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Hybrid Boost Converter for PV Applications

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Abstract:

This paper presents the design and analysis of a three-level hybrid boost converter based on a single-phase three-level T-type inverter. The proposed converter can provide high energy conversion efficiency and high voltage gain capability with a reduced component count. The pulse-width-modulation signals of the proposed converter are generated by comparing two duty cycles and two triangular carrier signals. The proposed converter consists of four power switches, four diodes, an inductor, and two capacitors. Detailed converter operations at each switching state with the corresponding voltage and current waveforms of each component are discussed. The functionality and performance of the proposed converter are verified through simulation and experimental results.

Keywords **—**Plug-in hybrid vehicle (PHEV), Vector Control, Grid-connected Photovoltaic (PV), Three-phase Hybrid Boost Converter,

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I. INTRODUCTION

Nowadays, renewable power generation particularly solar photovoltaic (PV) is gaining popularity due to the demand for clean energy and the need for reducing carbon emissions from fossil fuels. There are two main types of PV systems which are grid-connected and off-grid systems. The grid-connected PV system has been widely used in residential and commercial sectors as well as implemented in large utility-scale solar power stations. Meanwhile, off-grid PV systems are typically used in remote and isolated areas without grid connectivity. Typically, it has a large battery bank to store or supply the energy when required. Furthermore, it also provides a balance between PV output generation and load demand [1]. For a small solar PV system with a small number of PV modules, the amount of output power and output voltage that can be produced is relatively low. Therefore, a step-up DC-DC/boost converter is required to increase the PV voltage for producing the standard AC voltage by using a DC-AC converter. There are several types of step-up DC-DC converters that have been introduced for PV system applications which can be classified into non-isolated and isolated converters. The isolated converters typically consist of high-frequency transformers with a high turn ratio. However, high-frequency transformers typically contain leakage inductance which creates high voltage spikes that can cause damage to power switches and other components. Thus, the suppression method by using snubber circuits or other voltage clamping circuits is required [2–7]. In the case of PV system applications that do not require galvanic isolation, the non-isolated DC-DC converters are used owing to the fact that it has a simple structure. The duty cycle of the non-isolated DC-DC converters is varied accordingly to step up the PV output voltage by using the pulse-width-modulation (PWM) method. However, producing high output voltage using the conventional DC-DC converter requires a relatively high duty cycle which results in higher power losses, higher electromagnetic interference, severe diode recovery problem and lower conversion efficiency [8].Various newer topologies of non-isolated DC-DC converters have been proposed to overcome these common drawbacks. Some of the proposed converters use switched capacitors and coupled inductors to increase the voltage gain without using an extreme duty cycle, thereby reducing the voltage stress of power switches and alleviating the diodes' reverse recovery problem [9, 10]. Cancellation of ripple current of the coupled inductors can be done by using the interleaving technique, consequently reducing the conduction and switching power losses from power switches and diodes [11, 12]. There are also other topologies of non-isolated DC-DC converters that have been proposed based on different inductor-capacitor structures, magnetic coupling, and voltage multiplier cells to achieve not only high voltage gain but also high energy efficiency [13–15]. A voltage multiplier cell integrated with an auxiliary resonant cell has also been proposed to increase the voltage gain with a soft-switching technique [16]. However, more voltage multiplier cells are required as the voltage gain is increased.

II. PROPOSED SYSTEM

In this paper, a new converter is proposed for PV system application with a low PV string voltage comprising a few PV modules in a series connection. A PV system with low PV string voltage (up to 90 V) is suitable for implementation especially in the area subjected to partial shading conditions, for instance, a residential area surrounded by high-rise buildings or trees. Hence, the effect of partial shading can be reduced, consequently optimizing the overall system performance and energy efficiency. Although the use of microinverters can properly address this issue, the installation cost is higher since each PV module requires a microinverter for energy conversion. Alternatively, a hybrid boost converter derived based on a single-phase three-level T-type inverter is proposed.This development contributes to a new circuit topology that falls under the multilevel DC-DC converters.

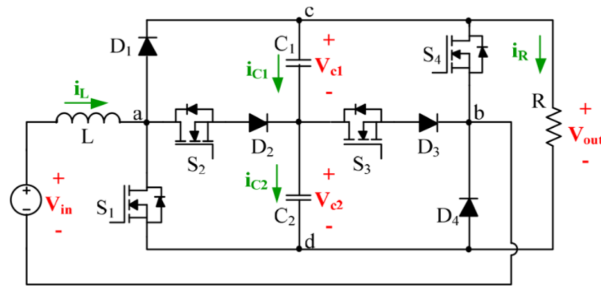

FIG.1. Proposedthree-levelhybridboostconverter

In comparison with the recent development works, theproposed converter has no leakage inductance issues associatedwithhigh-frequencytransformers.Owingtohighvoltagegaincapability, PV systems with low-voltage PV string or PV arrayinputemployingtheproposedhybridboostconvertercanbeconnecteddirectlytothethree-phasegridorload.Thisconfigurationisnotfeasibleiftheconventionalboostconverterthat has a very limited voltage gain is used. A direct performancecomparison with the recent T-type DC-DC converters and othermultilevelDC-DCconvertersisabitdifficultsincedifferentconverters usedifferentconfigurations,setups,anddevices.Therefore, a fairer comparison is made against the proposedconverter in [17] since the concept is similar but developed basedon NPC. The advantages of the proposed hybrid boost converter ascompared to the NPC-based converter are lower component countand higher energy efficiency. It also shares the same non-extremeduty cycle characteristic with high voltage gain and a wide inputrange.Nevertheless,thedrawbackisbothconvertersrequiretransformers for galvanic isolation. Having said that, the use oftransformers at the point of common coupling is typical for large-scalegrid-connectedapplications.Thispaperisorganizedasfollows.First,thebasicoperationprinciplesandconverteroperationsateachswitchingstatearediscussedindetail.Thisincludesanalysisofthevoltageandcurrentwaveformsofthe

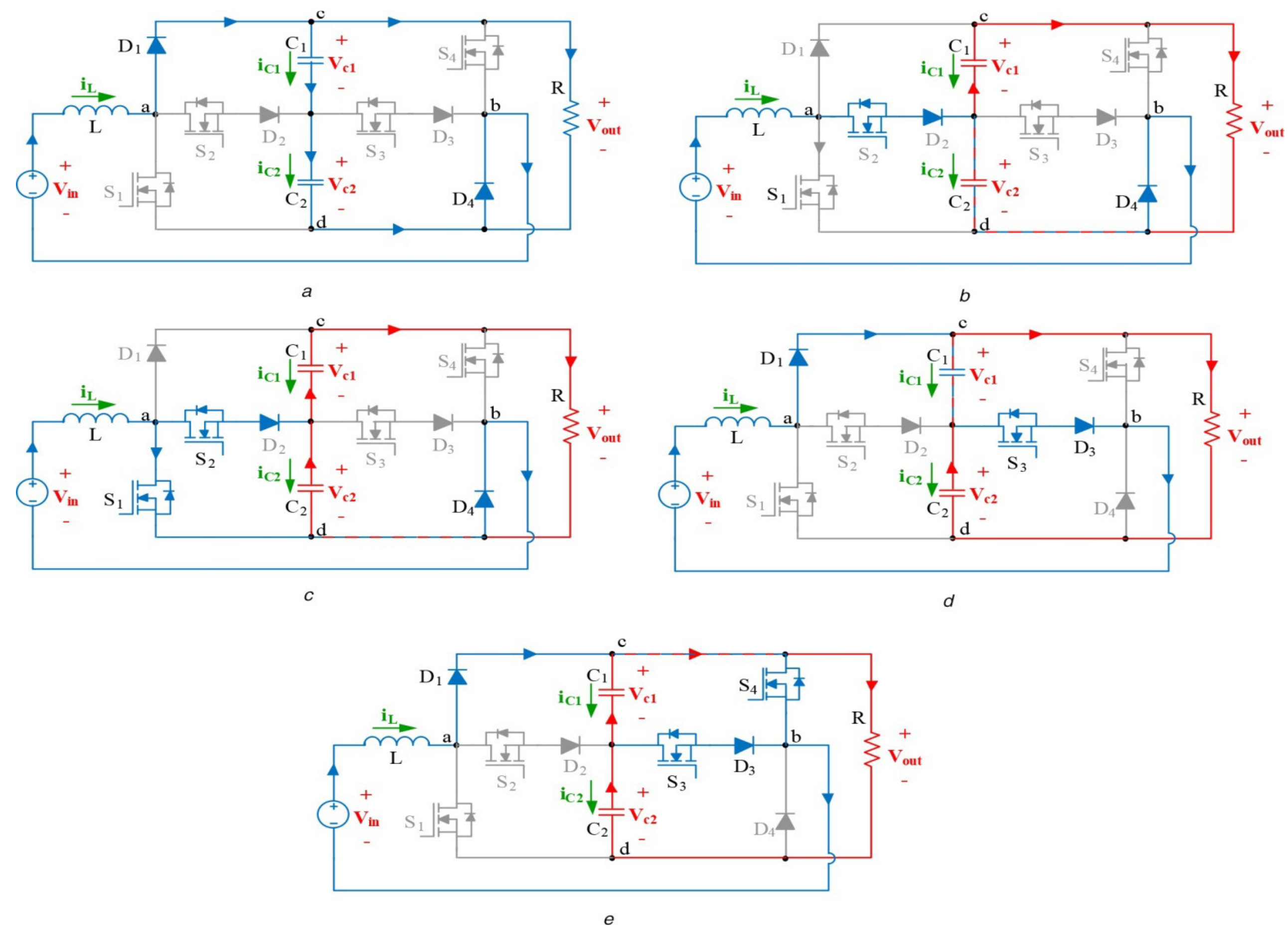

FIG.2. Detailedconverteroperationateachswitchingstate[$S_1S_2S_3S_4$] (a)0000,(b)0100,(c)1100,(d)0010,(e)0011

2.1.1 inductor and capacitors. Then, the input-output voltage relationshipisdefinedandthemathematicalexpressionstodeterminetherequiredinductanceandcapacitancevaluesforachievingthedesired operating conditions are derived. Both the input currentripples and the output voltage ripples can also be determined fromthe equations that have been obtained. Finally, in order to providean overview of the proposed hybrid boost converter with regard tothe basic structure and components, general comparison is madeagainstNPC-basedhybridboostconverter,theT-typeDC-DCconvertersand other recently publishedDC-DCconverters.

Switching state [0100]: When S_2 is ON, C_1 is discharged totheloadwhileC_2ismaintainedtobechargedasillustratedinFig. 6b. As a result, $V_{ad}$is ½$V_{out}$the which is also equal to V_{C2}.SinceV_{bd}remains 0, $V_{ab}$is also equalto ½V_{out}.

Switching state [1100]: From Fig. 6*c*, when $S_1$and S_2areON,chargingofC_2isbypassed,allowingtheinductortobeenergizedfromthedcpowersupply.Thus,both C_1andC_2simultaneously supply energy to the load, *R*. V_{ab} is equal to 0 sinceV_{ad} and V_{bd} are 0. It is noted that during period t_2 - t_3, S_2 can beturned OFF since $C_2$is not charged. Instead, $S_2$is maintained to beON from the previous state to reduce the number of commutations,henceminimizing the switchingpower losses.

Switching state [0010]: When only $S_3$is ON as can be seenin Fig. 6*d*, the stored energy in the inductor is used to charge C_1.During this switching state, C_2 supplies energy to the load. V_{ad} andV_{bd}equaltoV_{out}and½V_{out}respectivelyandthereforeV$_{ab}$becomes½V_{out}.

Switchingstate[0011]:WhenS_3andS_4areON,chargin gofC_1isbypassedwhichallowstheinductortobeenerg izedfrom can also be turned OFF since $C_1$is not charged but remained turnedONto reduce the switchingpowerlosses.

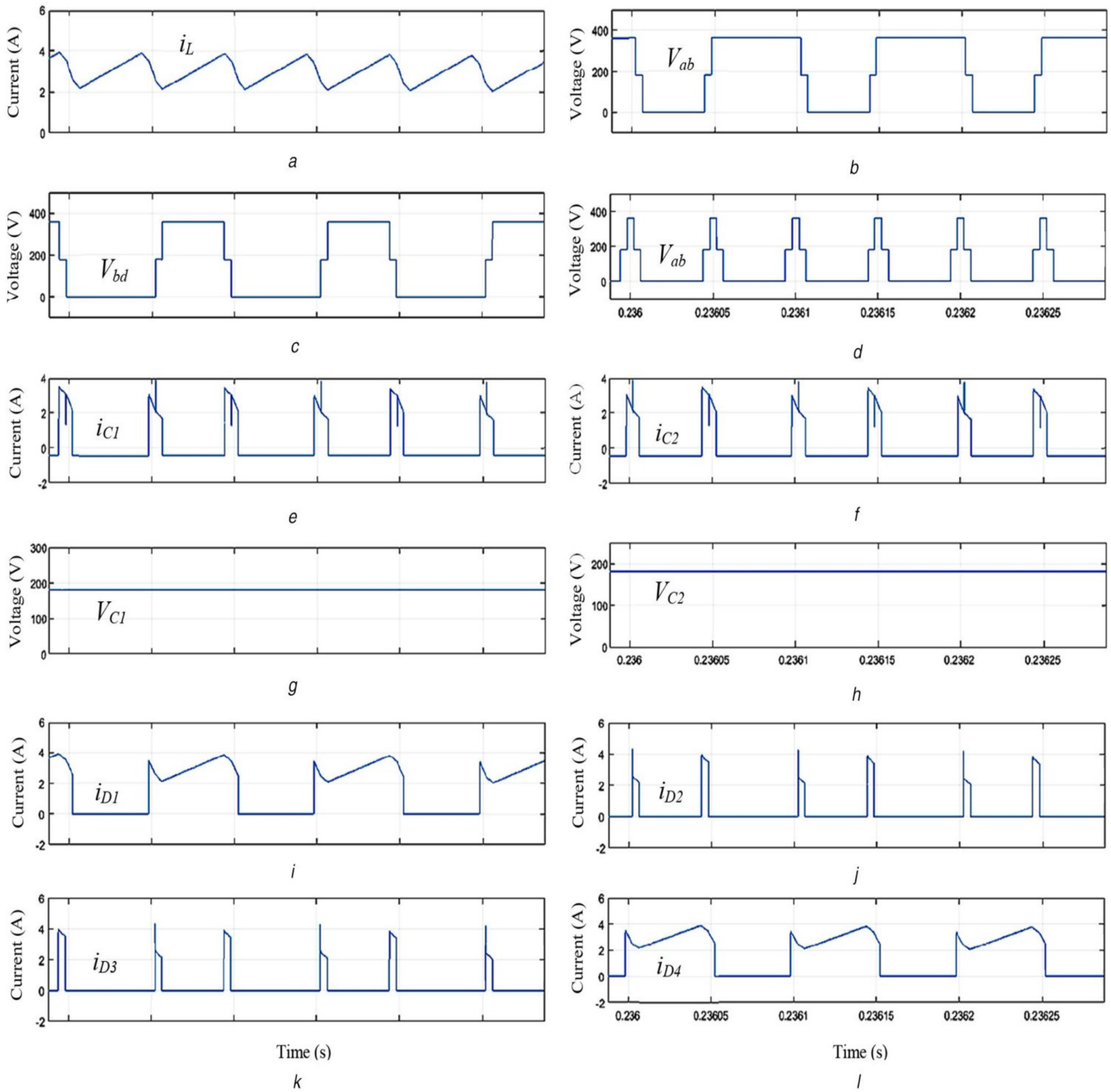

FIG.3.Simulationwaveformsofthe proposedconverter
(a) Inductorcurrenti_L,**(b)**Half-bridge1voltageV_{ad},**(c)**Half-bridge 2voltageV_{bd},**(d)**Voltagebetweenhalf-bridgesV_{bd},**(e)**Capacitor1currenti_{C1},**(f)**Capacitor2currenti_{C2},
(g) Capacitor1voltageV_{C1}, **(h)**Capacitor2voltage V_{C2},**(i)**Diode1 currenti_{D1},**(j)**Diode2currenti_{D2},**(k)** Diode3currenti_{D3},
(l) Diode4current i_{D4}

III.CONCLUSION

In this paper, a three-level hybrid boost converter developed basedonasingle-phasethree-levelT-typeinverterforPVsystem applications with low PV string voltage is proposed. It consists offour discrete power switches, four discrete diodes, an inductor, andtwo capacitors. The switching signals are generated by using twoduty cycles and two triangular carriers. The proposed converter canprovideamediumtohighvoltagegainathighconversionefficiency.Thebasicoperationprinciples,switchingstates,andPWM signals generation have been discussed in detail includinganalysisoftheconverteroutputanditsefficiency.Adetailedanalysisoftheconverterhasbeenperformedtodeterminetheinput-outputvoltagerelationshipandotherimportantdesignparameters. A comparison has also been made with NPC-basedhybridboostconvertersandotherrecentlypublishedboostconverters.Thefunctionalityandperformanceoftheproposedthree-level hybrid boost converter have been validated by usingsimulationandexperimentalresults.Futureworksmayincludecapacitorvoltagebalancing,outputvoltagecontrol,maximumpowerpointtracking,andconverteroperationsathigherpowerlevels.

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