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RESEARCH ARTICLE OPEN ACCESS

Application-Specific Energy Management Systems for Electric Vehicles Based on Charge and Discharge

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***Abstract*— This paper presents solar based electric vehicle (EV) charging circuit. Incremental Conductance MPPT Algorithm is used to extract maximum power from the solar PV at STC conditions. A battery of rating 100AH is charged with the solar PVpanelusingaboostconverterwhichgeneratesoutputvoltage of 400V. Then the voltage is stepped down for buck operation accordingto220Vbatteryrequirement.TheSOCcharacteristic is observed to be fully charged within short period. The passive parameters (filter components on the input and output) of the system are derived and appropriately used in the work. Also in the absence of solar PV energy, electric vehicle is charged from the grid. A PR (proportional plus resonant) controller is used with a corner frequency of 10rad/sec. A 400 V dc output voltage isobtainedthrougha H-bridge rectifierandappliedto aDC-DC bidirectional converter. It is observed that the battery SOC is accomplished within a small period. During charging and discharging modes the battery voltage and current is presented. It is clear that the grid voltage and current are in phase during charging. During discharging they are said to be out of phase indicatingthereversepowerflow.IGBTswitchesareconsidered to be operating at 10 kHz. On-board electric vehicle chargerscan be utilized at homes and parking places. The work reflects the usage of EV connected to solar exhibits less dependency on the grid with clean (zero emission) and smooth movement of the vehicle.**

***Index Terms*— Battery, Electric vehicle, maximum power point, proportional resonant controller, State of Charge.**

I. INTRODUCTION

Solar Energy can be utilized for electric vehicle (EV) battery charging applications in urban areas. Hence theburden on the grid gets reduced when EV's are directly integrated to the solar charging stations [1]. Therefore, in this work, a solar power based EV charging is proposed.

Fig. 1 shows the electric vehicle charging with solar PV, the electric vehicle charging with grid as well as with the solar PV [2]-[6]. In the day time the electric power generated by the solar PV is utilized to charge EV. In absence of the solarPVpower,theelectricvehicleischargedwiththepower grid.Electricvehiclechargingcircuitwithsolar PV configuration consisting of two stages is referred in [7]-[8]. First stage acts as a converter/inverter and the second stage consists of a DC-DC converter which acts as step-up converter during discharging and as a buck converter during charging. The battery is used to store electrical energy in the form of chemical energy in charging and energy is suppliedto grid during discharging.

In EV the battery plays an important role, SOC (stateof charge) of the battery is maintained within the limits for long life.Therearedifferenttypesofbatteries whichareused in the EV, they are Nickel-cadmium, Lead-acid and Lithium- ion batteries. Lithium-ion batteries are preferred for EV dueto high specific energy, good discharging capabilities andlong working life [9]. Section II deals with the EV circuit configuration and passive components design, section III deals with EV Charging with solar PV. Section IV deals with EV with proportional plus resonant controller (PR) in charging, section V deals with the EV Support to Grid.

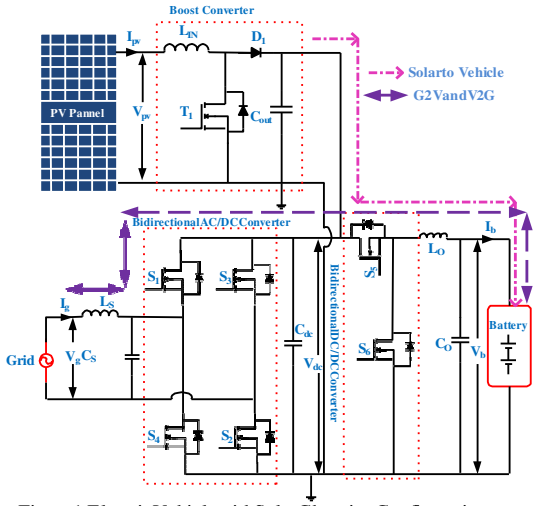

Figure1.ElectricVehiclewithSolarChargingConfiguration

II. VCIRCUITCONFIGURATIONANDDESIGN

An effective design of the passive filters used in the circuit is verymuchnecessaryforthebestoperationoftheEV.The design of passive components are presented here for the EV considered in the work [10].

(i)DCbus capacitor(C_{dc}):

In single phase converters output DC voltage consists of second order harmonics and hence a large value of dc Capacitor on the dc side is required. The dc capacitor is an energy storage device between the input and output. The capacitor value will be selected based on its energy storage. The input power is given by (1) assuming the input power factor to be unity,

$$P_{in}=v_{in}\times i_{in}=\frac{VI}{2}-\frac{VI}{2}\cos 2\omega t \quad (1)$$

Inputinductorpowerisgivenby(2)

$$P_L=\frac{\partial\left(\frac{1}{2}L(I\sin\omega t)^2\right)}{\partial t}=\omega LI^2\sin\omega t\cos\omega t \quad (2)$$

Theenergyflowsfrominputinductortothe H-bridge converter and charges the output dc capacitor. Neglecting the device power losses, power in the output capacitor is equal to the difference between the input power and inductor power. The power flow through the capacitor is obtained using (3)

$$P_C=P_{in}-P_L=\left(\frac{VI}{2}-\frac{VI}{2}\cos 2\omega t\right)-\omega LI^2\sin\omega t\cos\omega t \quad (3)$$

Inequation(3)DCcomponentissuppliedtoDCoutputand second order components will charge and discharge the capacitor which causes ripple in output DC voltage. For a haf cycle, the instantaneous power is calculated by simplifying and taking the integration, (4) represents the ripple energy

$$E_C=\int_0^{I}\sqrt{\frac{V^2I^2}{4}+\frac{\omega^2L^2I^4}{4}}\sin 2\omega t\,dt=\sqrt{\frac{V^2I^2}{4}+\frac{\omega^2L^2I^4}{4}}\Big/\omega \quad (4)$$

From the ripple energy in the capacitor, one can derive the relationbetweenDCcapacitor,DCvoltageandinputinductor as (5)

$$C_{dc}=\frac{\sqrt{\frac{V^2I^2}{4}+\frac{\omega^2L^2I^4}{4}}}{2\times V_{dc}\times\Delta V_{dc}\times\omega} \quad (5)$$

Using(5),C_{dc}isobtainedtobe2mF.

(ii)Inputsidefilter($L_s$andC_s):

Thefilterinductorisdesignedbasedontheripplecurrent flowing through the inductor (L_s).

$$L_s=\frac{V_{dc}\times\frac{V\sin\omega t}{Vdc}\left(1-\frac{V\sin\omega t}{Vdc}\right)}{2\Delta If_{sw}} \quad (6)$$

$V_{dc}$is the DC voltage with ripple and instantaneous value of input AC voltage is given by$V\sin\omega t$,$f_{sw}$is the switching frequencyandripplecurrentΔIistakenas10%oftheinput current. The harmonics of the output voltage is damped by using the input LC filter capacitor and is given by (7)

$$C_s=\left(\frac{1}{2\pi f_{sw}}\right)^2\times\frac{1}{L_s} \quad (7)$$

The capacitor filter $C_s$and inductor $L_s$are obtained as 20μF and 0.75 mH.

(iii)Outputfilter($L_o$andC_o):

The output filter inductor $L_o$and capacitor $C_o$are calculated using (8) and (9) respectively.

$$L_o=\frac{D(1-D)^2r}{2f_{sw}} \quad (8)$$

$$C=o\frac{(1-D)}{8L_o\left(\frac{\Delta V_o}{V_o}\right)f_{sw}^2} \quad (9)$$

The output side capacitor required is very large to maintain the output voltage constant .duty ratio is D,the internal resistance is r,f_{sw} switching frequency of the buck/boost converters ,$V_o$is

The output oltage, $\Delta V_O$is ripple voltage which is 5% of the Output voltage. $L_o$and $C_o$is obtained to be 41μH and 600 μF. A 120V rms 60Hz single phase system is considered in this work.

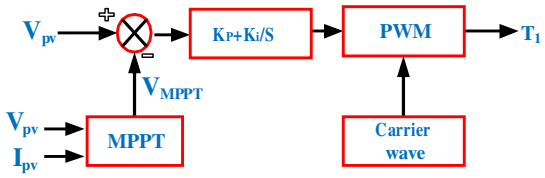

Figure2.PVBoostConverterControlCircuit

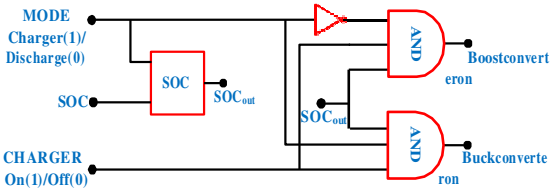

Figure3(a).Upperlevelcontrol

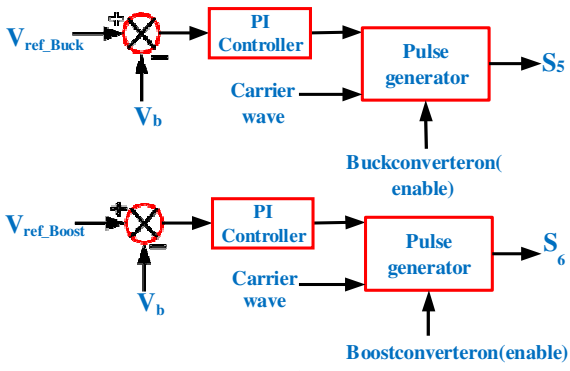

Figure3(b).LowerlevelcontrolforDC-DCConverter

Fig. 2 shows the solar PV boost converter control circuit, PV array voltage and the MPPT voltage is compared and voltage error is generated. Error voltage generated flows through proportional plus integral controller (PI) and PI controller output is compared with 10 kHz triangular carrier wave, according to it switching pulses are generated for PV boost converter. The upper level and lower level controllers for the bidirectional DC-DC converter is shown in Fig.3 (a) and 3(b). Inupper level control according to the batterySOC between 5% to 100% and mode of operation i.e. charging or discharging mode, $SOC_{out}$is derived. Then $SOC_{out}$and Charger ON/OFF are given to the logic circuits to produce signal for enable the buck or boost converter. Accordingly switchingpulsesaregeneratedusingFig.3(b)totheswitches oftheBuck/Boostconverter.Similarlyfor lower levelcontrol the switching pulses are generated based on the voltage error and buck converter on signal.

III. ELECTRICVEHICLECHARGINGWITHPV

The Electric vehicle battery is charging with the solar PV energy in the day time. The circuit configuration is as shown in Fig. 1. The PV panel voltage is boosted up to 400 volts by using a step-up converter. PV boost convertervoltage is step down according to the battery voltage requirements by using DC-DC converter. Here battery capacity of 100AH, 230 V (20 kWH) is considered. An Onboard charging circuit at Home or parking places can be realized.TableIshowstheBoostconverterdesignparameters and Fig. 4 shows the PV panel with input labels and table II shows array parameters used for simulation.

Simulationresults ofthe electric vehicle charging with the solar PV are discussed. Switching pulses obtained for the solar PV boost converter is shown in Fig. 5. The switching pulses obtained for the buck converter during charging is shown in Fig.6. Fig. 7 shows the characteristics of the solar PV at STC conditions (25ºC, 1000 Lumens). A 220 V open circuit voltageand 2.5 Ashortcircuit currentis obtained with PV panel parameters shown in Table II.

TABLEIPARAMETERSOFPVBOOST CONVERTER

Parameters	Value
BoostconverterinputVoltage	200V
OutputVoltage	400V
Inputinductor,L_{IN}	1.3mH
Outputcapacitor,C_{out}	2500µF
Dutyratio	0.5
Switchingfrequency	10kHz

Fig. 8 shows the solar PV voltage and MPPT voltagetracking, the PV array takes 0.122s time to track the MPPT reference voltage(V_{mppt})and0.5%steadystateerror.5%.Fig. 9 shows the boost converter output voltage 400V. BatteryFig. 10 shows the battery voltage and the current. Fig. 11 showsthebatterystateofchargeduringtheEVcharging.Itis observed that the electric vehicle is charged 100% with solar PV within a short period (10s).

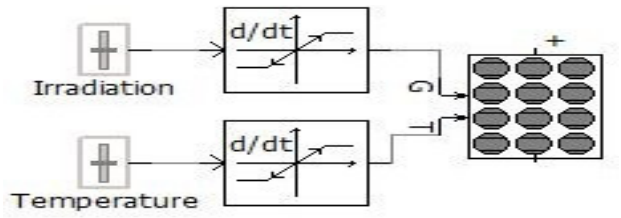

Figure4.PVpanelwithinputlabels(Source:PSCADSoftwareSimulator)

TABLEIIPARAMETERSOFPVARRAY

PVArray	Value
Modulesconnectedinseriesinonearray	7
Modulestringsinparallelinonearray	10
Cellsconnectedinseriesinonemodule	36
Cellstringsinparallelinonemodule	1
Irradiationtakenasreference	1000L
Cellreferencetemperature	25ºC

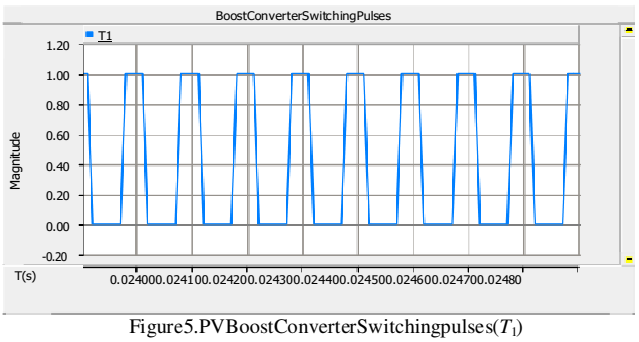

Figure5.PVBoostConverterSwitchingpulses(T_1)

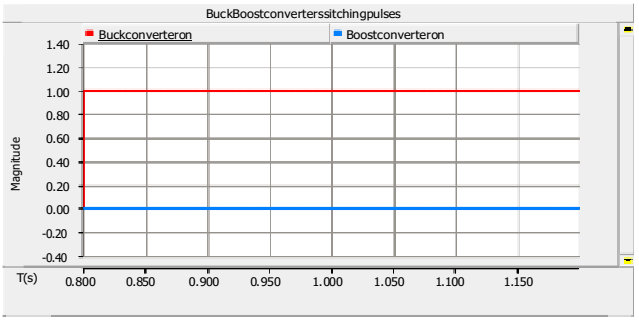

Figure6.BuckConverterSwitchingPulses(ON)andBoostConverter(OFF)

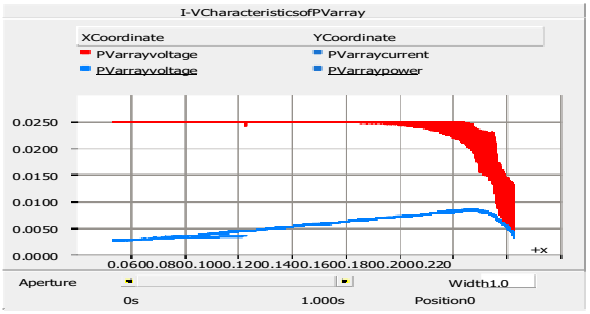

Figure7.CharacteristicsofsolarPV

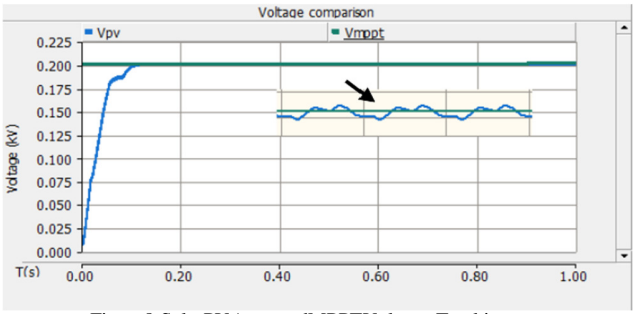

Figure8.SolarPVArrayandMPPTVoltagesTracking

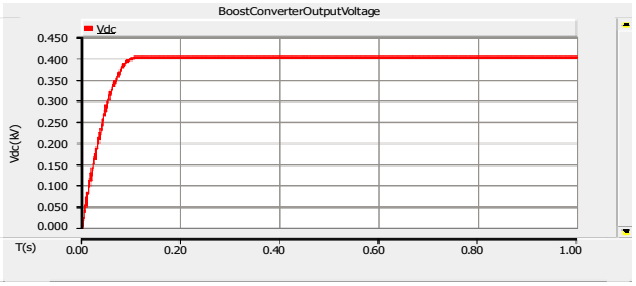

Figure9.BoostConverterOutputDCVoltage

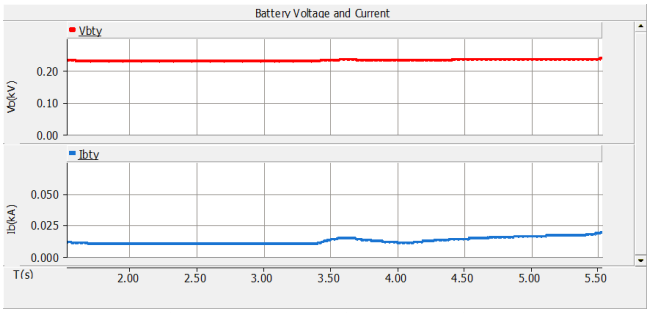

Figure10.BatterychargingVoltageandCurrent

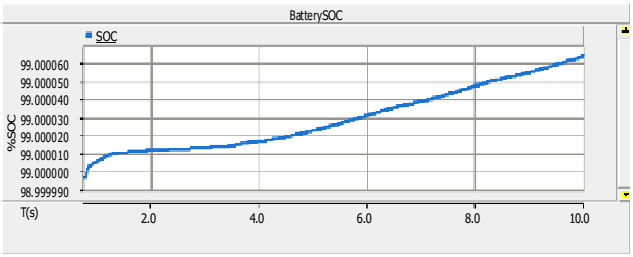

Figure11.BatteryStateofChargeduringcharging

IV. ELECTRICVEHICLECHARGINGFROM GRID

In this mode of operation the electric vehicle is charged from the grid. This mode operates in the absence of the solar power. The electric vehicle charging from grid circuit configuration is shown in Fig. 1 and system parameters used for simulation is shown in Table III. The switching pulses for the single phase H-bridge bidirectionalconverter is generated by using proportional pulse resonant (PR) controller. The controlblockdiagramofthePRcontrollerisshowninFig.12. PR introduces at the fundamental frequency an infinite gain andithasabilitytofollowthesinecurrentwaveform[11]with reduced steady state error. To avoid stability problems at infinitegain,anapproximatehighgainlowpassfilterwhichis basicallyasecondordertransferfunctionisusedasanon- ideal PR controller in this work.

ThePRcontroller$G_{PR}(s)$isgiven by(10)

$$G_{PR}(s)=k_p+k_i\frac{2\omega_c s}{s^2+2\omega_c s+\omega_o^2} \quad (10)$$

System dynamic response is determined by k_p, phase shift between the output and the reference input is adjusted by using k_i, cut off frequency $\omega_c<<\omega_o$, resonant frequency $\omega_o$is kept at 377 rad/s in this work. Here $k_i= k/ \omega_c$assumed to simplify the controller. It is taken here as unity so that the effect of $\omega_c$can more easily be understood [12]-[13].

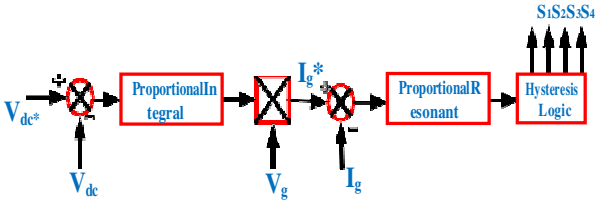

Figure12.PRControllerforEVcircuitconfiguration

Reference dc voltage and actual dc voltage are compared andthevoltageerrorobtainedispassedthroughaPIcontroller to generate the grid current reference for the current loop. Switching pulses for the IGBT switches of the single phase converter is generated by using hysteresis logic. Accordingly the frequency response characteristics shown in Fig. 13 are obtained for different values of $\omega_c$from 0 to 25 rad/s. The proportional gain is taken as 1. It is observed that the bode plots converge to 20db/dec for any value of ω_c.

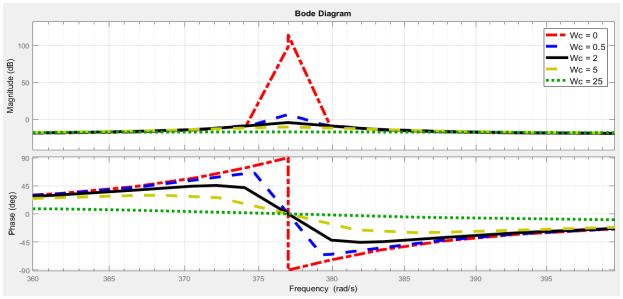

Figure13.Frequencyresponsecharacteristicforvariation in$\omega_c$and$k$=1

TABLEIIICIRCUITCONFIGURATIONPARAMETERS

Circuit Variables	Ratings
GridvoltageV_g	120Vrms
Powerfrequencyf_s	60 Hz
ACFilterinductorL_s	0.75mH
ACFiltercapacitorC_s	20 µF
DCCapacitorC_{dc}	2mF
InductorL_o	41µH
CapacitorC_o	600µF
Batterycapacity	100AH
Hysteresisband$h$	±0.5 V
PRControllerparametersK_p,T_i	100, 0.1ms

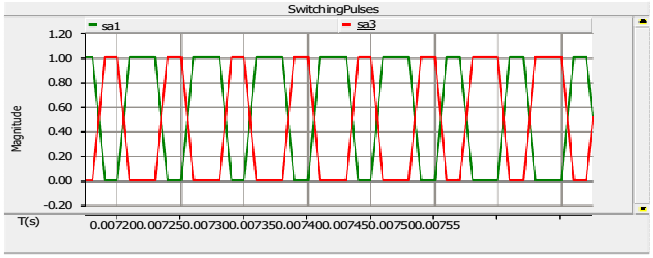

Figure14.SwitchingpulsestotheBidirectionalAC-DCConverter switches

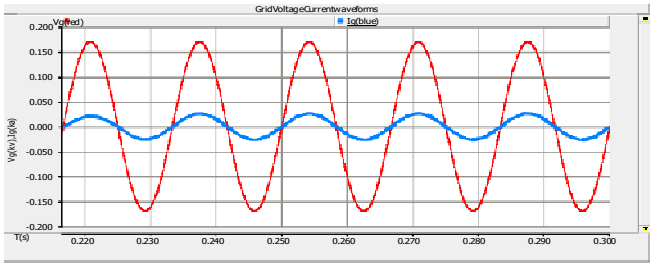

Figure15.GridVoltageandCurrentwaveformsduringcharging

TABLEIVGRIDVOLTAGEANDCURRENTHARMONICCOMPONENTS

Harmonic order	IndividualCurrent THD%	VoltageIndividual THD%
3	1.804	0.0220
5	1.604	0.0072
7	0.708	0.0203
9	0.192	0.0052
11	0.590	0.0078
13	1.235	0.0133

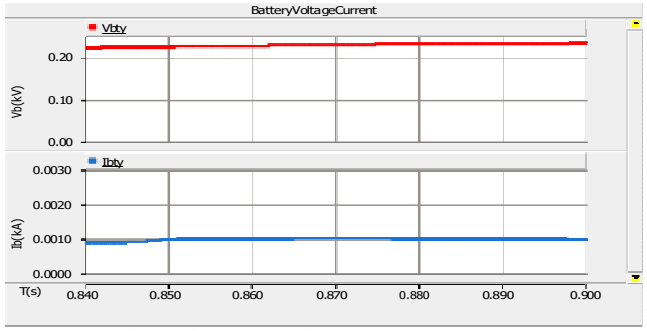

Figure16.BatterychargingVoltageand Current

Thepeakamplitudeofthegainmarginincreasewithlower valuesofω_c.Italsorevealsthattheinfinitegainonlyoccursat resonant frequency. Therefore the PR controller is sensitive between controller resonant frequency and fundamental frequency of the converter. Hence the sensitivity can be reduced bytakinga small value ofω_c.Inthis work10 rad/sis taken. A trade off should be made by properly selecting the value of k and ω_c.

Fig.14showstheswitchingpulsesappliedtobidirectional AC-DC converter during the charging of the electric vehicle. Fig. 15 shows the grid current and voltage in charging mode ofoperationwithPRcontroller.Theinputvoltageandcurrent is in phase with each other. Fig. 16 shows the battery current andvoltagewaveformsduringcharging,thevoltagewaveform has small increase and the current waveform is constant. Fig. 17 shows the battery SOC waveform during battery charging. Theoddorderharmoniccomponentpresentingridvoltage and current during the charging is shown in Table IV. It is observed that 3rd and 5th order harmonic component is more compared to 7th, 9th, 11th and 13th, voltage and currentTHD is within the *IEEE-519* standards.

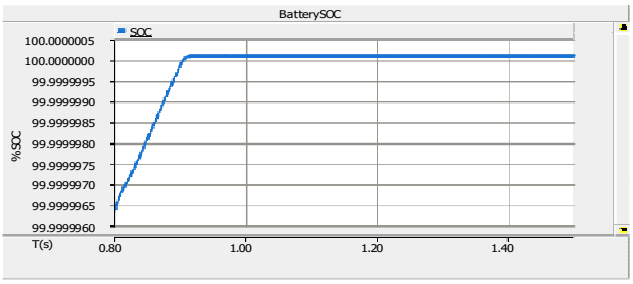

Figure17.SOCduringcharging

V. ELECTRICVEHICLESUPPORTTOGRID

In this mode of operation bidirectional AC-DC converter acts as an inverter and controls output grid current. The batterysuppliespowertogrid basedontherequirementofthe power grid and the convenience of the EV owner. The simulation results are presented in this section.

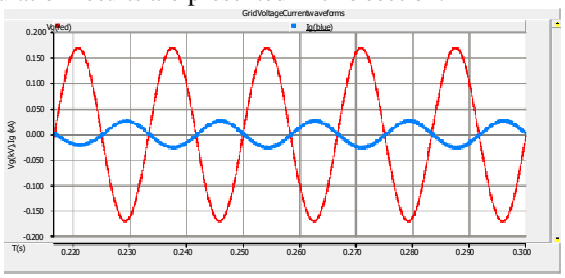

Figure18.GridCurrentand VoltageCurrentwaveforms

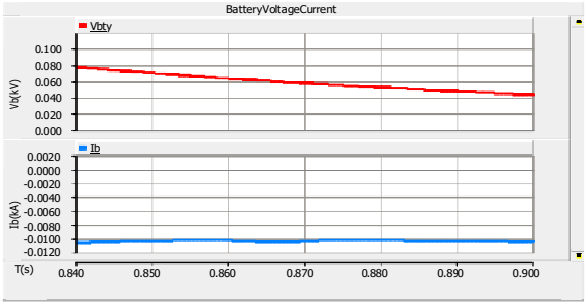

Figure19.BatterydischargingVoltageand Current

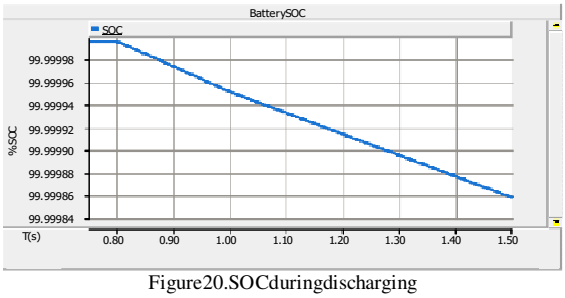

Figure20.SOCduringdischarging

Thegridvoltageandcurrentwaveformsduringdischargingis shown Fig. 18, in charging the grid voltage and current is in phasebutindischargingthe gridcurrentisoutofphasetothe gridvoltage.ItshowsthatpowerflowsfromEVbatteryto

the power grid. Fig. 19 shows the battery voltage and current waveforms during battery discharging, the voltage waveform is decreasing and current wave is constant. Fig. 20 shows the SOC of the battery during discharging.

VI. CONCLUSIONS

This paper presents an electric vehicle charging circuit with solar energy as a source. The PV array is tested under standard test conditions, the Current-Voltage and a Power-Voltage characteristic of the solar PV is obtained. Passive filter parameters design methodology is presented. The solar PVisdesignedtoproducetheoutputvoltageof200Vwhichis stepped to 400 V using a boost converter. The output voltage is filtered and this filtered voltage is step down according to EV Battery charging requirements by using a buck converter. ThePRcontrollerusedisefficientinchargingtheEVbattery. SOC is observed to be efficient during charging and discharging modes. A corner frequency of 10 rad/s has been selected properly based on frequency response characteristic. The EV charging from grid and battery energy fed back to grid are illustrated with voltage and current in-phase and out of phase respectively. Grid current and voltage THD levels follow IEEE 519 standards. The SOC of the battery is obtained during battery charging and discharging operation. Thecontrollerisgoodintrackingthereferencevoltageduring both charging and discharging with less steady state error.

Solar charging overcomes voltage problems and overloadinginthedistributednetworkduetomoregenerating units and increased demand of power due to more number of EVs charging from the grid.

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