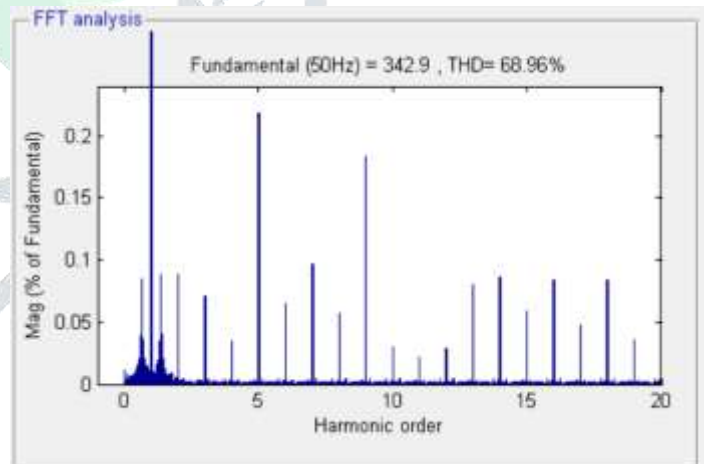


Fig 11.Total Harmonic distortion in case of conventional system

In our proposed work we have used an interleaved boost converter instead of conventional DC-DC boost converter and a five level diode clamped multilevel inverter instead of conventional H Bridge three phase inverter. The simulation model for the proposed work is shown below:

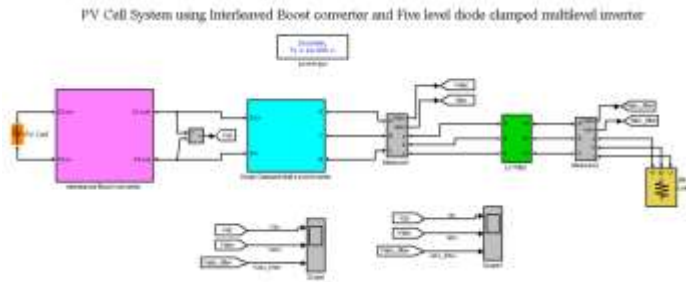


Fig 12. Matlab Model based on interleaved boost converter and five level diode clamped multilevel inverter

This model consists of a PV Cell system which act as a power source and voltage of this PV Cell system is chosen as 200 volt. Next block is interleaved boost converter which boost 200 volt to approximately 400 volt. This 400 volt is then fed to a five level diode clamped multilevel three phase inverter which converts it into three phase AC. To measure the output of Inverter we have used a three phase measurement block. After that we have used a LC filter to filter the harmonics in the AC output. Then again to measure the voltages and currents after filtering the harmonics, we used another three phase measurement block and finally a three phase 5KW load is used. Except interleaved converter and diode clamped inverter all other blocks are same as in case of conventional model. The simulation results of interleaved boost converter are as shown below:

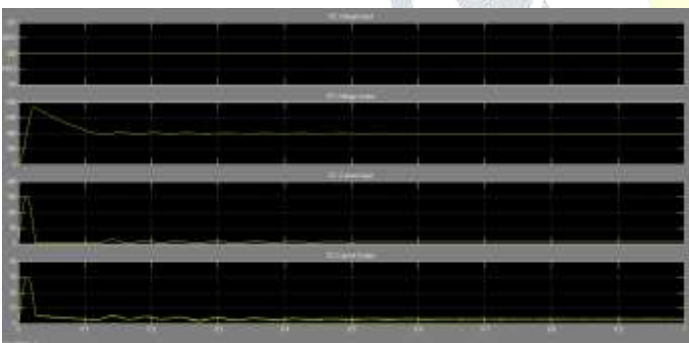


Fig 13. Voltage and Current waveforms of Interleaved boost converter

The first two graphs from the top are input and output voltages of boost converter. Since Input DC voltage is constant, hence we are seeing a straight line in the first graph. In the second graph we are seeing the output of Boost converter. Initially when boost start operating, we are seeing some voltage spike, which stabilizes after some time to 400 volts. In the third graph we are seeing the current drawn from the input source while in the fourth graph we are seeing the output current waveform of Boost converter. The simulation results of diode clamped Inverter is shown below:

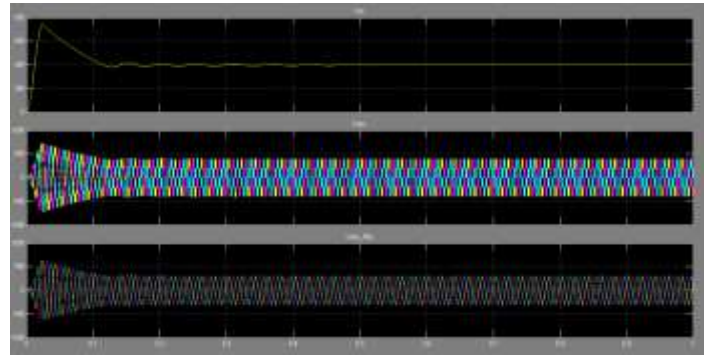


Fig 14. Voltage waveforms of diode clamped inverter

In the first graph we are seeing is the DC input voltage to inverter circuit, second graph is three phase AC voltage output of inverter while the third graph is three phase AC output voltage after filter. Similarly Current waveforms are shown below:

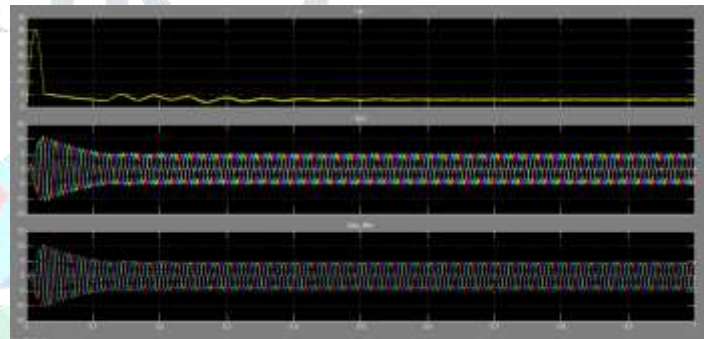


Fig 15. Current waveforms of diode clamped inverter

If we take a zoomed in view of the Voltage output of interleaved boost converter after it reaches steady state (after 0.8 seconds), we can measure ripples in output voltage. The zoomed in DC waveform is shown below:

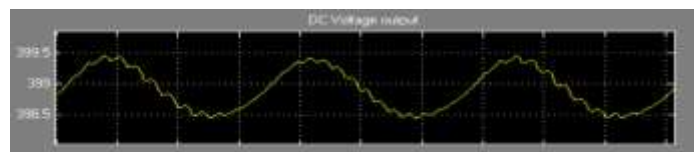


Fig 16. Zoomed in view of the Voltage output of interleaved boost converter

As it is clearly seen in the figure above, DC voltage varies between 398.5 volts to 399.5 volts. Hence voltage ripple is of 1 volt peak to peak. Total Harmonic distortion in case of proposed system is measures as 42.23% as shown below:

V CONCLUSION

With latest advancements in DG technology, acceptance of Distributed Generation is increasing because of high cost of traditional energy sources and positive impact of DG on environment. Introduction of DGs however makes the overall system more complex. If implemented well it may increase the stability of overall system but if not implemented in correct manner it may become more harmful than beneficial. In our proposed work we have used an interleaved boost converter instead of conventional DC-DC boost converter and a five level diode clamped multilevel inverter instead of conventional H Bridge three phase inverter. Simulink Models were created in MATLAB to compare proposed method with conventional method.

Simulation results suggest that boost converter DC voltage Output ripples in case of conventional method is around 4.5 volts peak to peak while that for proposed method it is just 1 volts. Similarly THD of conventional method is 68.96% while that of proposed method it is 42.23%. Settling time of overall system was faster in proposed method. Also inverter input current was lower as well as less fluctuating in our proposed method. So it is concluded that proposed method performs much better than traditional method for PV Cell system.

We have proposed our system for medium level power requirements. So for future work, for very high level power requirements future researchers may explore implementation of three or more level interleaved boost converters. Many other complex topologies may also be considered. Similarly for multi-level inverter, flying capacitor multi-level inverter and cascaded H-Bridge inverter may be considered. However these topologies are much costlier and more complex. Hence future work on the above should focus on applications with very high power requirements as priority. Research work is in progress in consideration of the structure complexity and the control circuits.

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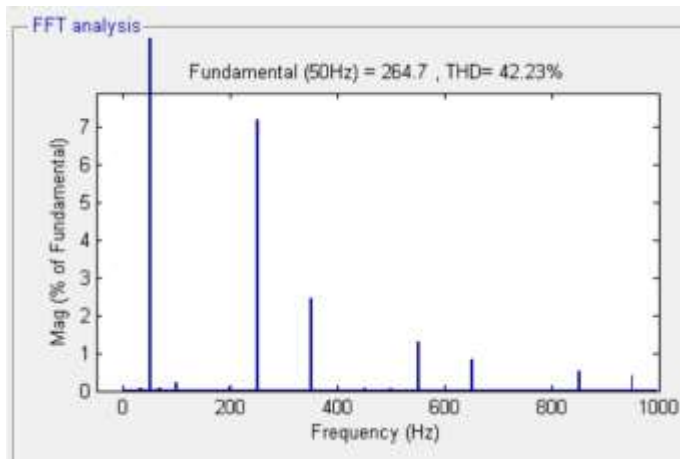


Fig 17.Total Harmonic distortion in case of proposed system

TABLE I

SUMMARY OF SIMULATION RESULTS

Parameter	Conventional	Proposed	Comments
Voltage ripples	4.5 volts peak to peak	1 volts peak to peak	Proposed method performs better
THD	68.96%	42.23%	Proposed method performs better
Settling time	Slower	faster	Proposed method performs better
Inverter Current Input	Higher and too fluctuating	Lower and more stable	Proposed method performs better

Hence based on summary we can conclude that proposed method performs much better than conventional PV Cell system.

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