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A NOVEL HIGH EFFICIENCY INTERLEAVED FLYBACK CONVERTER WITH SELF-DRIVEN SYNCHRONOUS RECTIFIER

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Abstract: Flyback inverter has the advantages such as compact conformation, simple control loop,electric isolation, high step-up ratio, high efficiency, etc., therefore is an attractive solution forphotovoltaic ac module applications. In this topology, BCM is more preferred compared to DCM andCCM, because of its higher power level, higher efficiency and wider switching frequency bandwidth.However, the control of BCM is more complicated due to its variable switching frequency. This alsoleads to the difficulty to get the accurate mathematical model between the output current iout and thereference current iref, which has a great influence on the THD of iout. This paper analyzes andproposes a mathematical model between iout and iref in BCM through theoretical derivation, andproposes a novel control strategy to generate the reference current that can decrease THD of outputcurrent. Meanwhile the realization of MPPT based on the mathematical model is also investigated. Finally, simulation and experiment results based on an improved flyback-inverter prototype arepresented, which validates the proposed mathematical model and the control strategy.
Index Terms: Continuous-conduction mode (CCM), discontinuous-conduction mode (DCM), flyback converter, synchronous rectification.

I. INTRODUCTION

Photovoltaic ac module (PV ACM), also named as micro-inverter, is a compact and modularstructure for small power PV generation system applications. This concept was conceived 30 years agoat Caltech's Jet Propulsion Laboratory. However, it is only recently reaching commercial realization.Nowadays, it's recognized as an attractive solution for the residential utility-interactive PV systems.PV ACM is defined as the integration of a single PV panel and a single-phase grid-tied (GT) inverter.The GT inverter is the direct interface between the PV panel and the residential utility, which convertsthe low dc voltage from the PV panel to the higher ac voltage of the grid. Compared to theconventional single- or multistring inverters in PV applications, advantages of PV ACM include moreflexibility and less installation cost in system expansion as a "plug and play" device, lowermanufacturing cost through mass production, lack of the power mismatch between PV modules, andhigher system-level energy harvesting ability under shaded conditions. However, the PV ACM mustmeet a series of harsh requirements, such as THD and islanding protection demanded by standards ofGT devices, maximum power point track (MPPT) and minimum power fluctuation demanded by PVpanels, high efficiency, high reliability, long lifetime, low cost, and easy installation demanded byusers. For satisfying these harsh requirements, many topologies and control methods have beenreported in references. Nowadays, a single stage flyback-type utility interactive inverter, whichcombined a voltage-controlled current-source flyback and a GT inverter as one single stage, isregarded as an attractive solution in PV ACM applications. Its major advantages include electricisolation, high power density, high efficiency, and high step-up ratio, which are based on the simplecontrol loop and compact structure. But its large input capacity and loss of leakage inductance energyare still the challenges for designers. At present, more and more works have been done on theimprovement for the flyback inverter, such as control loop, power decoupling, soft-switching andMPPT control. Three operation modes (CCM, DCM, and BCM) of the flyback inverter areinvestigated in the PV ACM applications. CCM can be realized with average-current control.However, the peak-current control of the secondary current is not appropriate for CCM, since thetransformer is incompletely demagnetized during each switching cycle, and the system will behave asa load-independent voltage source with peak-current control. Moreover, the flyback inverter at light load will slip into DCM operation around the zero crossing of grid voltage, which increases thedifficulty of control system design. DCM and BCM can be easily realized with peak-current control,which has no phase delay compared to the average current control. Meanwhile, DCM and BCM havethe ZCS feature naturally, so can have higher efficiency in comparison with CCM operation.Furthermore, the power density of BCM is usually higher than DCM. Hence, BCM is more preferred for PV ACM applications considering all the earlier research works. In the BCM with peak-current control, the output current iout is directly controlled by thereference current iref during each every switching cycle. Since the flyback inverter operates as an accurrent source, a variable switching frequency (VSF) control strategy must be applied. However, theVSF fs leads to the difficulty to get the accurate mathematical model between iout and iref. As theTHD of iout must comply with the standards of GT devices, the mathematical model is extremelyimportant in the design of iref.The purpose of this paper is to analyze and propose an accurate mathematical model betweeniout and iref through theoretical derivation. Based on the proposed mathematical model, therelationship between fs and iref is also analyzed. Then, a novel control strategy of iref is proposed todecrease THD of iout. Moreover, the realization of MPPT based on this control strategy is alsoinvestigated. Finally, the control strategy is verified based on an improved flyback-inverter topology.Both simulation and experiment results on this topology are shown in this paper.

II. PROPOSED SYSTEM

Given below is the block diagram of proposed system.

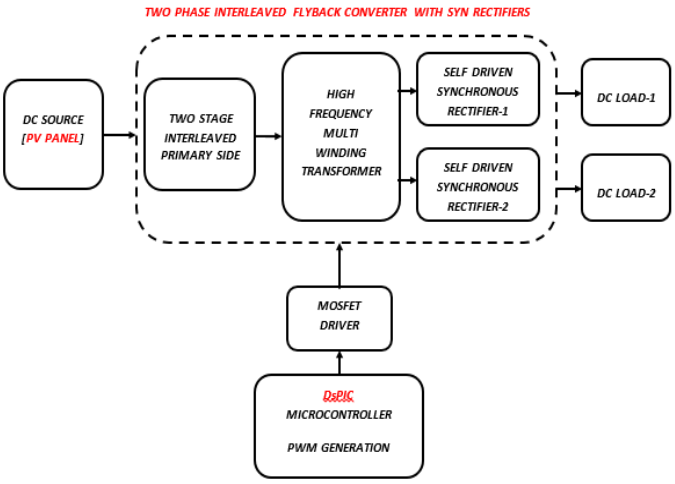

Fig. 1. Block diagram of the proposed system

A. Solar Panel

A solar panel (photovoltaic module or photovoltaic panel) is a packaged, interconnectedassembly of solar cells, also known as photovoltaic cells. The solar panel can be used as a componentof a larger photovoltaic system to generate and supply electricity in commercial and residentialapplications. Because a single solar panel can produce only a limited amount of power, manyinstallations contain several panels. A photovoltaic system typically includes an array of solar panels,an inverter, and sometimes a battery and interconnection wiring. Solar panels use light energy (photons) from the sun to generate electricity through thephotovoltaic effect. The structural (load carrying) member of a module can either be the top layer orthe back layer. The majority of modules use wafer-based crystalline silicon cells or thin-film cellsbased on cadmium telluride or silicon. The conducting wires that take the current off the panels maycontain silver, copper or other conductive (but generally not magnetic) transition metals. The cellsmust be connected electrically to one another and to the rest of the system. Cells must also beprotected from mechanical damage and moisture. Most solar panels are rigid, but semi-flexible onesare available, based on thin-film cells. Electrical connections are made in series to achieve a desiredoutput voltage and/or in parallel to provide a desired current capability. Separate diodes may be neededto avoid reverse currents, in case of partial or total shading, and at night. The p-n junctions of monocrystallinesilicon cells may have adequate reverse current characteristics that these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become lessefficient at higher temperatures and installers try to provide good ventilation behind solar panels. Some recent solar panel designs include concentrators in which light is focused by lenses or mirrorsonto an array of smaller cells. This enables the use of cells with a high cost per unit area (such asgallium arsenide) in a cost-effective wayDepending on construction, photovoltaic panels can produce electricity from a range offrequencies of light, but usually cannot cover the entire solar range (specifically, ultraviolet, infraredand low or diffused light). Hence much of the incident sunlight energy is wasted by solar panels, andthey can give far higher efficiencies if illuminated with monochromatic light. Therefore another design concept is to split the light into different wavelength ranges and directthe beams onto different cells tuned to those ranges. This has been projected to be capable of raisingefficiency by 50%. The use of infrared photovoltaic cells has also been proposed to increaseefficiencies, and perhaps produce power at night. Currently the best achieved sunlight conversion rate(solar panel efficiency) is around 21% in commercial product, typically lower than the efficiencies oftheir cells in isolation. The Energy Density of a solar panel is the efficiency described in terms of peakpower output per unit of surface area, commonly expressed in units of Watts per square foot (W/ft2).

B. Buck Converter(DC-DC)

A buck converter (dc-dc) is shown. Only a switch is shown, for which a device asdescribed earlier belonging to transistor family is used. Also a diode (termed as freewheeling) is usedto allow the load current to flow through it, when the switch (i.e., a device) is turned off. The load isinductive (R-L) one. In some cases, a battery (or back emf) is connected in series with the load(inductive). Due to the load inductance, the load current must be allowed a path, which is provided bythe diode; otherwise, i.e., in the absence of the above diode, the high induced emf of the inductance, asthe load current tends to decrease, may cause damage to the switching device. If the switching deviceused is a thyristor, this circuit is called as a step-down chopper, as the output voltage is normally lowerthan the input voltage. Similarly this dc-dc converter is termed as buck one.

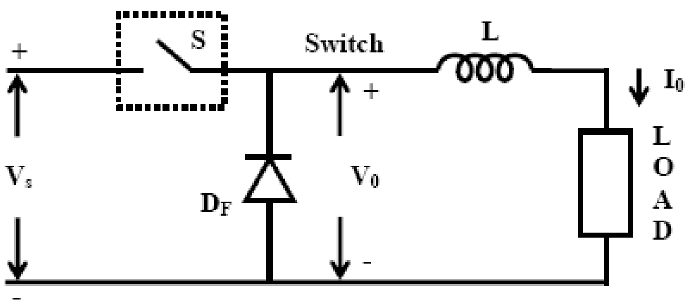

Fig.2. Buck Converter

C. Flyback Converter

The flyback converter is used in both AC/DC and DC/DC conversion with galvanic isolationbetween the input and any outputs. More precisely, the flyback converter is a buck-boost converterwith the inductor split to form a transformer, so that the voltage ratios are multiplied with an additionaladvantage of isolation. When driving for example a plasma lamp or a voltage multiplier the rectifyingdiode of the boost converter is left out and the device is called a flyback transformer.The two configurations of a flyback converter in operation: In the on-state, the energy istransferred from the input voltage source to the transformer (the output capacitor supplies energy to theoutput load). In the off-state, the energy is transferred from the transformer to the output load (and theoutput capacitor).

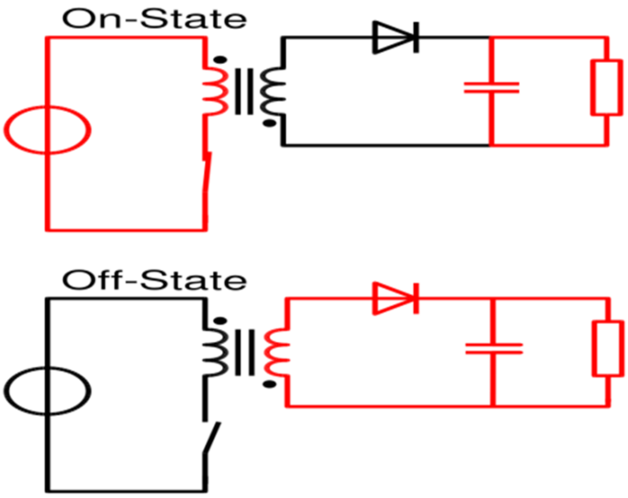

Fig.3. Flyback Converter

Waveform - using primary side sensing techniques - showing the 'knee point'. The schematic of a flyback converter can be seen in Fig.4. It is equivalent to that of abuck-boost converter with the inductor split to form a transformer. Therefore the operating principle ofboth converters is very close:

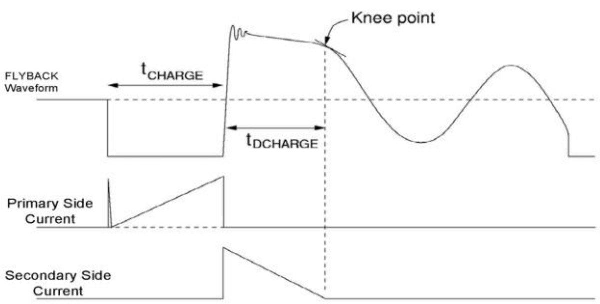

Fig. 4. Flyback Waveform

When the switch is closed (top of Fig. 4), the primary of the transformer is directlyconnected to the input voltage source. The primary current and magnetic flux in the transformerincreases, storing energy in the transformer. The voltage induced in the secondary winding is negative,so the diode is reverse-biased (i.e., blocked). The output capacitor supplies energy to the output load.When the switch is opened (bottom of Fig. 3), the primary current and magnetic flux drops.The secondary voltage is positive, forward-biasing the diode, allowing current to flow from thetransformer. The energy from the transformer core recharges the capacitor and supplies the load.The operation of storing energy in the transformer before transferring to the output of theconverter allows the topology to easily generate multiple outputs with little additional circuitry,although the output voltages have to be able to match each other through the turns ratio. Also there is aneed for a controlling rail which has to be loaded before load is applied to the uncontrolled rails, this isto allow the PWM to open up and supply enough energy to the transformer. The flyback converter is an isolated power converter. The two prevailing control schemes arevoltage mode control and current mode control (in the majority of cases current mode control needs tobe dominant for stability during operation). Both require a signal related to the output voltage. Thereare three common ways to generate this voltage. The first is to use an optocoupler on the secondarycircuitry to send a signal to the controller. The second is to wind a separate winding on the coil andrely on the cross regulation of the design. The third consists on sampling the voltage amplitude on theprimary side, during the discharge, referenced to the standing primary DC voltage.The first technique involving an optocoupler has been used to obtain tight voltage and currentregulation, whereas the second approach was developed for cost-sensitive applications where theoutput did not need to be as tightly controlled but up to 11 components including the optocouplercould be eliminated from the overall design. Also, in applications where reliability is critical,optocouplers can be detrimental to the MTBF (Mean Time Between Failure) calculations. The thirdtechnique, primary-side sensing, can be as accurate as the first and more economical than the second,yet requires a minimum load so that the discharge-event keeps occurring, providing the opportunitiesto sample the 1:N secondary voltage at the primary winding (during T discharge, as per Fig.4.) A variation in primary-side sensing technology is where the output voltage and current areregulated by monitoring the waveforms in the auxiliary winding used to power the control IC itself,which have improved the accuracy of both voltage and current regulation. The auxiliary primarywinding is used in the same discharge phase as the remaining secondaries, but it builds a rectifiedvoltage referenced commonly with the primary DC, hence considered on the primary side.Previously, a measurement was taken across the whole of the flyback waveform which led toerror, but it was realized that measurements at the so-called knee point (when the secondary current iszero, see Fig. 4.2) allow for a much more accurate measurement of what is happening on the secondaryside. This topology is now replacing ringing choke converters (RCCs) in applications such as mobilephone chargers.

III. PRINCIPLE OF OPERATION

A. Converter Interleaving

This can be thought of as a method of paralleling converters.However, it has additional benefits to offer in addition to those obtained from conventionalapproaches of paralleling converters.Widely used in personal computer industry to power central processing units.

Applications

• Low-power switch-mode power supplies (cell phone charger, standby power supply in PCs)
• Low-cost multiple-output power supplies (e.g., main PC supplies <250 W)
• High voltage supply for the CRT in TVs and monitors (the flyback converter is often combinedwith the horizontal deflection drive)
• High voltage generation (e.g., for xenon flash lamps, lasers, copiers, etc.)

B. Fly-Back Converter

Fly-back converter is the most commonly used SMPS circuit for low output power applicationswhere the output voltage needs to be isolated from the input main supply. The output power of flybacktype SMPS circuits may vary from few watts to less than 100 watts. The overall circuit topologyof this converter is considerably simpler than other SMPS circuits. Input to the circuit is generallyunregulated dc voltage obtained by rectifying the utility ac voltage followed by a simple capacitorfilter. The circuit can offer single or multiple isolated output voltages and can operate over wide rangeof input voltage variation. In respect of energy-efficiency, fly-back power supplies are inferior tomany other SMPS circuits but its simple topology and low cost makes it popular in low output powerrange. The commonly used fly-back converter requires a single controllable switch like, MOSFET andthe usual switching frequency is in the range of 100 kHz. A two switch topology exists that offersbetter energy efficiency and less voltage stress across the switches but costs more and the circuitcomplexity also increases slightly. The present lesson is limited to the study of fly-back circuit ofsingle switch topology.

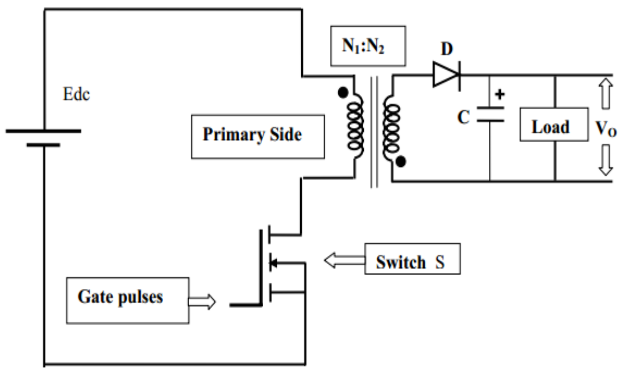

Fig.5. FlyBack Converter

C. Forward Converter

Forward converter is another popular switched mode power supply (SMPS) circuit that is usedfor producing isolated and controlled dc voltage from the unregulated dc input supply. As in the caseof fly-back converter (lesson-22) the input dc supply is often derived after rectifying (and littlefiltering) of the utility ac voltage. The forward converter, when compared with the fly-back circuit, isgenerally more energy efficient and is used for applications requiring little higher power output (in therange of 100 watts to 200 watts). However the circuit topology, especially the output filtering circuit isnot as simple as in the fly-back converter.It consists of a fast switching device 'S' along with its control circuitry, a transformer with itsprimary winding connected in series with switch 'S' to the input supply and a rectification and filteringcircuit for the transformer secondary winding. The load is connected across the rectified output of thetransformer-secondary.The transformer used in the forward converter is desired to be an ideal transformer with noleakage fluxes, zero magnetizing current and no losses. The basic operation of the circuit is explainedhere assuming ideal circuit elements and later the non-ideal characteristics of the devices are taken careof by suitable modification in the circuit design. In fact, due to the presence of finite magnetizingcurrent in a practical transformer, tertiary winding needs to be introduced in the transformer and thecircuit topology changes slightly. The circuit is basically a dc-to-dc buck converter with the addition of a transformer for outputvoltage isolation and scaling. When switch 'S' is turned on, input dc gets applied to the primarywinding and simultaneously a scaled voltage appears across the transformer secondary. Dotted sidesof both the windings are now having positive polarity. Diode 'D1', connected in series with thesecondary winding gets forward biased and the scaled input voltage is applied to the low pass filtercircuit preceding the load. The primary winding current enters through its dotted end while thesecondary current comes out of the dotted side and their magnitudes are inversely proportional to theirturns-ratio. Thus, as per the assumption of an ideal transformer, the net magnetizing ampere-turns ofthe transformer is zero and there is no energy stored in the transformer core. When switch 'S' is turnedoff, the primary as well as the secondary winding currents are suddenly brought down to zero. Currentthrough the filter inductor and the load continues without any abrupt change. Diode 'D2' provides thefreewheeling path for this current.The required emf to maintain continuity in filter-inductor current and to maintain the forwardbias voltage across D2 comes from the filter inductor 'L' itself. During freewheeling the filter inductorcurrent will be decaying as it flows against the output voltage (Vop), but the presence of relativelylarge filter capacitor 'C' still maintains the output voltage nearly constant. The ripple in the outputvoltage must be within the acceptable limits. The supply switching frequency is generally kept sufficiently high such that the next turn-on ofthe switch takes place before the filter inductor current decays significantly. Needless to say, that themagnitudes of filter inductor and capacitor are to be chosen appropriately. The idea behind keepingfilter inductor current nearly constant is to relieve the output capacitor from supplying large ripplecurrent. The inductor and the capacitor together share the load-current drawn from the output.Under steady state condition, mean dc current supplied by the capacitor is zero but capacitorstill supplies ripple current. For maintaining constant load current, the inductor and capacitor currentripples must be equal in magnitude but opposite in sense. Capacitors with higher ripple current ratingare required to have much less equivalent series resistor (ESR) and equivalent series inductor (ESL)and as such they are bulkier and costlier. Also, the ESR and ESL of a practical capacitor causes ripplein its dc output voltage due to flow of ripple current through these series impedances. Since the outputvoltage is drawn from capacitor terminal the ripple in output voltage will be less if the capacitor ismade to carry less ripple current. For better understanding of the steady-state behavior of the converter,the circuit's operation is divided in two different modes, mode-1 and mode-2. Mode-1 corresponds tothe 'on' duration of the switch and mode-2 corresponds to its 'off' duration. The following simplifying assumptions are made before proceeding to the detailed mode wiseanalysis of the circuit:

• ON state voltage drops of switches and diodes are neglected. Similarly, leakage currents through
the off state devices is assumed zero. The switching-on and switching-off times of the switch and
diodes are neglected.

• The transformer used in the circuit is assumed to be ideal requiring no magnetizing current,
having no leakage inductance and no losses.

• The filter circuit elements like, inductors and capacitors are assumed loss-less.

• For the simplified steady-state analysis of the circuit the switch duty ratio (δ), as defined in theprevious chapters is assumed constant.

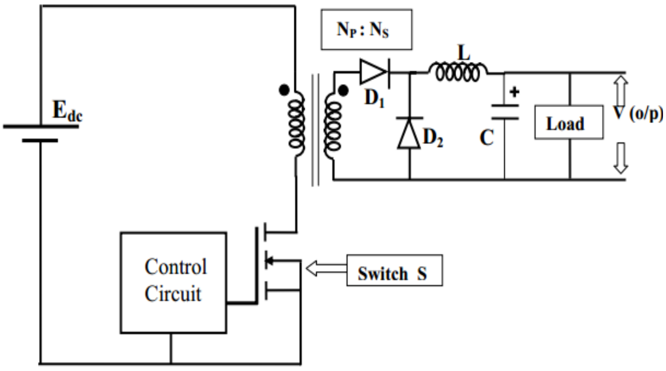

Fig.6. Forward Converter

Isolation transformers are designed with attention to capacitive coupling between the twowindings. The capacitance between primary and secondary windings would also couple AC currentfrom the primary to the secondary. A grounded Faraday shield between the primary and the secondarygreatly reduces the coupling of common-mode noise. This may be another winding or a metal stripsurrounding a winding. Differential noise can magnetically couple from the primary to the secondaryof an isolation transformer, and must be filtered out if a problem.

IV. SIMULATION AND RESULTS

Electrical power systems are combinations of electrical circuits and electromechanical deviceslike motors and generators. Engineers working in this discipline are constantly improving theperformance of the systems. Requirements for drastically increased efficiency have forced power systemdesigners to use power electronic devices and sophisticated control system concepts that tax traditionalanalysis tools and techniques. Further complicating the analyst's role is the fact that the system is often so nonlinear that the only way to understand it is through simulation .Land-based power generation fromhydroelectric, steam, or other devices is not the only use of power systems. A common attribute of thesesystems is their use of power electronics and control systems to achieve their performanceSim Power Systems is a modern design tool that allows scientists and engineers to rapidly andeasily build models that simulate power systems. Sim Power Systems uses the Simulink environment,allowing you to build a model using simple click and drag procedures. Not only can you draw the circuittopology rapidly, but your analysis of the circuit can include its interactions with mechanical, thermal,control, and other disciplines. This is possible because all the electrical parts of the simulation interactwith the extensive Simulink modeling library. Since Simulink uses MATLAB® as its computationalengine, designers can also use MATLAB toolboxes and Simulink block sets. Sim Power Systems and SimMechanics share a special Physical Modeling block and connection line interface.

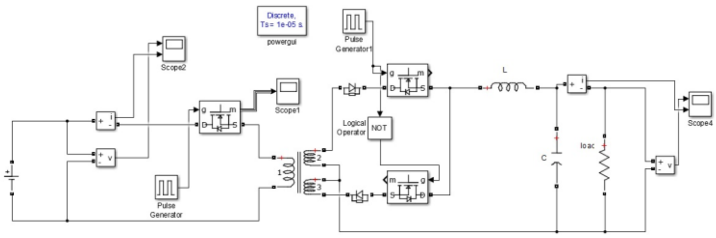

Fig. 7. Existing Simulation Circuit

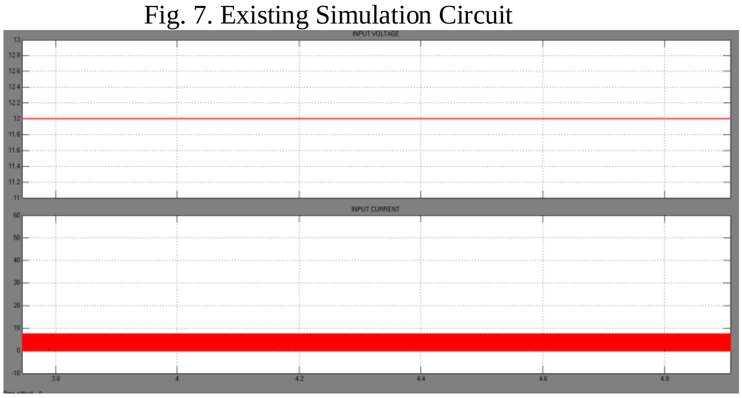

Fig.8. Simulation results of Input characteristics

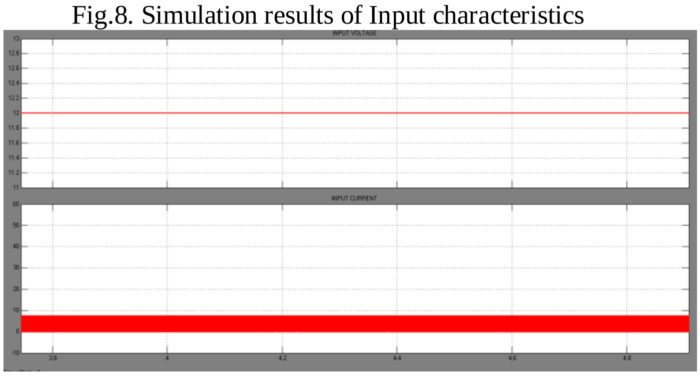

Fig. 9.Simulation results of Output voltage

The above wave shows the output voltage wave which is of about 110 V.

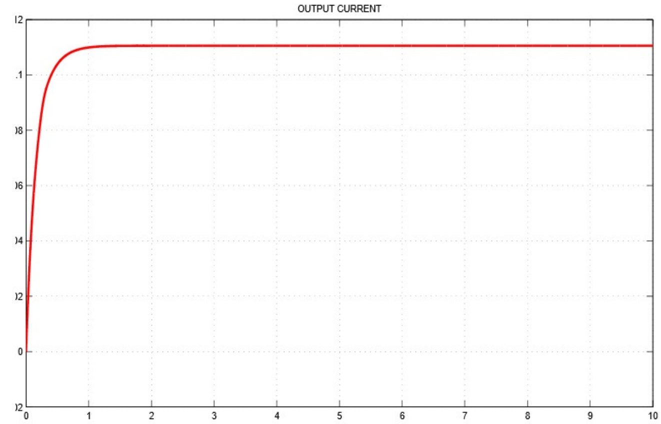

Fig. 10. Simulation results of Output Current

The above wave form shows the output current os the proposed system which is of about 0.1 A.

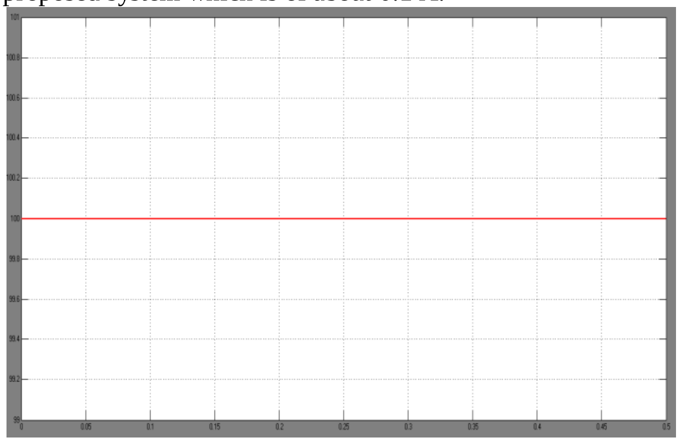

Fig. 11. Simulation results of Input voltage

The above waveform indicates the input voltage level of the system, which is of about 100V, Here in thesimulation the DC voltage is been produced with a DC voltage source to produce a constant voltage level.

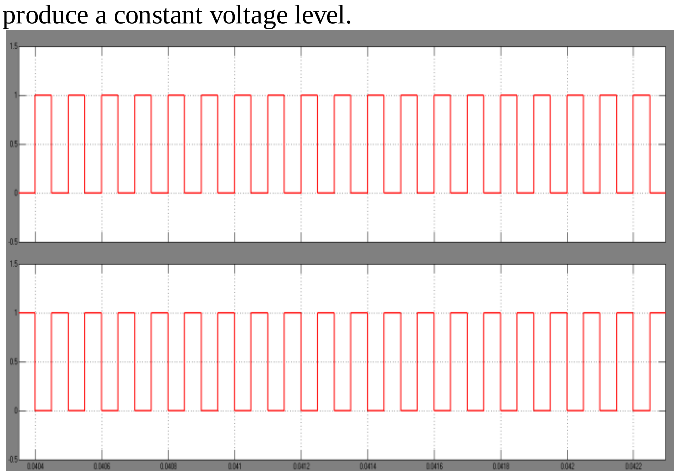

Fig. 12. Waveform for MOSFET

The above diagram is the pulse wave which is been given to the MOSFET switch which isconnected in the primary side of the transformer. The first wave is for the S1 and for the S2 the pulse isinverse as that of the other wave.

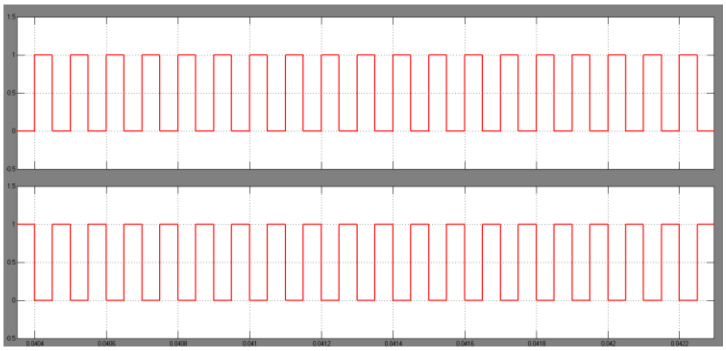

Fig.13. Output waveform of Converters

The above wave form shows the output voltage level of each fly-back converter. The below wave form is the output voltage of the interleaved flyback converter.

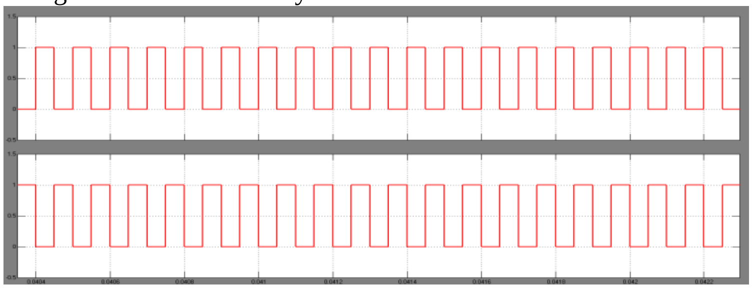

Fig. 14.Output voltage of interleaved flyback converter

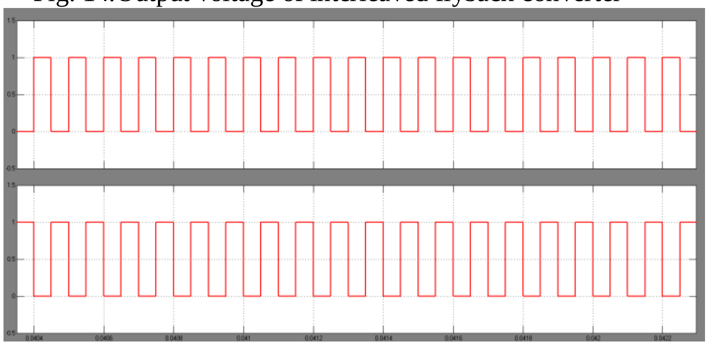

Fig. 15. Output current for interleaved flyback converter

The above wave form is the output current of the interleaved flyback converter.

V. CONCLUSION

Flyback inverter is an attractive solution for photovoltaic ac module application. As a gridconnecteddevice, flyback inverter should work as a current source and provides the sinusoidal outputcurrent that is synchronous with the grid voltage. Meanwhile, the flyback inverter should have high efficiency to satisfy user’s demand.In this topology, BCM is more preferred compared to DCM and CCM, because of its higherpower level, higher efficiency, and wider switching frequency bandwidth. However, the control of BCMis more complicated, due to its VSF. This also leads to the difficulty to get the accurate mathematicalmodel between output current iout and reference current iref , which has a great influence on THD of iout.In this paper, the relationship between ACM output current iout and reference current iref offlyback inverter in BCM is investigated, and an accurate mathematical model is proposed throughtheoretical derivation. Then, a novel control strategy of iref is proposed to decrease THD of iout .Moreover, the realization of MPPT based on this control strategy is also investigated. Finally, simulationand experiment results of an improved flyback-inverter topology are presented, which verifies theproposed control strategy.

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