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Parallel Operation of Modular Single-phase Transformerless Grid-tied PV Inverters with Common DC Bus and AC Bus

Gayathiri G[1], Jaisriram K[2], Santhosh V[2], Muniyappan.K[2], Pushpakaran.P[2]
[1]Assistant Professor, Department of EEE, Narasu's Sarathy Institute of Technology, Tamil Nadu, India
[2]Students, Department of EEE, Narasu's Sarathy Institute of Technology, Tamil Nadu, India

ABSTRACT

In order to eliminate the common-mode (CM) leakage current in the transformer less photovoltaic (PV) systems, the concept of the virtual dc bus is proposed in this paper. By connecting the grid neutral line directly to the negative pole of the dc bus, the stray capacitance between the PV panels and the ground is bypassed. As a result, the CM ground leakage current can be suppressed completely.

Meanwhile, the virtual dc bus is created to provide the negative voltage level for the negative ac grid current generation. Consequently, the required dc bus voltage is still the same as that of the full-bridge inverter. Based on this concept, a novel transformer less inverter topology is derived, in which the virtual dc bus is realized with the switched capacitor technology. It consists of only five power switches, two capacitors, and a single filter inductor. Therefore, the power electronics cost can be curtailed. This advanced topology can be modulated with the unipolar sinusoidal pulse width modulation (SPWM) and the double frequency SPWM to reduce the output current ripple. As aresult, a smaller filter inductor can be used to reduce the size and magnetic losses.

Keywords—PVSystem, TransformerlessInverter, SPWM, Virtual DC bus concept, Operation Modes of the circuit, Hardware Theory

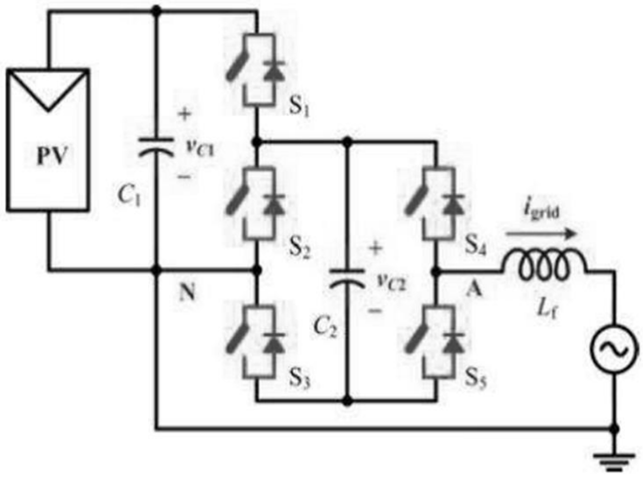
I. INTRODUCTION

The distributed photovoltaic (PV) power generation systems have received increasing popularity in both the commercial andresidential areas. In most occasions, the inverters are used tofeed the PV power into the utility grid. It is important for thePV inverter to be of high efficiency, due to the relatively highprice of the PV panels. Small size is also strongly desired forthe low-power and single-phase systems, especially when theinverters are installed indoor. The word "photovoltaic" combines two terms –"photo" means light and "voltaic" means voltage. Aphotovoltaic system in this discussion uses photovoltaic cells todirectly convert sunlight into electricity. Photovoltaic powergeneration employs solar panels composed of a number of solarcells containing a photovoltaic material. Materials presentlyused for photovoltaics include mono crystalline silicon,polycrystalline silicon, amorphous silicon, cadmium telluride,and copper indium gallium selenide/sulfide. Due to theincreased demand for renewable energy sources, themanufacturing of solar cells and photovoltaic arrays hasadvanced considerably in recent years. Solar photovoltaics is asustainable energy source where 100 countries are utilizing it.Solar photovoltaics is now, after hydro and wind power, thethird most important renewable energy source in terms of globally installed capacity. Installations may be groundmountedor built into the roof or walls of a building. (eitherbuilding-integrated photovoltaics or simply rooftop).

The largest recent shift in inverter technology is theavailability of transformer less inverters in the United States.

They have long been popular in Europe, but now most invertermanufacturers have added a transformer less option to theirexisting inverter line. Without a heavy transformer, they weigh about 50% to 70% less than a transformer-based inverter ofsimilar output, and the size of the inverter housing can be (butisn't always) reduced. Inverter efficiency is also increased thereare no longer losses associated with having a transformer tostep up the voltage. And because the transformer (which iscomprised of copper windings on an iron or steel core) iseliminated, they are less expensive to produce. The majority ofinverter manufacturers are now including a transformer lessinverter line. Exeltech, Ingeteam, and Solar Edge are fewexamples. They require the DC wiring to be ungrounded.Because neither the positive nor negative conductor isconnected to ground, they must meet more NEC requirements,including the use of PV wire (a double-insulated singleconductor cable having added sunlight and mechanicalprotection) for exposed wires (i.e., module interconnects andexposed home run wiring). Over current protection anddisconnect devices are required on both the positive andnegative conductors, since they are both ungrounded. Arraysthat require the positive conductor be grounded (those usingSun Power modules, for example) are not recommended for usewith transformer less inverters, because the array must beungrounded. SPWM technique is based on classical SPWMtechnique with carriers and reference sine waveform. Onlydifference between them is, in digital SPWM a sine tableconsisting of values of sine waveform sampled at certainfrequency is used. As result reference wave form in digitalSPWM represents a sample and hold wave form of sine waveform. A simple comparator with a sawtooth carrier can turn asinusoidal command into a pulse-width modulated output. Ingeneral, the larger the command signal, the wider the pulse asshown in Fig. Output stays high as long as the command isgreater than the carrier. Pulse-width modulation (PWM), as itapplies to motor control, is a way of delivering energy through a succession of pulses rather than a continuously varying(analog) signal. By increasing or decreasing pulse width, thecontroller regulates energy flow to the motor shaft. The motor'sown inductance acts like a filter, storing energy during the "on"cycle while releasing it at a rate corresponding to the input orreference signal. In other words, energy flows into the load notso much the switching frequency, but at the referencefrequency. The energy of each push is stored in the inertia of the heavy platform, which accelerates gradually with harder, more frequent, or longer-lasting pushes. The riders receive thekinetic energy in a very different manner than how it's applied.

Virtual DC bus Concept: The positive pole of the virtual bus is connected to theground point N, so that the voltage at the midpoint C is eitherzero or –Vdc. The dotted linein the figure indicates that thisconnection may be realized directly by a wire or indirectly by apower switch. With points B and C joined together by a smartselecting switch, the voltage at point A can be of three differentvoltage levels, namely +Vdc, zero, and –Vdc. Since the CMcurrent is eliminated naturally by the structure of the circuit,there is not any limitation on the modulation strategy, whichmeans that the advanced modulation technologies such as theunipolar SPWM or the double-frequency SPWM can be usedto satisfy various PV applications.



Grid Tie Inverter: Inverters take DC power and invert it to AC power soit can be fed into the electric utility company grid. The grid tieinverter must synchronize its frequency with that of the grid(e.g. 50 or 60 Hz) using a local oscillator and limit the voltageto no higher than the grid voltage. A high-quality modern GTIhas a fixed unity power factor, which means its output voltageand current are perfectly lined up, and its phase angle is within1 degree of the AC power grid. The inverter has an on-boardcomputer which will sense the current AC grid waveform, andoutput a voltage to correspond with the grid. However,supplying reactive power to the grid might be necessary to keepthe voltage in the local grid inside allowed limitations.Otherwise, in a grid segment with considerable power from renewable sources voltage levels might rise too much at timesof high production, i.e. around noon.Grid-tie inverters are alsodesigned to quickly disconnect from the grid if the utility grid goes down. This is an NEC requirement that ensures that in theevent of a blackout, the grid tie inverter will shut down toprevent the energy it transfers from harming any line workerswho are sent to fix the power grid.Properly configured, a gridtie inverter enables a home owner to use an alternative powergeneration system like solar or wind power without extensiverewiring and without batteries. If the alternative power beingproduced is insufficient, the deficit will be sourced from theelectricity grid.The proposed topology can also work with doublefrequencySPWM to achieve a higher equivalent switching frequency. In the double-frequency SPWM, the five power switches are separated into two parts, and are modulated with two inverse sinusoidal waves respectively. S1, S2, and S3 are modulated with ug1, while S4 and S5 are modulated with ug2.During the positive half grid cycle, the circuit rotates in thesequence of “state 4 – state 1 – state 2 – state 1,” and the outputvoltage vAN varies between +Vdc and the zero with twice of thecarrier frequency. During the negative half grid cycle, thecircuit rotates in the sequence of “state 4 – state 3 – state 2 –state 3,” and the output voltage vAN varies between −Vdc andzero.The aforementioned two modulation strategies bothhave their own advantages. The double-frequency SPWM canprovide a higher equivalent switching frequency so that the sizeand weight of the filter inductor can be reduced. On the otherhand, the unipolar SPWM can guarantee that the virtual dc busC2 is charged by the real bus every switching cycle, so that thecurrent stress on S1 and S3 caused by the operation of theswitched capacitor can be reduced. In this paper, the unipolarSPWM is chosen as an example for the performance evaluationand experimental verification. For all of the four operationstates, there is no limitation on the direction of the outputcurrent igrid, since the power switches with antiparallel diodescan achieve bidirectional current flow. Therefore, the proposed topology has the capability of feeding reactive power into the grid to help support the stability of the power system.The proposed topology is also immune againsttransient overvoltage of the grid. During the mains positivevoltage spikes, the voltage at point A is clamped at Vdc by C1and the antiparallel diodes of S1 and S4. Similarly, during thenegative voltage spikes, the voltage at point A is clamped at −Vdc by C2 and the antiparallel diodes of S2 and S5. Therefore,the mains transient over voltage does not pose a safety threatfor the inverter. A simulation design modulation technique as shownin Fig.1 & Fig.4 is implemented in MATLABSIMULINK with the help of pulse generators wherethe Unipolar & Double polar frequency is varied(Fig.2 & Fig.5). A modified circuit of the system ie aUnipolar and Double polar frequency Grid Tieinverter is also designed which is shown in Fig 1 & 7.The THD analysis is also compared for all the threesimulations which is shown below in Fig 3 & 6.

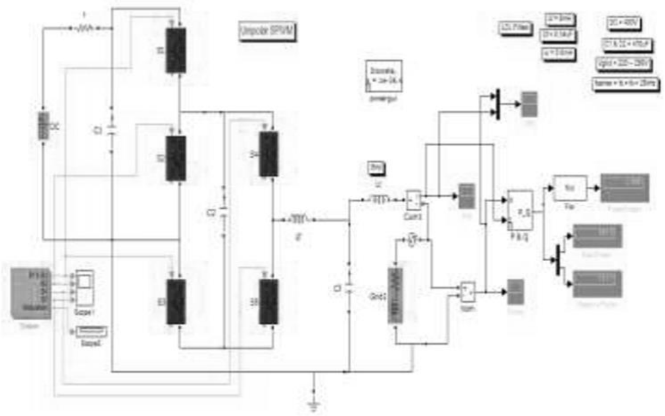


Fig. 1. Proposed Unipolar Frequency Grid Tie Inverter

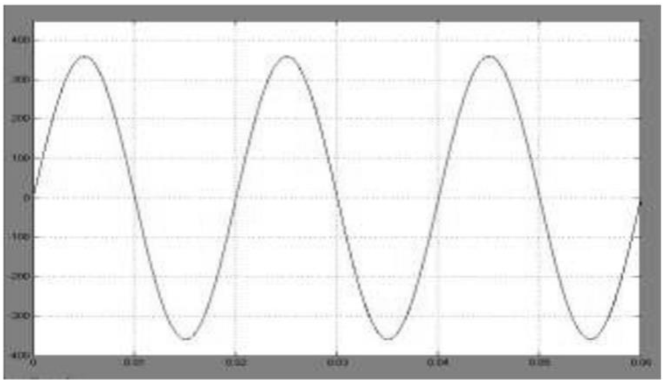


Fig. 2. Output Voltage Waveform

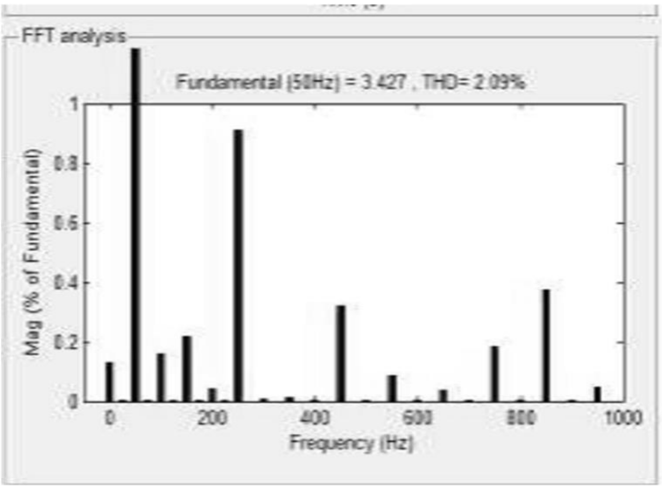


Fig. 3. O/P Current Distortion

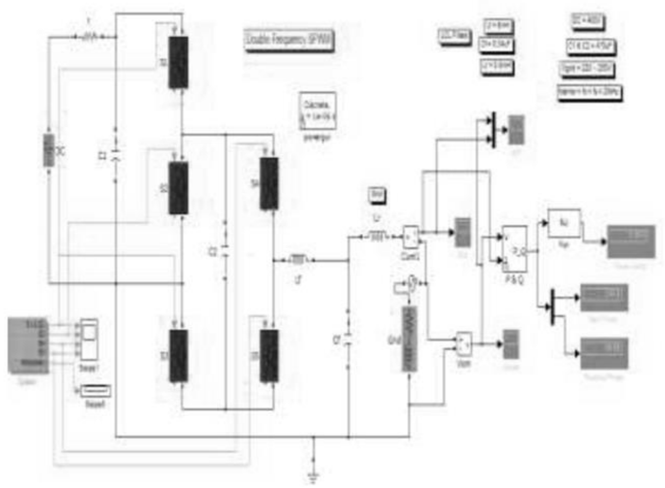


Fig. 4 Proposed Double SPWM GTI

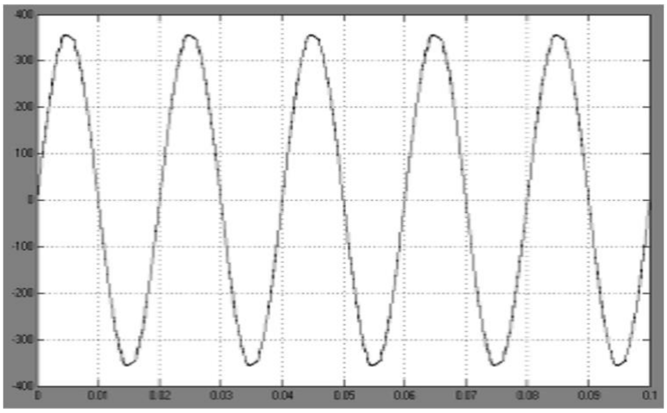
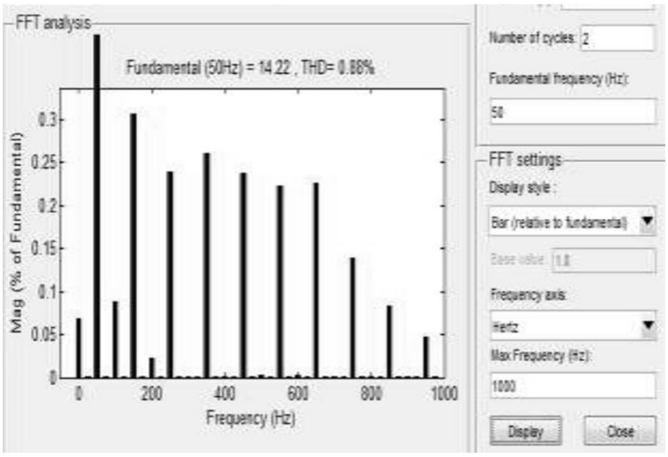


Fig. 5. O/P Double SPWM Voltage Waveform

The concept of the virtual dc bus is depicted. By connecting the grid neutral line directly to the negative pole of the PVpanel, the voltage across the parasitic capacitance CPV isclamped to zero. This prevents any leakage current flowing through it. With respect to the ground point N, the voltage at midpoint B is either zero or +Vdc, according to the state of theswitch bridge.The purpose of introducing the virtual dc bus is togenerate the negative output voltage, which is necessary for theoperation of the inverter. If a proper method is designed totransfer the energy between the real bus and the virtual bus, thevoltage across the virtual bus can be kept the same as the realone.The positive pole of the virtual bus is connected to theground point N, so that the voltage at the midpoint C is eitherzero or –Vdc. The dotted line in the figure indicates that thisconnection may be realized directly by a wire or indirectly by apower switch. With points B and C joined together by a smartselecting switch, the voltage at point A can be of three differentvoltage levels, namely +Vdc, zero, and −Vdc. Since the CMcurrent is eliminated naturally by the structure of the circuit,there is not any limitation on the modulation strategy, whichmeans that the advanced modulation technologies such as theunipolar SPWM or the double-frequency SPWM can be usedto satisfy various PV applications.



Number of cycles: 2

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig. 6. O/P Current Distortion

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II. DERIVED TOPOLOGY AND MODULATION STRATEGY

Based on the virtual dc bus concept, a novel invertertopology is derived as an example to show the clear advantagesof the proposed methodology. It consists of five powerswitches S1–S5 and only one single filter inductor Lf. The PVpanels and capacitor C1 form the real dc bus while the virtualdc bus is provided by C2.With the switched capacitortechnology, C2 is charged by the real dc bus through S1 and S3to maintain a constant voltage. This topology can be modulatedwith the unipolar SPWM and double-frequency SPWM. Thedetailed analysis is introduced as follows.

Unipolar SPWM: The waveform for the unipolar SPWM of theproposed inverter is displayed. The gate drive signals for thepower switches are generated according to the relative value ofthe modulation wave ugand the carrier wave uc.During thepositive half grid cycle, ug>0. S1 and S3 are turned ON and S2is turned OFF, while S4 and S5 commutate complementally withthe carrier frequency. The capacitors C1 and C2 are in parallelDuring the negative half cycle, ug<0. S5 is turned ONand S4 is turned OFF. S1 and S3 commutate with the carrierfrequency synchronously and S2 commutates in complement tothem. The circuit rotates between states 3 and 2. At state 3, S1and S3 are turned OFF while S2 is turned ON. The negativevoltage is generated by the virtual dc bus C2 and the inverteroutput is at negative voltage level. At state 2, S1 and S3 areturned ON while S2 is turned OFF. The inverter output voltagevAN equals zero; meanwhile, C2 is charged by the dc busthrough S1 and S3.Double-Frequency SPWMThe proposed topology can also work with doublefrequencySPWM to achieve a higher equivalent switchingfrequency, as shown in Fig. 9. In the double-frequency SPWM,the five power switches are separated into two parts, and aremodulated with two inverse sinusoidal waves respectively. S1,S2 , and S3 are modulated with ug1, while S4 and S5 are modulated with ug2. During the positive half grid cycle, thecircuit rotates in the sequence of “state 4 – state 1 – state 2 –state 1,” and the output voltage vAN varies between +Vdc andthe zero with twice of the carrier frequency. During thenegative half grid cycle, the circuit rotates in the sequence of“state 4 – state 3 – state 2 –state 3,” and the output voltagevAN varies between –Vdc and zero.and the circuit rotates between states 1 and 2.

During the negative half cycle, ug<0. S5 is turned ONand S4 is turned OFF. S1 and S3 commutate with the carrierfrequency synchronously and S2 commutates in complement tothem. The circuit rotates between states 3 and 2. At state 3, S1and S3 are turned OFF while S2 is turned ON. The negativevoltage is generated by the virtual dc bus C2 and the inverteroutput is at negative voltage level. At state 2, S1 and S3 areturned ON while S2 is turned OFF. The inverter output voltagevAN equals zero; meanwhile, C2 is charged by the dc busthrough S1 and S3. Double-Frequency SPWM The proposed topology can also work with doublefrequency SPWM to achieve a higher equivalent switching frequency, as shown in Fig. 9. In the double-frequency SPWM,the five power switches are separated into two parts, and aremodulated with two inverse sinusoidal waves respectively. S1,S2 , and S3 are modulated with ug1, while S4 and S5 are modulated with ug2. During the positive half grid cycle, thecircuit rotates in the sequence of “state 4 – state 1 – state 2 –state 1,” and the output voltage vAN varies between +Vdc andthe zero with twice of the carrier frequency. During thenegative half grid cycle, the circuit rotates in the sequence of“state 4 – state 3 – state 2 –state 3,” and the output voltagevAN varies between –Vdc and zero.

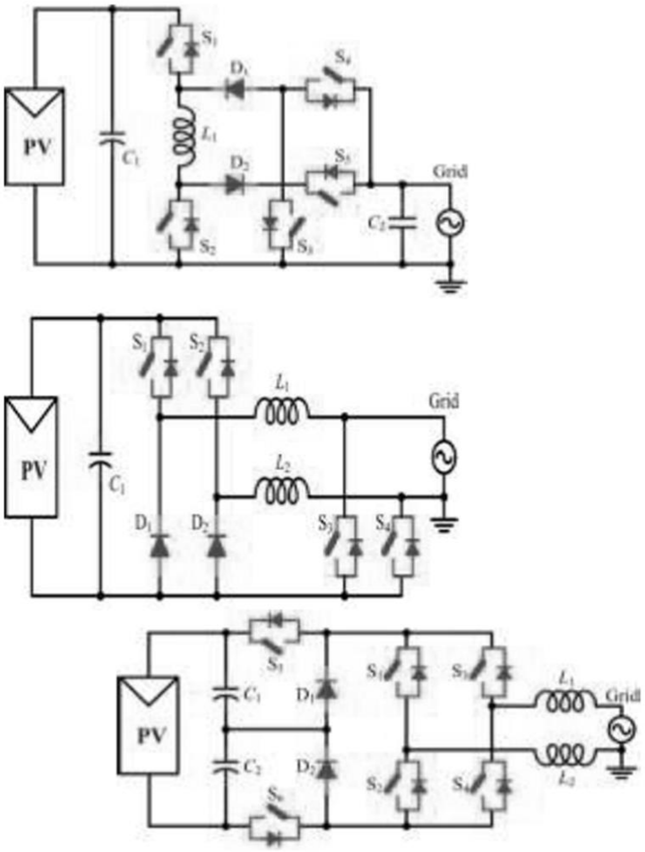

Fig.7. SVPWM Modulation

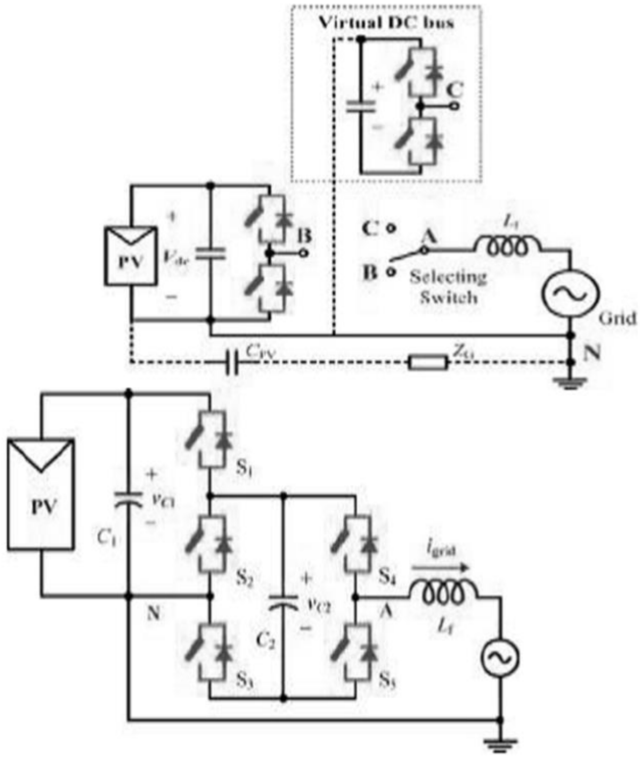

Fig.8. SVPWM Modulation

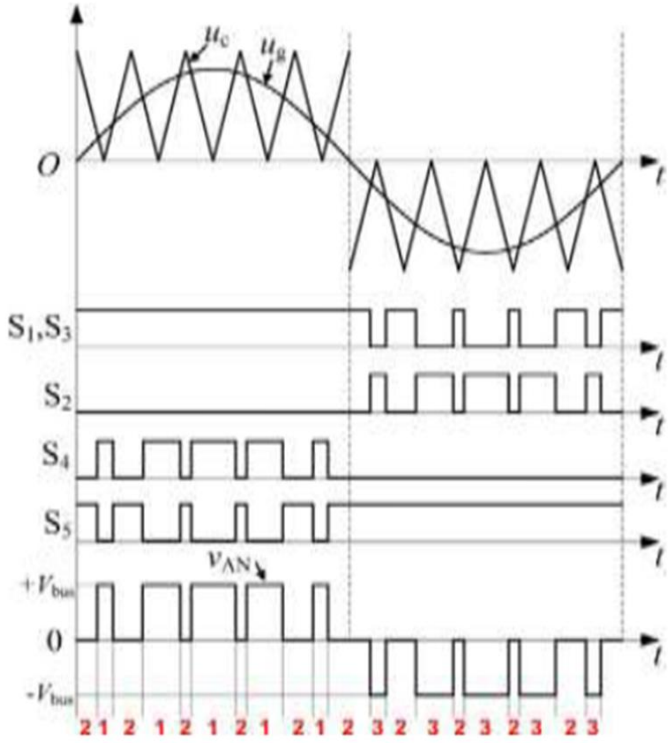

Fig 9.Unipolar Waveform

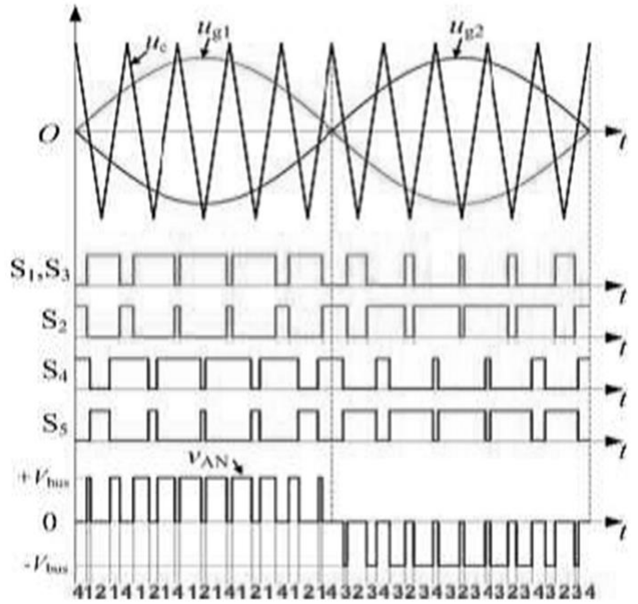

Fig 10. Double Frequency SPWM

The aforementioned two modulation strategies both havetheir own advantages. The double-frequency SPWM canprovide a higher equivalent switching frequency so that the sizeand weight of the filter inductor can be reduced. On the otherhand, the unipolar SPWM can guarantee that the virtual dc busC2 is charged by the real bus every switching cycle, so that thecurrent stress on S1 and S3 caused by the operation of theswitched capacitor can be reduced. In this paper, the unipolarSPWM is chosen as an example for the performance evaluationand experimental verification. For all of the four operationstates, there is no limitation on the direction of the outputcurrent igrid, since the power switches with antiparallel diodescan achieve bidirectional current flow. Therefore, the proposedtopology has the capability of feeding reactive power into thegrid to help support the stability of the power system.

The proposed topology is also immune against transientovervoltage of the grid. During the mains positive voltagespikes, the voltage at point A is clamped at Vdc by C1 and the antiparallel diodes of S1 and S4. Similarly, during the negativevoltage spikes the voltage at point A is clamped at –Vdc by C2and the antiparallel diodes of S2 and S5. Therefore, the mainstransient overvoltage does not pose a safety threat for theinverter.

Switching Losses:During the positive half cycle, only two switches,namely S4 and S5, commutate at the carrier frequency, so theswitching losses are the same as the traditional full-bridgeinverter. During the negative half cycle, S1, S2, and S3commutate at the carrier frequency. Although the number ofhigh-frequency switches increases to 3, it can be seen from thefollowing analysis that the switching losses almost keep thesame.

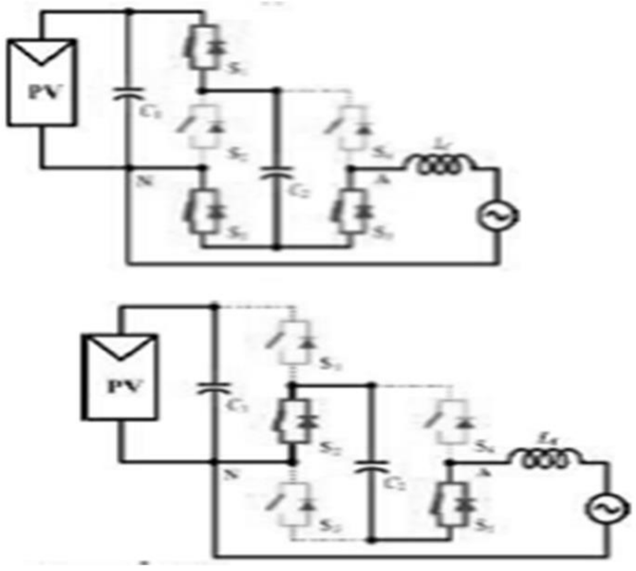

Fig11

III. CONCLUSION

This review has covered some of the standards that inverters for PV and grid applications must full fill, which focus on power quality injection of dc current to the grid, detection of islanding operation, and system grounding. The demands stated by the PV modules have also been reviewed. The role of power decoupling between the modules and the grid has been investigated. An important result is that the amplitude of the ripple across a PV module should not exceed 3V in order to have a utilization efficiency of 98% at full generation Finally the basic demands defined by the operator have also been addressed, such as low cost, high efficiency, and long life time .t he next part of the review was a historical summary of the solutions used in the past, where large areas of PV modules were connected to the grid by means of centralized inverters. This included many short comings for which reason the string inverters emerged. A natural development was to add more strings, each with an individual dc–dc converter and MPPT, to the common dc–ac inverter, thus, the multi-string inverters were brought to light. This is believed to be one of the solutions for the future. Another trend seen in this field is the development of the ac module, where each PV module is interfaced to the grid with its own dc– ac inverter

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