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Modelling and Simulation of Powertrain System for Electric Car

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Abstract – *It is widely believed that electric cars hold the key toward a greener mode of transport in the wake of an increased global energy consumption and greenhouse gas emission. However, on the downside, electric vehicles suffer from limited drive range and insufficient battery pack energy. Due to limited energy storage, effective power utility and energy efficiency are regarded as important for battery powered automobiles. To increase energy saving and provide better electric motor efficiency of an electric car, control algorithms such as field-oriented control strategy and space vector modulation can be used. This paper presents a study using Matlab/Simulink on vehicle parameters based on modelling and simulation of an electric car dynamics when integrated with an induction motor powered by Li-ion battery. It shall also describe a modelling of the electric powertrain leading to an analysis of on-board-to-wheel energy conversion. To achieve the model goals, the vehicle powertrain was simulated and the results further confirmed that both vehicle torque and speed correlate with an electric car acceleration index.*

Keywords: Electric car, powertrain, induction motor, field oriented control

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1.0 INTRODUCTION

The growing demand for motorised vehicles to suit today's travelling needs has unfortunately led to the transportation sector being blamed for an increase in global energy consumption and greenhouse gas emission. In order to mitigate the effects of powered road vehicles for public and private use, improvement of energy efficiency is required. According to Kushnir and Sandén (2011), the energy economy presented by electric powertrain is about 80 % greater than that of an internal combustion engine (ICE), which stands at 25% of the total energy input during operation.

As such, Electric Vehicles (EVs) are currently being touted as a greener mode of transport in the wake of an increased global energy consumption and greenhouse gas emission. Due to this reason, vehicle manufacturers are looking at vehicle electrification and alternative forms of propulsion to enhance energy efficiency and saving of electric vehicle drivetrain to meet market demands, in an effort to reduce the impact of transportation for private and public cars. Campanari et al. (2009) and Sciarretta et al. (2015), on the other hand, suggested that on-board-to-wheel energy conversion hold the key toward energy efficiency of private cars.

Energy conversion (i.e. on-board-to-wheel) is the process where energy is transformed – by the drive system to mechanical form via transmission – down to the wheels. Hence, such mechanical energy is converted into potential and kinetic energy necessary for motion. However, this energy transformation process results in significant energy loss as on-board to wheel energy is affected by vehicle resistance parameters including Rolling Resistance (RR), Aerodynamic Drag Resistance (ADR), Grading Resistance (GR), vehicle total weight, aside from road topology and terrain (drive cycle) used by the vehicle. In order to enhance on-board to wheel energy conversion efficiency, both low level abstraction upgrade of the components used and the entire integrated system need to be carried out.

To evaluate power consumption due to vehicle load conditions, simulation tools can be used to investigate and analyse EV powertrain parameters. It has been noted that simulation serves as the backbone for the rapid advancement of EV technology. Simulation helps to decrease the cost and length of EV model cycle. It does so by assessing the design and energy management techniques before prototype construction begins (Mohd et al., 2015a). To understand the behaviour of EV, some studies have underlined the benefits of modelling different peripherals (Fadul et al., 2017). The EV model involved depends on the objectives of simulation (Marmaras et al., 2017).

This paper focuses on a study to determine the effects of vehicle dynamic parameters and its powertrain based on a simulation and model of an Electric Vehicle (EV) dynamics when integrated with an induction motor (Mohd et al., 2015b). Analysing energy efficiency is important for battery powered electric vehicles due to the limited stored energy. Consequently, the study uses field oriented control to achieve enhancement in energy saving and better efficiency for induction motor within an electric vehicle. A modest EV model will be implemented to accomplish powertrain objectives in the drive system.

The paper is arranged into various sections. Section One shall discuss the key components of the EV powertrain along with the induction of motor control strategy (FOC) used in the aforementioned study. Section Two presents the model development parts for vehicle design and a general description of vehicle movement. The third section shall address a case study of the vehicle through simulation in Matlab/Simulink while Section Four reveals the results obtained from the simulation. Finally, the paper shall present a conclusion based on the research findings.

2.0 THE KEY COMPONENTS OF EV POWERTRAIN

The current global energy crisis coupled with the thinning of our ozone layer has resulted in the invention of powered road vehicles being considered the most popular field of science. Hybrid Electric Vehicles (HEVs) and foremost, Electric Vehicles (EVs) are presumed to be a lasting solution to limit the tremendous emission of hazardous gasses into the environment caused by tailpipe vehicles. The EV comprises a battery pack, electric motor, both AC-DC and DC-DC power converters, vehicle interface and power management/control unit which monitors the power flow as depicted in Figure 1. An accelerator pedal is attached to the

Electronic Control Unit (ECU) to decide how much power from the battery pack is to be supplied to the electric motor in order to overcome the actual vehicle load in different situations. Therefore, in the EV application, a powertrain can generate power and deliver it to the road surface. This section briefly introduces the EV electric powertrain, which consists of the following components:

- Electrical Machines (EM);
- Power Electronic Converters;
- Electric Energy Storage System (EESS); and
- Energy Management System (EMS) and Control.

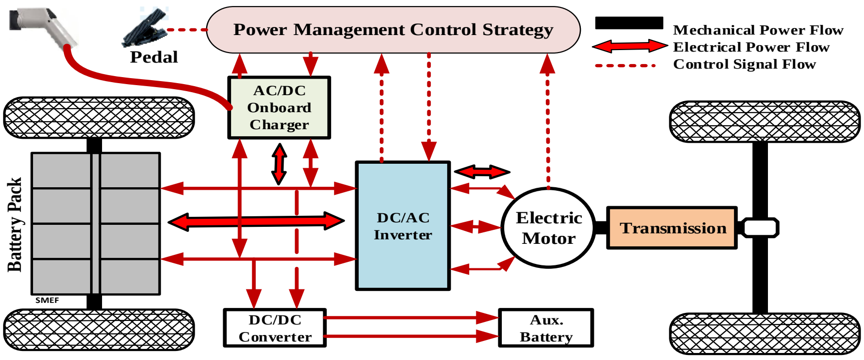

Figure 1: Structure of general EV based on the energy point of view

2.1 Electrical Machines

Because of their particular torque-speed characteristics, electric machines can provide a high starting torque. The determined rated speed and maximum speed of the drive motor must conform with requirements of the torque-speed characteristics of the motor.

As soon as the car begins to move, the electric motor acceleration is minimal and will operate in the constant torque condition, as long as velocity is larger compared to the rated speed it operates in the continuous power status as represented in Figure 2-A. AC motor is generally used for high-performance EV as it can perform in the four quadrants. These operating quadrants demonstrate four combinations of polarities of the torque and speed as highlighted in Figure 2-B. Induction Motor (IM) drives will continue to be implemented in EVs due to its reliable operation, high efficiency, ruggedness, and low maintenance requirements. Nevertheless, a precise and accurate control of the induction motor is not easily realizable due to its complexity, non-linearity and the inability to directly access and measure rotor variables. Hence, controlling the induction motor becomes a monotonous process and a critical issue, especially for EV applications where both fast transient and stable steady state responses of the speed and torque performances are required. Therefore, one of the techniques used to address these issues require controlling the electric motor through Field Oriented Control (FOC). Application of FOC to induction motor is performed mainly based on the motor model fixed in dq-axis to the stationary reference frame. As shown in Figure 3, FOC control along with space vector modulation are used to determine precise pulses fed to power inverter to supply the IM with three phase currents. The operating quadrants illustrate four combinations of polarities of torque and speed.

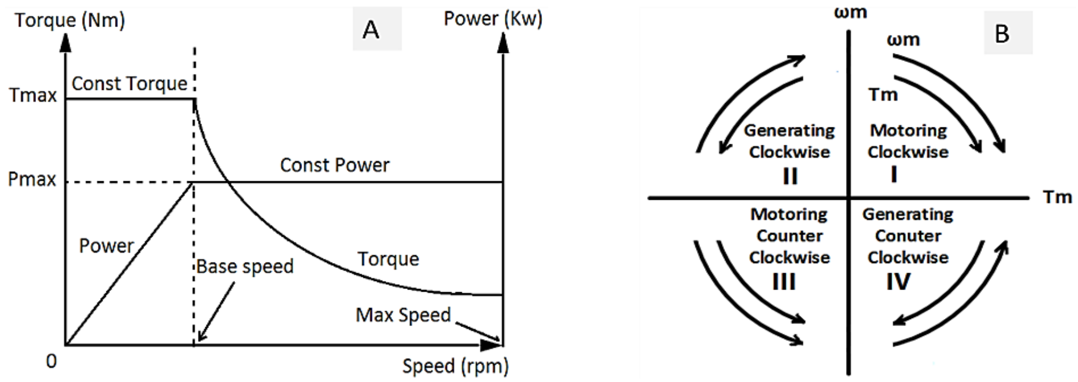

Figure 2: (A) Typical traction electric motor characteristics; (B) Operating quadrants in the (ω_m, T_m) plane

2.2 Power Electronic Converters

This sub-section shall provide explanation of the inverter, DC-DC converter and rectifier.

2.2.1 Inverter

In an electric vehicle, inverters convert DC power, typically from a battery pack voltage, to alternating phases of power to drive electric motors. The two key performance measures are power capabilities and efficiency. Typical motor control functions include driving IGBT/relevant power stages, sensing the motor speed/position accurately and diagnosing and driving the system safely to avoid any malfunction to the inverter. DC/DC converters increase or decrease battery voltages.

2.2.2 DC-DC Converter

The DC-DC converter is used in EV as an interface circuit between battery pack and DC link Bus. It allows power flow from the high voltage to low voltage when acting as a buck converter while the power flow from the low voltage to high voltage requires the converter to act as a booster. As a result, the use of bidirectional DC-DC converter allows the use of multiple energy storage, and offers advantage of flexible DC-link voltages which can enhance system efficiency and reduce component sizing. However, the converter must be highly efficient, reliable, cost effective and simple to control to be used in EV.

2.2.3 Rectifier

The rectifier converts AC from electric grid to DC to charge on-board battery pack (Pan & Zhang, 2016). Also during regenerative stage in EV, when braking or slowing the vehicle down, a considerable amount of energy is generated which needs to be stored in the battery pack. Currently, the converter acts as a rectifier to recharge the battery.

2.3 Energy Storage System

Fulfilling the demand of mileage endurance requirements necessitates an understanding of the parameters that control the battery operation (Affanni et al., 2005; Schmalstieg et al., 2014). Many battery manufacturers for HEV and EV such as NiMH and Li-ion determine the battery voltage and capacity. For EV propulsion, the battery pack must supply voltage and current according to the vehicle's motor requirements and peak power requirement in the typical driving cycle (Kroeze & Krein, 2008; Tremblay & Dessaint, 2009). These parameters are defined below as:

- Energy density and specific energy; theses parameters determine at what voltage can the battery deliver current over time per volume and weight respectively.
- Maximum sustainable discharge rate; this determines the ability of the battery to deliver power in watt continuously without damage.
- Life cycle; determines the number of time for charging and discharging before the battery loses a specific amount of its capabilities.
- Operating temperature; as the battery is charged and discharged, it will change its temperature. Battery performance will vary substantially.
- Capacity and State of Charge (SOC); determines the current that the battery can deliver to the load. SOC also determines a remaining of battery capacity depending on the battery operating conditions such as load current and temperature.

2.4 Energy Management System and Control

The energy management system and control unit apply both software and hardware controls to maximize energy efficiency and drivability. The powerful variable speed control of three-phase induction motors needs to balance three-phase set of voltage variables from DC voltage with variable frequency using power-semiconductor devices such as IGBT or MOSFET. As the AC three-phase voltage is generated when using one of the modulation techniques, voltage and frequency of the generated waveform can be controlled by the control algorithm. This algorithm can also control the torque or speed; with an open or closed loop. Many algorithms are used to control the IMs such as volts per hertz, slip control, vector control, sensorless vector control and field orientation. In this particular study, FOC and SVM are used to control the IM drive system. FOC not only can control the torque but also can mitigate electric drive losses. Hence, FOC combined with the space vector modulation can provide an optimal approach to control the EV traction motor.

Applying FOC technique requires measuring two instantaneous currents using current sensors, before using the Clarke and Park transformation to convert them into variant and invariant systems, respectively. The main loop for FOC is executed as the interrupt service routine. This loop must be able to measure and convert the current, read and calculate the speed of the rotor, supervise the PI controllers, calculate the slip and check the modulation strategy, as well as search and check for any fault. Figure 3 shows a loop of vector control that executes the interrupt service routine program for every predetermined time.

A response of electric torque T_e of vector controlled IM drive is stated in Equation 1. The current i_{qs}^{e} is torque component and i_{ds}^{e} is flux component. For requiring high speed of IM, the direct current component via the IM has to be controlled. For achieving good torque response, the flux component must be constant and the torque component must be varied. This means i_{dref} is constant while i_{qref} is the desired variable torque signal as illustrated in Figure 3.

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} i_{qs}^{e} i_{ds}^{e} \tag{1}$$

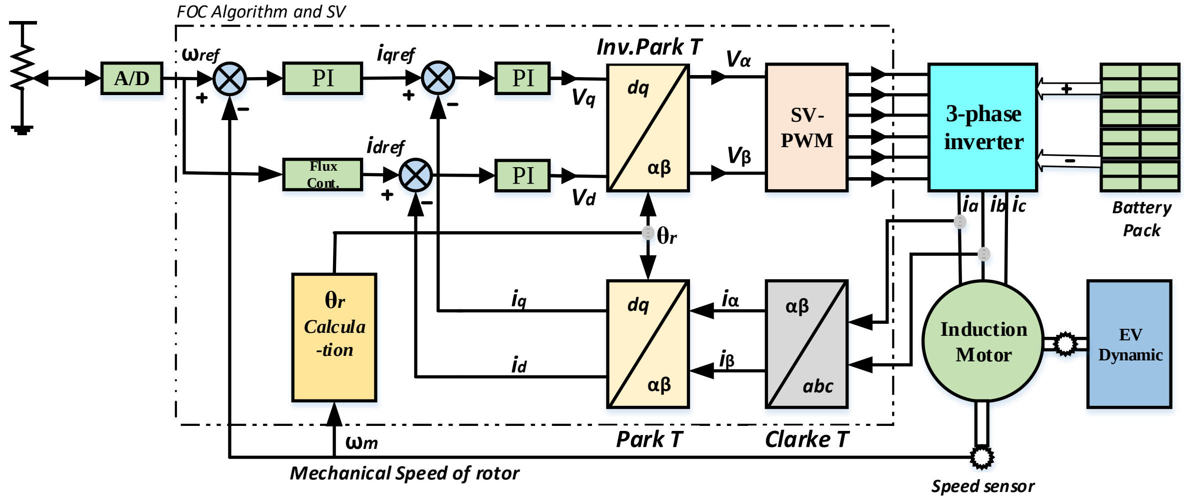

Figure 3: A block diagram of FOC

3.0 GENERAL DESCRIPTION OF VEHICLE MOVEMENT

The vehicle dynamics represent the motion influence on the overall system. As mentioned earlier, the energy transformed to the vehicle wheel is converted once more to energy for displacement. The tires dynamics represent the force applied to the ground. Accordingly, the overall consumed energy at the tire can be obtained from the time integral of the power as:

$$E_{wheel} = \int_0^t P_{wheel}(t)dt \tag{2}$$

For the electric powertrain that transmits the instantaneous tractive power to the wheels, P_{wheel}, in order to sustain a certain speed level, road grade and acceleration along with displacement is determined by the tractive force and vehicle speed as:

$$P_{wheel} = \int_0^t v(t)\ F_t(t)dt \tag{3}$$

where v is the vehicle's speed and F_t is transited traction force by the powertrain to the wheels. Hence, during regenerative braking if the F_{wheel} is negative, p_{wheel} will also be negative, and therefore, the total consumed energy over time will be reduced.

On the other hand, as shown in Figure 4, the description of vehicle movement can be entirely determined by analysing the resistive forces acting on it in the direction of movement. When the vehicle moves, it encounters resistive force that tries to retard motion. The resistive forces include:

- Rolling resistance;
- Aerodynamic drag; and
- Grade resistance.

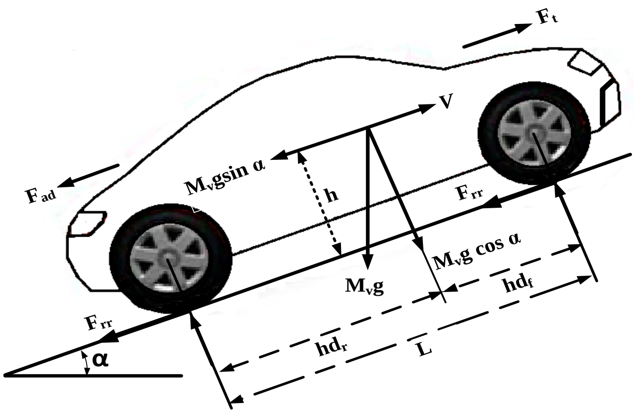

Figure 4: Forces acting during vehicle movement

The equation of movement along the electric vehicle's longitudinal axis is represented by the following equation (Eshani et al., 2010):

$$F_t = F_{rr} + F_{ad} + F_{hc} + F_{ac} \tag{4}$$

where F_t, F_{rr}, F_{ae}, F_{hc}, F_{ac} and F_{wa} represent total tractive force, road rolling resistance, aerodynamic resistance, grading resistance, and acceleration resistance, respectively. The details are given in the following section.

3.1 Rolling Resistance

The rolling resistance F_{rr} is produced by friction of the vehicle tyre at the roadway contact surface during rolling. The repeated deflection can affect the tire producing a hysteresis within the tire material. Rolling resistance also depends on vehicle speed, tyre pressure and type and road surface characteristic, which makes estimation of rolling resistance through analytical modelling very difficult.

Therefore, the rolling resistance force, F_{rr} acting on a vehicle in the longitudinal direction, is usually expressed as the effective normal load of the vehicle multiplied by the dimensionless rolling resistance coefficient. Rolling resistance can be stated as:

$$F_{rr} = C_{rr} M_v . g . \cos(\propto) \tag{5}$$

where C_{rr}: Tire rolling resistance coefficient, g is acceleration constant [m/s2] and α is road angle [radians]

3.2 Aerodynamic Drag Resistance

F_{ad} occurs as air flows over the vehicle. The force is a function of the frontal area, the shape, etc. This drag resistance can be written as:

$$F_{ad} = \frac{1}{2} p_a c_{ad} A_f (v_v + v_{wind})^2 \tag{6}$$

where ρ_a is air density; C_{ad} aerodynamic drag coefficient; A_f is vehicle frontal area; v_v is vehicle speed, and v_w is headwind velocity.

3.3 Grading Resistance

Grading resistance is the required force to drive a vehicle up a slope when the vehicle weight component acts along the slope. This grading resistance force F_{hc} opposes the forward motion uphill and helps downward motion. It can be written as:

$$F_{hc} = M_v . g . \sin(\propto) \quad (7)$$

where α (rad/s) is the angle between the level road and the horizontal plane as in

$$\alpha = \arctan(\text{rise}/\text{run}) = \arctan((\%\text{grade})/100) \quad (8)$$

3.4 Acceleration Resistance

An additional force is required when the speed of the vehicle varies. This force will provide the linear acceleration of the vehicle.

$$F_{ac} = M_v a \quad (9)$$

where a: vehicle acceleration.

Using the Newton's second law of movement, the fundamentals of vehicle design include basic principles of physics. The dynamic equation of the vehicle movement along the longitudinal direction is specified by vehicle acceleration that can be stated as:

$$\frac{dv}{dt} = a = \frac{F_t - (F_{rr} + F_{ad} + F_{hc})}{M_v} \quad (10)$$

The traction force that can overcome the vehicle resistive forces which act on the vehicle can be expressed as:

$$F_t = \frac{60 N_g \eta_g P_m}{2\pi n_{m,max} r_d} \; [N] \quad (11)$$

where η_g is gear efficiency, N_g is gear ratio and r_d is the wheel radius, $n_{m,max}$ is the maximum rpm of the motor and P_m is electric motor power.

To calculate the total traction force, Table 1 is used to provide dynamic parameters for the electric car, which leads to the definition of motor size and power needed to propel the EV.

Table 1: Vehicle basis dynamic parameters

Parameter	Value
Vehicle mass (kg)	1300
Aerodynamic drag	0.25
Wheel rolling resistance	0.01
Wheel radius (m)	0.25

4.0 A CASE STUDY OF ELECTRIC CAR

Providing the specification for electric powertrain of EV is the main step in developing a process to analyse the powertrain efficiency. Both modelling and simulation methods have been used in this study. Upon considering the vehicle performance criteria, power sizing of the electric motor and developed model are simulated in Matlab/Simulink.

Figure 5 shows the EV Simulink model comprising a lithium ion battery pack of 156V with 200Ah. The control system design consists of the energy management, control unit and other connected interfaces. In addition to that, the EV model consists of other blocks namely; three phase Induction Motor (IM), power converters and vehicle dynamics load. A lithium-ion battery pack which acts as the main power source to the EV supplies the three-phase induction motor which propels the vehicle. In order to supply a stable three phase currents for the IM, an inverter was used to invert DC voltage from the battery into three phase AC voltage.

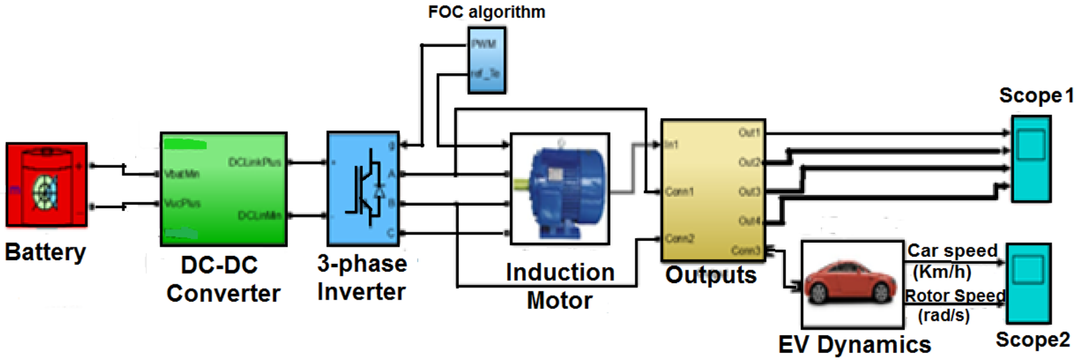

Figure 5: Model of electric vehicle drivetrain in Matlab/Simulink

To distribute power from the storage energy accurately, the energy management and control unit block performs a variety of tasks. First it controls the DC-DC converter which regulates the DC link voltage and current. Because the block contains FOC algorithm, it can determine the reference signals to govern the gates of power inverter which control the motor dynamics.

This study reveals a multi-domain simulation of a battery EV powertrain based on SimPowerSystems and SimDriveline. Figure 6 shows the pedal position (A), battery state of charge (B), battery power (C) and battery current (D). In Figure 6-A, an accelerator pedal represents a reference signal to energy management and control unit during the 16-sec interval.

During that time, the battery state-of-charge should be maintained between 85% and 40% to prevent voltage collapse. This was done by controlling the power required from the battery. Accordingly, the battery depletion rate was at 0.05%. Moreover, the simulation showed the operating mode of the battery over predetermined time during the accelerating mode. It can be seen that a battery power and battery current started at zero and reached about 26 kW and 100A respectively.

On the other hand, drive torque and drive power reached an average of 60Nm and 75kW, respectively in order to propel the car from its starting point, as can be seen in Figure 7-E and 7-F. In addition, motor supplied power was approximately 30kW while the supplied three phase current was 250 amperes (Figure 7-G and 7-H). The drive power and torque resulted in IM speed to reach the base speed of 4000 rpm (Figure 8-I). This allowed the speed of the car to reach around 80km/h during the 16-sec cycle (Figure 8-K).

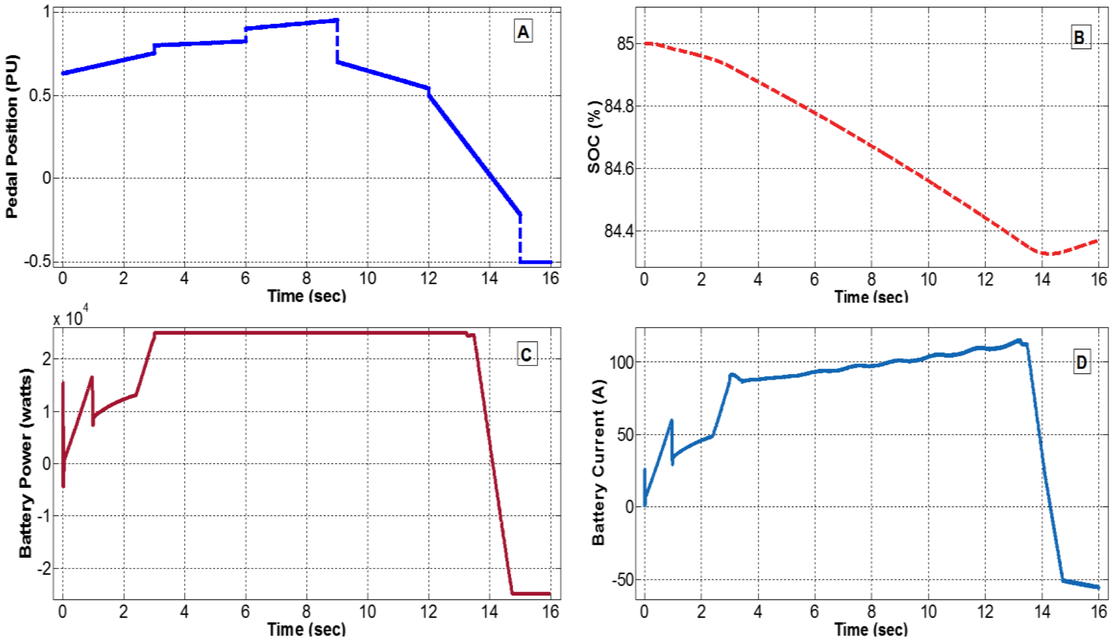

Figure 6: (A) pedal position; (B) Battery state of charge; (C) Battery power; (D) Battery current

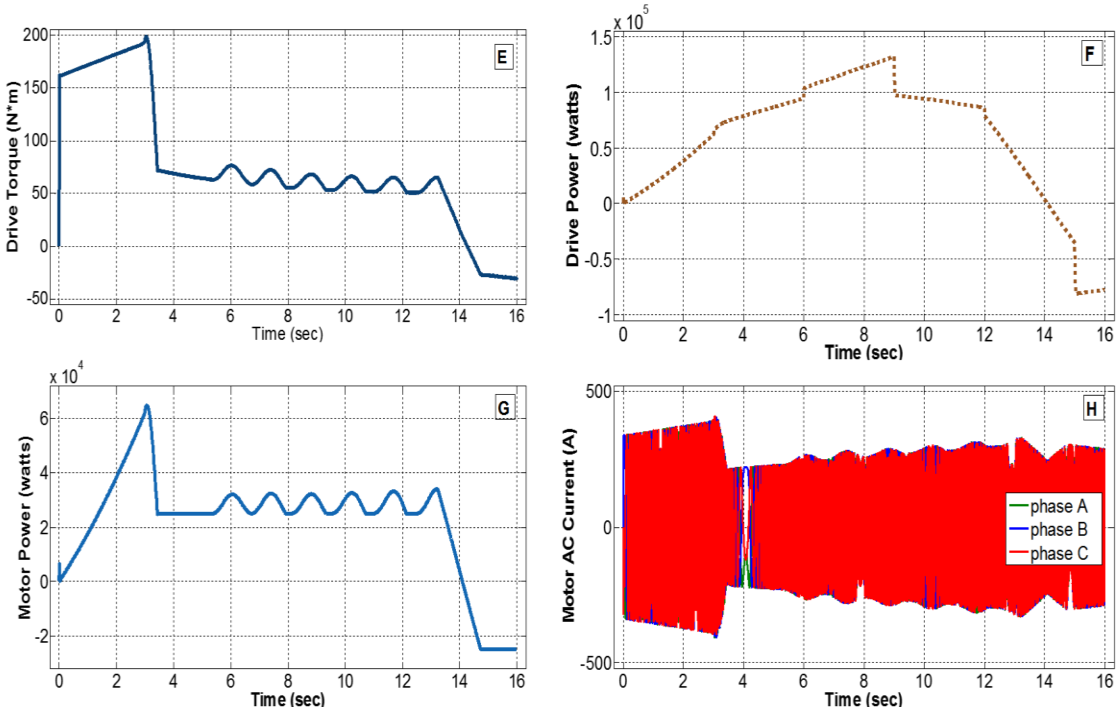

Figure 7: (E) Drive torque; (F) Drive power; (G) IM power; (H) IM three phase voltages

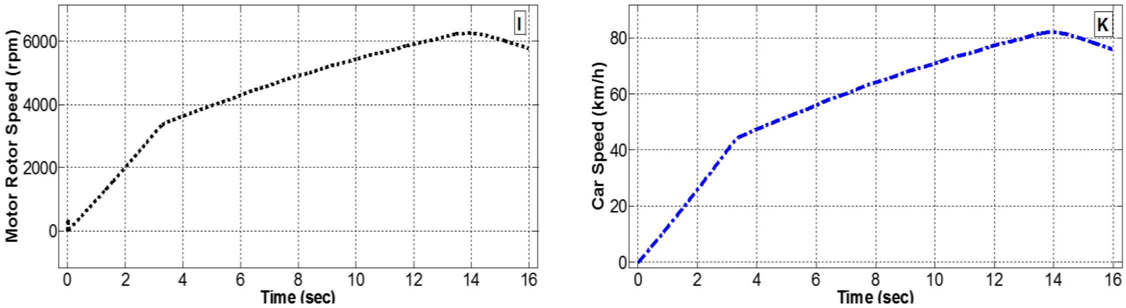

Figure 8: (I) Speed of the IM motor rotor; (K) Speed of the electric car

5.0 CONCLUSION

Overall, this paper has highlighted the key components of EV powertrain along with FOC approach. Moreover, the results of simulation indicated that the vehicle model had good dynamic performance. This modelled powertrain shows that the vehicle reached about 70km/h during a 10-second acceleration time. Such result confirmed that the car speed fulfilled the acceleration index for powered road vehicles.

Although the study focuses on analysing effective power and efficient energy for battery powered electric automobiles through modelling and simulations, the findings may have a bearing on the presence of thermal effect on car performance for more energy saving. Taken together, such results suggest that further work is required to establish the viability of a complex EV powertrain that includes the thermal effect on its performance.

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