Performance Optimization of an eCAR by Parametric Analysis

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Abstract—In this paper a method for performance optimization of an electric Car (eCAR) is proposed based on acceleration rate, maximum speed, and tractive force. Since the total tractive force is exerted by propulsion motor alone, the driving performance of an eCAR depends on the power of the propulsion motor and its control. The proposed pre-sizing methodology depicts the optimum power of the propulsion motor, and for the optimized motor the impact of road dynamics, acceleration rate, change in mass, and gear ratio on the eCAR's drive range are analyzed. The proposed electric propulsion system is modeled and the performance characteristics are analyzed using MATLAB to validate the behavior of an eCAR propulsion.

Keywords—drive cycle; eCAR; propulsion system; road dynamics; mass; gear ratio and range

I. INTRODUCTION

In urban areas, there is a prodigious concern on intensifying air pollution caused by fossil fuels. Hence, the use of zero emission vehicles emerged as a need. Electric Vehicles (EVs) have been developed into battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs), making a considerable impact in the automotive market. Nowadays, EVs accomplish the performance indices of traditional sport utility vehicles (SUVs). The EV eCAR is gaining more attention in the current automotive market being a zero emission vehicle offering higher energy efficiency, hushed operation and, frequent start-stop driving capability. The Government of India and its State Governments have initiated the “Smart City”, Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles (FAME-I & FAME-II) schemes with thrust on providing “e-Mobility” for citizens. Authors in [1] discussed several aspects essential in creating an affluent EV market in India. Authors in [2] specified some considerations to determine the local and global environment impact of the autonomy electric transport in contrast with gasoline vehicles. Authors in [3] exemplified the real-world emissions and real driving behavior in real, cold, Nordic climates. Authors in [4] enlightened the transition of the automotive industry to electric mobility. Authors in [5] presented some advancements in technology, compact, economic and high energy efficient batteries are still in developing stage and are expensive. Batteries with integrated on-board and/or off-board charging facility, offering quick charge of less than 10 minutes and

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normal charging of 30-60 minutes through the utility grid have been introduced. An integrated on-board charger is more compact, with higher efficiency.

Authors in [13] evaluated a variety of DC-DC converter topologies for application in BEVs. Authors in [14] introduced an advanced on-board vehicular battery charger used for BEV application, which attains high power density by assimilating a bidirectional AC/DC converter and a DC/DC converter. Authors in [15] described a procedure for estimating battery capacity, power, and cost. Authors in [16] investigated the development in design and optimization of propulsion motors for General Motor BEVs. Authors in [17] elaborated the developments in design and optimization of propulsion motors for General Motor BEVs. Authors in [18] developed a method to choose electric traction motors for BEVs. Authors in [19] developed driving cycles based on empiric data from a large-scale field operational test for BEVs. Authors in [20] performed an analysis on real time Indian road drive cycles (IRDC) in terms of acceleration and deceleration rate, top speed, and average speed with road length.

In this paper, a method for performance optimization of an eCAR is proposed based on acceleration rate, maximum speed, and tractive force of the vehicle. Motor performance characteristics are analyzed in MATLAB.

II. PROPOSED METHODOLOGY

Consider the position of the eCAR shown in Figure 2 with the applied forces on the vehicle, where M represents its mass in kg, V represents the linear velocity in m/sec, g represents the gravitational acceleration in m/s², h represents the height of the vehicle from center to ground level, and α represents the gradient in degrees. Thus, acceleration is computed for the given speed and power rating by using (1):

\[ \text{acceleration} = a = \frac{F_{ac}}{M} = \frac{dV}{dt} \] (1)

The acceleration force \( F_{ac} \), is the force required to accelerate the eCAR during linear speed variations and is governed by Newton’s second law as given in (2):

\[ F_{ac} = M \times a = M \frac{dV}{dt} \] (2)

![Fig. 2. eCAR and applied forces](image)

The tractive effort needed to drive the eCAR in the forward direction neglecting vehicle dynamics is given by (3):

\[ F_t = F_{ac} = M \times a \] (3)

The friction of the eCAR wheels at the road surface is the only force existing at first. The coefficient of rolling friction \( C_r \) between the tire and the road varies with the type and the size of the tire. The expression for rolling resistance is:

\[ F_r = C_r \times M \times g \text{ for } V=0, -C_r \times M \times g \text{ for } V \neq 0 \] (4)

The aerodynamic drag is a function of speed and can be determined by the density of air \( D \) in kg/m³, air drag coefficient \( C_d \), vehicle frontal area \( A_f \) and velocity \( V \). Thus, the aerodynamic drag force is:

\[ F_{ad} = \frac{1}{2} D C_d A_f V^2 \] (5)

The gradient force depends on \( M, \alpha, \) and \( g \). The expression for this force is:

\[ F_g = M \times g \times \sin \alpha \] (6)

\( F_r, F_{ad}, \) and \( F_g \) are summed up as road load \( F_{rl} \):

\[ F_{rl} = F_r + F_{ad} + F_g \] (7)

Commonly, the tractive force \( F_t \) to propel the eCAR has to surmount the sum of the rolling resistance force \( F_r \), aerodynamic drag force \( F_{ad} \), and hill climbing of gradient force \( F_g \). And consequently, the total tractive effort is the summation of acceleration force and road load and is given by (8):

\[ F_t = F_{ac} + F_{rl} \] (8)

The velocity of the vehicle is calculated by integrating acceleration and is given by (9):

\[ V = \frac{1}{M} \int (F_t - F_{rl}) \, dt \] (9)

The time required to reach maximum speed and power rating of the motor are determined using (10), (11) and (12):

\[ t_r = M \int \frac{dV}{F_{ac}} = M \int \frac{dV}{P_{motor}/V} \] (10)

\[ P_{motor} = M/t_r \int dv = M/2t_r V^2 \] (11)

or

\[ P_{motor} = F_t \times V \] (12)

\[ E_{motor} = P_{motor} \times t \] (13)

At first, the tractive effort required to propel the eCAR is found from (8). The product of tractive effort by the eCAR velocity gives the amount of power required and is found from (12). Assuming conversion efficiency factors, the energy required to propel is given in (13). To determine the optimum power size of the propulsion motor, a step by step procedure is presented in this paper and is as follows:

- Input speed and compute acceleration using (1).
- Compute the value of acceleration force \( F_{ac} \) for the given M using (2).
- Compute the amount of road load \( F_{rl} \) using (7) by considering dynamics.
- Estimate total tractive force \( F_t \) required by the propulsion using (8).
- Compute the value of maximum speed of an eCAR by (9).
- Measure and compare the actual speed of an eCAR with maximum speed. If the measured speed is equal to
maximum speed then determine the value of motor power rating using (11) and end the process, else repeat the first step.

The output of the algorithm resolves the optimum power of the propulsion motor based on the maximum speed that an eCAR can manage.

III. RANGE DETERMINATION

To forecast the range of an eCAR, the energy essential to propel it at every instant of the drive cycle is to be calculated, and the effect of this energy trench to be observed. The eCAR range for varying mass M, gear ratio G, and air drag coefficient C_d for Federal Urban Driving Schedule (FUDS), Simplified FUDS (SFUDS), European Urban Driving Schedule (EUDC) - (ECE-47), and New European Drive Cycle (NEDC) are given in Table I. Note that the range is maximum when M is 1200kg, gear ratio is 10.8 and C_d is 0.3, which are considered the optimum values. This procedure is further continued with 90% depth of discharge of the battery. The effects of change in M, G, and C_d for SFUDS cycle are depicted in Figures 3-5 respectively.

TABLE I. DRIVE CYCLES ACCOMPLISHED IN A SINGLE CHARGE

| Drive cycle | Number of cycles |
|-------------|------------------|
| Varying mass | Varying G | Varying C_d |
| G=10.8, C_d=0.3 | M=1200, C_d=0.3 | M=1200, G=10.8 |
| 1540 1320 1200 | 30 10.8 6.8 | 0.8 0.3 0.01 |
| FUDS | 241 254 260 | 270 260 245 | 260 260 261 |
| SFUDS | 112 139 156 | 208 156 101 | 153 156 159 |
| ECE-47 | 100 120 134 | 166 134 95 | 132 134 135 |
| NEDC | 110 137 154 | 206 134 99 | 151 154 157 |

As acceleration increases the time required to reach the desired speed decreases. Higher acceleration demands more tractive force which increases the required power of the motor. For given mass and fixed acceleration of 3.36m/s^2 the power required to propel the eCAR to a maximum speed of 120km/h from zero speed is determined using (16). At zero road load condition the thick line curve shown in Figure 7, depicts that a 90kW motor takes about 14s to propel the eCAR and a 30kW motor takes about 35s. Considering road load the dotted curve illustrates that a 30kW motor takes 60s and a 90kW motor requires 14s (Figure 8).
To reach 120km/hr speed with a tractive force of 1127Nm the power of the motor needed is computed from (17) and is 88.9kW which is approximately 90kW. Based on the derived conclusions, it is decided that the optimum power of the motor to drive an eCAR is 90kW. The specifications of considered optimum propulsion motor of an eCAR are given in Table IV.

| Specification | Value |
|---------------|-------|
| Motor Power rating, $P_{motor}$ | 90kW |
| Nominal voltage, $V_n$ | 380V, RMS |
| Current rating, $I_n$ | 200A |
| Variable frequency, $f_s$ | 0-400Hz |
| Constant power | 90kW @ 12000rpm |
| Constant torque | 120Nm @ 7200rpm |
| Motor inertia, $J_{motor}$ | 1.5kgm$^2$ |
| Pole pairs, $p$ | 2 |
| Nominal stator flux, $\psi_s$ | 0.98Wb |

The MATLAB Simulink model of the electric propulsion system of an eCAR is shown in Figure 9. The subsystem of the Simulink model representing the applied vehicle dynamics is shown in Figure 10 where constants $A=72.84$, $B=0.0384$, and $C=0.32$ represent the rolling friction coefficient, the gradient, and the aerodynamic drag coefficient respectively. The torque-speed curves for the optimized three phase induction motor as eCAR propulsion motor are shown in Figure 11. The torque versus time characteristics for the 90kW motor with varying gear ratio $G$ are shown in Figure 12. The power versus time characteristics for the 90kW motor with varying gear ratio $G$ are shown in Figure 13. The velocity curves for different gear ratios for the 90kW induction motor as a propulsion motor of an eCAR are shown in Figure 14.
operating in field weakening mode, this can be achieved with the help of field oriented control or direct torque control techniques [21-23].

A method for performance optimization of an eCAR based on vehicle parameters is examined considering the impact of road dynamics, acceleration rate, change in mass and gear ratio of an eCAR. The output of the proposed algorithm resolves the optimum power size of the propulsion motor based on the maximum speed and is derived as 90kW. From the acceleration characteristics, a 90kW motor may suffice the required tractive force to propel the eCAR, attaining a speed of 120km/h in 14s with an acceleration of 2.38m/s², which meets the customer’s needs. The eCAR propulsion motor counting road dynamics is modeled with the help of mathematical relations. The performance characteristics of the 90kW induction motor for different gear ratios were obtained. It is seen that for higher gear ratios the maximum speed attained by the vehicle decreases, therefore a gear ratio of 10.8 is considered as optimum for the eCAR. The proposed optimization technique is simple, efficient and can be applied on any configuration of the eCAR.

IV. CONCLUSIONS

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