PROPULSION SYSTEM DESIGN OF ELECTRIC VEHICLES

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Abstract:

There is a growing interest in electric vehicles due to environmental concerns. Recent efforts are directed toward developing an improved propulsion system for electric vehicle applications. This paper is aimed at developing the system design philosophies of electric vehicle propulsion systems. The vehicle's dynamics are studied in an attempt to find an optimal torque-speed profile for the electric propulsion system. This study reveals that the vehicle's operational constraints such as: initial acceleration and grade can be met with minimum power rating if the powertrain can be operated mostly in constant power region. Several examples are presented to demonstrate the importance of the constant power operation. Operation of several candidate motors in the constant power region are also examined. Their behaviors are compared, and conclusions are made.

I. Introduction

The ICE automobile at the present is a major source of urban pollution. According to figures released by the US Environmental Protection Agency (EPA), conventional ICE vehicles currently contribute 40-50% of ozone, 80-90% of carbon monoxide, and 50-60% of air toxins found in urban areas [1]. Besides air pollution, the other main objection regarding ICE automobiles is its extremely low efficiency use of fossil fuel. Hence, the problem associated with ICE automobiles are three fold, environmental, economical, as well as political. These concerns have forced governments all over the world to consider alternative vehicle concepts. The California Air Resource Board (CARB) is among the few who acted first through the declaration of the Clear Air Act of September, 1990. This act requires that 52% of all vehicles sold in that state be either Low Emission Vehicles (LEV's)- 48%, Ultra Low Emission Vehicles (ULEV's)- 2%, or Zero Emission Vehicles (ZEV's)- 2%, by the year of 1998 [2]. Similar measures are considered in other states and nations, as well.

The concept of Electric Vehicle (EV) was conceived in the middle of previous century. After the introduction of internal combustion engine (ICE), EVs remained in existence side by side with ICE for several years. The energy density of gasoline is far more than what the electrochemical battery could offer. Despite this fact, the EV continued to exist, especially in the urban areas due to its self starting capability. However, soon after the introduction of electric starter for ICE early this century, despite being energy efficient and nonpolluting, EV lost the battle completely to ICE due to its limited range and inferior performance. Since then ICE has evolved, improved in design, and received wide spread acceptance and respect. Although this essentially being the case, EV interest never perished completely, and whenever there has been any crisis regarding the operation of ICE automobiles, we have seen a renewed interest for EV. The early air quality concerns in the 60's and the energy crisis in the 70's have brought EVs back to the street again. However, the most recent environmental awareness and energy concerns have imposed, for the first time since its introduction, a serious threat to the use of ICE automobiles.

Electric Vehicles offer the most promising solutions to reduce vehicular emission. Electric vehicles constitute the only commonly known group of automobiles that qualify as Zero Emission Vehicle (ZEV). These vehicles use an electric motor for propulsion, and batteries as electrical energy storage devices

This paper presents the EV propulsion system design philosophies. The paper is organized as follows. Section II describes the design constraints and the variables for EV system. Design philosophies of EV propulsion systems are presented in sections III. Section IV examines several most commonly used motors for EV system design. Section V compares our designed EV with the General Motors IMPACT. Summary and conclusions are presented in Section VI.

II. Specifications of EV Propulsion System Design

A. System Design Constraints

Vehicle operation consists of three main segments. These are, i) the initial acceleration, ii) cruising at vehicle rated speed, and iii) cruising at the maximum speed. These three operations provide the basic design constraints for the EV drivetrain. A drivetrain capable of meeting these constraints will function adequately in the other operational regimes. Refinements to these basic design constraints are necessary for an actual commercial product, but those are beyond the scope of this paper. The objective here is to meet these constraints with minimum power. The variables defining the above design constraints are:

(i) Vehicle rated velocity, v_{rv}.

(ii) Specified time to attain this velocity, t_f.

(iii) Vehicle maximum velocity, v_{max}.

(iv) Vehicle mass, and other physical dimensions.

B. System Design Variables:

The main component of EV is its electrical powertrain. The electric propulsion design variables are:

i) Electric motor power rating.

ii) Motor rated speed.

iii) Motor maximum speed.

iv) The extend of constant power speed range, beyond the rated speed.

v) Gear ratio between motor shaft and the wheel shaft (transmission).

As mentioned earlier, the main design objective is to find the minimum drive weight, volume and cost that will meet the design constraints with minimum power.

C. Road Load Characteristics

The road load (F_w) consists of rolling resistance (f_{ro}), aerodynamic drag (f_l), and climbing resistance (f_{st}) [3].

$$F_W = f_{ro} + f_l + f_{st} \qquad (1)$$

The rolling resistance (f_{ro}) is caused by the tire deformation on the road:

$$f_{ro} = f \cdot m \cdot g \qquad (2)$$

where f is the tire rolling resistance coefficient. It increases with vehicle velocity, and also during vehicle turning maneuvers. Vehicle mass is represented by m, and g is the gravitational acceleration constant.

Aerodynamic drag, f_l, is the viscous resistance of air acting upon the vehicle.

$$f_l = 0.5\xi C_W A (v + v_0)^2 \qquad (3)$$

where ξ is the air density, C_W is the aerodynamic drag coefficient, A is the vehicle frontal area, v is the vehicle speed, and v_0 is the head wind velocity.

The climbing resistance (f_{st} with positive operational sign) and the down grade force (f_{st} with negative operational sign) is given by

$$f_{st} = m \cdot g \cdot \sin\alpha \qquad (4)$$

where α is the grade angle.

The following assumptions will be made in the analysis prsented in the following sections, unless otherwise specified.

(i) velocity independent rolling resistance

(ii) zero head wind velocity

(iii) level ground

These assumptions do not change the general trend of the solution and can be easily relaxed.

The motive force F available from the propulsion system is partially consumed in overcoming the road load, F_W. The net force, $F-F_W$, accelerates the vehicle (or decelerates when F_W exceeds F). The acceleration is given by

$$a = \frac{F - F_W}{k_m \cdot m} \qquad (5)$$

where k_m is the rotational inertia coefficient to compensate for the apparent increase in the vehicle's mass due to the on-board rotating mass.

III. EV System Design

The main component of EV drivetrain is its electric motor. The electric motor in its normal mode of operation can provide constant rated torque up to its base or rated speed. At this speed, the motor reaches its rated power limit. The operation beyond the base speed up to the maximum speed is limited to this constant power region. The range of the constant power operation depends primarily on the particular motor type and its control strategy. However, some electric motors digress from the constant power operation, beyond certain speed, and enter the natural mode before reaching the maximum speed. The maximum available torque in the natural mode of operation decreases inversely with the square of the speed. This range of operation is neglected in the analysis presented in this section, unless otherwise specified. It is assumed that the electric motor operates in the constant power region beyond the base speed and up to the maximum speed. Nevertheless, for some extremely high speed motors the natural mode of operation is an appreciable part of its total torque-speed profile. Inclusion of this natural mode for such motors may result in a reduction of the total power requirement. Of course, power electronic controls allow the motor to operate at any point in the torque speed plane, below the envelop defined by the mentioned limits. However, it is the profile of this envelop that is important in the motor drive selection and design.

In order to free up the motor speed from the vehicle speed, for design optimization, gearing between the motor shaft and the drive shaft is required. In our design, we will make the following assumptions.

(i) single gear ratio transmission operation: power electronic control allows instantaneous matching of the available motor torque with the required vehicle torque, at any speed. Therefore, multiple gearing in order to match the motor torque-speed to the vehicle torque-speed is no longer a necessity.

(ii) ideal loss free gear: without loss of generality, the gear losses can be incorporated at the end of analysis.

The gear ratio and size will depend on the maximum motor speed, maximum vehicle speed, and the wheel radius. Higher maximum motor speed, relative to vehicle speed, means a higher gear ratio and a larger gear size. The selection criterion for the maximum motor speed will be further discussed later. The torque speed diagram of a typical motor is drawn in Fig. 1, but in terms of tractive force and vehicular speed for different gear ratios. Notice now the electric motor base speed and maximum speed, in terms of the vehicle speed, depend on the gear ratio. A design methodology based on the three regions of operation will now be presented.

A. Initial Acceleration:

The force-velocity profile of a typical motor is redrawn once again in Fig. 2. In this figure, v_{rm} is the electric motor rated speed, v_{rv} is the vehicle rated speed and v_{max} is the vehicle maximum speed. The motor maximum speed must correspond to this v_{max}, after the gear ratio transformation.

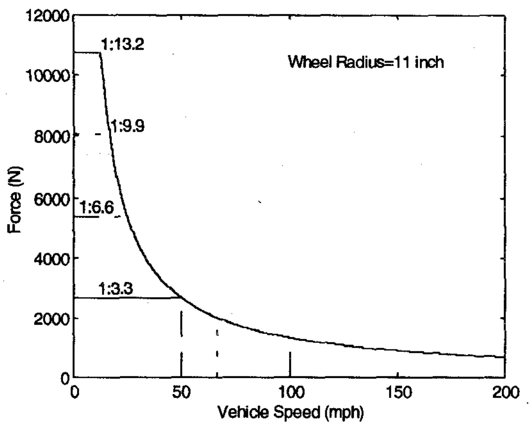

Fig. 1. Torque-speed diagram of an electrical motor in terms of tractive force and vehicular speed with gear size as the parameter.

The range of operation for initial acceleration is 0-v_{rv}. For now, we will focus our attention only on this interval. For maximum acceleration the motor operates in constant rated force (torque), $F_{vrated}=P_m/v_{rm}$ up to the motor rated speed v_{rm}, and in constant power ($F_v=P_m/v$) at speeds beyond the base speed, up to the vehicle rated speed v_{rv}. Here, P_m is the motor rated power. We assume $v_{rv}>v_{rm}$. The wisdom of this assumption will become clear, shortly. The differential equation describing the performance of the system is given by eq. (5) and is repeated here for convenience.

$$a=\frac{dv}{dt}=\frac{F-F_W}{k_m \cdot m}$$

F is the motive force available from the propulsion system and F_W is the running resistance (road load). The boundary conditions are

at t=0, vehicle velocity v=0.

at $t=t_f$, vehicle velocity $v=v_{rv}$.

To gain insight, we will solve eq. (5) under the most simplifying assumptions:

i) The vehicle is on a level ground.

ii) The rolling resistance is zero.

iii) Aerodynamic drag is zero.

we will relax these assumptions later for a more realistic solution. The above assumptions will result in a closed form solution for the motor rated power P_m. The insight gained from the closed form solution is also valid for the more practical design involving running resistances.

With these simplifying assumptions the governing differential equation reduces to:

$$a=\frac{dv}{dt}=\frac{F}{m} \text{ (assuming } k_m\text{=1)}$$

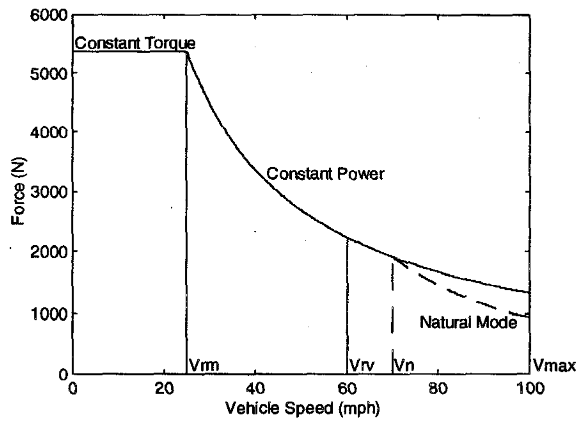

Fig. 2. Typical torque-speed profile of electric motor in terms of tractive force and vehicular speed.

This differential equation is solved with the previous boundary conditions and the force-speed profile of Fig. 2. The differential equation is integrated within the acceleration interval of 0-v_{rv} in 0-t_f seconds, in order to get a closed form solution for the rated power P_m.

$$m\int_0^{v_{rv}}\frac{dv}{F}=\int_0^{t_f}dt \qquad (6)$$

The left hand side integral is broken into two parts, the 0-v_{rm} constant force operation and the v_{rm}-v_{rv} constant power operation

$$m\int_0^{v_{rm}}\frac{dv}{P_m/v_{rm}}+m\int_{v_{rm}}^{v_{rv}}\frac{dv}{P_m/v}=t_f \qquad (7)$$

Now solving for P_m, we get

$$P_m=\frac{m}{2t_f}(v_{rm}^2+v_{rv}^2) \qquad (8)$$

For minimum motor power, differentiating P_m with respect to v_{rm} and setting it to zero gives

$$v_{rm}=0 \qquad (9)$$

This establishes a theoretical limit for minimum motor power. For v_{rm}=0, the electric motor operates entirely in the constant power region. Therefore, if the motor is performing 0-v_{rv} in t_f seconds in constant power alone, the power requirement is minimum. On the other hand, if the motor operates in the constant torque (force) region during the entire 0-t_f period, we will have $v_{rm}=v_{rv}$. In this case, eq. (8) shows that the power requirement is twice that of constant power operation. The solid line curve of Fig. 3 shows an example of the motor power requirements between these two extremes. Of course, operation, entirely in constant power regime, is not practically realizable. However, this theoretical discussion demonstrates that longer constant power range of operation will lower the motor power.

Having discussed the simplified resistanceless case, we now solve the more realistic case, involving the running resistance. The vehicle differential equation (5) can

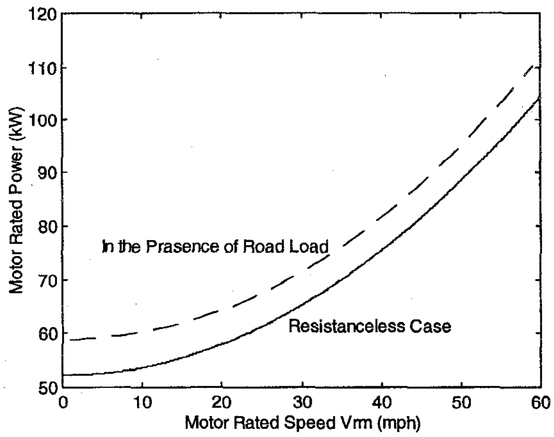

Fig. 3. Acceleration power requirement as a function of motor rated speed. Solid line curve- resistanceless case, dashed curve- in the presence of road load.

be solved under the same boundary conditions as before with the presence of the running resistance F_W. In this case, a closed form solution is feasible. However, the result is a transcendental equation involving rated motor power P_m, rated motor velocity v_{rm}, rated vehicle velocity v_{rv}, acceleration time t_f, and all the other system constants, e.g.; vehicle mass m, rolling resistance coefficient f, aerodynamic drag coefficient C_W, etc. The resulting equation can be solved numerically for P_m for a specific motor rated velocity v_{rm}, using any standard root seeking method such as the secant method [4].

Let's assume that it is desired to obtain P_m for the following case

- 0-26.82 m/s (0-60 mph) in 10 seconds.
- vehicle mass of 1450 kg.
- rolling resistance coefficient of 0.013.
- aerodynamic drag coefficient of 0.29.
- wheel radius of 0.2794 m (11 inch).
- level ground.
- zero head wind velocity.

a plot of the resulting motor rated power vs. motor rated speed, in terms of vehicle speed, is shown in Fig. 3 (the dashed curve).

Examination of Fig. 3 (the dashed curve) results in the following conclusions:

i) Rated power versus v_{rm} curve shows the same general trend of the resistanceless case.

ii) Rated motor power requirement is minimum for continuous constant power operation (v_{rm}=0).

iii) Rated motor power is roughly twice that of continuous constant power operation for constant force (torque) operation ($v_{rv}=v_{rm}$).

iv) Rated motor power remains close to its minimum up to about 20 mph of rated motor speed and then grows rapidly.

B. Cruising at Rated Vehicle Velocity:

A powertrain capable of accelerating the vehicle to the rated velocity v_{rv} will always have sufficient cruising power at this speed. Hence, the constraint of cruising at rated vehicle speed is automatically met for the case of EV. Of course, cruising range is another issue, related to the battery design, which is outside the scope of this paper. However, minimizing power of the drive will help the battery size.

C. Cruising at Maximum Vehicle Velocity:

The power requirement to cruise at maximum vehicle speed can be obtained as

$$P_{v\max} = (f_{ro} + f_{st}) \cdot v_{\max} + f_1(v) \cdot v_{\max} \qquad (10)$$

Since aerodynamic drag dominates at high speeds, this power requirement increases with the cube of maximum vehicle velocity. If this vehicle power requirement is greater than the motor power calculated previously ($P_{vmax}>P_m$), then P_{vmax} will define the motor power rating. However, in general P_m will dominate P_{vmax}, since modern vehicles are required to exhibit a high acceleration performance. As mentioned before, some extremely high speed motors usually have three distinct modes of operation. The initial constant torque operation, followed by a range of constant power operation, then to the maximum speed in natural mode (see Fig. 2). For such a motor it may be advantageous to use the entire constant power range for initial acceleration of the vehicle. The operation beyond that would be in the natural mode. This would allow a longer constant power operation in the initial acceleration. Consequently, the motor power requirement will be lower. This scheme will work provided the motor has adequate torque in natural mode to meet the constraints at the maximum vehicle speed. Otherwise some part of the constant power operation has to be used for the vehicle operation beyond the rated vehicle speed.

Natural mode of motor operation is not the preferred mode beyond the rated vehicle speed, unfortunately no control algorithm exists, presently, to operate some high speed motors entirely in constant power beyond their base speed. However, the natural mode, if included, can lower the overall power requirement. The speed at which the electric motor can enter the natural mode and still meet the power requirement at maximum vehicle speed is obtained from

$$V_N = V_{max}\sqrt{\frac{P_{v\,max}}{P_m}} \quad (11)$$

Note that the initial acceleration power is also a function of v_N (extended constant power range). Hence, v_N and P_m have to be solved iteratively. Also, the gear ratio between the drive shaft and the motor shaft is to be determined by matching v_N with the motor speed at which it enters the natural mode. More discussion about the natural mode of operation appears in section IV. The rest of the analysis is done assuming constant power operation beyond the base speed up to the maximum speed.

The importance of extending the constant power speed range can be better understood by comparing the required motor power for different constant power speed ranges (as a multiple of its base speed). Table I shows an example of power requirement for several constant power ranges for the following case:

i) Maximum motor speed is 10,000 rpm.

ii) Maximum vehicle speed is 44.7 m/s (100 mph).

iii) Other system variables and constants are the same as the previous example.

Here, the required gear ratio, to match the maximum motor speed to the maximum vehicle speed, for a wheel radius of 0.2794 m (11 inches), is 1:6.55. The results of Table I suggest an extended range of 4 to 6 times the base motor speed in order to significantly lower the motor power requirement.

Finally, we examine the effect of maximum motor speed and the extended constant power range on the overall system performance. The power requirement is not a function of the motor maximum speed. Motor maximum speed only affects the gear size. However, maximum speed has a pronounced effect on the rated torque of the motor. An example of this is illustrated in the surface plot of Fig. 4. Low speed motors with extended constant power speed range have a much higher rated shaft torque. Consequently, they need more iron to support this higher flux and torque. Furthermore, higher torque is associated with higher motor and power electronics currents. This will also impact the power converter silicon size and conduction losses. Extended speed range, however, is necessary for initial acceleration as well as for cruising intervals of operation. Therefore, the rated motor shaft torque can only be reduced through picking a high speed motor. This would however affect the gear ratio. A good design is the result of a trade off between maximum motor speed and the gear size. However, this tends to be more in favor of selecting a medium or high speed motors. For an extremely high speed motor, a sophisticated gear arrangement might be necessary for speed reduction. Planetary gear arrangement [5] could be the choice, that is compact but allows high speed reduction. Extended constant power range, on the other hand, will increase drive shaft torque and stress on the gear. Hence, another design tradeoff is involved between the gear stress and the extended constant power range. It can be seen from the results of table I that after a certain point there is not any appreciable power reduction with extended constant power range. Any further extension of constant power range beyond this point will only adversely affect the gearing and drive shaft appreciably without reducing the power requirement. This will set the upper limit of the extended range of the constant power operation.

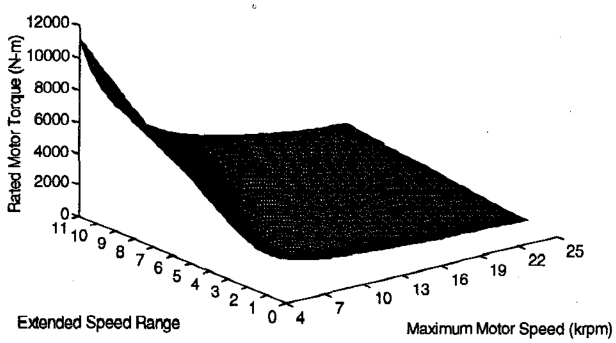

Fig. 4. Rated motor shaft torque as a function of maximmum motor speed.

Overall, the EV drive system design philosophy can be summarized as:

i) Power requirement for acceleration decreases as the range of constant power operation increases. More specifically, as the ratio of the vehicle rated speed to motor rated speed increases.

ii) The gear ratio between the electric motor and the drive shaft is determined by the motor and vehicle maximum speeds.

iii) Power requirement for cruising at the maximum vehicle speed is obtained directly from the road resistance at maximum speed. In general, this power requirement will be lower than the initial acceleration power requirement.

iv) High speed motors would be more favorable for EV application, in general.

Table I: EV Power requirement as a function of constant power range.

	Extended Constant HP Speed Range					
	1:1	1:2	1:3	1:4	1:5	1:6
Motor Rated Power (KW)	110	95	74	67	64	62

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