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Design and Evaluation of IBC for EV Applications

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***Abstract*—Electric vehicles (EVs) have gained popularity due to their eco-friendly nature. This paper discusses the types of EVs along with the charger types and their power levels.The battery electric vehicles (BEVs), fuel cell electric vehicles (FCHEVs) and plug-in hybrid electric vehicles (PHEVs) are discussed. Furthermore, the AC-DC converters and various DC-DC converter topologies that are essential for EV chargers areexplainedwiththeirprosandconsequences. Anon-isolated conventional DC-DC boost converter and two-phase interleaved boost converter (IBC) is designed and analyzed in the MATLAB®/Simulink environment. The result shows that the IBC has low ripples in the input current and the output voltage. Thus, they are more suitable as compared to conventional DC-DC converter.**

Keywords— boost converter, DC-DC converters, electric vehicles, interleaved boost converter

I. INTRODUCTION

Thesolicitudetowardsthecleanenvironmentenergyand thenecessitytobeunboundedfromfossilfuelsexpenseshas clearly shown an exponential rise in demand as well as popularityoftheelectricvehicles(EVs)[1]-[3].Sincemost of the country's transportation system is largely dependent onfossilfuelsthatareexportedbyfewcountriesanditleads to an adversehealth conditionaswellasdrawsan economic hindranceforthedevelopingnations.Manycountriesaround the world came together to draw a draft to reduce CO_2 emission for the next 10 years, the initiatives by the multi- government policies led to expedite the adoption of EVs around the world [4]. This electric-based transportation proposesnotonlytoovercomethedependenceoffossilfuels but also shows the concept of electric power trading for the EV users [5]. Over the years, the electric vehicle has been categorized over the different mode of operation, based on external sources and hybridization with energy storage. The electric vehicle utilizes a battery to store energy and to provide power to the electric motor, while these powers are transferred by external sources. However, contemporary studyshowsthattheintegrationofrenewableenergysources (RES) [6] with EV technology has certainly eliminated the primary challenge of the driving range anxiety. Types of EVs are summarized as battery-based EV (BEVs), fuel cell EV (FCEVs) and Plug-in hybrid EVs (PHEVs). These EVs are discussed in detail as:

A. *Batteryelectricvehicles(BEVs)*

These EVs are powered by batteries only. The high-capacity battery requires a systematic operational charger which provides smooth power flow between the external source and battery. Such a battery charging system can be classified into two categories, namely (a) on-board and (b) off-board chargers, accompanied by unidirectional and bidirectional power flow capabilities. Moreover, the overall

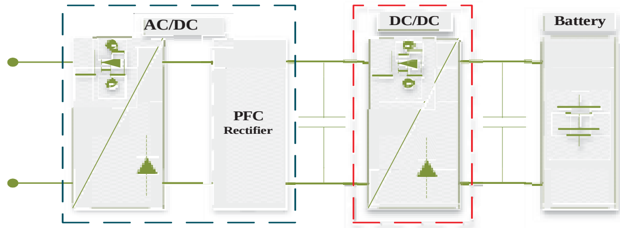

Fig.1.Blockdiagramofon-boardchargerforEV.

weight of the vehicle has reduced with an alternate mechanical drivetrain as electrical energy conversion and also it reduces noise pollution. In addition, EV has simple and low components compared to ordinary fuel-based vehicles. On the other hand, EVs has limited driving range and speed, the driving range is governed by the battery capacity used in the EV. EVs takes 22-24 hours to 43-20 minutes to achieve full charge, depending on their power levels[7],[8].Chargecycleandchargetime isan important factor in determining a battery life which is associated with battery charger, as battery plays a crucial role in EVs. A battery charger must draw line current from utility with low total harmonic distortion (THD) and must ensure unity power factor (UPF) to achieve high power quality [9]. Nevertheless, the researchers have been studying to overcometheselimitationsandchallengestoprovideabetter and efficient mechanism for users.

B. FuelCellElectricVehicles(FCEVs)

Fuel cell electric vehicles (FCEVs) have come out to asa replacement for traditional vehicle and the powertrain of FCEV is analogous to the BEV. Depending upon the requirement fuel cell can be primary or secondary energy source [10]. However, fuel storage in FCEVs is either in a tank mounted in the vehicle or it is being extracted from the fuel processor. The conversion of energy in a fuel cell is between chemical energy and electrical energy through electrolyte medium. The repercussion of this conversion gives heat and water as a by-product. Several prototype fuel cell is under-development and some fuel cell, like direct methanol fuel cells (DMFC), proton exchange membrane fuel cells (PEMFC), alkaline electrolyte fuel cells (AFC), phosphoric acid fuel cells (PAFC) tends to operate under lower temperature [10]. Many motor car manufacturers namely Honda, Toyota, Hyundai and more have used fuel cell technology in their vehicles [11] to provide high performances. On the other hand, minimizing fuel consumption, power losses and improvising overall efficiency are the challenges faced by these technologies.

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TABLEI. VARIOUSTYPESOFEVMODELSWITHTHEIRPOWERCHARGINGLEVELS

Types ofEV	VehicleModel	DescriptionofPowerlevelCharging		
		Charginglevel	ChargerLocation	Powerlevel
FCEV	FordFusionEnergi	Level1/Level2	Singlephase/3-phase On-board	3.3kW
FCEV	MercedesC350Plug-in Hybrid	Level2	Singlephase/3-phase On-board	3.3kW
FCEV	MercedesS550Plug-in Hybrid	Level1/Level2	Singlephase/3-phase On-board	3.3kW
FCHEV	PorschePanameraSE-Hybrid	Level1/Level2	Singlephase/3-phase On-board	2.3kW
FCHEV	ToyotaPrius1.82015	Level1/ Level2	Singlephase/3-phase On-board	3.3kW
FCHEV	AudiA3E-Tron	Level1/ Level2	Singlephase/3-phase On-board	3.3kW
EV	ChevySpark EV	Level1/Level2/ DCcharging	Singlephase On-board/Off-board	3.7kW
EV	NissanLEAFE-Plus	Level1/Level2/Level3	Singlephase/3-phase On-board/Off-board	3.7kW/11kW/50kW
EV	TeslaModelS	Level1/Level2/ Supercharger	Singlephase/3-phase On-board/Off-board	3.7kW/22kW/50kW

C. *Plug-inHybridElectricVehicles(PHEVs)*

The advancement of hybrid EV makes plug-in hybrid electric vehicles (PHEVs) in which hybridization of the internal combustion engine (ICE) and a battery that can be chargedfromthepowergridisutilizedforthemotionofthe vehicle. Furthermore, the PHEVs can be designed from any HEV[10] by addition of charger which matches the power requirement of battery. The hybridization of EV requires electric motor, controllers, and the internal combustion engine and power electronic components that also include battery energy storage system.Interestingly, the splitting of power strategy on either running on just ICE or the EM or both, which makes the car manufacturer invest in without compromising its performance. The best utilization ofPHEV is to minimize the power drawn from the engine but allow the vehicle to run on the electric motor for maximum time. However, this approach makes the vehicle more competent in driving in cities as well as highways. Despite these advancement overall efficiency is about 14% [12] the battery storage of PHEV has larger size as compared to a typical hybrid electric vehicle which increases the cost and weight of the vehicle. For these reasons, more research and developmentisrequiredtoboost-uptheperformancesofthe vehicle.

II. POWERLEVELFOREVCHARGERS

Charging power levels assist the user to understand its parameters that includes cost, charging time, components, charging locations and effect on the power grid. Charging station standardization, demand & distribution (DD) policies, regulatory procedures and time and extension for charging (TEC) are the issues that are vital to be acknowledged for the deployment of electric vehicle supply equipment (EVSE) and charging infrastructure. Availability ofcharging infrastructurewith on-board minimizescostand energy storage system. The charging codes, connectors, charge stands on a different area (public or residential locations), various plug-ins, power outlets and protective equipment are core components for EVSE [9],[3]. EV owners choose the charging time during night at home as illustratedbyElectricPowerResearchInstitute(EPRI)[13]. Therefore,theprimechoicewillbepowerlevel-1andpower level-2 equipment [14].

A. *PowerLevel-1*

The charging time is quite high as compared to other powerlevelsforEV.Atresidentialareasthepowerlevel-1is suitable as no extra infrastructure is required; also during night the demand required is low. Thus, the research and development in this field shows a positive vision for the adjustment of this charging power level in EV.

B. *PowerLevel-2*

This type charging level is concerned for commercial as well as private locations which include shopping malls, rest areas and various parking lots. To lessen the power electronics,thischarginginfrastructurecanbeon-board.Due to availability of 240V service at household and public places, this charging level requires a well-equipped and a properconnectionforinstallation.Sincethisishighcharging level the SAE's J1772 has a combo connector [15] which could supply AC and also DC fast charging.

C. *PowerLevel-3*

The charging time could take less than 1 hour which is the fastest among all the charging power levels. Due to less charging time, it operates under high supply (480V or 3-phase circuit) and for higher supply voltage this cannot be installed at the residential areas. This type of charging level couldbeinstalled atthehighwaystationsrequiresoff-board chargerswitharegulatedAC-DCconversion.However,this charging level could be used for emergency purposes as it provides high power density, risking an EV battery life.

Hence, a low-level charging power has a lead on minimumpeakimpact[16]ofthepowergrid.Thesocietyof automotive engineers (SAE) standard recommended that power charging level 1 & 2 should be placed inside the vehicle. For power level-2/-3, the distribution system has repercussions like system reliability, power or transformer losses, voltage deviations, efficiency and thermal loading. Researchers must contemplate about thedesigningof EV so that the heat load including power electronic converters and batteries should be arranged effectively. To control these impacts from high power charging levels smart controlling strategy, appropriate communication system must be installed [9].

III. CONVERTERTOPOLOGIESFOREVCHARGING

Differentviableconvertertopologiesofabatterycharger isacriticalelementinthepowersupplyconfigurationofEV. These converters are required for making an interface between DC-link and BEV, FCEV or PHEV. Different convertershasitsownspecialtyintermsoftheirusage,some has advantages over output and input ripple reduction without compromising with the size of the system, others havehighsensitivityandstabilityintheloadvariationsorto improve the overall efficiency and reliability of the system. However, each converter topologies should be selected based on the system's requirements, as different converters have different configuration to work on. All in all, to design aconverterforEV itisessential to considersome aspects to give better and efficient performance. Larger weight and volume of the converters are the causes for maximum drainage of power therefore, it is necessary to design a converter with low weight and low volume through which a user can avail maximum efficiency from EV. Whilst the converter boost the voltage it is also necessary to lower the currentrippledrawnfromsuppliesorinthiscasefuel-cellor battery.Variouscontrollingschemesareavailabletocontrol the power flow of DC-DC converter.

A. AC-DC converter

OtherthanDC-DCconverters,theAC-DCconvertersare thesubstantialelementintheEVchargingsystems.Various studies shows that AC-DC converter is pivotal to EV charger'sdevelopmentprocess.Thefundamentalworkingof this converter is to change AC input from mains to isolated DCoutput,moreovertheseconvertersaredesignedinsucha waythattheprocessimplementsintwostages.Firstly,toget middle level of voltage the rectification is necessary while various methods could be performed to improve performanceofpowerfactor.Secondly,tochargeEVbattery a desired dc voltage is required therefore the input must be converted. All in all, the development of AC-DC converter wasbasedontheconcepttoproducemaximumpowerfactor and reduce harmonic distortion to secure power networks. The main topology of conversion needs to be considered upon selection and these aspects are:

- Powerfactorcorrection.
- Costofelectric&magnetic components.
- Techniquesforcontrollingcircuitsandhardware structures.
- Switchingstress.
- Efficiency&durabilityofthesystem.
- Overallharmonicdistortionscausedbytheutility.

In [17] various power factor correction techniques for AC-DC converters are illustrated. For fast EV charging 3-phase AC-DC topologies, Neutral Point Clamped (NPC) converters, Bridgeless Boost converter (BBC) and Vienna Rectifierarediscussedin[18]basedontheirswitchingstress, complex control strategies and simple structures. Some of the discussed AC-DC boost topologies in[19] for EV charging are compared based on their parameters which includes: active power switches, size of boosting inductors, presence of rectifier bridge and finally, the level of output voltage. Also, it proposes the bridgeless interleaved boost converter which is capable of achieving the low EMI and with less components.

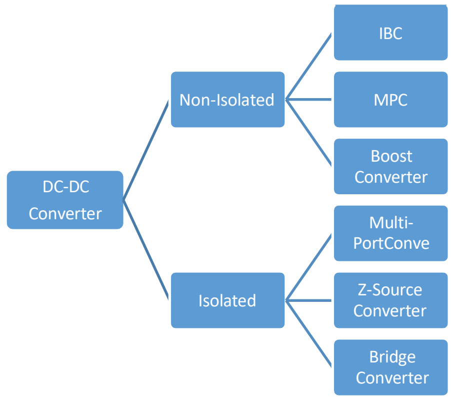

Fig.2.ClassificationofDC-DCconvertersfordifferenttypesofEVs

B. DC-DCconverter

Presently, various EVs are designed which utilizes DC-DC converters to increase their efficiency and to maximize their switching frequency [20], [21]. The basic function of DC-DC converter is to store the input energy either in magnetic field storage or electric field storage and then based on the requirement it releases energy to elevate the output voltage level. Most of the part, these converters primarily transfer power in uni-direction (from input to output) but also it have the ability to transfer power are bi-directional (i.e. from input to output or vice-versa). Fig. 2 illustrates the various DC-DC converter topologies used in BEV and PHEV powertrains. Selected DC-DC converter topologies are summarized which has the capability to chargeandmeettherequirementsofEV. Based on system's specifications these topologies could be grouped into two categories. The non-isolated converters are often used in applicationwherehighandmediumvoltageareneededwith no electrical isolation between input and output. Whereas, isolated DC-DC converters are commonly used in vehicular application for medium and low voltage with an absolute electrical isolation to output from input.

IV. ISOLATEDANDNON-ISOLATEDDC-DCTOPOLOGIES

This section summarized the discussion on selective isolated and non-isolated DC-DC topologies. In addition to that, in Fig. 2 the topologies which are selected for EV application are illustrated into two groups. Mostly, in electrical isolated vehicular applications, a high frequency transformerisutilized.Therearenumerousconverterswhich are categorized under isolated group but some of the discussed topologies here are: Z-source converter (ZSC), sinusoidal amplitude high voltage bus converter (SAHVC), multi-portconverter(MPC)andfull-bridgeconverter(FBC). However,undernonisolatedgroupthetopologieswhichare reviewed are as follows: interleaved boost converter (IBC), multi-port converter (MPC) and a conventional type boost converter (BC). Overall, these topologies are controlled by power switches and their working operations, power flow direction or power levels designate themselves under their categories.

A. BoostDC-DCconverter (BC)

The conventional type of DC-DC boost converter has basic function to elevate the input voltage and subsequently decrease the input current. The simple operation of boost converter, an inductor is connected in series with the input voltagetoreducescurrentrippleandacapacitorisconnected inparallelwithloadthatactsasafiltertoeliminateoutput voltage ripple. Controlling strategies adopted for this convertertoprovidelessvoltagestress,switchinglossesand high voltage gain [17]. For this topology, switching operation and architecture is quite easy and simple, also it couldbeusedinEVchargerdueitslowcost.Inaddition,its efficiency is less than 90% when used at full load [22]. However, to boost a low input voltage it requires a large capacitor which eventually increase the volume and size of the charger. Moreover, the power management [23] for switches are not suitable for EV chargers.

B. *InterleavedDC-DCboostconverter(IBC)*

The interleaved boost converter (IBC) topology is applicable for high power applications, the introduction of inductors at different levels allows reduction in current and voltage ripples. Implementing IBC topology has advantages which include: small inductor size due to addition of other inductors at different levels, supplying the input voltage at differentlevelsofinductorshelpstoreduceswitchingstress, electromagnetic interferences and conduction losses which ultimately gives higher performances than the simple boost converter. Due to these benefits, employing IBC will result in higher efficiency which is more than 90%[22] than the conventional type boost converter. As an outcome of these befittingperformances,thistopologyhasthepossibilitytobe chosen for EV chargers. However, this topology is highly sensitive to the duty cycle ratio, also interleaving of inductors will lead more number of power devices and therefore will increase the cost.

C. *Multi-portDC-DCconverter(MPC)*

Whenaninputisconnectedtomorethanonesourcesfor uninterruptiblepowersupplytotheloadamulti-portDC-DC converter comes into effect. The advantage of having a systemwithmultiinputswillgiveabetterperformancesthan a single source. In addition to that, this topology permits power flow in both the direction resulting into higher performances of the converter. Moreover, due to its specifications this topology is actively participated for high powerEVapplications.Presently,studiesin[24],[25]shows that the EV battery has the capability to be charged with more than a single source. Furthermore, in[18], the two port is used one as principle power source and other as auxiliary power source which combines and give constant output voltage,alsointerleavingstrategyisusedtolowertheripples in input current and output voltage. The method of phase interleaving and using high switching frequency could reduce the volume, weight and cost. In contrast to multiport IBC, due to addition of various inputs components have increased, the difficulty in analyzing at steady and transient states [26], [27] because of complexity in circuits and the converter is highly sensitive when there is an alter in load step.

V. DESIGNOFDC-DCBOOSTCONVERTER

Fig.3 shows a DC-DC boost converter with a single inductor and capacitor which has a major function of boosting. Also, a switch and a diode is connected though power supply. Thistopologyboostsconstantdcvoltageinto a higher voltage at the output stage through energy storage elements,alsotheinductorsandcapacitorsactasafilterto mitigate the problem of ripples in input current and output voltage respectively.

A. *DesignofDC-DCBoostconverter*

The circuit parameter of single boost converter is shown in the Table-II. When the power switch is turned ON, the energy is being stored in the inductor L and current in inductorincreaseslinearly till I_{Lmax}.When thepowerswitch isturnedOFF,itactasanopenswitchandduringthisperiod an inductor losses the stored energy to the load through diode. Moreover, to analyze the final output voltage and the inductor current the system is operated under continuous conductionmode.Here,atdifferentvalueofdutyratio,ideal waveforms are shown in Fig.4.

1) *Designequationsforboost converter:*

a) Voltagegain ratio

The duty cycle δ and voltage gain (Vo/Vi) has relationship thatisgivenas

$$\frac{Vo}{Vi} = \frac{1}{(1-\delta)} \tag{1}$$

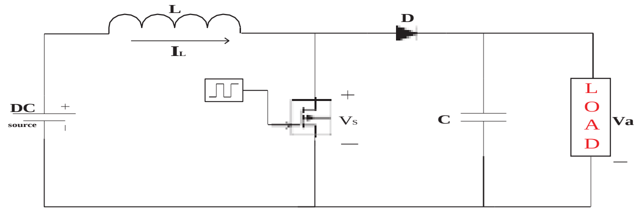

Fig.3.Circuitdiagramofconventionalboostconverter.

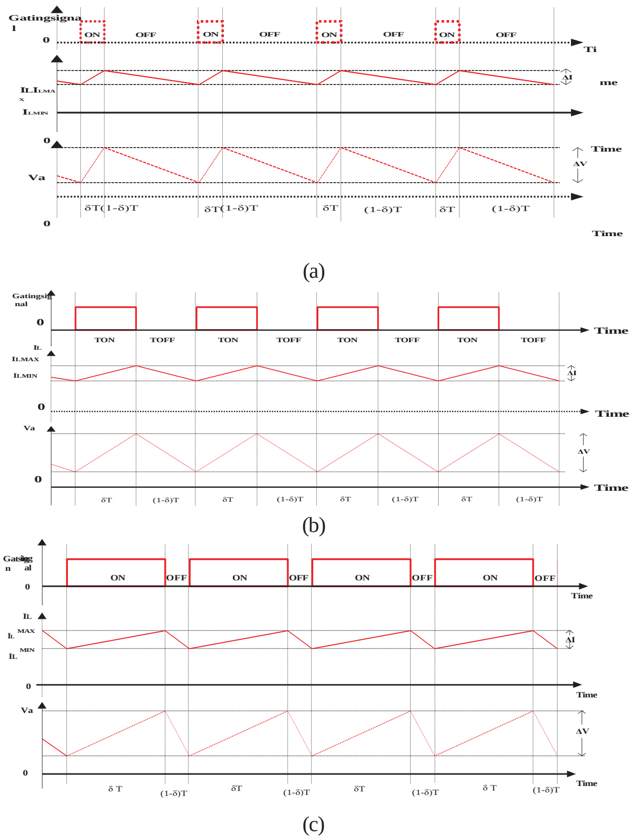

Fig.4.Ideal waveforms of boost converter at duty cycleδ: (a) 20%, (b)50% and (c) 80%.

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Here, V_o is theoutputvoltage supplied by a constant voltage V_i.Thisvoltage gain ratio isgoverned by the duty cycle δ of the switching signal in MOSFET.

b) Selectionoffilters

As discussed in the above section, electric field and magnetic field components has pivotal role in energystorageandfilteringouttheripples.Theinductor Lcouldbe used to determine the working operation of the converter whether inductor current $I_L$runs at continuous or discontinuous mode, such that the value of the inductor is obtain by using-

$$L \geq \frac{\delta(1-\delta)^2 R}{2fs} \quad (2)$$

where, $f_s$is the switching frequency and R is the resistive load connected across the capacitor. Value of capacitance is calculated by-

$$C \geq \frac{\delta Vo}{Rfs\Delta Vo} \quad (3)$$

where, $\Delta Vo$is the output voltage ripple. All the parameters in Table 2 are calculated and simulated from the above equations.

VI. DESIGNOFINTERLEAVEDBOOSTCONVERTER

The interleaved boost converter (IBC) topology is applicable for high power applications, the introduction of inductors at different levels allows reduction in current and voltage ripples. Implementing IBC topology has advantages which include: small inductor size due to addition of other inductors at different levels, supplying the input voltage at differentlevelsofinductorshelpstoreduceswitchingstress, electromagnetic interferences and conduction losses which ultimately gives higher performances than the simple boost converter. Due to these benefits, employing IBC will result in higher efficiency which is more than the conventional type boost converter. As an outcome of these befitting performances, this topology has the possibility to be chosen forEVchargers.Fig.5showthecircuitdiagramoftwophaseIBC.

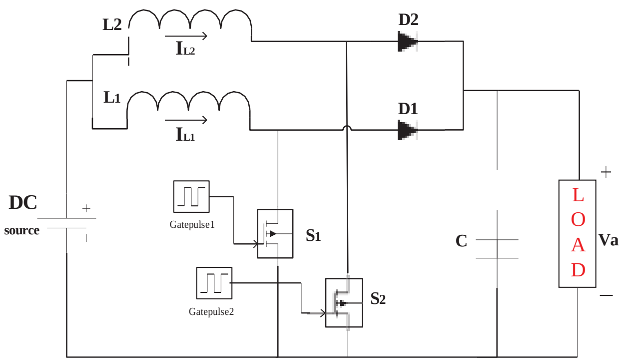


Fig.5.Circuitdiagramofatwo-phaseDC-DCinterleavedboostconverter.

The configuration of IBC depends upon the number of phases, the number of inductors and power switches are sameasnumberofphases.Thegatingpulsefortwoswitches has a phase difference of (360/*N*), where *N* is the number of converters connected in parallel. However, the equations used in boost converter are same as in interleaved boost converter. Implementing IBC topology has advantages which include: small inductor size due to addition of other inductors at different levels, supplying the input voltage at differentlevelsofinductorshelpstoreduceswitchingstress, electromagnetic interferences and conduction losses which ultimately gives higher performances than the simple boost converter.

TABLEII. SIMULATIONPARAMETERSFORTWO-PHASEINTERLEAVED BOOST CONVERTER

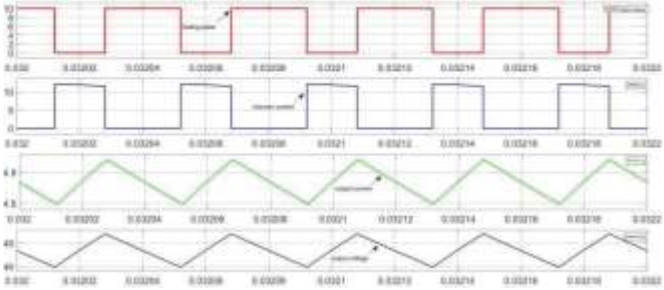
Design Symbols	SimulationParameters	
	DesignatorMeaning	*Values*
V_i	Inputvoltage	25V
I_o	Outputmeancurrent	9.351A
V_{orms}	RMSOutputvoltage	93.40A
I_{orms}	RMSOutputvoltage	18.85A
V_o	Outputvoltage	93.51A
f_s	Switchingfrequency	25kHz
L	Inductor(L_1=L_2=L)	2.56mH
C	Capacitor	160µF
R	Resistance	10Ω
ΔV_o	Outputvoltageripple	0.60V
ΔI_o	Outputcurrentripple	0.233A

VII. SIMULATIONRESULTS

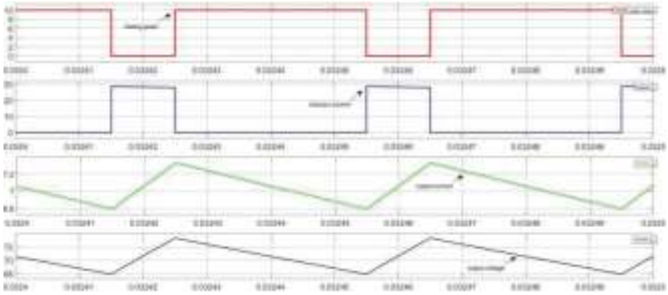
In the Table-II and Table-III, simulation parameters for conventional DC-DC boost converter and two phase IBC is summarized. The duty cycle δ plays a vital role in the determining the output voltage in conventional boost converters and two phase IBC. The simulation results in Fig.6 shows that the two phase IBC has less voltage and current stress on the MOSFET switches. Fig. 6 (d) shows less input current and output voltage ripples as compared to conventional boost converter.

TABLEIII. SIMULATIONPARAMETERSFORTWO-PHASEINTERLEAVED BOOST CONVERTER

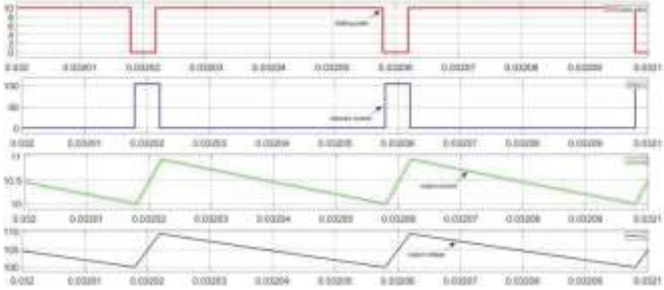
Design Symbols	SimulationParameters			
	DesignatorMeaning	*Value at δ=0.20*	*Value at δ=0.50*	*Value at δ=0.80*
V_i	Inputvoltage	20V	20V	20V
I_o	Outputcurrent	4.738A	7.065A	10.47A
V_o	Outputvoltage	47.38A	70.64V	104.7V
f_s	Switching frequency	25kHz	25kHz	25kHz
L	Inductor	0.8mH	0.8mH	0.8mH
C	Capacitor	40µF	40µF	40µF
R	Resistance	10Ω	10Ω	10Ω
ΔV_o	Output voltage ripple	2.84V	1.58V	2.30V
ΔI_o	Output current ripple	0.579A	0.211A	0.23A
ΔI_L	Inductorvoltage ripple	0.284A	0.12A	0.117A



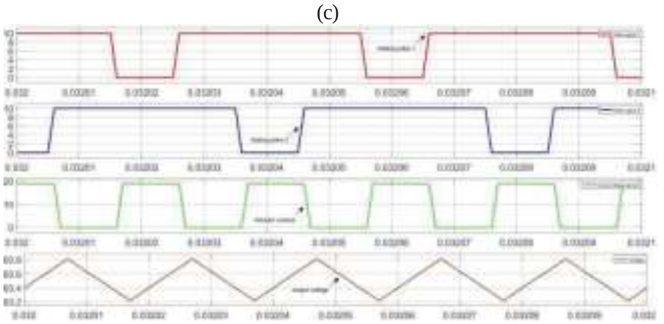
(a)



(b)



(c)



(d)

Fig.6.Waveform of voltage gain, output current and output voltage areillustrated at different values of Duty-cycle: (a) δ=0.20, (b) δ=0.50 and (c)δ=0.80. In (d) two-phase IBC gating signals of two MOSFET switches $S_1$and $S_2$with output current and voltage is shown.

VIII. CONCLUSION

In this paper different types of EVs has been studied which requires different power levels for their charging. Moreover, a comparative study of AC-DC converters and DC-DC converters are discussed in detailed in addition to the isolated and non-isolated DC-DC boost converter topologies. The conventional DC-DC boost converter; interleaved boost converter (IBC) and multi-port DC-DC converter (MPC) with their advantages and disadvantages arediscussed.Inaddition,thispaperalsopresentsthedesign parameters and simulation results of non-isolated conventional DC-DC boost converter and two-phase IBC. Clearly, the result shows the low input current ripples and output voltage ripples in two-phase IBC topology as comparedtoconventionalDC-DCboostconverter,thusIBC is suitable for EV applications.

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