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Computational models of an inductive power transfer system for electric vehicle battery charge

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Abstract. One of the issues to be solved for electric vehicles (EVs) to become a success is the technical solution of its charging system. In this paper, computational models of an inductive power transfer (IPT) system for EV battery charge are presented. Based on the fundamental principles behind IPT systems, 3 kW single phase and 22 kW three phase IPT systems for Renault ZOE are designed in MATLAB/Simulink. The results obtained based on the technical specifications of the lithium-ion battery and charger type of Renault ZOE show that the models are able to provide the total voltage required by the battery. Also, considering the charging time for each IPT model, they are capable of delivering the electricity needed to power the ZOE. In conclusion, this study shows that the designed computational IPT models may be employed as a support structure needed to effectively power any viable EV.

1. Introduction

Taking into account high oil prices and environmental awareness, the development of electric vehicles (EVs) is considered as a healthier mode of transportation. This is because the electricity they consume can be generated from a wide range of sources which include fossil fuel, nuclear power and renewable sources (e.g. hydroelectricity, solar power etcetera) [1, 2].

According to [3], it was stated that inductive power transfer (IPT) systems for EV battery charge can be successful if issues such as interoperability between systems of different manufacturers, vehicle design towards effective integration of the inductive charging system, parking guidance and fundamental evaluation of the environmental impacts of the electromagnetic fields are solved.

This paper focuses on the aspect of improving the efficiency of the electric power transferred to the on-board battery storage system of EVs. Regarding this aspect, several studies have been presented in [3–7]. Nonetheless, to achieve the aim of this paper, 3 kW single phase and 22 kW three phase computational IPT models for EV battery charge are designed in MATLAB/Simulink and computed based on the technical specifications of the lithium-ion battery and charger type of Renault ZOE.

2. Analysis of IPT Transformer and Effects of Capacitive Compensation

The most significant part of IPT systems is its air-cored transformer. Its aim is to provide maximum electric power to the on-board battery storage system of EVs. However, it is faced



with the problem of weak coupling (i.e., suffers from poor efficiency) due to the relatively large leakage reactances which is associated with its primary and secondary coils. Before presenting the computational models of 3 kW single phase and 22 kW three phase IPT systems, the behaviour of IPT transformer and the effects of applying capacitive compensation are studied based on Figs. 1 and 2.

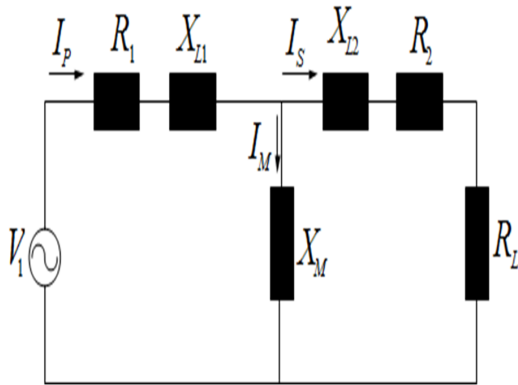


Figure 1. Equivalent circuit of a single-phase IPT transformer.

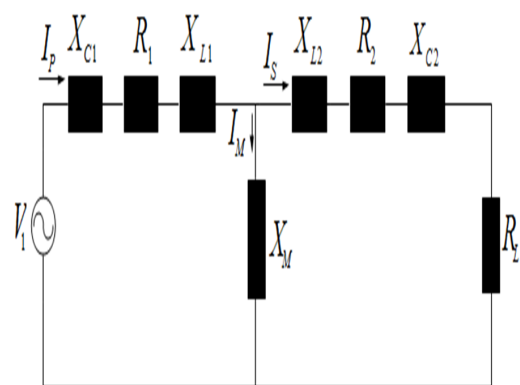


Figure 2. Compensated equivalent circuit.

where I_P , I_M and I_S are the primary, mutual and secondary currents respectively, R_1 , R_2 and R_L are the primary, secondary and load resistances respectively, X_{L1} and X_{L2} are the series leakage reactances, X_{C1} and X_{C2} are the capacitive reactances and V_1 is the root mean square (RMS) AC voltage. In addition, X_M is the mutual inductance between the coils. It is given by $2\pi fM$, where $M=k\sqrt{L_1L_2}$; k is the coupling coefficient, f is the operating frequency while L_1 and L_2 are the series leakage inductances.

Based on Fig. 1, the equivalent impedance of the circuit as seen by the AC voltage source is given by

$$Z_{eq} = R_1 + jX_{L1} + \frac{jX_M R_2 + jX_M R_L - X_M X_{L2}}{jX_M + jX_{L2} + R_2 + R_L} \quad (1)$$

By applying current divider rule, the current division ratio is given by

$$K_c = \frac{I_S}{I_P} = \frac{jX_M}{R_2 + R_L + j(X_{L2} + X_M)} \quad (2)$$

Also, based on Fig. 1, the power transfer efficiency is given by

$$\eta = \frac{R_L I_S^2}{R_L I_S^2 + R_2 I_S^2 + R_1 I_P^2} = \frac{R_L}{(R_L + R_2) + R_1 \left(\frac{R_2 + R_L + j(X_{L2} + X_M)}{jX_M} \right)} \quad (3)$$

Amongst other capacitive compensation techniques proposed in [3–5], series-series (SS) technique is employed because it helps to improve the power transfer capability of the transmission line due to its partial compensation of the series leakage reactances.

Based on Fig. 2, the equivalent impedance of the circuit as seen by the voltage source is given by

$$Z_{eq} = jX_{C1} + R_1 + jX_{L1} + \frac{jX_M(jX_{L2} + R_2 + jX_{C2} + R_L)}{jX_{L2} + R_2 + jX_{C2} + R_L + jX_M} \quad (4)$$

For an exactly compensated transmission link of the IPT transformer, the following reactance conditions are vital [4]:

$$\begin{aligned} X_{C1} + X_{L1} + X_M &= 0 \\ X_{C2} + X_{L2} + X_M &= 0 \end{aligned} \quad (5)$$

Thus, substituting (5) into (4) gives the compensated equivalent impedance of the circuit as

$$Z_{eqC} = \frac{R_1 R_2 + R_1 R_L + X_M^2}{(R_2 + R_L)} \quad (6)$$

Based on Fig. 2, the compensated current division ratio is given by

$$K_{cc} = \frac{I_S}{I_P} = \frac{jX_M}{R_2 + R_L} \quad (7)$$

Also, the compensated power transfer efficiency is given by

$$\eta_C = \frac{R_L I_S^2}{R_L I_S^2 + R_2 I_S^2 + R_1 I_P^2} = \frac{R_L}{(R_L + R_2) + R_1 \left(\frac{R_2 + R_L}{jX_M} \right)} \quad (8)$$

3. Discussion of Results for IPT Transformer

Figure 3 shows the variation of K_c and K_{cc} as a function of frequency f for different values of mutual inductance M and resistive load R_L . It is obtained by computing equations (2) and (7) in MATLAB M-File. In the case without compensation, the values of K_c increase as f increases. However, at higher frequencies, they become constant in spite of the change in R_L but, different values of K_c are obtained for different values of M . In the case with capacitive compensation, the values of K_{cc} kept increasing as f increases but, different values are obtained for different values of M and R_L .

The result obtained in Fig. 3 shows that SS capacitive compensation helps to improve the power transfer capability of the IPT transformer (see values obtained for K_c and K_{cc}). In addition, based on the IPT parameters used for MATLAB simulation (see Table 1), the results obtained show that the IPT system considered in [9] must be operated above 100 kHz.

Figure 4 shows the power transfer efficiency of the IPT transformer with and without SS capacitive compensation. It is obtained by computing equations (3) and (8) in MATLAB. Without compensation, a maximum power transfer efficiency of 78.14% is obtained while with capacitive compensation, 93.18% is obtained. Thus, indicating that with SS capacitive compensation, the power transfer efficiency is increased by 15.04%.

Table 1. Parameters for IPT Transformer [8]

Physical Parameters	Description	Values
L_1	Leakage inductance of primary coil	103.4 μH
L_2	Leakage inductance of secondary coil	12.67 μH
R_1	Resistance of primary coil	0.1530 Ω
R_2	Resistance of secondary coil	0.0660 Ω

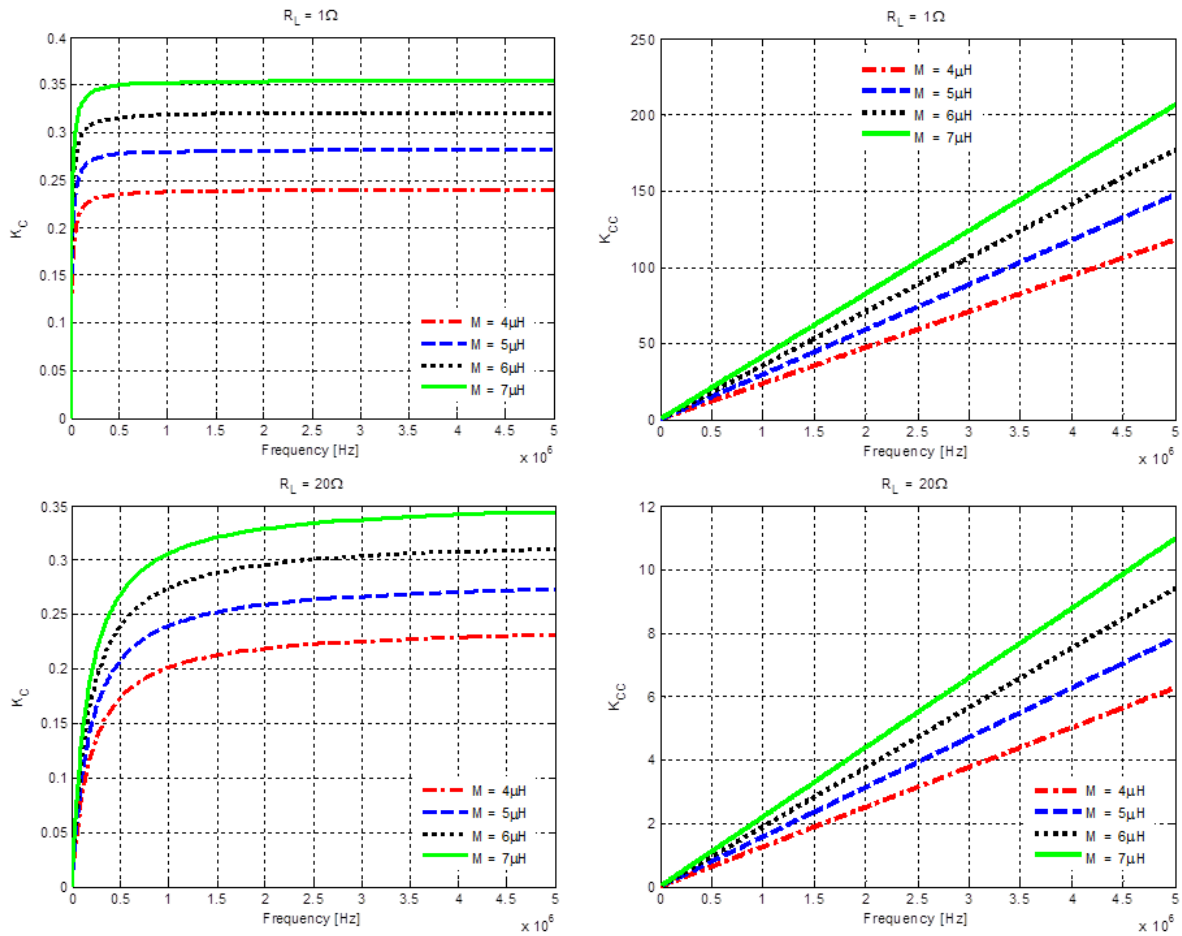


Figure 3. Variation of K_c and K_{cc} as a function of frequency f for different mutual inductances M and resistive loads R_L .

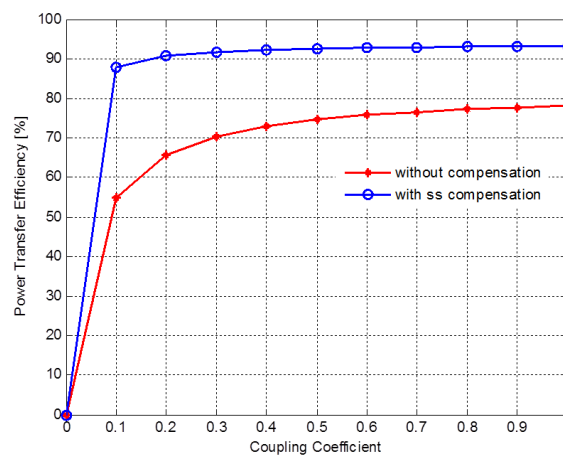


Figure 4. Power transfer efficiency vs coupling coefficient.

4. Computational IPT Models for Electric Vehicle Battery Charge

Figures 5 and 6 show the computational models of 3 kW single phase and 22 kW three phase IPT systems for EV battery charge designed using MATLAB/Simulink.

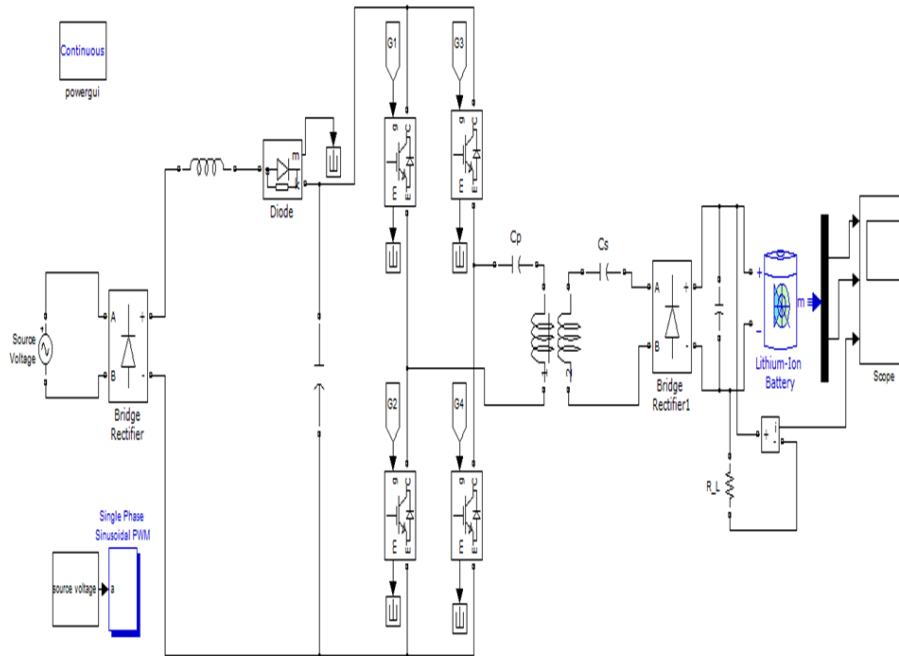


Figure 5. 3 kW single phase IPT model.

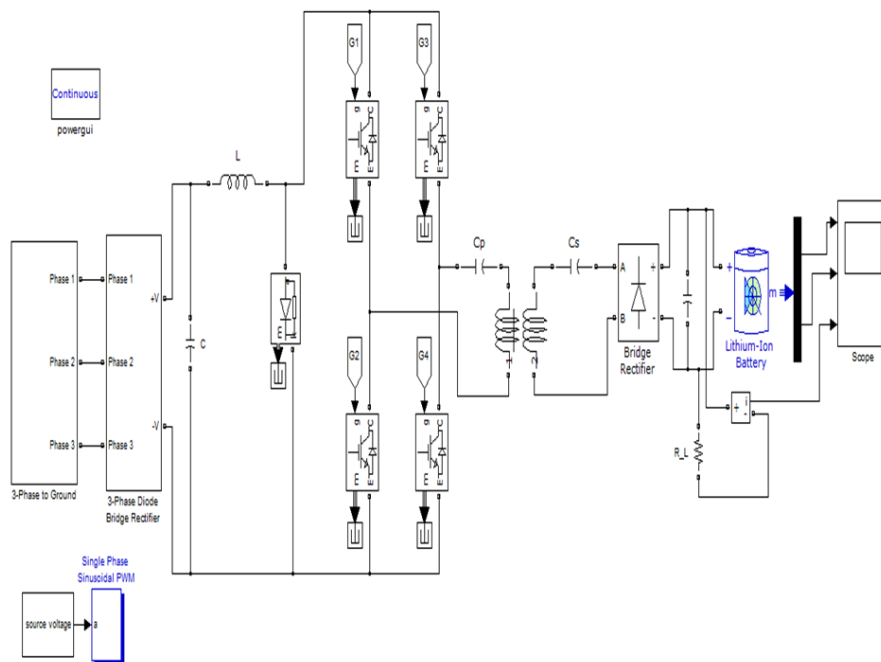


Figure 6. 22 kW three phase IPT model.

The waveforms of 3 kW single phase AC source voltage, its full wave varying DC voltage and stepped up DC voltage as well as the 22 kW three phase AC source voltage, its full wave constant DC voltage and stepped down voltage are shown in Fig. 7. With a single-phase uncontrolled bridge rectifier (UBR), the AC source voltage (i.e., 220 V) is transformed to a full wave varying DC voltage. In order to meet the demands of the lithium-ion battery, boost converter is used to produce a stepped up voltage of 400 V as input for the primary full bridge inverter “IGBT”. Also, with a three-phase UBR, the AC source voltage (i.e., 380 V) is transformed to a full constant DC voltage and a buck converter is used to provide stepped down voltage of 400 V.

Figure 8 shows the waveform of the voltage supplied to the primary coil while Fig. 9 provides a better visibility of the waveform. The single phase pulse width modulation (PWM) (see Figs. 5 and 6) is used to control the switching of the gates of IGBT.

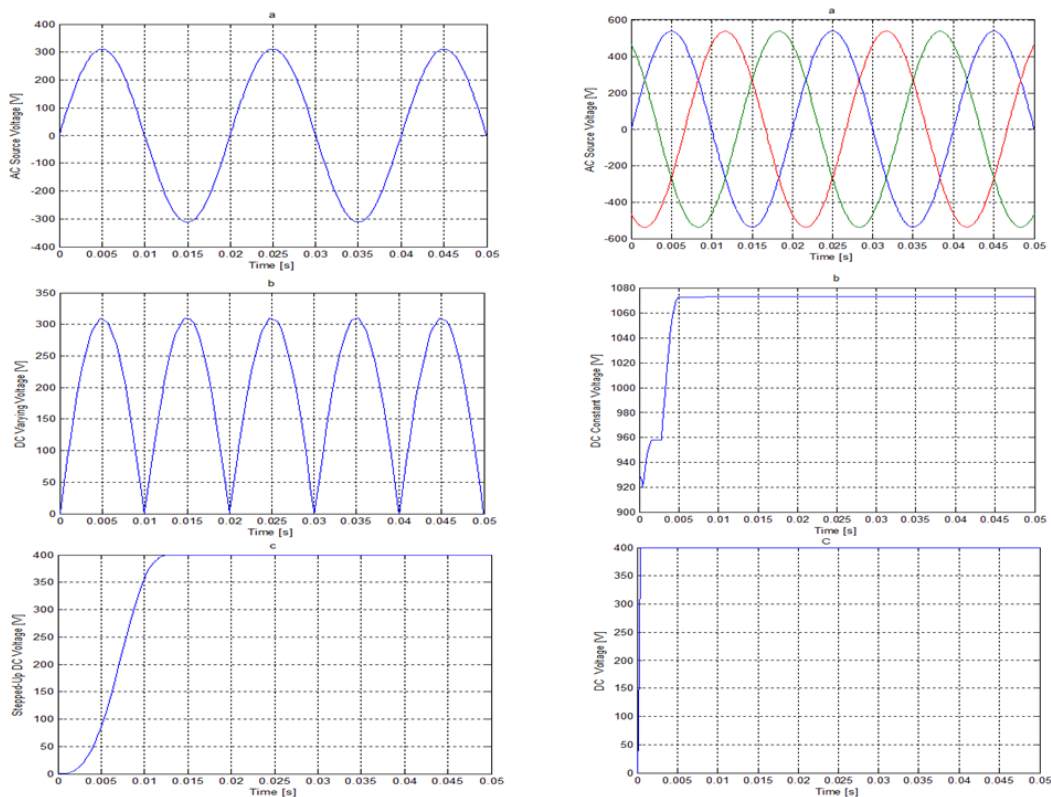


Figure 7. 3 kW (a) single phase AC source voltage, (b) full-wave varying DC voltage and (c) stepped up DC voltage. Also, 22 kW (a) three phase AC source voltage, (b) full-wave constant DC voltage and (c) stepped down voltage.

Based on the technical specifications given in [9], the IGBT is able to convert the direct voltage of 400 V to a higher and fixed frequency of 40 kHz AC voltage. Thus, the primary coil is able to generate a higher frequency electromagnetic field which is then coupled with the secondary coil. Furthermore, in order to guarantee maximum power transfer to the lithium-ion battery, the useful information presented in sections 2 and 3 regarding the application of SS capacitive compensation is incorporated in the designed computational IPT model. Furthermore, the battery charger unit consists of UBR and capacitor filter. This unit is responsible for creating the connection between the IPT system and the lithium-ion battery to be charged. The UBR is used to convert the high frequency AC voltage into a direct voltage while the capacitor filter is added to its output to reduce voltage ripples.

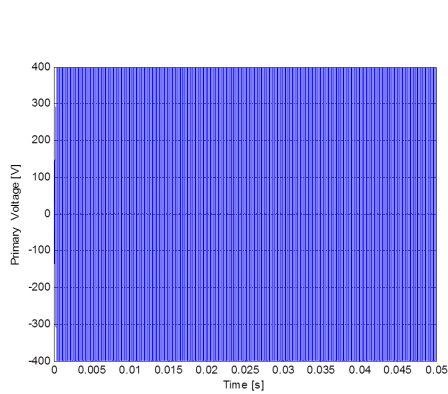


Figure 8. Voltage supplied to the primary coil.

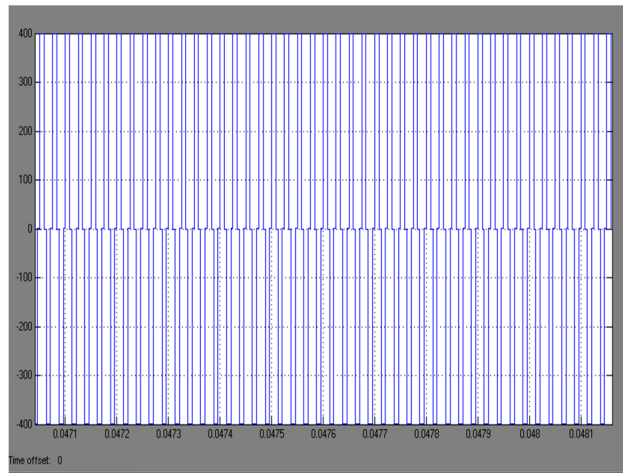


Figure 9. Better visibility of the primary voltage.

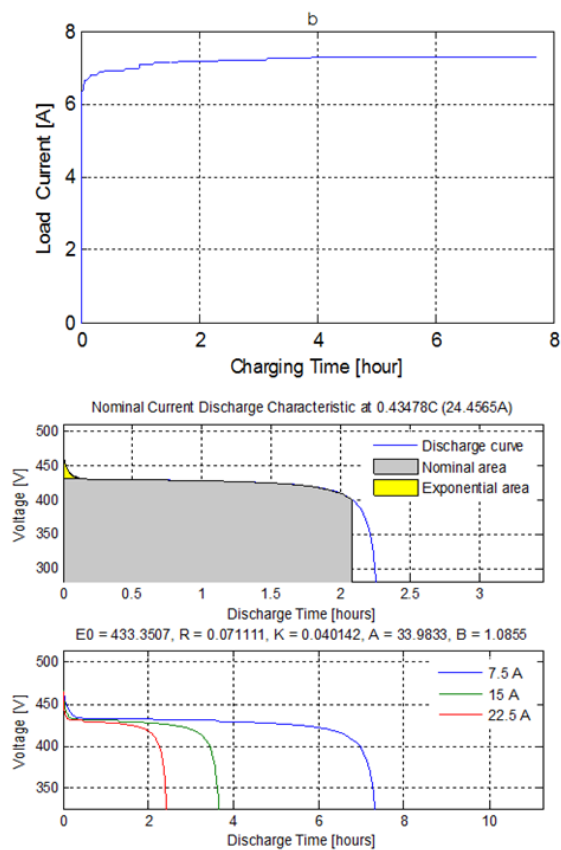
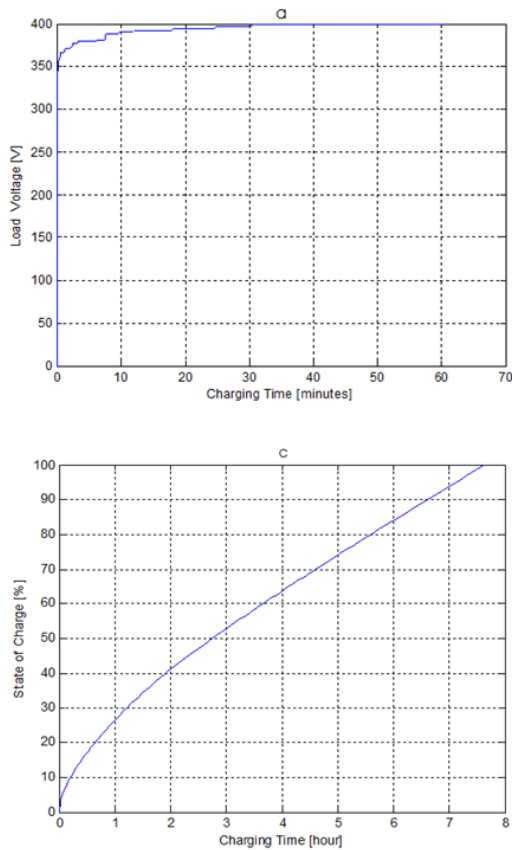


Figure 10. 3 kW IPT model (a) load voltage, (b) load current, (c) state of charge and (d) discharge characteristics of the battery.

The computation of the IPT models given in Figs. 5 and 6 is achieved based on the technical specifications of the lithium-ion battery and charger type of Renault ZOE as presented in [9]. The results (see Figs. 10 and 11) obtained for the load voltage, load current, state of charge of the battery and its discharge characteristic show that the computational models are able to

provide the total voltage required by the battery. Also, considering the charging time for each IPT model, they are capable of delivering the electricity needed to power the battery of the Renault ZOE.

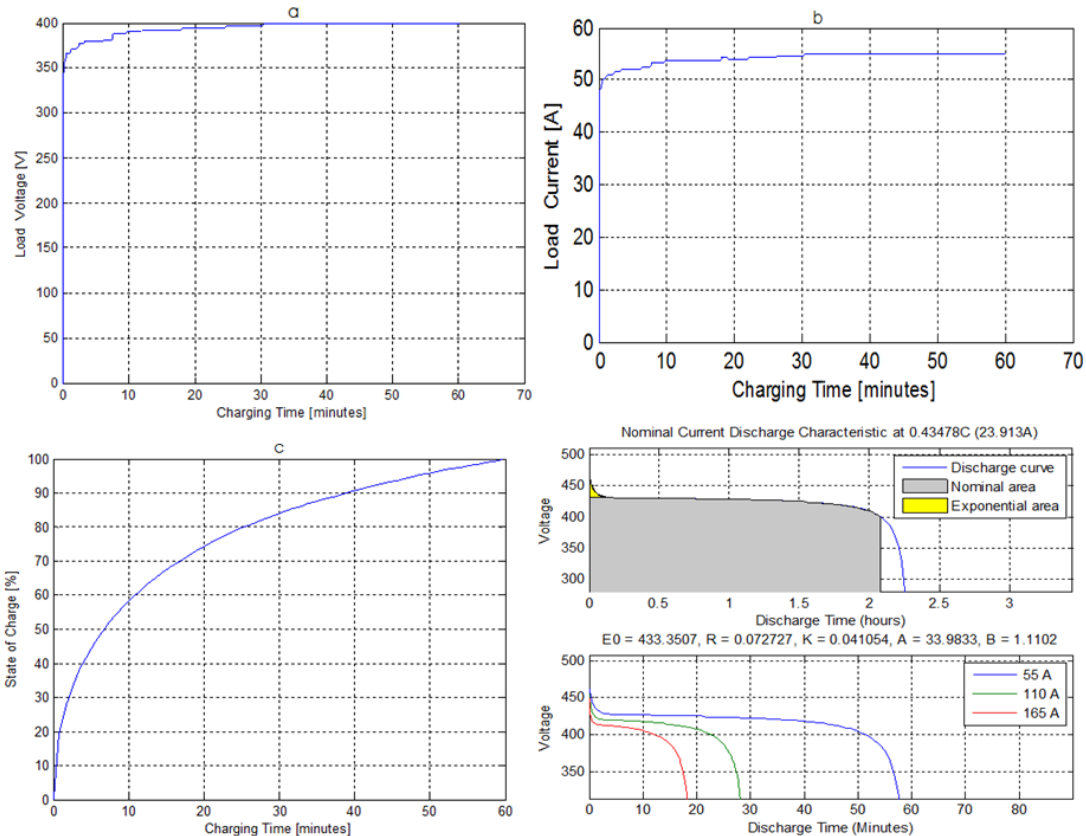


Figure 11. 22 kW IPT model (a) load voltage, (b) load current, (c) state of charge and (d) discharge characteristics of the battery.

5. Conclusion

In this paper, computational models of an inductive power transfer (IPT) system for EV battery charge are presented. To achieve this task, 3 kW single phase and 22 kW three phase IPT systems for Renault ZOE are designed in MATLAB/Simulink. The results obtained based on the technical specifications of Renault ZOE show that the IPT models may be employed as a support structure needed to effectively power any viable EV.

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