TRACTION MOTOR SELECTION BASED ON THE PERFORMANCE ANALYSIS OF PURE ELECTRIC VEHICLE UNDER DIFFERENT DRIVING SCENARIOS

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Abstract: *Selecting the appropriate powertrain components for electric vehicles, in terms of size and efficiency became a challenging task, especially the traction motor that requires special care. Since it is the only source of traction power, its selection may affect the performance of the electric vehicle. Therefore, an analysis of the vehicle performance with various motors types and design is necessary to outline its importance and to verify the impact of its selection on the entire vehicle system. The Permanent Magnet Synchronous Motor (PMSM) and the Induction Motor (IM) were tested during different driving cycles using the ADVISOR tool, designed based on Matlab/Simulink, for rapid analysis of the performance and fuel consumption of conventional hybrid and electric vehicles. The 2WD GM EV1 model from General Motors Company has been selected to investigate the electric vehicle performance during different driving scenarios, such as dealing with high aggressive acceleration, or several stops and start situations*.

1. INTRODUCTION

The electric vehicle is the result of combining several engineering fields such as electrical, mechanical, automation, chemical, and electronics. The major components of this technology are the storage system, power electronics converters, the electric motor and its controller, and the transmission system. These parts connect to form the electric vehicle powertrain where the electric motor represents its heart, since it is the only source of traction that delivers torque to the wheel. The vehicle performance determined by the Torque-Speed or

Power-Speed characteristic of the traction motor [1]. While designing an electric vehicle, the first and foremost component to be selected is an electric motor [2] that has some specific characteristics which required for traction purpose. The desired options of an electric motor drive for traction application (electric and hybrid vehicles) are high torque at the low speed region for fast acceleration, hill climbing and obstacle negotiation, and low torque at high speed for cruising. Also, the electric motor drive is required to have a long constant power range to meet the torque and speed demand [3]. We cannot compare the traction motor to drives used in industrial plants or manufacturing processes because an EV motor drive needs to face different circumstances such as frequent start/stop, or operating under many environmental conditions [4]. The electric motor drive must have high torque generating capacity and high acceleration.

As the vehicle needs to run on any terrain and in harsh environments, it must have a high torque when operating at slow speeds with high efficiency as well [4]. The process of selecting the appropriate electric propulsion systems should be performed at the system level [5]. Different types of motor exhibit many characteristics which makes it necessary to evaluate motors under different driving cycles to choose a particular motor type for EVs. It should have some features such as simple design, high specific power, and low maintenance cost [6]. However, the selection of traction motors for the EV propulsion systems is an important step that requires special attention. The automotive industry is still seeking the most appropriate electric propulsion system [7].

In literature, the selection of the motor started from the comparison between electric traction motors regarding certain factors like the energy efficiency, power to weight ratio, Torque-Speed characteristics, the maturity of the technology, reliability and the cost for both motor and controller [4][6][8]. Others made the selection based on several factors related to the driver expectation, power source, and the vehicle constraints [7]. In this paper, a comparison between AC induction motor (IM) and Permanent Magnet Synchronous Motor (PMSM) has been made based on the Torque-Speed characteristic, effect on battery SOC (State Of Charge), the overall system performance, and motor/controller efficiency for generating and motoring mode. Acceleration and grade-ability tests considered as well.

For the sake of this paper, ADVISOR (ADvanced VehIcle SimulatOR) tool as an open and free simulation tool developed by NREL (National Renewable Energy Laboratory) for vehicle design used to make this comparison done. ADVISOR tests the impact of variations in electric components or other changes that might affect the vehicle performance parameters. By selecting components types and sizes the user can alter simulation results. It is flexible enough to model specific components and vehicle performance configurations for the needs of users [9].

2. VEHICLE DYNAMIC MODEL

In this paper, the GM EV1 model has been selected from ADVISOR vehicle configuration menu to study the vehicle performance with different motor characteristics and types. In this study, we only focused on the longitudinal model, and a simplifying hypothesis developed when we did not consider the displacement on the transversal, vertical direction, rotation, rolling and pitching.

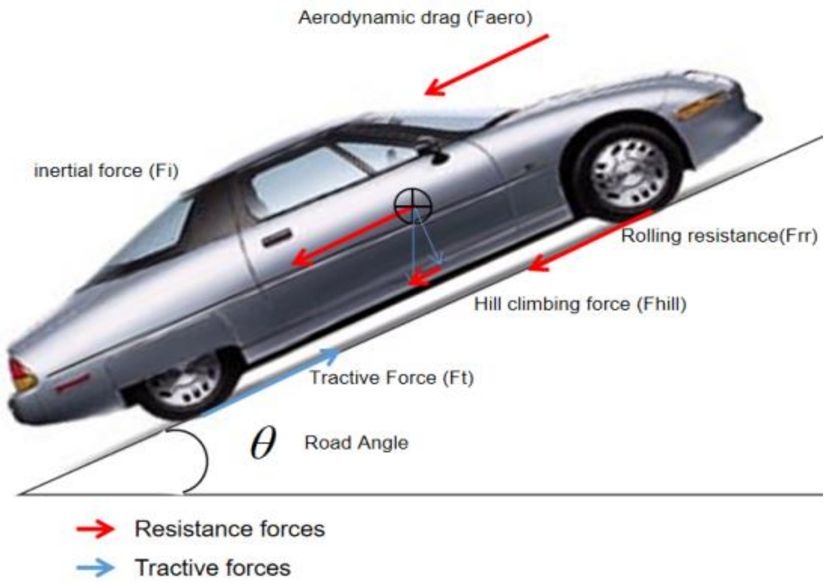


Fig. 1. Electric vehicle longitudinal model

2.1. Rolling resistance Force

Rolling resistance is the force that resists vehicle movement on a surface. It is approximately constant and it barely depends on vehicle speed.

$$F_{rr} = C_{rr} mg \cos(\theta) \tag{1}$$

In (1), C_{rr} is the rolling resistance coefficient, its typical value being from 0.015 down to 0.005 for electric vehicle tires [13], g is acceleration of gravity and m is vehicle weight.

2.2. Aerodynamic drag

Aerodynamic drag caused by the friction of the vehicle body moving through the air, we can notice from the equation (2) that force F_{aero} is a function of vehicle shape and size defined by drag coefficient and weight respectively. Drag coefficient C_d typical value is between 0.25 and 0.3, but some electric vehicle designs have achieved values as low as 0.19 [13] like GM EV1.The later is directly affected by the shape of the vehicle.

$$F_{aero} = \frac{1}{2}\rho A C_d v^2 \tag{2}$$

where ρ is density of the air and 1.25 kg/m^3 is a reasonable value to use in most cases [13], A is the frontal area, v is the vehicle velocity.

2.3. Grade or hill climbing force

Grade force F_{hill} or hill climbing, sometimes called gravitational force is required force to drive a vehicle uphill, and it is proportional to vehicle mass and grade angle.

$$F_{hill} = mg\sin(\theta) \tag{3}$$

2.4. Inertial force

If the velocity of the vehicle v is changing, then clearly a force F_i will need to be applied in addition to previous force. This force will provide the *linear and angular acceleration* of the vehicle, and is given by well-known equation derived by Newton's second law [11]. The angular acceleration force F_{wa} will be slightly smaller than the linear acceleration force F_{la}, in this case the F_{wa} will be ignored, and the vehicle mass will be increased by 5% as a reasonable approximation [11].

$$F_{la} = ma \tag{4}$$

$$F_{wa} = I\frac{G^2}{\eta_g r^2}a \tag{5}$$

where I is moment of inertia, G *is* gear ratio, r is wheel radius and η_g is gear system efficiency.

$$F_i = F_{la} + F_{wa} = m_i a \tag{6}$$

where m_i is the vehicle inertial mass, and $m_i = m \cdot 1.05$.

2.5. Tractive effort

Is a total traction force, or a summation of all the previous resistive forces (inertial force (F_i), hill climbing force (F_{hill}), aerodynamic drag (F_{aero}) and rolling resistance force (F_{rr}) needed to move a vehicle forward or backward.

$$F_t = F_i + F_{hill} + F_{aero} + F_{rr} \tag{7}$$

3. ADVISOR AS A VEHICLE PERFORMANCE ANALYSIS TOOL

ADVISOR has been developed by the National Renewable Energy Laboratory for the US DOE. It is a tool that can be used to evaluate and quantify the vehicle level impacts of advanced technologies applied to vehicles. It is written in the Matlab/Simulink environment (see *figure 3*) and is freely distributed on the Internet [11].

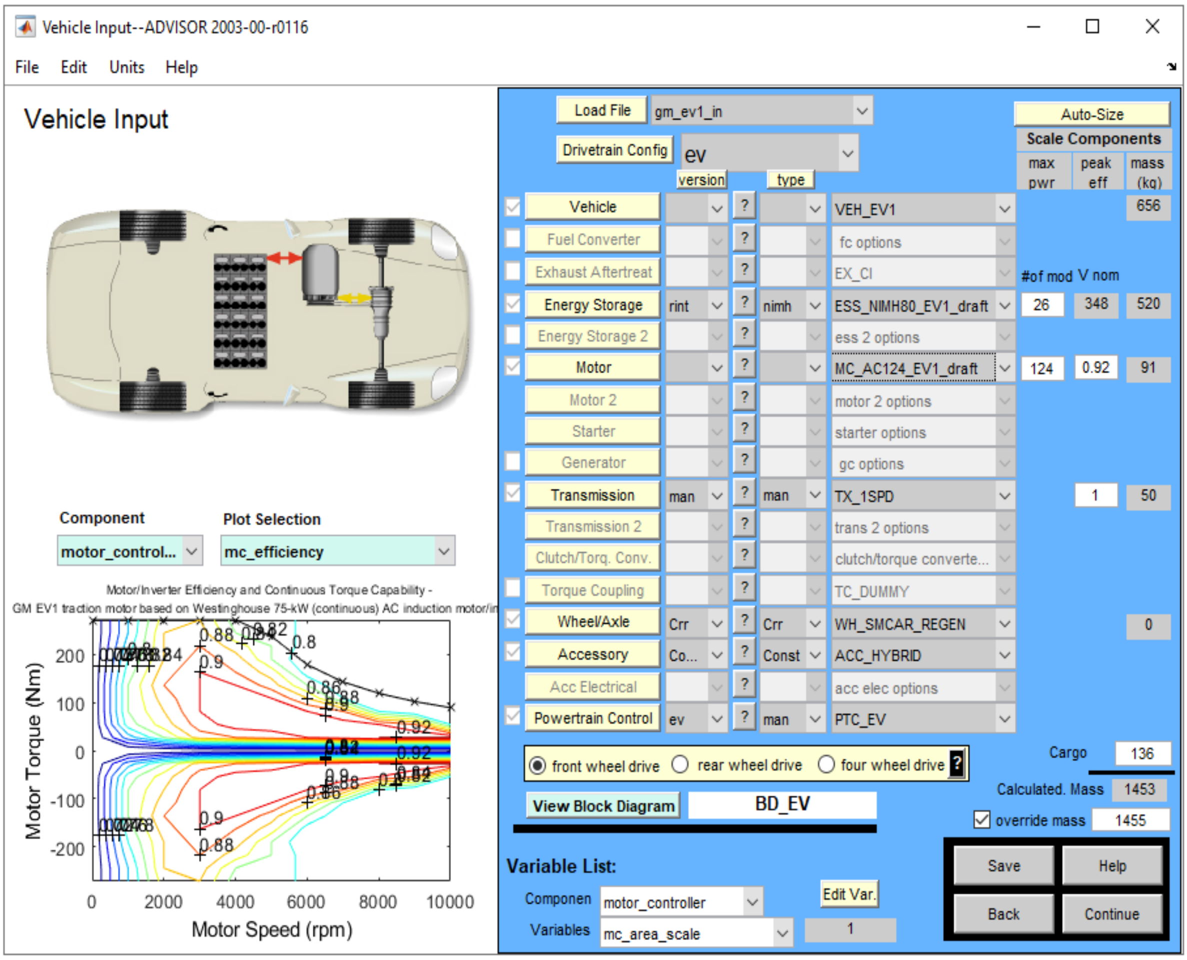


Fig. 2. ADVISOR main interface

It provides the vehicle engineering community with an easy to use, flexible, yet robust and supported analysis package for advanced vehicle modelling [11]. We can see from the *figure 2* that shows the flexibility of this tool when the user can build a vehicle of interest by selecting its configuration (electric, hybrid, or conventional), and drive-line components from pull-down menus. It primarily used to quantify the fuel economy, the performance, and the emissions of vehicles that use alternative technologies including fuel cells, batteries, electric motors, and internal combustion engines in hybrid (i.e. multiple power sources) configurations [11]. ADVISOR supports backward facing and forward facing approaches for vehicle simulation. For the first approach it takes the required/desired speed as an input, it determines what drive-train torque, speed, and power would be to meet that vehicle speed. On the other hand, the forward facing approach includes a model of the driver who senses the required speed, and responds with accelerator and brake position to which the drive responds with torque. This type of simulation is well suited to the design of control systems and implementation [12]. The models in ADVISOR are mostly empirical relying on drive-train components. Input/output relationships measured in the laboratory, and quasi-static using data collected in steady-state (for example the constant torque and speed) tests and correcting them for transient effects such as the rotational inertia of drive-train components [12].

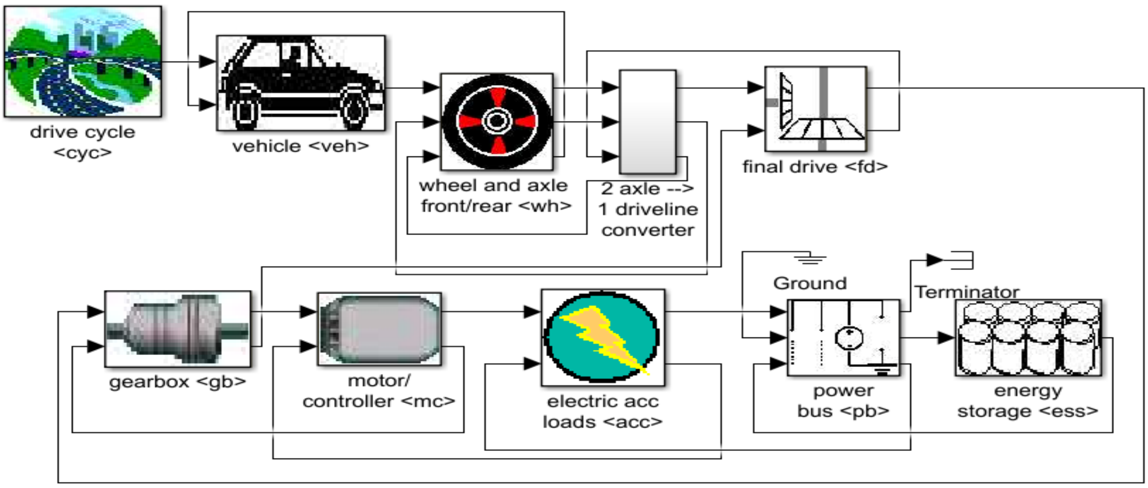


Fig. 3. Simulink block diagram of ADVISOR for 2WD-Electric vehicle model

The Limitation of this tool is developed as an analysis tool not originally intended as a detailed design tool. Its component models are quasi-static, and cannot be used to predict phenomena with a time scale of less than a tenth of a second or so. Physical vibrations, electric field oscillations and other dynamics cannot be represented using ADVISOR. However, linkages with other tools such as Saber, Simplorer, and Sinda/Fluent allow a detailed study of these transients in these tools with the vehicle level impacts linked back into ADVISOR [12]. ADVISOR used by researchers at NREL, industry, government, and academia to understand the effect of various technologies on the performance, fuel economy and emissions of a vehicle. Typical applications include requirements definition, system optimisation, and energy usage assessments [11].

4. RESULTS AND DISCUSSIONS

4.1. PM/controller and IM/Controller Operating points for motoring and generating modes

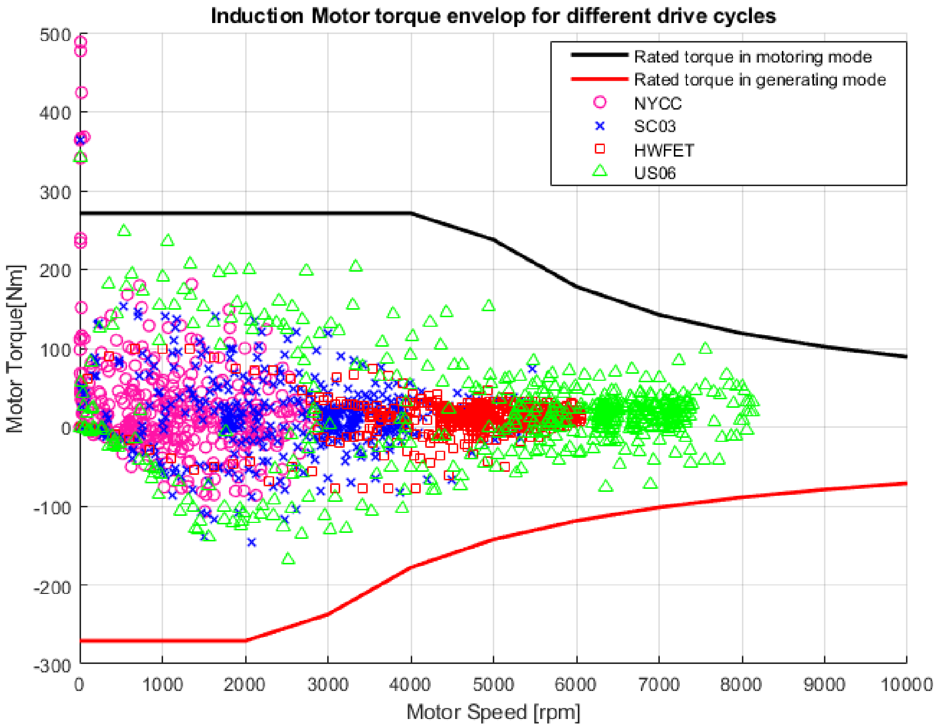


Fig. 4. Torque-speed envelope for IM during many driving scenarios, and scatter plot of motor operating points

Figure 4 and *figure 5* show the envelope of rated torque during motoring and generating modes. They refer to the operating points of PM and IM for different driving cycles. We see from figures that coloured dots in case of IM are entirely within this envelope, and this is a good sign for this motor design (This motor has used by GM EV1 is based on AC75 that has been modified by 'Tony Markel' to better represent the motor in GM EV1). But it is not the case for PM (refer to Appendix for more details) where some operating points are outside of the torque-speed envelope, especially for US06 drive cycle that simulates an aggressive driving behaviour. The high density of points in low torque region or constant power region tells us that this motor is considerably operating in this region during US06 and HWFET drive cycle. The same thing for high dots density in low power region or high torque region during NYCC and SC03. Also, we can notice that the spread of these dots is directly related to the way of driving, or where we intend to drive this car.

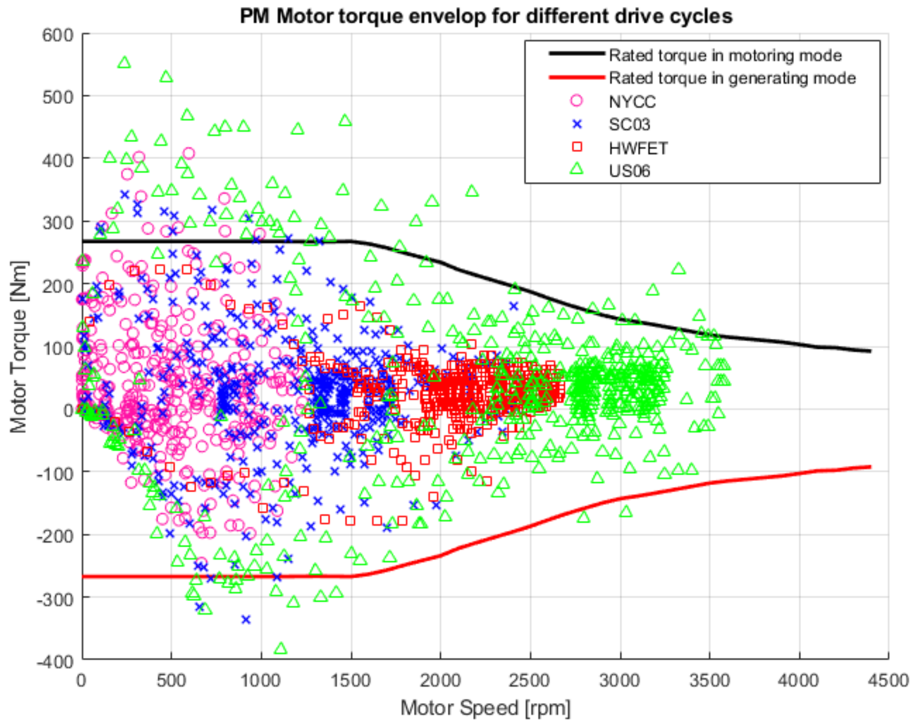


Fig. 5. Torque-speed envelope for PMSM during many driving scenarios, and scatter plot of motor operating points

For high speed and high acceleration driving styles like HWFET and US06, the motor needs to rotate at high RPM (from 4000 to 8000 rpm in case of IM and from 2000 to 3500 rpm in case of PM) to respond to driver demand. It differs from the low-speed driving style like driving a car within a city (NYCC) where the stop-and-go behaviour is needed. We can see also that the regenerative braking system is operating well at the low-speed region from 500 rpm to the base speed for PM, and from 1000 rpm to the base speed as well for IM. We can make a great decision from this kind of information like resize the motor to be larger or smaller to meet the drive cycle that we need. As a result, motor design and selection for electric vehicle application has a strong relationship with the driving styles.

4.2. Vehicle grade-ability and acceleration tests

Vehicle performance usually includes acceleration performance evaluated by the time used to accelerate the vehicle from zero speed to a given speed (starting acceleration), or from a low-speed to a given high speed (passing ability). The grade-ability evaluated by the maximum road grade that the vehicle can overcome at a given speed and the maximum speed that the vehicle can reach [1]. The acceleration performance of the vehicle still almost depend on the speed-torque characteristic of the traction motor [3].

In this section, two performance tests have been done for different motor types (PM, IM) to estimate the vehicle performance as showed in Table 1.

Table 1: Acceleration and grade-ability test results for PM and IM

Acceleration and grade test	PM	IM
Time in (s) for 0-26.82 m/s	8.5	7.6
Time in (s) for 17.88- 26.82 m/s	3.5	3.5
Time in (s) for 0-37 m/s	15.8	14.6
Maximum acceleration (m/s^2)	4.96	4.69
Distance in 5 s (m)	46.42	57.06
Time in (s) for 402.336 m	16.7	16
Vehicle Maximum speed (m/s)	43.54	43.50
Grade ability test (%)	11.5	24.8

The first one is the acceleration and maximum speed test. The objective is to measure the vehicle acceleration from 0-26.82 m/s, 17.88-26.82 m/s and 0-37 m/s, and to determine the maximum acceleration and speed which the vehicle can achieve. Also, it included the maximum distance achieved by the car in five seconds.

The second one is the grade-ability test when we measure the high grade that the vehicle can overcome for both motor types, and investigate the effects of motor selection on vehicle performance. We can note from Table 1 the induction motor shows a good performance especially the covered distance in 5s. Another parameter that makes IM the best choice for the tough road is the grade-ability. The test shows a big difference between PM and IM in this area when the IM reaches 24.8% of grade-ability rather than 11.4 % for PM, and this happened because the long constant power region of IM compared to PM that enhanced the vehicle grade-ability.

4.3. Motor/controller efficiency comparison under different driving behaviour

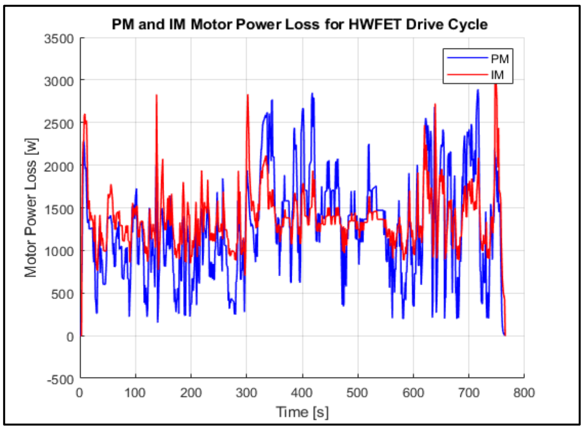
Electric motors utilized in the electric vehicle can be used as a generator for capturing braking energy to be stored in the battery. Their effectiveness varies according to their design and type as well as the way of driving a car. For that reason, many tests for different driving scenarios have conducted to investigate the efficiency of IM and PM motors for both modes (motoring and generating). As we can see from Table 2 that the PM motor showed to be a right candidate for the electric vehicle when it kept the efficiency in the range of 84-88% for motoring mode, and from 82-88% for generation mode. This supposed to extend the vehicle range. The same thing happened to IM except for NYCC (simulate low-speed urban drive with many stops) drive cycle when the motor suffers from low efficiency due to stop/go driving cycle.

Table 2. Motor/controller efficiency during several drive cycles as motor and generator

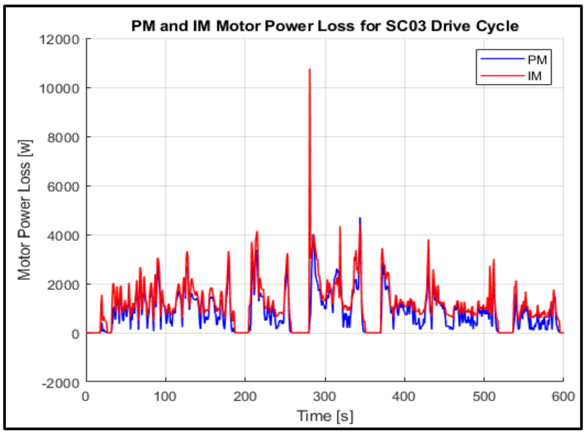
	PM		IM	
	Motor	Generator	Motor	Generator
HWFET	0.86	0.87	0.81	0.86
NYCC	0.84	0.82	0.69	0.75
SC03	0.88	0.86	0.84	0.82
US06	0.88	0.88	0.88	0.86

4.4. Motor power loss during different driving styles

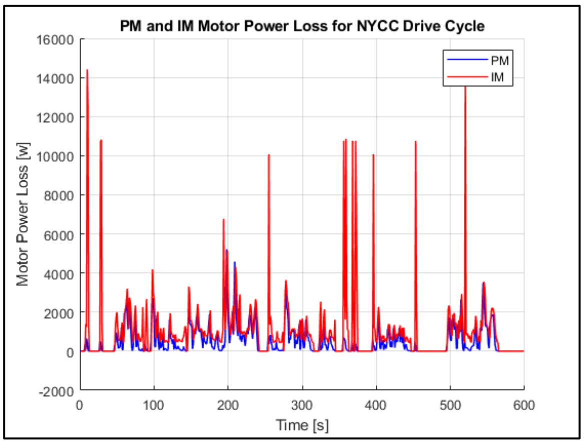
Comparing motors power loss during all the above drive cycles was necessary to understand the electric motor behaviour for each case. As we can see from the *Figure 6* the performance of the electric motors varied according to the driving style. At high-speed (HWFET, US06). The IM consume less energy than PM unlike the low-speed (NYCC, SC03) where the IM motor performs worse. Generally, the average PM power loss is less than the losses produced by the IM even at high-speed.



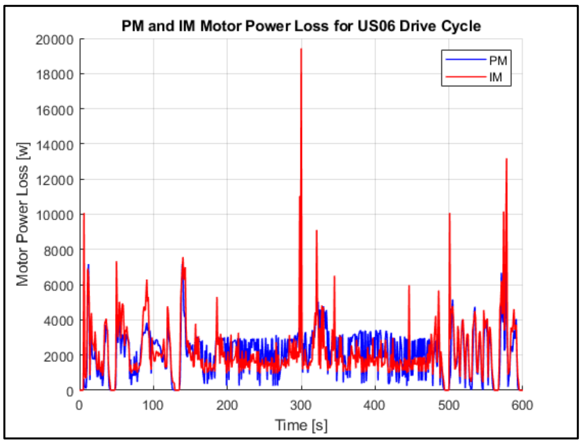
(a) HWFET



(b) SC03



(c) NYCC

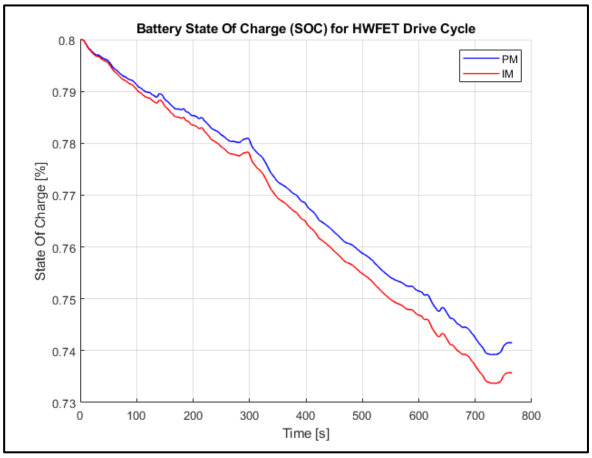


(d) US06

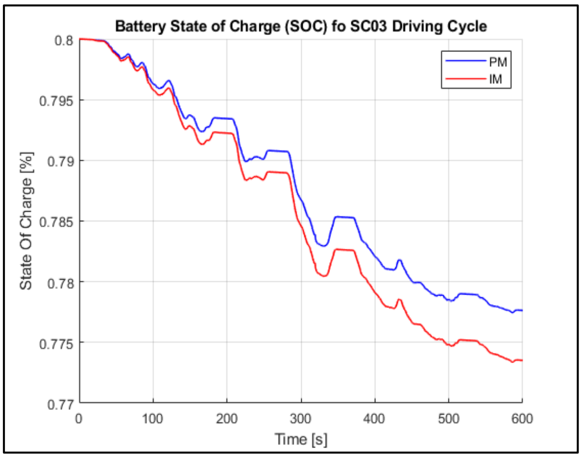
Fig. 6. Power loss for PM and IM motors

4.5. Battery state of charge (SOC) during many driving scenarios

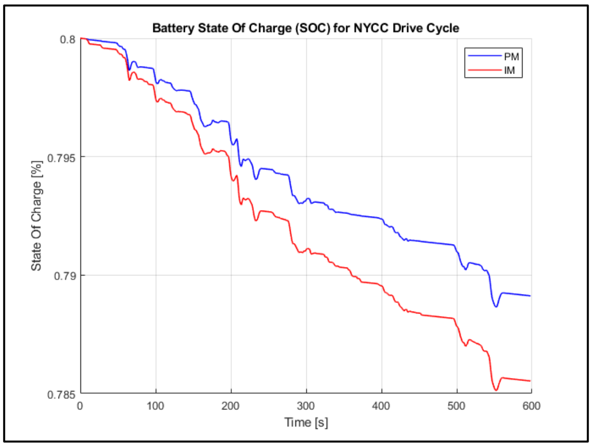
Battery State-of-charge (SOC) represents an important parameter to evaluate the Electric vehicle performance. Since the electric motor is the heart of the electric car, it was worth to make a comparison between PM and IM to see its characteristics effect on battery SOC as a motor, and as a generator when the vehicle is slowing down. In this test, the initial SOC fixed at 80%. From *Figure 7* we can see that both motors drain more power from the battery in the case of driving at high speeds. On the contrary to driving a car at low speeds, or within the city where the vehicle could recover some of its battery energy through the use of regenerative braking system, and this would help to extend the vehicle range, and it doesn't mean improving vehicle efficiency because driving a car at low speed will hurt the overall system efficiency even with the presence of regenerative braking (refer to table 3).



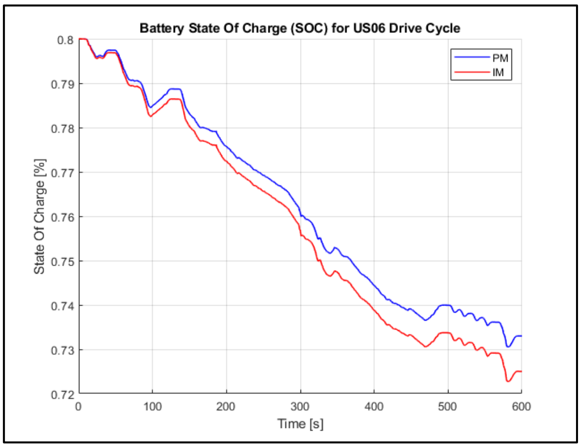
(a) HWFET



(b) SC03



(c) NYCC



(d) US06

Fig. 7. Battery State Of Charge (SOC) during different driving cycles for IM and PM motor.

The comparison results also show that the PM motor performed better at low-speed scenarios when the battery SOC has dropped slowly then the case of IM.

4.6. Vehicle efficiency for different motor type under many driving styles

Table 3 shows the overall system efficiency under different driving styles and for two motors. The results for both motors are almost equal. We denote that the PM could be a choice for high way roads like HWFET and US06 cycles when the vehicle reaches a high performance. On the other hand, driving a car in an urban (SC03), or within a city (NYCC) has a profound effect on vehicle performance, especially with the presence of the Induction Motor (IM) when the vehicle suffers from low efficiency (14%). However, Vehicle efficiency not only depends on the power-train components like the case of IM and PM motors, but it strongly depends on the driver behaviour.

Table 3. Electric Vehicle efficiency for different traction motor types

	Vehicle efficiency [%]	
Driving cycle	PM	IM
HWFET	0.599	0.545
NYCC	0.189	0.142
SC03	0.38	0.344
US06	0.519	0.506

5. WHAT WE CONSIDER WHEN WE SELECT AN ELECTRIC MOTOR FOR EV APPLICATION

Through the performed tests and the published papers, and some expert opinions concerning the topic of selecting the right, or an appropriate electric motor for electric vehicle application. We conclude that the choice is not an easy matter, and it depends on many factors and circumstances stated as follows:

5.1. Motor maximum torque and power

The maximum power enables the vehicle to reach and maintain a constant speed under stringent slope and speed conditions. To calculate the maximum-power you need a simulator that takes into account the drag and friction coefficients of the vehicle in addition to the forces required for the climb [14]. As we can see from the Table 4 the induction motor with higher power limit (124 kW) has achieved a grade-ability of 24.8%, and it could maintain a vehicle speed at 50 miles/hour during this road condition. Compared to PM which only achieved 11.4%. For the maximum torque, it enables the vehicle to start at any given slope, and it is possible to calculate the maximum rated torque of the motor based on the maximum-grade that the car can overcome considering the differential, and gearbox and maximal weight that also have to be taken into consideration [14].

5.2. Efficiency

Electrical efficiency of an electric motor gives us the relation between electrical input and useful mechanical output of the motor. Generally, given by the ratio of shaft power output and motor input power [6]. When the electric motor used in an electric vehicle, the electric motor will operate at different loads. Therefore, the efficiency at different loads has to be considered to make the right selection [6].

5.3. Driving cycle

The way of driving a vehicle has to be taken into account when choosing a traction motor. The motor performance changed according to driving styles. A drive cycle with many stop/start phases like NYCC would cause much more losses. On contrary to highway experience when the driver supposed to maintain a vehicle at a certain speed. Consequently, knowing where we are going to drive a car could help us to select a battery pack size and other vehicle components.

5.4. Torque-speed characteristics

This characteristic could tell us where the motor is operating most at low power region (or high torque) where frequent stop and start is required, or at constant power region (or low torque region) while driving a vehicle at high speed. Based on these characteristics, we can see the spread of motor operating points which will help us to decide if the motor is suited for the suggested drive cycle.

5.5. Specific power

Specific power is defined as the power-to-weight ratio and is calculated by dividing the motor peak power by its mass. Selecting a motor that has a high specific power value could be the right choice to improve the vehicle efficiency because the overall vehicle weight will be reduced.

5.6. Vehicle maximum speed

Before selecting an electric motor, we have to define a vehicle speed requirement. Based on the vehicle targeted speed and other vehicle parts design like wheel radius and gearbox specifications which will be helpful to calculate the maximum speed of traction motor.

5.7. Torque density

The torque density is an important parameter that should be taken into account when we select a traction motor which indicates the amount of torque per unite volume. It represents the torque capability of the electric motor which has a specific weight and space. However, many other factors to consider when choosing a traction motor for EVs application such as the price if it meets the requirements of the project, and the required power density to fit the reserved volume within a car design.

6. CONCLUSION

In this work, a comparison between PM and IM conducted to analyse their performance during different driving scenarios. Electric motors designed for a traction application have some features which supposed to influence the vehicle system performance as a whole in terms of speed, acceleration and grade-ability.

From the conducted tests we found that the PM could be the right candidate for high way roads when the vehicle reaches a high performance. On the other hand, driving a car in city has a profound effect on vehicle performance, especially with the presence of the Induction Motor (IM) when the vehicle suffers from too low efficiency. Generally, the average PM power loss is less than the losses produced by the IM even at high-speed.

The selection of the appropriate motor for EVs depends on many factors including what is related to its design like the specific power, efficiency, and torque density. Factors related to the environment like driving on a highway or driving in cities. However, among the features mentioned above the high torque at starting, and long or extended power region at cruising are the principal features for traction applications to deal with a different situations.

REFERENCES

[1] X.D. Xue, K. W. E. Cheng and N.C. Cheung, *Selection of electric motor drives for electric vehicles.* Proocedings of Australian Universities Power Engineering Conference, NSW, pp. 1-6, 2008.

[2] T. Porselvi, M. K. Srihariharan, J. Ashok, and S. A. Kumar, *Selection of power rating of an electric motor for electric vehicles*, International Journal of Engineering Science and Computing IJESC, vol. 7, issue 4, pp. 6469 -6472, 2017.

[3] M. Ehsani, Y. Gao and S. Gay, *Characterization of electric motor drives for traction applications*, Proocedings of 29th Annual Conference of the IEEE Industrial Electronics Society, IECON'03, vol. 1, pp. 891-896, 2003.

[4] G. Luthra, *Comparison of characteristics of various motor drives currently used in electric vehicle propulsion system*. International Journal of Mechanical and Production Engineering, vol. 5, no.6, 2017.

[5] M. Zeraoulia, M. E. H. Benbouzid, and D. Diallo, *Electric motor drive selection issues for HEV propulsion systems: A comparative study*. IEEE Transactions on Vehicular Technology, vol. 55, no. 6, pp.1756-1764, 2006.

[6] S. R. Jape and A. Thosar, *Comparison of electric motors for electric vehicle application*, International Journal of Research in Engineering and Technology, vol. 6, no.09, p. 12-17, 2017.

[7] B. Tabbache, S. Djebarri, A. Kheloui and M. Benbouzid, *A power presizing methodology for electric vehicle traction motors,* International Review on Modelling and Simulations, vol. 6, no. 1, 2013.

[8] P. Bhatt, H. Mehar and M. Sahajwani, *Electrical Motors for Electric Vehicle a Comparative Study*. Available at SSRN 3364887, 2019.

[9] P. K. Prathibha, E. R. Samuel and A. Unnikrishnan, *Parameter Study of Electric Vehicle (EV), Hybrid EV and Fuel Cell EV Using Advanced Vehicle Simulator (ADVISOR) for Different Driving Cycles.* In Green Buildings and Sustainable Engineering, Springer, Singapore, pp. 491-504, 2020.

[10] C. Gang, W. Long and W. Lei, August. *Redevelopment of ADVISOR for Design and Simulation of Plug-in Hybrid Electric Vehicle*. In 2015 AASRI International Conference on Circuits and Systems, CAS, Atlantis Press, 2015.

[11] J. Larminie and J. Lowry, *Electric vehicle technology explained*. John Wiley & Sons, 2012.

[12] T. Markel, A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O’Keefe, S. Sprik, and K. Wipke, *ADVISOR: a systems analysis tool for advanced vehicle modeling*, Journal of power sources, vol. 110, no. 2, pp.255-266, 2002.

[13] *ADVISOR, NREL’s ADvanced VehIcle SimulatOR,* http://adv-vehicle-sim.sourceforge.net/.

[14] C. Pronovost, *10 things to consider when choosing an electric motor*, https://www.danatm4.com/blog/10-things-consider-choosing-electric-motor/, 2016, viewed May 17, 2020.

Appendix

Battery: voltage = 348V, power = 26kW, mass =520kg.

Motors characteristics used in this paper: PM-UQM100 (manufacturer: UQM) and AC75 (manufacturer: Westinghouse 75 kW (cont))

Table 4. PM and IM characteristics

Characteristics	PM	IM
Weight [Kg]	101.9	91
Maximum power [kW]	100	124

Maximum Rated torque [Nm]	300.1	271.14
Peak torque [Nm]	550.6	488.52
Specific power [kW/Kg]	0.98	1.36
Minimum Voltage [V]	180	120
Maximum speed [rpm]	4400	10000
Peak Efficiency [%]	94	92
Maximum current [A]	400	480