GENERALIZED DESIGN OF TRANSFORMERLESS PHOTOVOLTAIC INVERTER FOR ELIMINATION OF LEAKAGE CURRENT AND PULSATING POWER IN RL LOAD CONNECTED SYSTEM

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***Abstract*—This paper presents a transformerless invertertopology, which is capable of simultaneously solving leakagecurrent and pulsating power issues in RL load-connected photovoltaic (PV) systems. Without adding any additional components to the system, the leakage current caused by the PV-to-ground parasitic capacitance can be bypassedby introducing a common-mode (CM) conducting path to the inverter. The resulting ground leakage current is therefore well controlled to be below the regulation limit. Furthermore, the proposed inverter can also eliminate thewell-known double-line-frequency pulsating power that isinherent in single-phase PV systems. By properly injecting CM voltages to the output filter capacitors, the pulsating power can be decoupled from the dc-link. Therefore, its possible to use long-lifetime film capacitors instead of electrolytic capacitors to improve the reliability of the PV system. The mechanism of leakage current suppression and the closed-loop control of pulsating power decoupling are discussed in this paper in detail. A 500-W prototypewas also built and tested in the laboratory, and both simulation and experimental results are finally presented to show the excellent performance of the proposed PV inverter.**

***Index Terms*—Leakage current, power decoupling,single-phase system, transformerless photovoltaic (PV) inverter.**

A. INTRODUCTION

TRANSFORMERLESS grid-connected photovoltaic (PV)inverters are widely accepted in the PV market mainlybecause of their high efficiency, low cost, small volume, andlight weight. These features may not be possessed by theirtransformer galvanically isolated counterparts . However,since the PV panels in such systems have direct electricalconnection with the power grid, the PV-to-ground parasiticcapacitance, the PV inverter, and the utility load may thenform a conduction loop. High-frequency common-mode (CM)voltage-induced leakage current can flow through this loopif the unipolar modulation strategy is adopted for full-bridgeinverters The leakage current is definitely adverse to thesystem performance, and it may potentially lead to a series ofproblems, e.g., harmonic current, increased power losses, safetyissues, and electromagnetic interference issues . Therefore,the leakage current must be suppressed into a certain level inorder to comply with the standard and improve the reliability of PV systems .Various inverter topologies have recently been proposed toaddress the leakage current issue in transformerless PV systems,and the basic idea is to introduce new freewheeling pathsinto the inverter so that the PV panel can be isolated fromthe RL load during freewheeling modes . *This can beachieved by cutting off the CM current conducting path when*zero voltage vectors are applied to the full-bridge inverter, andit can be implemented either on the dc side or on the ac side.Example topologies include the H5 inverter from SMA theHERIC inverter from Sunways and many of their derivativesrecently reported . Another possible solutionis to directly clamp the potential of PV terminals with respectto the ground of the RL load. This can be implemented eitheron the midpoint of the dc bus, e.g., in the half-bridge inverter,the neutral point clamped (NPC) inverter, and the T-type NPCinverter commercialized by Conergy, or on the negative bus ofthe PV terminal, e.g., in the Karschny inverter the virtualdc bus inverter proposed in and the negative groundinginverter proposed in . Even though these topologies arevery effective in leakage current reduction, they still have somedrawbacks. The half-bridge-based topologies may require ahigh dc bus voltage that is double of the full-bridge case. For theremaining transformerless topologies, additional semiconductorswitches have to be used along with more complicated activegate circuits and control signals. The system reliability andlifetime will also be deteriorated due to the increased number of active components. In a modified full-bridge inverter ispresented to suppress the leakage current without using extra switches, and only small CM filters may be required to form aCM current bypassing loop.Although being effective in leakage current elimination, anothercritical issue that is closely related to the reliability of PVsystems, especially for single-phase systems, is not addressedin which is the well-known double-line-frequency pulsatingpower. Conventionally, very bulky dc-link capacitorshave to be employed to keep a relatively constant PV voltageso that the maximum power point tracking (MPPT) efficiency will not be compromised. Unfortunately, because of the large capacitance requirement, these dc-link capacitors are usually of electrolytic type, whose operation lifetime is quite limited and may be contradictive to the high reliability requirement of PV systems . Therefore, the dc-link capacitors have to be overdesigned in order to gain a longer operation lifetime. The same issue may also exist in unbalanced three-phase systems. A number of active power decoupling circuits have recently been proposed in order to reduce the dc-link capacitance requirement, so that long-lifetime film capacitors can be used instead of electrolytic capacitors in the dc-link to improve the reliability of single-phase power converters .The main idea is to introduce auxiliary circuits to absorb the pulsating power, which can be stored either by inductors or film capacitors. Inductors are reliable, but when used for energy storage purpose, they will be very bulky and may induce high power losses due to their high equivalent series resistance (ESR).Therefore, more research attentions have been put on film-capacitor-based power decoupling circuits, and it is demonstrated in that the capacitance requirement can be significantly reduced with the help of decoupling circuits. Unfortunately, the power decoupling function may again be realized at the expense of more semiconductor switches and higher power losses. Reference presents a differential buck converter which does not require additional switches for powerdecoupling. However, only the autonomous mode is studied, and its grid-connected mode, especially the leakage current issue under transformerless operation, remains unexplored. Simultaneous solving leakage current and pulsating power issues may impose a design challenge to the PV systems, and this research topic is not discussed in the literature. In view of this, this paper presents a transformerless inverter topology that can simultaneously eliminate the leakage current and pulsating power in grid-connected PV systems. Its attractiveness is that it does not require any additional switches to resolve these two difficulties, and the circuit configuration is very simple, with only one additional current sensor introduced for current control. The leakage current can be controlled by introducing a CM conducting path inside of the PV inverter, so that it will not flow through the ground. By further injecting CM voltages to the output capacitors, the second-order pulsating power that originated from the ac side can be decoupled, and it will not be seen by the dc-link as well as the PV input. In this case, the dc capacitance requirement can be substantially reduced, and it is feasible to design an all-film-capacitor supported PV inverter with high efficiency and high reliability. The mechanism of leakage current suppression and the closed loop control of pulsating power decoupling are discussed in this paper in detail. A 500-W prototype was also built and tested in the laboratory, and both simulation and experimental results are finally presented to show the excellent performance of the proposed PV inverter. The proposed system output RL load fundamental (50Hz) is change the total harmonics distortion is reduced. The design has been simulated and verified using MATLAB R2009b.in [22], which is the well-known double-line-frequency pulsating power [23]. Conventionally, very bulky dc-link capacitors so that the maximum power point tracking (MPPT) efficiency will not be compromised. Unfortunately, because of the large capacitance requirement, these dc-link capacitors are usually of electrolytic type, whose operation lifetime is quite limited and may be contradictive to the high reliability requirement of PV systems [24]. Therefore, the dc-link capacitors have to be overdesigned in order to gain a longer operation lifetime. The same issue may also exist in unbalanced three-phasesystems.

A number of active power decoupling circuits have recently been proposed in order to reduce the dc-link capacitance requirement, so that long-lifetime film capacitors can be used instead of electrolytic capacitors in the dc-link to improvethe reliability of single-phase power converters [25]–[32].The main idea is to introduce auxiliary circuits to absorb the pulsating power, which can be stored either by inductors or film capacitors. Inductors are reliable, but when used for energy storage purpose, they will be very bulky and may induce high power losses due to their high equivalent series resistance (ESR). Therefore, more research attentions have been put on film-capacitor-based power decoupling circuits, and it is demonstrated in [30]–[32] that the capacitance requirement can be significantly reduced with the help of decoupling circuits. Unfortunately, the power decoupling function may again be realized at the expense of more semiconductor switches and higher power losses. Reference [33] presents a differential buck converter which does not require additional switches for power decoupling. However, only the autonomous mode is studied, and its grid-connected mode, especially the leakage current issue under transformerless operation, remains unexplored. Simultaneous solving leakage current and pulsating power issues may impose a design challenge to the PV systems, and this research topic is not discussed in the literature. In view of this, this paper presents a transformerless inverter topology that can simultaneously eliminate the leakage current and pulsating power in grid-connected PV systems. Its attractiveness is that it does not require any additional switches to resolve these two difficulties, and the circuit configuration is very simple, with only one additional current sensor introduced for current control. The leakage current can be controlled by introducing a CM conducting path inside of the PV inverter, so that it will not flow through the ground. By further injecting CM voltages to the output capacitors, the second-order pulsating power that originated from the ac side can be decoupled, and it will not be seen by the dc-link as well as the PV input. In this case, the dc capacitance requirement can be substantially reduced, and it is feasible to design an all-film-capacitor supported PV inverter with high efficiency and high reliability. The mechanism of leakage current suppression and the closedloop control of pulsating power decoupling are discussed in this paper in detail. A 500-W prototype was also built and testedin the laboratory, and both simulation and experimental results are finally presented to show the excellent performance of the proposed PV inverter.

B.CIRCUIT CONFIGURATION AND LEAKAGE CURRENT ELIMINATION

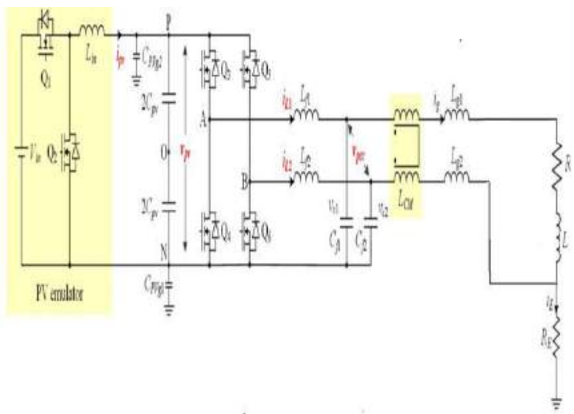

Fig.1. Circuit diagram of the proposed transformerless inverter for RL-connected PV systems.

The proposed transformerless PV inverter is essentially derived from a conventional full-bridge inverter with an output *LC* filter. The *LC* filter is split into two identical parts, having $Lf1 = Lf2 = Lf$ and $Cf1 = Cf2 = Cf$. They are distributed into the two switching legs as shown in Fig. 1. More advanced *LCL* or *LLCL* filters can also be adopted, but they may increase the complexity of the system. The midpoint of the two capacitors is then connected to the negative dc bus in order to provide a conducting path for the CM current. Because of the symmetrical circuit configuration, its differential mode (DM) operation, i.e., active power injection and reactive power support, will not be affected. In order to investigate the ground leakage current, the equivalent CM circuit is presented in Fig. 2, where the RL load voltage is neglected because it is of fundamental frequency only.

For a stiff ac power grid where the grid impedance is negligible, the ground leakage current in such systems will be very small because the value of the filter capacitors is usually in the microfarad range, while for the parasitic capacitors it is normally around 100 nF for a 1-kW PV system. Moreover, the grounding resistance is usually not zero, and 10 and 15 Ω are considered in Therefore, the impedance of $Cf1$ and $Cf2$ will be much lower than that of the grounding loop in the switching frequency range. In this case, most of the CM currents will be bypassed by the two filter capacitors, and it is possible to limit the ground leakage current to comply with the standard.Variousinvertertopologies haverecentlybeenproposedto addresstheleakagecurrentissueintransformer less PVsystems,andthebasicideaistointroducenewfreewheelingpaths intotheinvertersothatthePVpanelcanbeisolatedfrom theRL loadduringfreewheeling modes.Thiscanbe achievedbycuttingofftheCMcurrent conductingpathwhen zerovoltagevectorsareappliedtothe full-bridgeinverter,and itcanbeimplementedeitheronthedcsideorontheacside. ExampletopologiesincludetheH5 inverterfromSMA,the HERICinverter fromSun ways,andmanyoftheirderivativesrecentlyreported

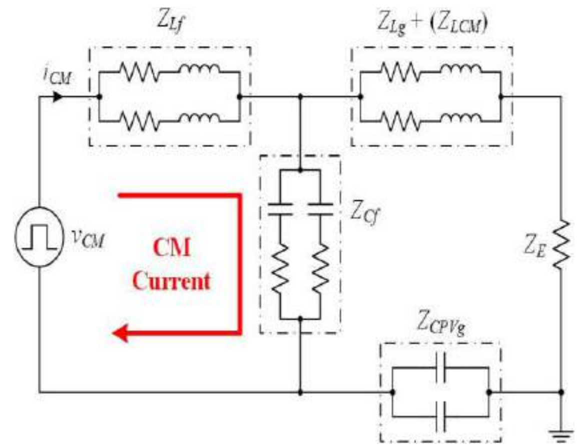

Fig2.CM equivalent circuit of the proposed PV inverter

Anotherpossiblesolution istodirectlyclampthepotential ofPVterminals withrespect tothegroundoftheacgrid.Thiscanbeimplementedeither onthemidpointofthedcbus,e.g.,inthehalf-bridgeinverter, theneutral point clamped(NPC)inverter,andtheT-typeNPC invertercommercializedbyCo energy,oronthenegativebusof thePVterminal,e.g., intheKarschnyinverter,the virtual dcbusinverterproposed in,andthenegative grounding inverter proposed. Eventhoughthesetopologies are veryeffectiveinleakagecurrentreduction,theystillhavesome drawbacks.

Thehalf-bridge-based topologiesmayrequirea highdcbusvoltagethatisdoubleofthefull-bridgecase.Forthe remainingtransformerless topologies,additionalsemiconductorswitcheshavetobeused alongwithmorecomplicatedactive gatecircuitsandcontrol signals.Thesystemreliability and lifetimewillalsobedeteriorateddueto theincreasednumber ofactivecomponents.Amodifiedfull-bridgeinverteris presentedtosuppress theleakagecurrent withoutusingextra switches,andonly smallCMfiltersmay berequiredtoform a CMcurrentbypassingloop.

This system can simultaneouslyeliminatetheleakagecurrent andpulsatingpoweringrid-connectedPVsystems.Itsattractivenessisthatitdoesnotrequire anyadditional switchesto resolvethesetwodifficulties,andthecircuitconfigurationis verysimple,withonlyoneadditionalcurrentsensorintroduced forcurrentcontrol.Theleakagecurrentcanbecontrolled by introducinga CMconductingpathinsideofthePVinverter,so thatitwillnotflowthroughtheground.ByfurtherinjectingCM voltagestotheoutputcapacitors,thesecond-order pulsating powerthatoriginatedfromtheacsidecanbedecoupled,and itwillnotbeseenbythedc-linkaswellasthePVinput.In thiscase,thedccapacitance requirement canbesubstantially reduced,anditisfeasibletodesignanall-film-capacitorsup-portedPVinverterwithhighefficiencyandhighreliability.

C. CONTROL BLOCK DIAGRAM

Theclosed-loop controllerdesignoftheproposed transformerlessPV inverterbecomesstraightforwardif the twooperation modesareseparatelyanalyzed. ItsDMequivalent circuitisessentiallyaconventionalunipolar-modulated full-bridgeinverteroperatedinthegrid-connected mode thevoltageatthe pointofcommoncoupling(PCC)andthePVoutputcurrent,the ycanbetreatedasthedisturbances andcancelledby feed forwardcontrol. Sincetheresponse ofthevoltagecontrol loopisusuallymuchslowerthanthatofthecurrent control loop,thedynamicsofv_{PV}canbeneglected

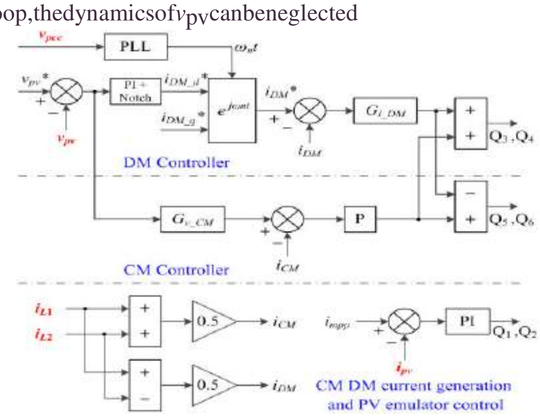

Fig3.Overall controlblock diagram for the proposed transformerless PV inverter.

Itispossibletoarriveatthefinalmodulation signalsfortheDMoperation.FortheCMcontrollerdesign,Fig. 2.3canbeused,andthe groundleakageloopcanbeneglectedbecauseitdoesnotaffect thepowerdecouplingcontrol.Inthiscase,theequivalentcircuit underCMoperation becomestwoparalleledbuckconverters, witheachofthemloadedbyLCimpedance,i.e.,$L_f$and C_fBasedonthisequivalentcircuitmodel.

D.SIMLATION DIAGRAM

The proposed system came from the existing system.proposed system is been modified by its output load power.the existing system first were connected through grid system, knowit been connected to RL loadand its benefits the proposed system to reduced the harmonicsdistortion

This chapter deals with the simulation circuits and results. The circuit has been simulated using MATLAB R2010a software with Simulink toolbox. Simulink is a software package for modeling and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in discrete time, continuous time, sampled time or a hybrid of above.

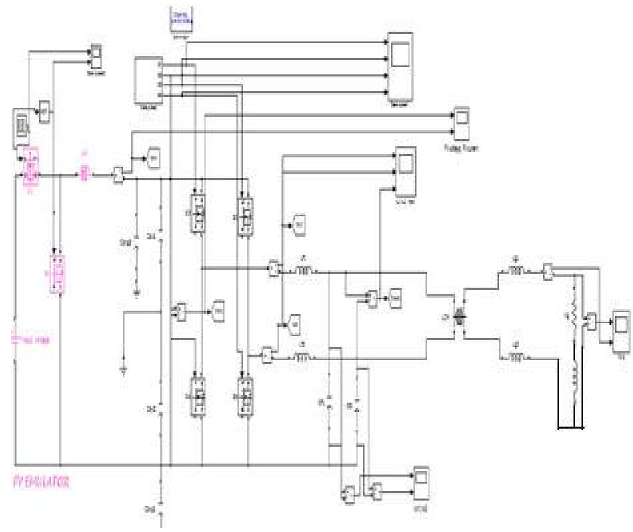

Fig 4simulation diagram of the proposed transformer less inverter for RL-connected PV systems

E.TOTAL HARMONICS DISORTION OF SYSTEM

The system output were connected to RL load selected signal as 50 cycles and FFT window 1 cycle, have change of the comparison of two systems fundamental, harmonic order is changed. Finally the modified output changed in simulation as fundamental 50(Hz) =5.524 and total harmonics distortion (THD) =2.8%.

Table 1

GRID LOAD	RL LOAD
▪ **Fundamental frequency** **6.23** ▪ **Total harmonics distortion** **3.97%**	▪ **Fundamental frequency** **5.524** ▪ **Total harmonics distortion** **2.83%**

FFT ANALYSIS TO LOAD

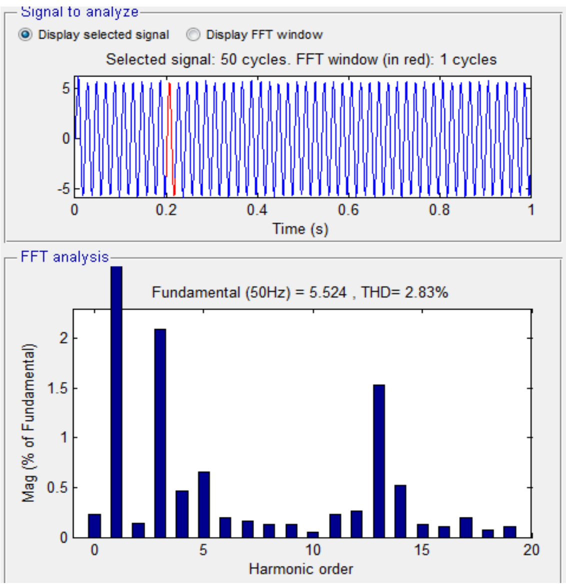

Fig 5.FFTanalysis of harmonic order

V. SIMULATION RESULTS

Simulations were conducted with PLECS, based on the system shown in Fig. 1. The main objectives were to showthe low ground leakage current and the effectiveness of the proposed power decoupling control. The system parameters can be found in Table I, and the resulting resonance frequency of the output *LCL* filter is at 1062 Hz, which is less than 1/6 of the sampling frequency. In this case, the DM current control will be inherently stable because converter-side current feedback is adopted here [45]. It should be noted that only a 30-μF film capacitor was used in the dc-link, and this can better show the performance improvement achieved by the proposed power decoupling control.

Fig. 5shows the simulated steady-state results when thepower decoupling control is not implemented. In this case, theinherent pulsating power in single-phase systems may propagate to the PV side, giving rise to the severe ripple components in both PV voltage and PV current. Therefore, the system cannot be stabilized around the MPP, and the energy yields from PV panels will be much reduced. However, the injected grid current is still sinusoidal with low total harmonic distortion (THD). This is mainly due to the second-order notch filter inserted into the dc-link voltage control loop. Even though the worst case of *Lg* is chosen in the simulation, the ground leakage current is very small, and its rms value is only 13.0 mA, which is far below the 300 mA limit.

Fig. 8 shows the simulated steady-state results when thepower decoupling control is enabled. It is clear that the ripple components in the PV voltage and PV current can be effectively reduced to almost zero. The grid current is still a clean sinusoidal, and this result can be even achieved without the second order notch filter. This is because there is no disturbance from the dc-link, and its voltage controller can generate a harmonic free current reference for the inner current regulation.

With aCM voltage applied to the filter capacitors, the ground leakage current is noted to increase a little bit, but the rms value is only 19.7 mA, which still complies with the standard. The filter inductor currents and the filter capacitor voltages are in the similar level as those for the previous case, indicating that the power losses of semiconductors and the lifetime of film capacitors will not be deteriorated.

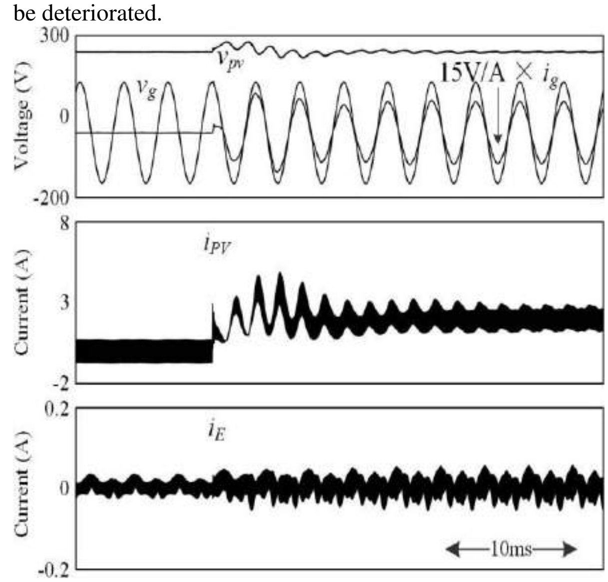

Fig.6. Dynamic results showing the no-load to full-load step change.

Fig.6shows the dynamic response of the system when it is subjected to a no-load to full-load step change. As seen,the leakage current is always in a very low level, and it will not mistrigger the RCD protection even under the worst case operation.

F.EXPERIMENTAL RESULTS

`To experimentally validate the proposed transformerless PV inverter, a 500-W prototypewas built in the laboratory, based onthe same parameter values listed in Table I and the circuit configuration shown in Fig. 1. However, the actual filter inductance and capacitancemay deviate from their nominal values because of the tolerance of the passive components. The control algorithms were executed on a dSPACE1006 control platform, and the sampling frequency is synchronized with the PWM, which is also 19.2 kHz.The Simulink of solar panel subsystem. The photovoltaic panel produces an output of 24V.The solar subsystem consists of Photovoltaic panel which has the input parameters of Irradiation level, temperature and the voltage.The energy management is designed for the irradiation level varying from900 w/m2 to 1400 w/m2 during day time.It consists of a solar cell, each cell having its own voltage.

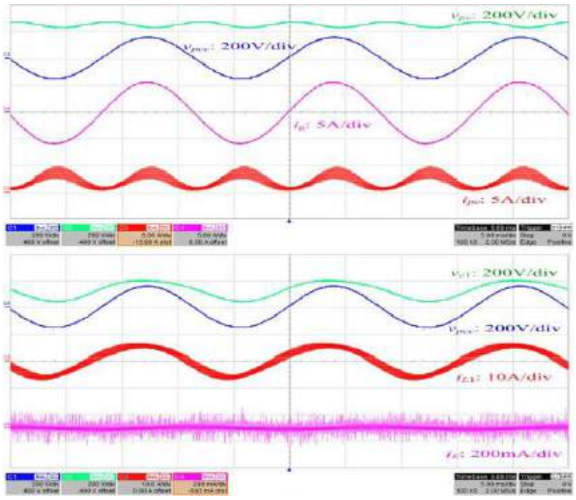

Fig 7. Experimental steady-state results without the power decouplingcontrol

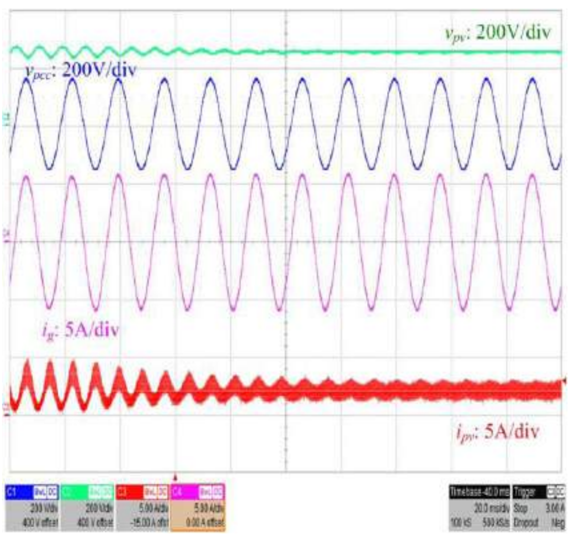

Fig 8.Experimental results showing the transition waveforms ofenabling the power decoupling control

Fig. 8presents the transition waveforms. It is clear that the ripple components of *v*pv and *i*pv can smoothly diminish to zero,and the grid current regulation is not disturbed. As mentioned, this is because the DM operation of the inverter is not affected by the CM power decoupling control. The settling time can be further shortened by removing the second-order notch filter and optimizing the controller gains.

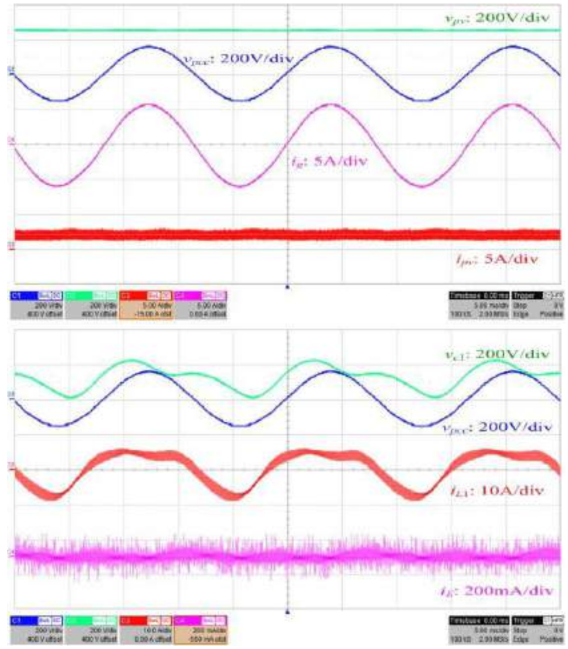

Fig 9. Experimental steady-state results with the power decouplingcontrol.

Another set of experimental results was captured, after thesystem was settled in the new steady state, and the waveforms are presented in Fig. 9. Again, they are in very good agreement with those presented in the rms value of the ground leakage current is increased to 19.8 mA. As discussed, this value can be further limited by introducing a CM choke on theoutput of the inverter. The THD of the grid current in this case is 1.91%, and it is slightly increased from 1.83%, which is theresult obtained before enabling the power decoupling control.This is mainly due to the CM harmonic injection.

The first set of experimental results is presented in Fig. 10 in order to show the steady-state performance of the proposed PV inverter without the power decoupling control. As it can be seen, the PV voltage and PV current are pulsating at double of the fundamental frequency, which is consistent with the ones shown in Fig. 7. The other waveforms are also very close to the simulation results. The rms value of the ground leakage current was measured to be 14.7 mA, and it is in the similar level as the simulation result.

The dynamic response of the system when the PV current reference is suddenly changed from0.5 to 2 A, corresponding to a 360-W load change.As seen from Fig. 10, the dc-link overshoot voltage is less than 25 V, which is very small considering that only a 30-μF film capacitor was used. The grid current as well as the input current can settle down within five line cycles, and there is no severe overcurrent during the entire load transient

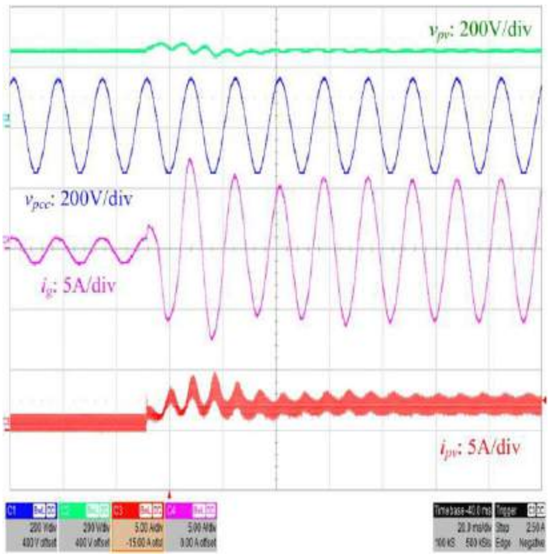

Fig. 10.Experimental dynamic results under a 360-W load change

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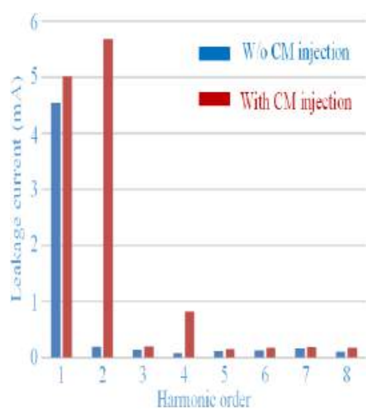

Fig. 11.Spectrum of the leakage current before and after enable

Fig. 11shows the harmonic spectrums of the leakage current before and after enabling the power decoupling control. As seen, the second and fourth orders are increased due to the injection of CM voltage, and their amplitudes are governed by 2*kωnC*PVg*v*cm_*k*, where *k* is the harmonic order. As mentioned before, the parasitic capacitance *C*PVg can reach the microfarad, the efficiency of the PV inverter was measured by aPM3000A universal power analyzer, and under rated load operation,it is around 96%, which is only 0.5% lower than that of the conventional H-bridge inverter constructed using the same components. The efficiency drop is mainly due to the higher switching current induced by the CM signal, and its impact tothe lifetime of the inverter is very limited. As compared to the transformerless topologies which directlyclamp the neutral point to the dc bus, the proposed PV inverter may generate a higher leakage current because a smallamount of the CM current can still "leak" to the.

G.CONCLUSION

In this paper, a single-phase transformerless inverter topology has been presented for grid-connected PV applications. By introducing a CM conducting loop into the inverter system, the ground leakage current issue can be solved without adding additional active componentscircuit, and the system cost and complexity can be reduced. The inherent pulsating power in single-phase PV systems can also be eliminated by injecting proper CM signals to the modulation of the inverter. Therefore, long-lifetime film capacitors can be used in the dc-link to replace those less reliable electrolytic capacitors. A dual-mode closed-loop controller has also been proposed to completely decouple the pulsating power even in the presence of system uncertainties and disturbances. Comprehensive experimental results have been presented to show the excellent performance of the proposed inverter, and the proposed system output RL load fundamental (50Hz) is change the total harmonics distortion is reduced. The design has been simulated and verified using MATLAB R2009b.

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