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Effect on Vehicle Performance of Extending the Constant Power Region of Electric Drive Motors

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ABSTRACT

The effect on vehicle performance of extending the constant power operating mode of electric drive motors for electric and hybrid vehicles is presented in this paper. Modern electric and hybrid vehicle designers have the selection of several technologies to choose from when selecting an electric drive motor. Each motor technology exhibits a particular torque vs. speed characteristic. Many of these technologies, most notably the switched reluctance machine, have capitalized on iron and copper utilization, extending their useful speed range. However, the extended speed capabilities of these motor drives have vehicle performance consequences.

It is presented that vehicle performance is affected by changing the torque-speed characteristics of the drive motor. The extended constant power speed range motor can have smaller rated power than otherwise but suffer high speed passing performance. Traditional extended constant power range motors (about two times the rated speed) have to have a higher rated power but exhibit superior performance capability.

INTRODUCTION

The electric motor is of primary importance to the electric and hybrid vehicle designer. In an electric or a series hybrid vehicle the electric drive is the only propulsion mechanism and much attention needs to be paid to cost, weight, and performance. Depending on the architecture, electric motor drives in parallel hybrid designs can be utilized as peak power devices, load sharing devices, or only as a small transient torque source. Some parallel hybrid concepts even allow the drivetrain to revert to an electric-only mode, relegating all propulsion to the electric drive. In parallel applications like these, the motor technology is equally critical as in the cases of EV or series HEVs.

An electric motor can operate in two modes, the normal mode and the extended mode (Figure 1). In the normal mode, or the constant torque region, the motor exerts constant torque (rated torque) over the entire speed range until the rated speed is reached. Once past the rated speed of the motor, the torque will decrease proportionally with speed, resulting in a constant power (rated power) output. The constant power region eventually degrades at high speeds, in which the torque decreases proportionally with the square of the speed. This is known as the 'Natural Mode' and is usually neglected for most motor technologies. Please note that Figure 1 denotes a 1:3 type motor, where the constant power region extends beyond the constant torque region by a factor of 3.

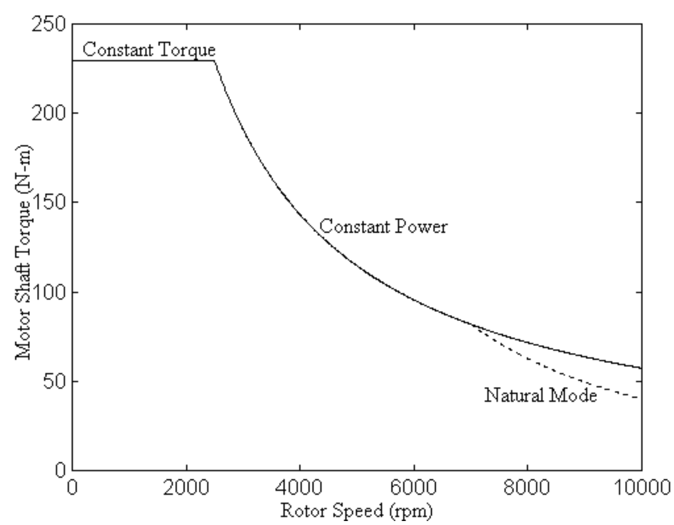

Figure 1. Typical Motor Characteristics

Three major motor technologies were chosen for illustrative purposes: the induction motor, the brushless DC (BLDC) motor, and the switched-reluctance (SRM) motor. Specifications for each motor technology were chosen from commercially available samples, and do not represent maximum possible performance for each technology.

Table 1. Electric Motor Technologies

	Rated Speed	Maximum Speed	Power Ratio
Induction	1750	8750	1:5
BLDC	4000	9000	1:2.25
SRM	4000	20000	1:3

It must be noted that the SRM is capable of operating in the natural mode up to 20,000 rpm.

Induction machine drives are the present leading technology for EV and HEV power trains [1,2]. Both the GM EV-1 and Nissan FEV employ the induction motor. Permanent magnet (PM) motors are particularly known for their high efficiency and high power density. PM motors can be broadly classified into sinusoidally fed PM synchronous motor (PMSM) and rectangular fed brushless dc (BLDC) motor. The high efficiency of operation of these motors has attracted EV applications. Specially designed varients of these motors are used in the BMW E1/E2 and U2001, whereas the Ford/GE ETX-II use PMSM motor [3-5]. The major shortcoming of PM motors is the cost due to the high energy magnets. Safety is another issue because the PM field may cause severe consequences during a short circuit fault [6]. BLDC motors suffers from poor field weakening capability due to the surface mounting of the permanent magnet field that may necessitate a multi-gear transmission with the operation of this motor [6]. The interior magnet PMSM motor has reluctance torque in addition to reaction torque and this may help in getting a long constant power operation [7]. However, interior mounting of the permanent magnets further increases the cost and may reduce the maximum speed.

The switched reluctance motor is gaining lot of attention for its simplicity and safe operation. This motor is commercially used in the Chloride Lucas EV. Test results showed superior operation and higher power density when compared to an induction motor [8]. Because of its simple construction and low rotor inertia, the SRM has very rapid acceleration and extremely high speed operation. Because of its wide speed range operation, the SRM is particularly suitable for gearless operation in EV/HEV propulsion.

VEHICLE DYNAMICS

A simple vehicle dymanics model to evaluate vehicle performance is presented. A simplified vehicle model load (F_w) consists of rolling resistance (f_{ro}), aerodynamic drag (f_l), and climbing resistance (f_{st}) [9].

$$F_w = f_{ro} + f_l + f_{st} \tag{1}$$

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

$$f_{ro} = f_r \cdot m \cdot g \tag{2}$$

where f_r is the tire rolling resistance coefficient. It is nonlinear and increases with vehicle velocity, and also during vehicle turning maneuvers. These nonlinearities are not taken into account in this model. 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)

$$f_l = \frac{1}{2} \cdot \rho_e \cdot C_D \cdot A_f \cdot (v + v_0)^2 \tag{3}$$

where ρ_e is the air density, C_D is the aerodynamic drag coefficient, A_f 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

$$f_{st} = m \cdot g \cdot \sin\alpha \tag{4}$$

where α is the grade angle.

A typical simplified road load characteristic as a function of vehicle speed is shown in Figure 2.

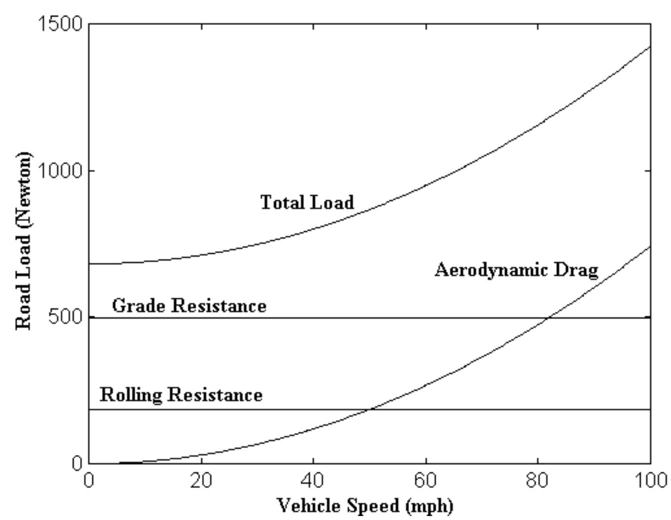

Figure 2. Figure 2. Typical Vehicle Load Function

This graph represents the load function of the vehicle with the characteristics of Table 2. Notice that this graph does not take into account a headwind, a variable grade, or the nonlinearities of tire deformation and rolling resistance. A gear ratio between the motor and the driveshaft is specified for a later example.

Table 2. Example Vehicle

Parameter	Value
Mass	1450 kg
Rolling Resistance Coefficient	0.013
Aerodynamic Coefficient	0.29
Gear Ratio	0.71
Wheel Radius	0.279 m

MOTOR SIZING

An electric vehicle with the basic characteristics given in Table 2 will be used to evaluate the desirability of extending the constant power range of electric machines. First, the required power must be computed. Starting with the definition of acceleration where F is defined as the amount of available propulsion force,

$$a = \frac{dv}{dt} = \frac{F}{m} \qquad (5)$$

and integrating over a time interval t_f to a terminal velocity of v_f,

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

the rated power P_m can be found. The left hand side of the equation can be broken into separate constant torque (motor speeds up to v_{rm}) and constant power (motor speeds from v_{rm} to v_{rv}) integrals:

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

Now solving for the required motor power P_m, we get:

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

where the motor operates in constant torque mode until speed v_{rm} is reached, and then operates in constant power until terminal velocity v_{rv} is reached at time t_f. For our example vehicle to reach 60 mph (26.8 m/s) in 10 seconds (v_{rv} = 26.8 $^m/_s$ and t_f = 10 sec), the required rated motor power P_m is dependant on the ratio of v_{rm} and v_{rv} (Figure 3 and Table 3):

Table 3. Power Requirement as a Function of the Constant Power Range Ratio.

	Extended Constant Power Range							
	1:1	**1:2**	**1:3**	**1:4**	**1:5**	**1:6**	**1:7**	**1:8**
Motor Power (kW)	110	94	74	67	64	62	61	60.6

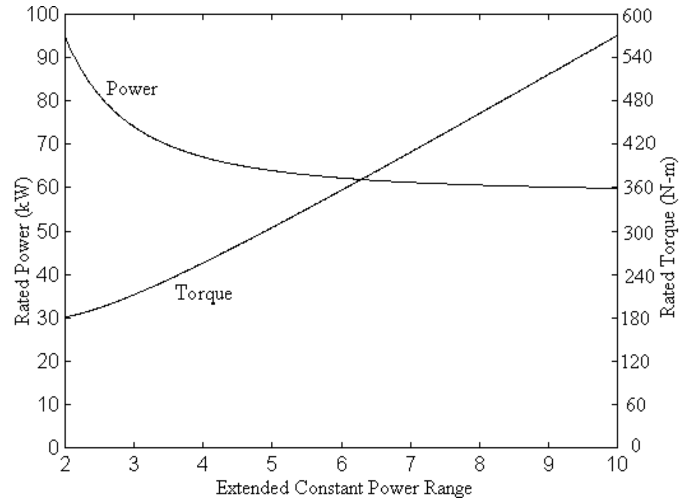

Figure 3. Rated Power and Torque vs. Extended Constant Power Range

Notice that the required torque ratings of extended constant power range motors must be significantly higher, but the required power is lower. After a ratio of about 1:4, the benefit of getting to use a lower power motor begins to become less significant.

PERFORMANCE ANAYLSIS

As shown in Table 3, the required power to reach velocity v_{rv} in time t_f is dependent on the ratio of the constant torque region and the constant power region of the electric motor. Even though the vehicle will reach v_{rv} in time t_f in each case, the nature of the acceleration is variable.

To compute a time t_a for an acceleration to an arbitrary speed v_a while operating in the constant torque region,

$$t_a = \int_0^{Va} \frac{m\cdot\delta}{F_m - f_{ro} - j_l}\cdot dV \qquad (9)$$

where F_m is the force from the electric motor, f_{ro} is the rolling resistance force (Eq. 2) and f is the areodynamic losses (Eq. 3). Headwinds and climbing resistance are assumed to be negligible in this example, but can easily be added in.

$$t_a = \int_0^{Va} \frac{m\cdot\delta}{\frac{T_{rm}\cdot i_t\cdot\eta_e}{r} - m\cdot g\cdot f_r - \frac{1}{2}\cdot\rho_e\cdot C_D\cdot A_f\cdot V^2}\cdot dV$$

where T_{rm} is the rated torque, i_t is the gear ratio between the motor and the driveshaft, and r is the wheel radius. η_e is the speed of the motor, which is dependent on the instantaneous velocity of the vehicle:

$$\eta_e = \frac{60\cdot V\cdot i_t}{2\cdot\pi\cdot r} \qquad (11)$$

To compute the distance S_a covered during this acceleration,

$$S_a = \int_0^{Va} \frac{m \cdot \delta \cdot V}{\frac{T_{rm} \cdot i_t \cdot \eta_e}{r} - m \cdot g \cdot f_r - \frac{1}{2} \cdot \rho_e \cdot C_D \cdot A_f \cdot V^2} \cdot dV$$

To compute the time t_b to accelerate from the rated speed of the motor v_{rm} to any greater speed v_b in the constant power region of operation,

$$t_b = \int_{Vrm}^{Vb} \frac{m \cdot \delta}{\frac{P_m \cdot i_i}{r} - m \cdot g \cdot f_r - \frac{1}{2} \cdot \rho_e \cdot C_D \cdot A_f \cdot V^2} \cdot dV$$

where P_m is the rated power of the motor. Distance can be computed with an equation similar to the constant torque case. Now, by varying the ratio between the constant torque region and the constant power region but keeping the same 0-60mph acceleration in 10 seconds, the acceleration profiles can be seen (Figure 4):

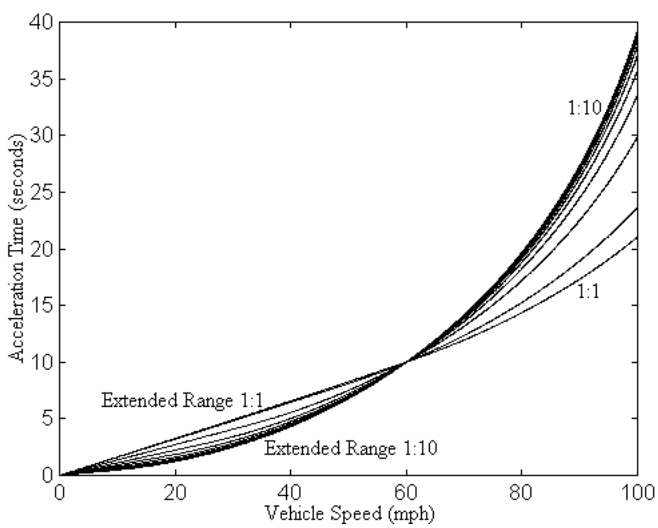

Figure 4. Acceleration Profiles for Different Ratios

Notice that all motors will accelerate to 60 mph in the 10 Seconds but the acceleration curves are different. The extended speed range motors accelerate much more quickly in the beginning and then the acceleration becomes slower at higher speeds. This uneven acceleration affects the distance covered (Figure 5):

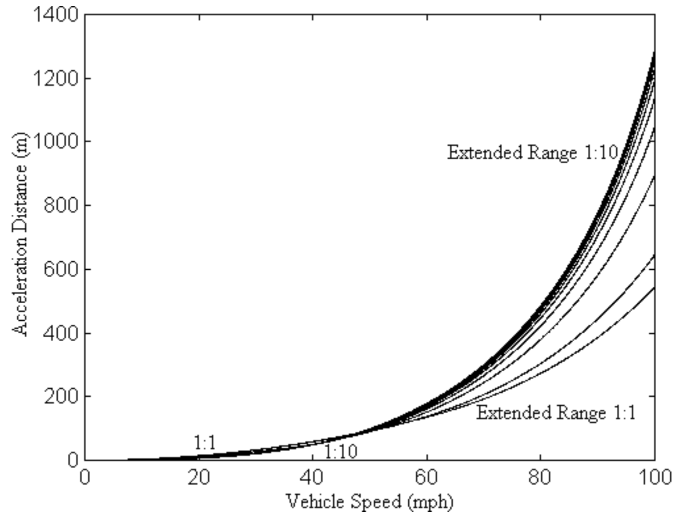

Figure 5. Distance Covered

Notice that vehicles with very low extended constant power ranges (which requires a higher P_m according to Table 3) accelerate to 60 mph in the 10 Seconds but in less distance. This affects passing performance significantly (Figure 6):

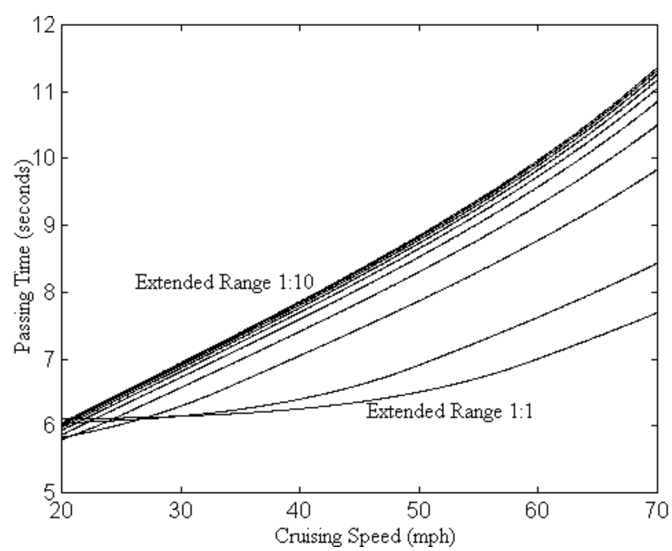

Figure 6. Passing Times

The motors with longer constant power range perform better (shorter passing time) at lower speeds (20 mph), however, the higher power motors (shorter constant power range) perform better at higher speeds. The total distances covered during passing are shown in Figure 7:

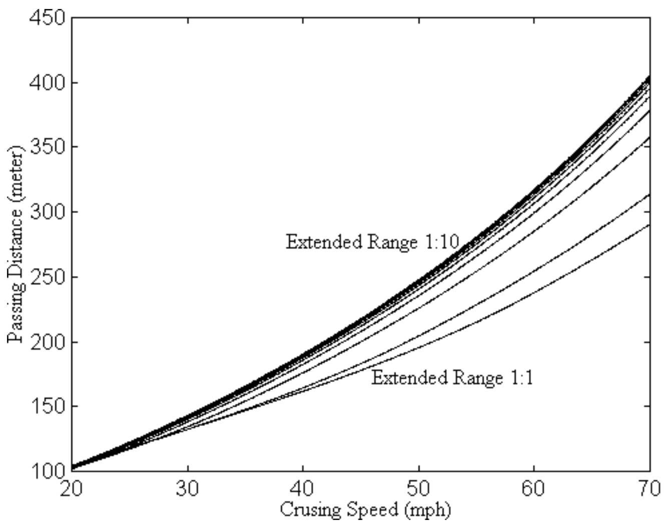

Figure 7. Passing Distance

CONCLUSION

In summary, for simple EV or series HEV designs,

- The power requirement for acceleration decreases as constant power region ratio increases. This results in a smaller motor controller.
- Conversely, the torque requirement for acceleration increases as the constant power region ratio increases. This results in a larger motor size and volume.
- Passing performance suffers considerably as the constant power region ratio increases.

A motor's maximum speed has a pronounced effect on the required torque of the motor. Low speed motors with extended constant power speed range have a much higher rated shaft torque. Consequently, they need more iron and copper to support this higher flux and torque. As motor power decreases (due to extending the range of constant power operation), the required torque is increasing. Therefore, although the converter power requirement (hence the converter cost) will decrease when increasing the constant power range, the motor size, volume, and cost will increase. Increasing the maximum speed of the motor can reduce the motor size by allowing gearing to increase shaft torque. However, the motor maximum speed can not be increased indefinitely without incurring more cost and transmission requirements. Thus there is a multitude of system level conflicts when extending the constant power range.

Several candidate motor technologies were discussed for EV or HEV applications, the induction motor, the brushless DC motor (BLDC) and the switched reluctance motor (SRM). The induction motor has a clear advantage of achieving very high constant power range ratios, but suffers by requiring a very high torque rating. The relatively low maximum speed of the induction motor compounds this problem, because the motor cannot be geared down to the driveshaft an appreciable amount.

The SRM achieves a balance of a modest extended constant power range and a very high maximum speed. Extending the constant power range beyond what the SRM offers yields very little additional benefits (Table 3 and Figure 3). The high maximum speed allows for the SRM to be geared at twice the gear ratio of the induction or BLDC motors, halving the required maximum torque.

The examples presented in this paper form a methodology for evaluating tradeoffs between the power requirement, torque requirement, acceleration performance, and passing performance for different motor technologies. Initial studies indicate that the switched reluctance motor is a good candidate by achieving an optimal balance of these criteria. The same evaluation techniques can be implemented on more complex designs, including parallel or series-parallel type hybrid electric vehicles.

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