Drive Selection and Performance Evaluation of Electric and Hybrid Electric Vehicles

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***Abstract*—Today's automobile world is turning towards Electric and Hybrid Electric Vehicles (EV and HEV) due to their numerous advantages over a conventional vehicle such as reduced emissions, higher efficiency etc. Different motors are used to provide the total propulsion power for an EV and combined with engine for HEV. For these motors, various control strategies can be implemented to improve the motor performance and hence the enhanced performance of EV/HEV. In this paper, EV and HEV models are analyzed for their performances by considering the cases of Permanent magnet Synchronous Motor (PMSM) and Induction Motor (IM) drivetrains. First, the EV and HEV models are developed in MATLAB/SIMULINK environment along with PMSM and Induction motor drives in different cases. The motor controllers and supervisory controllers are appropriately tuned to achieve the required speed-torque demands and vehicle performance. The results of simulation of EV and HEV under the two case examples of motor types are compared to analyze the relative performance in terms of efficiency, response and fulfilling load demands of the respective motor drives under various operating conditions. This will enable choosing the appropriate drive for the Electric and Hybrid Electric Vehicle application. Based on the comparative results appropriate motors are suggested for different requirements and under various operating conditions for EV and HEV.**

***Keywords*—EV, HEV, PMSM, Induction motor, vector control**

I. INTRODUCTION

Presently, air pollution concerns, oil dependence on politically unstable regions and high oil prices are some of the biggest problems. The United Nations estimated that over 600 million people in urban area worldwide were exposed to traffic-generated air pollution with immense quantities of cars which targeted the Internal combustion (IC) engines for global warming issues [10]. These have caused a flurry of activity in the areas of efficient EV and HEV contributing to the development of an environment friendly transportation sector.

The EV architecture consists of electric motor powered EV energized through a battery. The use of battery accounts certain problems such as huge battery mass and more time charging time requirement. Also total available propulsion power is restricted due to limited battery range. These limitations of EV have laid the use of hybrid vehicles. Hybrid electric vehicles (HEV) use electric motor in association of engine. [11].

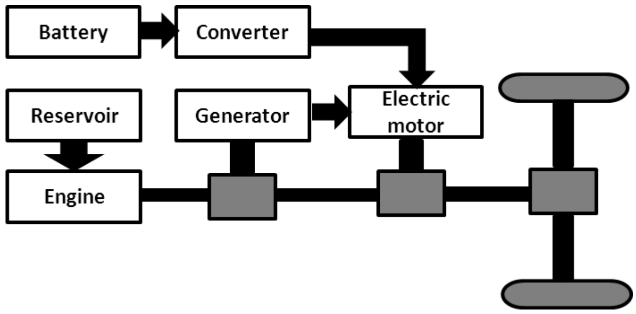

Fig. 1. HEV architecture

Fig. 1 shows the series-parallel architecture of HEV which is similar to the Toyota Prius Hybrid system. In series-parallel architecture, the HEV operation is divided in different modes which offer shutting the engine off when not required [8]. The improvements come from regenerative braking and shutting down the engine when not required can improve the fuel economy and reduce tailpipe emissions with a smaller and more efficient engine.

Various papers have been published in the literature on drive selection as well as modeling of EV/HEV. Drive selection is associated with a comparison (for different parameters) of commonly used motors in case of EV/HEV and selecting the appropriate motor based on their performance characteristics [1], [2]. The control strategies are implemented to improve the motor performance. The control strategy preferably used for AC motors is based on vector control which is studied in detail and verified using MATLAB/SIMULINK [3]. Along with a vector controlled motor drive the HEV is modeled in SIMULINK based on Toyota Prius Hybrid system and its performance is evaluated [5]. Similarly Electric go-kart is modeled with induction motor for the performance evaluation [6]. Comparison of PMSM and Induction motor for HEV applications is done to conclude the design considerations [4].

In this paper, both EV and HEV models are analyzed for their performances by using Permanent magnet synchronous motor (PMSM) and Induction motor drivetrains in MATLAB/SIMULINK environment. The drive selection criterion for EV/HEV is studied in section II. Vector control is most widely used control strategy for PMSM and induction motors which is studied in section III. Section IV is associated with model descriptions. The supervisory controller is integrated to have a controlled vehicle operation under different operating conditions. The results of simulation of EV and HEV under different case examples of motor types are compared to analyze the relative performance (in terms of efficiency, response and fulfilling load demands) and the behavior of the controllers under various operating conditions in section V. Finally based on the results, this paper concludes the best suitable drive in case of EV and HEV considering the different operating conditions in section VI.

II. SELECTION CRITERION FOR DRIVES USED IN EV/HEV

In parallel and series– parallel hybrid vehicles, the electric motor is one of the torque sources that contributes to the peak torque (power) to meet the vehicle performance requirement. Thus, the development of compact, lightweight, high efficiency and proper torque-speed profile becomes crucial [2].

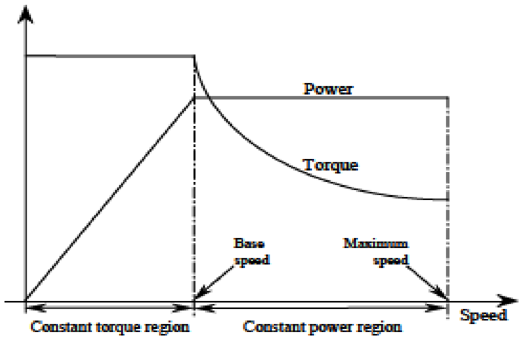

Fig. 2. Required drive characteristics for EV/HEV

A well-controlled electric motor drive has the torque-speed profile close to the ideal one as shown in Fig. 2 [2]. It includes two distinguishable regions namely constant torque and constant power. The corner speed is usually called base speed. The lower base speed results in a larger max torque at a given power and maximum speed rating. It clearly shows that a motor drive with a long constant power range is preferred [1]. The constant power profile can maximize the vehicle acceleration performance at given power rating or minimize the power rating at given vehicle acceleration performance [2].

With reference to above drive characteristics commonly used motors for EV/ HEV applications are DC motor, Induction motor, Permanent magnet synchronous motor (PMSM), Brushless DC motor (BLDC) and Switched reluctance motor (SRM). These drives can be compared for their performances in EV and HEV [1], [2].

With the primary comparison, PMSM and induction motor drives are preferably used for vehicle applications due to their suitable characteristics and developed control strategies [1]. The PMSM motors and induction motors are also compared for their designs. There is common perception that the permanent magnet motor is the correct solution for the application and offers considerable advantages in terms of performance and efficiency. But proper design considerations can offer the use of induction motors for vehicle applications [4]. This paper offers a direct comparison of EV and HEV performances for alternate PMSM and induction motor drives along with the evaluation of individual motor drive performances in order to choose the suitable drive based on vehicle performance.

III. VECTOR CONTROL STRATEGY

In the traditional control methods of voltage-fed and current fed inverter drives, the voltage or current and frequency are the basic control variables of the induction motor. Both the torque and air gap flux are functions of voltage and frequency. This coupling effect is responsible for the sluggish response of the AC motor [9]. This limitation can be overcome by applying vector control method, in which an AC machine is controlled like a separately excited dc machine. In this method the machine operation is considered in a synchronously rotating reference frame, where the sinusoidal variables appear as dc quantities. This strategy is applicable to both PMSM and induction motors.

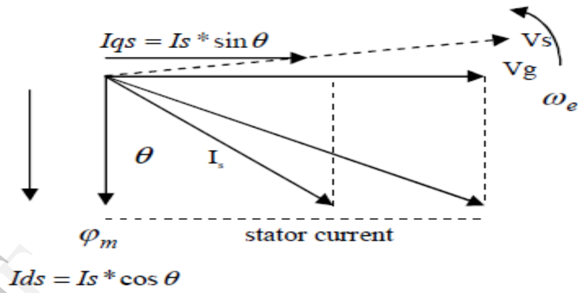

Fig. 3. Phasor diagram showing d-q axis representation

AC motors with inverter and control is associated with two inputs, I_{ds} and I_{qs}. All the motor parameters are transformed to d-q reference frame with Park transformation. So the currents I_{ds} and I_{qs} are the direct-axis and quadrature-axis components respectively, of the stator current. In vector control, I_{ds} is analogous to the field current I_f and I_{qs} is analogous to the armature current I_a of a dc machine [3].

The phasor diagram is shown in Fig.3 with the air gap voltage V_g aligned with the q_e axis. The stator current I_s lags the voltage V_g by $(90 - \theta)^0$ where θ is the rotor position.

Hence, $I_{qs} = I_s * \sin\theta$ (1)

$$I_{ds} = I_s * \cos\theta \quad (2)$$

These currents are applied to the machine model through inverter and actual motor currents are taken as feedback to have a close loop controlled operation. The torque equation can be expressed as,

$$T = K_t * I_{qs} * I_{ds} \quad (3)$$

Hence the torque calculation is identical to that of dc machine. The variables I_{qs} and I_{ds} are mutually decoupled and can be independently varied without affecting the orthogonal component [3].

IV. MODEL DESCREPTION OF EV AND HEV

The EV and HEV models are integrated in MATLAB/SIMULINK environment. The ratings of various components and their respective parameters are mentioned in Appendix A.1 and A.2 for EV and HEV, respectively.

A. EV Model

Simulation model for Electric vehicle is based on [6] and is comprised of three subsystems namely Energy management subsystem, Electrical subsystem and vehicle dynamics. The Energy management subsystem calculates the torque reference for motor based on the driver acceleration demand. This subsystem is associated with battery management system which indicates whether battery state of charge (SOC) is within the limit (40% and 90%) in this case. Electrical subsystem consists of a motor along with its controller. The motor control strategy used is based on vector control. The controller is tuned to achieve the required performance. The vehicle dynamic subsystem is associated with longitudinal vehicle dynamics, the differential and tire dynamics. The performance of EV is evaluated with Induction motor and PMSM whose models are used from standard SIMULINK library.

B. HEV Model

The HEV simulation model based on [5] having series-parallel architecture as shown in Fig. 1 is supplied with constant DC source. The new model is modified with a battery source which enables the performance evaluation of HEV in regenerative braking mode of operation. The model incorporates different subsystems namely Energy management subsystem (EMS), Electrical subsystem, IC engine, Planetary gear subsystem and Vehicle dynamics. The EMS is associated with a supervisory controller which is responsible for hybrid mode on/off and reference signal generations for the electric motor drive, the electric generator drive and the IC engine in order to have efficient distribution of the power from different sources. Hybrid mode on/off is controlled to operate the engine efficiently depending on mode of operation. The vehicle is supplied via battery to power up the motor when hybrid mode is off.

In normal operating conditions engine power is divided by the power split device which turns the generator on to drive the motor and rest of the power drives the wheels directly. Extra power needed for additional acceleration is supplied from the battery, while the engine and high-output motor provide smooth response, for improved acceleration characteristics. The motor acts as a generator, driven by the vehicle's wheels in braking application in which system recovers kinetic energy as electrical energy further stored in the battery. The engine drives the generator to recharge the battery when necessary. Supervisory controller controls the power allocation to maximize efficiency.

The Battery management system maintains the State-Of-Charge (SOC) between prescribed limits. Electrical subsystem consists of a motor along with its controller. The motor control strategy used is based on vector control. The controller is tuned to achieve the required performance. The vehicle dynamic subsystem is associated with longitudinal vehicle dynamics, the differential and tire dynamics. Engine and planetary gears are also modeled. The HEV model is altered by using PMSM and induction motor to observe their relative performance.

V. SIMULATION RESULTS AND ANALYSIS

The simulation results with PMSM and Induction motor drive for EV and HEV are plotted and the comparison is done to evaluate their respective performances in vehicles. For simulating different operating conditions in both the cases accelerator pedal is started and maintained at 70% (starting) for 4s, 85% (acceleration) for 5s and finally set to -70% (braking) till the end of simulation time. The pedal position is maintained at 25% for EV and 10% for HEV in cruising mode of operation in between stating and acceleration mode.

A. EV Model

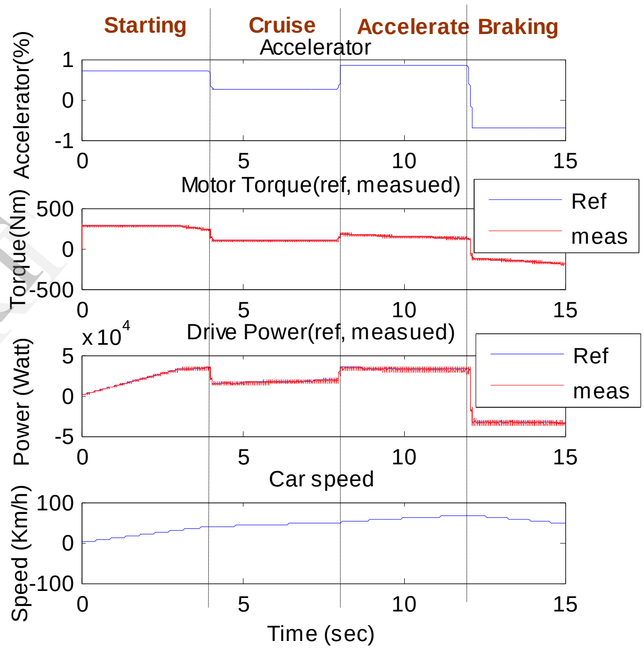

Fig. 4. Torqur, Power and speed achieved by EV for given accelerator demand with Induction motor drive

Fig. 4 and Fig.5 shows the results for torque, power and speed with given accelerator under different operating conditions of loads using induction motor and PMSM drive respectively. The simulation shows EV operation over a complete cycle that includes accelerating, cruising and regenerative braking, brought about by movement of the accelerator pedal. Initial SOC is considered to be 90%. The comparative results are as shown in Table I. Both the motors can satisfy the torque demand but induction motor takes higher active and reactive power as compared to PMSM.

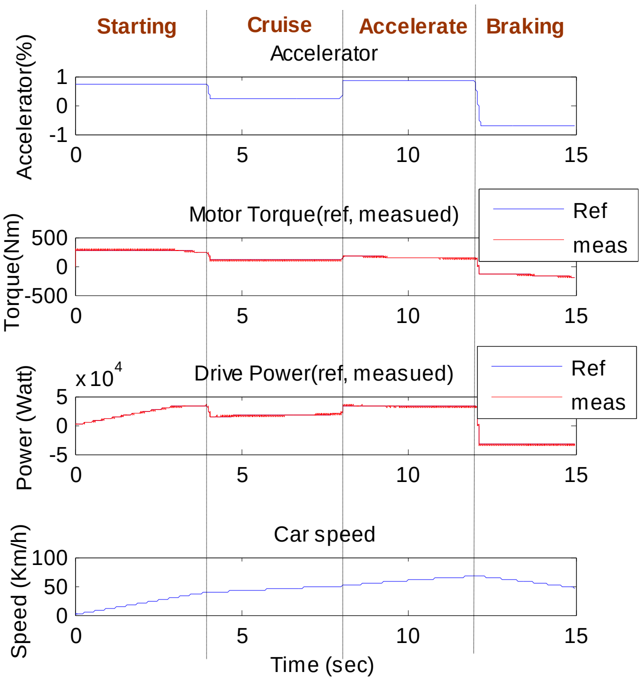

Fig. 5. Torqur, Power and speed achieved by EV for given accelerator demand with PMSM drive

Hence the power factor and efficiency is less in case of induction motor. The car speed achieved is less in case of induction motor driven EV. The induction motor response time is also more. The power demand is more with induction motor drive in all the operating modes and regeneration power produced in braking mode is less as compared to PMSM.

TABLE I. RESULT COMPARISON

Sl. No.	EV Results		
	Variables	***PMSM***	***Induction motor***
1	Max Car speed achieved (Kmph)	66.86	66.65
2	Max Torque achieved by vehicle (Nm)	280	280
3	Max power achieved by vehicle (Kw)	34	36
4	Max Motor current (A)	265	275
5	Motor starting current (A)	270	325
6	Fall in SOC (%)	0.4	0.41
7	Power factor	0.8	0.7
8	Response time for torque (sec)	0.001608	0.0168

B. *HEV Model*

The HEV model simulation results with PMSM and Induction motor drives are plotted and their comparison is done. Fig. 6 and Fig. 7 shows the results for PMSM driven HEV model while Fig. 8 and Fig.9 shows the results with induction motor drive. Similar to EV the simulation shows different operating modes of the HEV over one complete cycle including accelerating, cruising, recharging the battery while accelerating and regenerative braking. Fig. 6 shows the operation of HEV in battery recharging mode while acceleration. After 10s the battery SOC falls below 40%. Part of generator power is used to charge the battery. Hence the drive power is not following the reference in case of PMSM as shown Fig. 6.

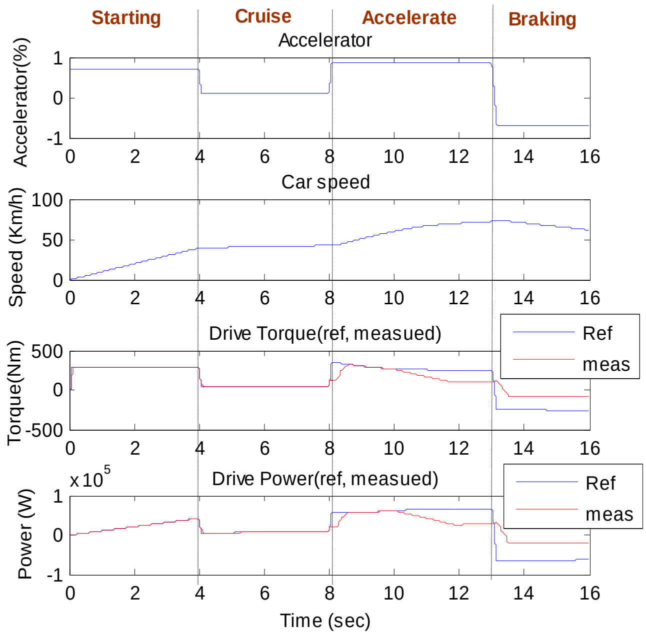

Fig. 6. Car speed profile and Vehicle Torque and power depending on the accelerator percentage with PMSM drive

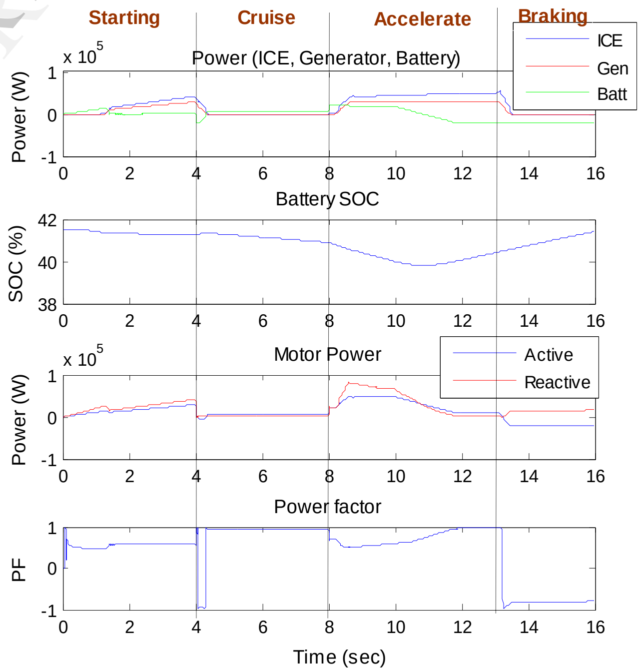

Fig. 7. Engine, genereator, battery power variation along with motor active, reactive power and power factor with PMSM drive.

However in case of induction motor SOC level is maintained above 50% in acceleration mode hence HEV follows the reference drive power as shown in Fig. 8. The comparative results of performance values are shown in Table. II. The maximum speed achieved by HEV with PMSM is 1.5% more as compared to that with induction motor drive. The maximum torque and power delivered by PMSM is 20% and 7% more respectively as compared to that of Induction motor.

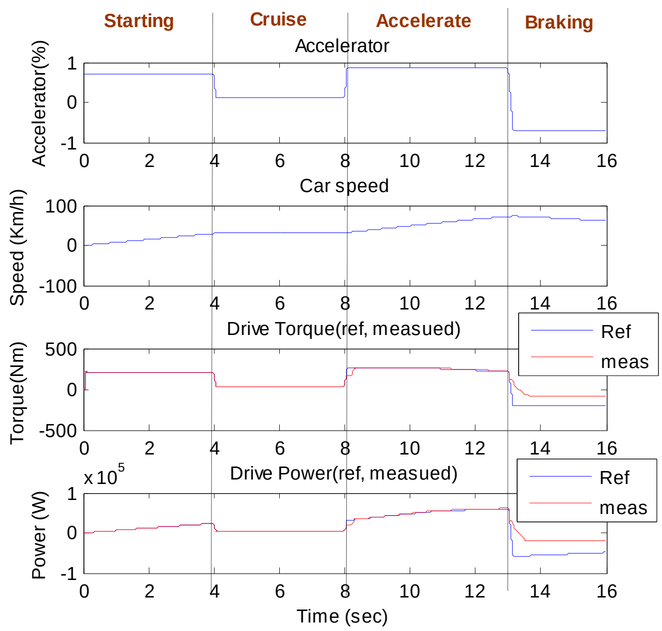

Fig. 8. Car speed profile and Vehicle Torque and power depending on the accelerator percentage with Induction motor drive

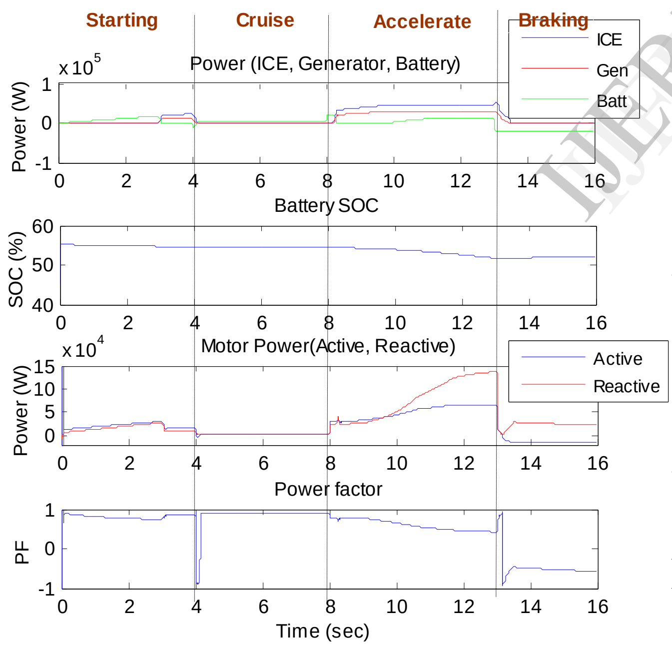

Fig. 9. Motor, genereator, battery, engine power variation along with throttle position and hybrid mode on/off requirement with Induction motor drive.

Induction motor consumes more active as well as the reactive power in all operating modes as compared to PMSM. Hence, the power factor in case of Induction motor drive is 16% lower. Also the speed and torque response time is 23% more in case of Induction motor driven HEV. The efficiency of both the motors is also estimated. The efficiency of PMSM is 20% higher as compared to Induction motor. The performance of PMSM motor shows better results as compared to induction motor but its cost is very high.

TABLE II. RESULT COMPARISON

Sl. No	HEV Results		
	Parameters	***PMSM***	***Induction motor***
1	Max Car speed achieved (Kmph)	73	72
2	Max Torque achieved by vehicle (Nm)	320	260
3	Max power achieved by vehicle (Kw)	58	60
4	Max Motor power delivered (Kw)	47	44
5	Max Generator power delivered (Kw)	30	30
6	Max Battery power delivered (Kw)	21	21
7	Max Motor torque (Nm)	280	210
8	Motor current (A)	230	290
9	Power factor	0.96	0.8
10	Response time for speed & torque (sec)	0.1215	0.15

To validate, these simulation results are compared with the results obtained by LMS imagine.lab AMESim EV and HEV models. The results are compared in different modes of operation.

VI. CONCLUSION

In this paper the performance of PMSM and induction motors along with EV and HEV models is analyzed. It is observed that PMSM motor in general offers various advantages over induction motor such as higher achievable maximum car speed, less active and reactive power consumption resulting in high power factor and efficiency. The response time taken by PMSM is also less. In case of EV the use of PMSM drive offers less power demand and fast acceleration. Certain demerits are associated with induction motor. In case of HEV using an induction motor the maximum car speed achieved is less. The lower motor efficiency will affect the engine loading. Also response time is more in case of induction motor hence it takes more time for power development resulting in poor acceleration and hence the pick-up performances. However, the SOC level in an HEV using induction motor does not fall substantially during acceleration mode as compared to PMSM. To achieve better performances in both EV and HEV PMSM motors can be preferred. But the cost of PMSM is higher as compared to induction motor. To have cost effective EVs and HEVs at moderate performance induction motors can be preferred.

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APPENDIX A.1

Sl. No.	Component specifications for EV		
	Component	***Parameter***	***Values (units)***
1	Vehicle	Mass	1325 kg
		Frontal area	2.57 m^2
		Drag coefficient	0.26
2	Permanent magnet Synchronous Motor	Maximum dc voltage	500 V
		Maximum power	50 kW
		Maximum torque	400 Nm
3	Induction Motor	Maximum ac voltage	460 V
		Maximum power	50 kW
		Maximum torque	300 Nm
4	Battery	Capacity	6.5 Ah
		Initial voltage	201.6 V
		Initial state-of charge	33.33 %
		Maximum power output	21 kW

APPENDIX A.2

Sl. No	Component specifications for HEV		
	Component	***Parameter***	***Values (units)***
1	Vehicle	Mass	1325 kg
		Frontal area	2.57 m^2
		Drag coefficient	0.26
2	Permanent magnet Synchronous Motor	Maximum dc voltage	500 V
		Maximum power	50 kW
		Maximum torque	400 Nm
3	Induction Motor	Maximum ac voltage	460 V
		Maximum power	50 kW
		Maximum torque	300 Nm
4	Battery	Capacity	6.5 Ah
		Initial voltage	201.6 V
		Initial state-of charge	33.33 %
		Maximum power	21 kW
5	Engine	Maximum power	57 kW
		Speed at maximum power	523.33 rad/s
		Maximum speed	628 rad/s