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Modelling and Analysis of Single-Phase Onboard Battery Charger for Electric Vehicle Using Active and Reactive Power Control

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Abstract:

The automotive industry is undergoing advancements in technology, particularly in the pursuit of eco-friendliness. As a result, Electric Vehicles (EVs) are gaining prominence within this sector. EVs are powered by batteries, and it is crucial to develop a charger that can efficiently and rapidly charge these batteries while minimizing any impacts to the power source. For on-board charger the size of the charger should be small and compact meeting the specification specified by the standards. This paper discusses about electrical vehicle battery and it's charging system. The electric vehicles are available in a variety of models with varying ranges and capabilities. Now in market, two major battery technologies used in EVs are nickel metal hydride (NiMH) and lithium ion (Li-ion). The single phase, level 1 onboard charger with real and reactive power control is presented in this research. By using a SPWM (Sinusoidal Pulse Width Modulation) technique, the charger able to control against variable references power inputs in simulations. The converter is modelled and simulated in Matlab/Simulink and the results prove that the proposed converter is feasible with good accuracy and performance.

Keywords — **Electric Vehicle, Battery Charger, Real and Reactive Power Control, AC/DC Bidirectional Converter,**

I. INTRODUCTION

The advantage of EVs (Electric Vehicles) extend beyond reducing the pollution and increasing the dependency on renewable energy sources, especially more progress made in the power electronics field. In fact, most of research papers have shown that the massive integration of grid-connected vehicles such as EVs, PHEVs (Plug-In Electric Vehicles), and FCVs (Fuel Cell Vehicles) provides help to the electric grid. Batteries of the vehicles act as storage element for renewable energy source when it connected to the grid that are being used in an increased rate of today's electricity production [1].

The Electric Vehicles operate with the power supply from the batteries and these batteries are to be charged on timely basis. There are several types of charging available; there are on-board chargers and off-board chargers. Off-board chargers are the charging stations where the number of vehicles gets charged. Onboard chargers are the one where the charging equipment is in the vehicle itself, and only need to plug-in a connecting cord to charge the battery. There are again 2 types, it is battery charging through Alternate current and other through Direct current. The Direct current charging is very fast charging than AC charging, but the available source current is AC, therefore a charger which charges the battery very fast through AC current is required [2].

In this paper, single phase, level 1, onboard charger is modelled and analyzed. The conventional synchronous reference frame control cannot be used with single phase charger. Thus, the voltage and current control schemes are commonly used with single phase charger. To improve the charging performance and power quality control, the real and reactive power control is introduced in this paper. The modeling is done with Matlab/Simulink and the performances are analyzed based on simulation results.

II. CURRENT TECHNOLOGIES FOR CHARGING OF ELECTRIC VEHICLE

Despite the limited time that electric vehicles have been used for, they have received significant technological improvements such as better performing batteries, much more deployed infrastructure and better performance of the vehicles. The electric vehicle (BEV) or Plug-in Electric vehicle (PHEV) is generally defined as a light vehicle that draws electricity from a battery with a capacity of at least 4 kWh and is capable of being charged from an external source. The current commercial PEVs are listed in Table 1. [3]

TABLE I
Current EVs and Their Specifications with Charging Characteristics [3]

Model	**Type**	**Battery Capacity (kWh)**	**Electric Range, EPA (km)**	**Charge Characteristics**	
				Time (hr)	**Power (kW)**
Mitsubishi iMiEV	BEV	16	100	7	3.1
Nissan Leaf	BEV	24	118	8	3.3
Tesla Model S	BEV	60/85	335/425	8.5	11
Chevrolet Volt	PHEV	16.5	61	3	3.3
Toyota Prius	PHEV	5.2	18	1.5	3.3
Ford Fusion Energy	PHEV	7.5	34	2.5	3.3

But for the charger there has always been a lack in “smartness” in the sense that EVs have always been considered as pure loads, and therefore sometimes burdens for the grid, and not as potential supportive generators. For smart charging systems where the bidirectional charger could be used at their ultimate stage, where they interface with the vehicle. These systems consider different aspects and variables in order to optimize various processes but their common target is to reduce losses and costs. Depending on the complexity of the algorithms they can consider the user’s necessities, the load level of the grid, the battery’s status, the electricity price in the nearest node, losses, the most convenient route for the closest charging station and user’s driving behavior. All these variables are collected and carefully evaluated by a Central control system that gives them different priorities and formulates an optimization algorithm whose outcome is a charging pattern; this is high level control. According to this charging procedure, that is low level control, an appropriate converter is instructed to charge or discharge the battery. This means that there are two types of connection:

- the power connections transfers energy from the grid to the battery or vice versa;
- the control and communication connections collect information about those involved and provides commands to the active parts.

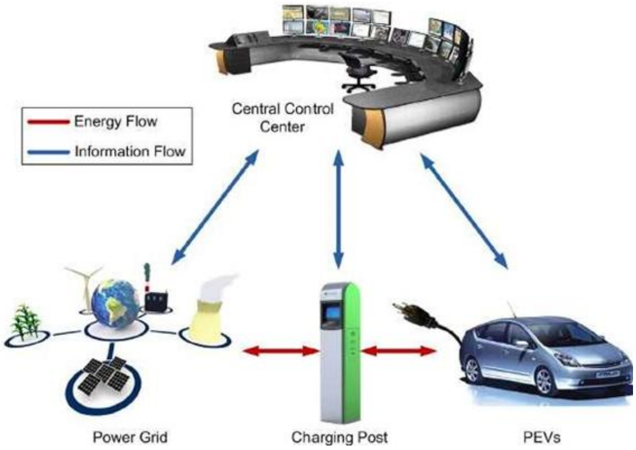


Fig. 1 Control System and Relevant Energy/Information Flows for Charging of Electric Vehicle [4]

There are four types of charging method as follow:

- Controlled charging;
- Uncontrolled charging;
- Delayed charging;
- Off-peak charging.

In uncontrolled charging, the charging starts as the car is connected, with large deployment of electric vehicles, the grid is put under serious stress. The components of the grid like transformers and cables face high load that results in a decrease of the reliability. In order to prevent this issue, an intelligent scheduling of the charging process has to be done, which means that an appropriate amount of power has to be drawn from the grid with controlled charging. This will prevent congestion, decrease the losses, the cost of the electricity, the voltage deviation, the line current, increase the reliability, less impact on peak capacity, balance of the load profile, stability of the grid and at the same time it’s possible to have high penetration of electric vehicles without violating any limit. However, there are drawbacks: in order to implement vehicle to grid (V2G) services, bidirectional power flow has to be available and communication between EVs and an independent central system operator is fundamental. The off-peak charging is a passive strategy and no control is required: this consists of charging the EVs during night because it is economically profitable.

III. CHARGING LEVELS OF ELECTRIC VEHICLE

There are 4 charging levels according to IEC 61851:

- Level 1; slow charging from a house-hold type socket-outlet in AC; the charger is passive with no control; the voltage is 230/400 and the current doesn't have to exceed 16A;
- Level 2; slow charging from a house-hold type socket-outlet with an in-cable protection device in AC; it's again a passive connection but ensures earth protection, residual current, overcurrent protection etc. and the voltage is 230/400 with the current not exceeding 32A;
- Level 3; slow or fast charging using a specific EV socket-outlet with control and protection function installed in AC; the connection can be active with proper communication pin; it provides earth protection and the voltage is 230/400 whereas the current doesn't have to exceed 250A;
- Level 4; fast charging using an external charger in DC; it can be divided in two sublevels: (i) level 1 where the V< 500V, I < 80A and Pmax= 40kW and (ii) level 2 where the V< 500V; I < 80A and Pmax= 100kW.

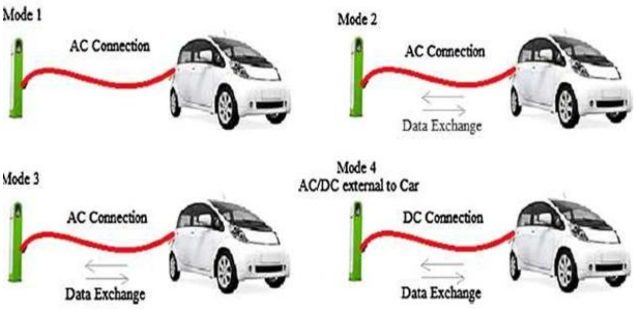


Fig. 2 Different Charging Levels and Types of Connections [4]

Usually in the first three levels the charger is inboard while in the fourth level the charger is off board. This is due to the rating of the charger: in the first three levels the power exchanged with the EV is relatively small whereas in the DC charging mode, since it does first charge, the power exchanged is bigger and therefore it's safer and space-friendly having an external charger.

IV. CONTROL ALGORITHM FOR SINGLE PHASE ONBOARD BATTERY CHARGER

The single-phase onboard battery charger consists of the converters, the interfacing components, such as inductor and capacitors and the controller. The controller has to condition the battery and control the DC voltage and current applied to the battery.

A. *Active and Reactive Power Control*

The charging of battery is the power transfer between the system (grid) and the inverter. Between the grid and inverter, there is a system impedance. In low voltage system, the system impedance is the series combination of resistance and inductance whilst in large system, the resistance is small and thus neglected. The value of system impedance depends on the short circuit level of the system. In the high voltage grid and even in the medium voltage grid, the connection between grid and load is mainly inductive, whereas in low voltage nets the connection is more resistive. Since both the inverter and rectifier operating modes are kept in consideration with a semi-active switch converter, to explain the operations the inverter mode is considered. In this mode the inverter generates alternating voltages so it will be represented in this way.

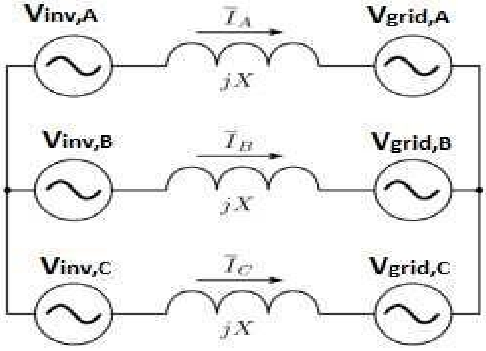


Fig. 3 Three Phase Model of the Grid and Voltage Generated by Inverter [4]

B. *Power Exchange between Grid and Inverter*

By considering the phasor of the grid voltage as reference, the phasor diagram can be draw as shown in Figure 4.

$XI\cos(\varphi) = V_{inv}\sin(\delta) = V_{qinv}$

$$\mathrm{I}\cos(\varphi) = \mathrm{I_d} = \frac{\mathrm{V_{qinv}}}{\mathrm{X}}$$

$$\mathrm{P} = 3\,\mathrm{V_{grid}}\,\mathrm{I}\cos(\varphi) = 3\,\mathrm{V_{grid}}\,\mathrm{I_d} = \frac{3\,\mathrm{V_{grid}}\,\mathrm{V_{qinv}}}{\mathrm{X}}$$

So, the active power exchange is controlled by varying $\mathrm{V_{qinv}}$.

$$\begin{aligned}\mathrm{XI}\sin(\varphi) &= \mathrm{V_{inv}}\cos(\delta) - \mathrm{V_{grid}} \\ &= \mathrm{V_{dinv}} - \mathrm{V_{grid}}\end{aligned}$$

$$\mathrm{I}\sin(\varphi) = \mathrm{I_q} = \frac{\mathrm{V_{dinv}} - \mathrm{V_{grid}}}{\mathrm{X}}$$

$$\begin{aligned}\mathrm{Q} &= 3\,\mathrm{V_{grid}}\,\mathrm{I}\sin(\varphi) = 3\,\mathrm{V_{grid}}\,\mathrm{I_q} \\ &= \frac{3\,\mathrm{V_{grid}}\,(\mathrm{V_{dinv}} - \mathrm{V_{grid}})}{\mathrm{X}}\end{aligned}$$

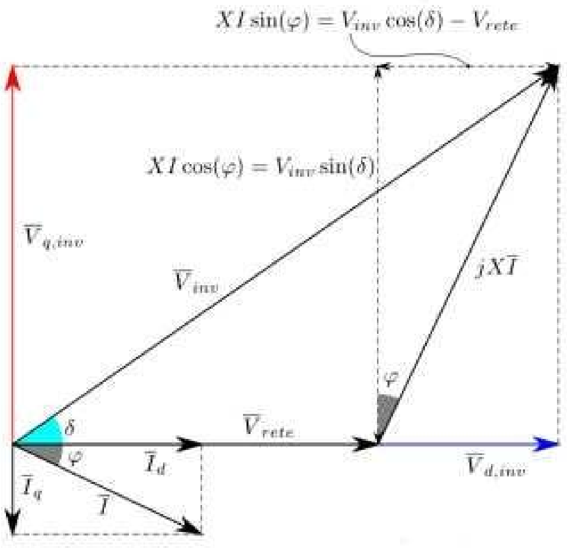


Fig. 4 Phasor Diagram of the Involved Dimensions in d-q Orientation [4]

The reactive power exchange is controlled by varying $\mathrm{V_{dinv}}$ or better the voltage drops in the inductor. In this paper, onboard charger is controlled using active and reactive power controller. In single-phase controller, the d-q transformation is not feasible because it requires three dimensions that are shifted in phase by 120°. With active and the reactive power control, the output voltage of the AC/DC active bridge can be controlled. In this case, the active power exchange is related to the amplitude of the output voltage and the reactive power exchange is related to the phase shift of the output voltage or the power angle.

V. MODELING OF LEVEL 1 BATTERY CHARGER WITH REAL AND REACTIVE POWER CONTROL

In this paper, the modelling and simulation is done for single phase, level 1 onboard charger. The power capacity is 1.4 kVA. Other important system parameters are shown in Table 2. [3], [4]

TABLE II
IMPORTANT PARAMETERS FOR SINGLE PHASE, LEVEL 1 ONBOARD CHARGER

SN	Parameter	Unit	Value
1	Power	kVA	1.4
2	Grid voltage	V	230
3	Grid frequency	Hz	50
4	Switching frequency	kHz	20
5	DC-link voltage (Max.)	V	425
6	DC-link capacitance	mF	6.487
7	Battery side filter capacitor	µF	1000
8	Battery side filter inductance	µH	34
9	Li-ion Battery Voltage	V	363
10	Battery Capacity	Ah	72

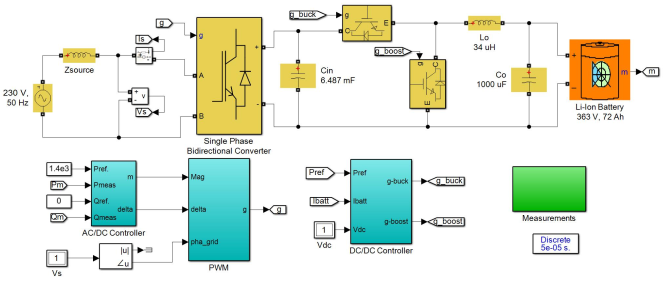


Fig. 5 Simulink Model for Single Phase, Level 1, Onboard Battery Charger

Figure 5 shows the Simulink model for single phase, level 1, onboard battery charger. The model consists of single-phase AC source, AC/DC active bidirectional rectifier, DC/DC buck/boost converter and Li-ion battery. For the proper operation of battery charger, two controllers are used as shown in Figure.

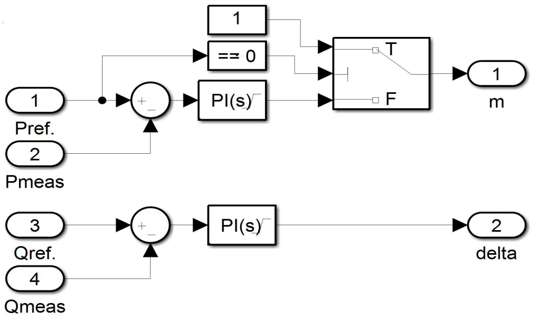


Fig. 6 Model of AC/DC Controller Using Real and Reactive Power Control

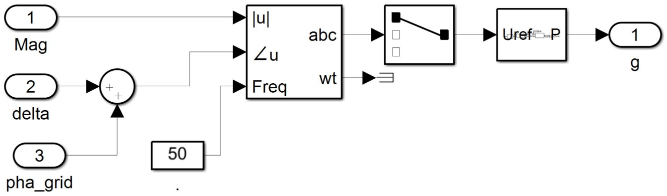


Fig. 7 Model of PWM Based on Voltage Magnitude and Angle Measurement

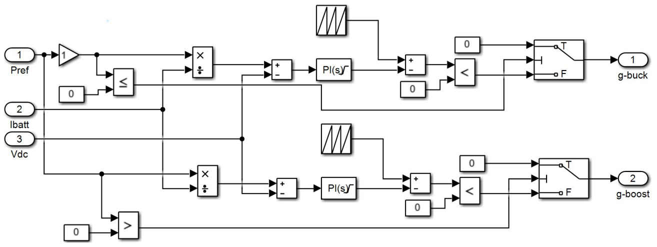


Fig. 8 Model for DC/DC Buck/Boost Controller

The simulation models for controllers are shown in Figure 6 through Figure 8. For control of AC/DC converter, the real and reactive power control is used. For reference input voltage to PWM generator, the voltage magnitude is calculated from real power difference and the phase angle is calculated from reactive power difference. The control of DC/DC converter is executed based on the DC link voltage magnitude and battery terminal voltages. All controllers used the proportional plus integral (PI) controls.

VI. SIMULATION AND ANALYSIS

To observe the performance of onboard charger with real and reactive power control, the simulations are carried out with various real and reactive power reference inputs. The simulation time is set as 1 second. The initial battery SoC is set as 30 %. The following figures show the simulation results for reference real power 1.4 kW and reference reactive power 0 kVAR.

Figure 9 illustrates the AC output voltage and current waveform. As the reference reactive power is 0 kVAR, the voltage and current waveforms are in phase. The maximum voltage is 325.26 V and maximum current is 8.608 A.

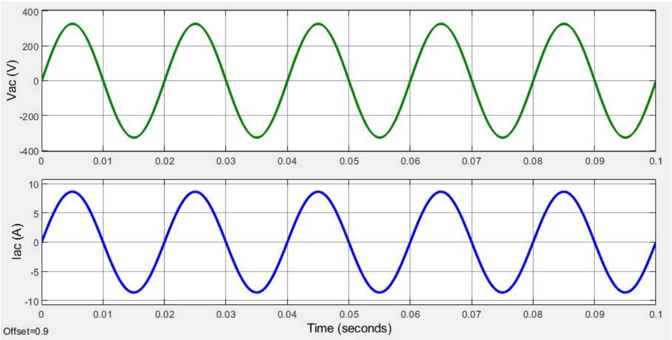


Fig. 9 AC Output Voltage and Current Waveform

Figure 10 shows RMS output voltage and current. According to the simulation results, the RMS output voltage is 230.0 V and current is 6.087 A. The AC source output real and reactive power are shown in Figure 11. The real power is 1400 W which is the same as the reference real power input. The reactive power is -11 VAR whilst the reference reactive power is 0 VAR. The presence of reactive power is due to inductive and capacitive elements used with converters.

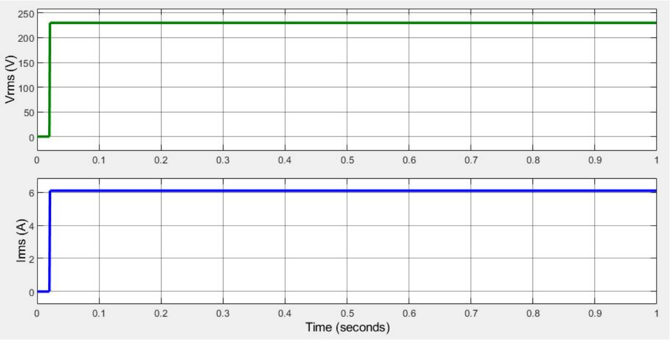


Fig. 10 RMS Output Voltage and Current

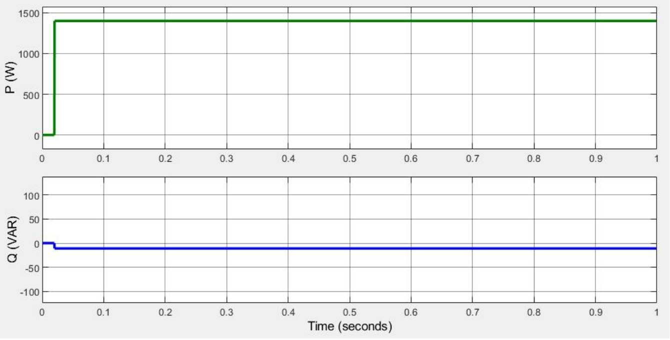


Fig. 11 AC Source Output Real and Reactive Power

In the simulation study, the measurements are also carried out for DC bus voltage and at battery. Figure 12 shows DC voltage at AC/DC converter output. According to the measurement, this voltage is about 380 V.

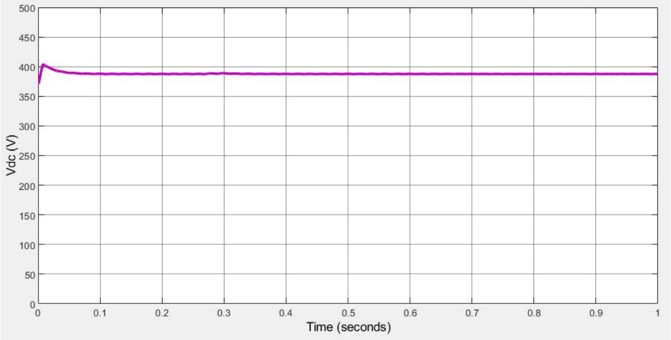


Fig. 12 DC Voltage at AC/DC Converter Output

Figure 13 shows, the voltage, current and power at battery terminal. The battery voltage is about 387.7 V and current is about - 3.611 A. Battery current is negative since the battery is charging. The power is the product of voltage and current and it is about - 1400 W. The negative value means the battery is charging.

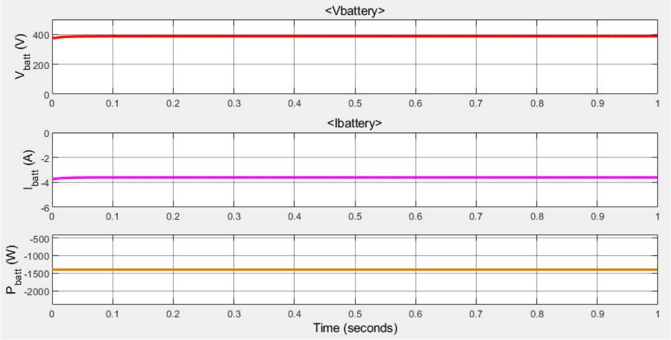


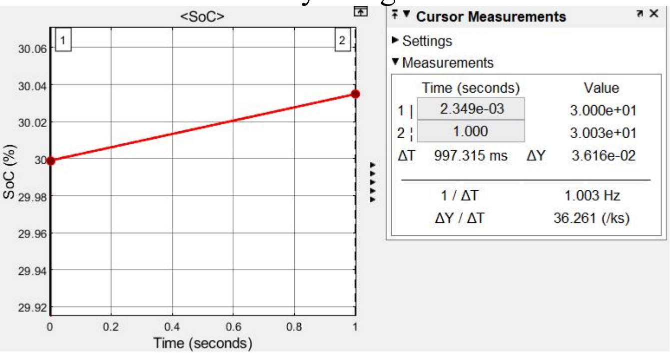
Fig. 13 Voltage, Current and Power at Battery Terminal

Figure 14 shows the state of charge (SoC) condition for 1.4 kW real power reference. As the battery is charging, SoC is increasing from initially set 30 % condition. During 1 second simulation time, the SoC increase about 0.03616 %. The simulations are also carried out for 1.183 kW/1.183 kVAR reference inputs and 0 kW/1.4 kVAR reference input conditions. The simulation results for different real and reactive power reference conditions are shown in Table 3.

TABLE III
SIMULATION RESULTS FOR DIFFERENT REAL AND REACTIVE POWER REFERENCES

	P_{ref} = 1.4 kW Q_{ref} = 0 kVAR	P_{ref} = 1.183 kW Q_{ref} = 1.183 kVAR	P_{ref} = 0 kW Q_{ref} = 1.4 kVAR
V_{rms} (V)	230	230	230
I_{rms} (A)	6.087	7.274	6.087
P_{mea} (W)	1400	1192	11
Q_{mea} (VAR)	-11	1174	1400
VDC (V)	387.7	387.7	438.4
$V_{battery}$ (V)	388.5	388.5	387.7
$I_{battery}$ (A)	3.611	4.315	3.611
$P_{battery}$ (W)	1400	1673	1400
SoC (%)	30.00~30.03	30.00~30.04	30.00~30.03

As shown in Table 3, the real and reactive power flows from AC supply are nearly the same as the set power inputs. The SoC is increased for all cases since the references are positives i.e., charging to the battery. When reactive power reference is only set with zero real power condition, VDC voltage is much higher compared to other cases. When both real and reactive power inputs are set, the AC input current and battery charging currents are large compared to other cases. According to the simulation results, the real and reactive power control scheme can perform well for charging of EV with onboard battery charger.



	Time (seconds)	Value
1	2.349e-03	3.000e+01
2	1.000	3.003e+01
ΔT	997.315 ms	ΔY 3.616e-02
1 / ΔT		1.003 Hz
ΔY / ΔT		36.261 (/ks)

Fig. 14 State of Charge (SoC) Condition for 1.4 kW Reference Condition

VII. CONCLUSION

This paper presents the modeling and analysis of single phase, level 1 onboard charger for EV with real and reactive power control. The battery charger rating is 1.4 kVA and the battery is 363 V, 72 Ah, Li-ion battery. The charger consists of two portions as the AC/DC bidirectional converter and DC/DC converter. The control action is carried out using PI controller. To observe the performance of the charger, the simulations are carried out with various reference power inputs. According to the simulation results, the charger can control the power inputs from the AC source and exhibit the acceptable voltage and current levels. For further study, the studies should be proceeded with intelligent controllers in place of PI controllers and results should be compared and analyzed.

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