Performance Investigation of SRM Based In-wheel Electrical Vehicle

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Abstract: In this paper, performance of the SRM based, battery operated in-wheel electrical vehicle is investigated. The model of 500W, 8/6 pole, four phase SRM is used with asymmetric bridge converter and low-frequency PWM controller. Passive loading scheme is used to simulate the complete system model of the in-wheel SRM drive. Top speed, kilometer per charge, time to accelerate from 0 to 60 km/hour, peak current, peak power, average power, Furthermore fixed-angle control based regenerative braking scheme is proposed to improve the efficiency of the drive.

Keywords: electric vehicle; reluctance motor; regenerative braking.

1. Introduction

The comparison of the SRM drive over other drives has been well documented in the literature [1-9]. It is proven that the SRM drive offers superior performance over others in varying applications; however practical use of SRM is still limited to the few industrial and domestic applications.

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General advantages of the SRM are low cost (motor and converter), small size and higher efficiency, which make it suitable candidates for the industrial and domestic fan, blowers, compressor and pumps. Capability of high speed range makes it suitable for the textile spinning and vacuum cleaner. The possibility of the wide-speed range operation is beneficial for the washing machines wherein single motor can used in spin, dry and wash cycles. Special features of the SRM like shape adoptability, countable cycle (number of revolution) and fast stop makes it advantageous to the food processor applications. Gear-less operation or reduction of the gear ratio is also favourable for some applications. High low-speed torque and integrated management capability makes it suitable for the automotive application like power steering and wiper. Features like high starting torque, wide constant power region and higher efficiency at varying load make the SRM as most suitable candidates for the electric vehicle propulsion system. Many literatures have been published recently to demonstrate energy efficient operation of an SRM for the electrical vehicle system [19-21]. The investigation is carried out here to analyse the performance of SRM based in-wheel two-wheeler vehicle.

2. Modelling and Simulation

Performance of the 500W, 8/6 pole, four phase SRM is investigated for an in-wheel electric vehicle system. The SRM drive consists of asymmetric bridge converter and PWM current controller. A 48V battery is used to supply the power to the drive. Passive loading scheme is proposed which makes it possible to develop a simulation model of the in-wheel electric vehicle system from the separate model of the SRM and vehicle system.

Simulation model of conventional bridge converter is used with the model of four phase SRM. The model of the MOSFET IRFP450 is used as a power switch. The fixed frequency (1.67 KHz) PWM control is incorporated to control the speed while hysteresis current control is used to limit the maximum current. The turn-ON and turn-OFF angles are fixed to the 27° and 57°, respectively. The generic battery model from the 'Electrical source' library is used to supply the power to the converter. The parameters of the equivalent circuit of the battery can be modified to represent a particular battery type, based on its discharge characteristics. The Li-Ion type battery model is used in this application having parameters as under -

Nominal voltage (V) = 48

Internal resistance (ohm) = 0.02

Full charged voltage (V) = 55

Nominal discharge current (A) = 10.5

Rated capacity (Ah) =24

A mathematical model has been created for an electric vehicle with two wheels of equal size, capable of moving in either direction along its longitudinal axis. The vehicle's geometry is illustrated in Figure 1. It is assumed that the vehicle is in a state of vertical balance, ensuring that the wheels remain perpendicular to the horizontal plane at all times. The vehicle parameters are assumed by considering 150 Kg two wheeler.

The vehicle model's output is the longitudinal velocity generated by applying longitudinal force to both the front and rear wheels. In the case of rear wheel drive, the vehicle requires longitudinal force at the rear wheel to accelerate with a velocity of Vx.

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$$F_x = F_{xR} = m\frac{dv_x}{dt} - F_d + mg\sin(\beta) \qquad (1)$$

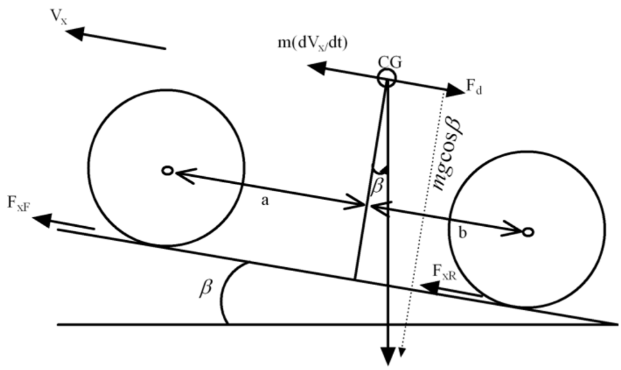


Fig. 1 Geometry of the vehicle

Simply,

$$m\frac{dv_x}{dt} = F_{xR} + F_d - mg\sin(\beta) \qquad (2)$$

Where, aerodynamic drag force,

$$Fd = -\frac{1}{2}C_d \cdot \rho \cdot A \cdot V_x^2 \cdot \mathrm{sgn}(V_x) \qquad (3)$$

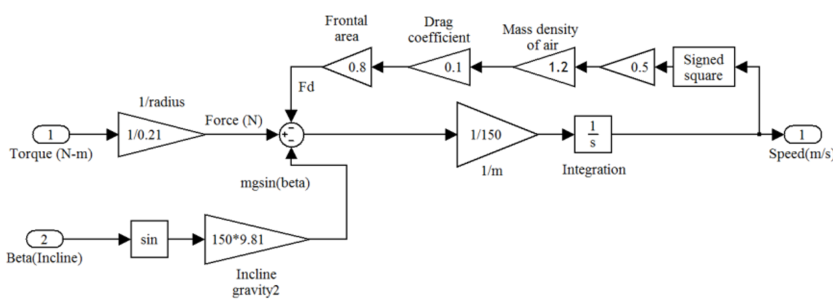


Fig. 2 Simulation diagram of the vehicle model

Dynamic model of the vehicle system is simulated in the MATLAB simulink environment from the (2) and (3) as shown in Fig. 2.

A comprehensive mathematical model of the in-wheel SRM drive, loaded with the exact vehicle model, is essential to analyze its behavior accurately. Separate models are utilized for the SRM and the electric vehicle. In the vehicle model, torque serves as an input while instantaneous velocity is the output. On the other hand, the SRM model requires a load torque as an input signal. The SRM model generates electromagnetic torque solely for measurement purposes. Therefore, a passive loading scheme is implemented to integrate the SRM model with the vehicle model, completing the in-wheel electric vehicle system.

The passive loading scheme consists of two distinct parts. The first part involves utilizing the vehicle system model. A constant torque is applied to the vehicle model as an input in order to determine the steady state speed of the vehicle. The steady state speed for various torque inputs is obtained from the model, as depicted in Figure 3. This information is then stored in a look-up table, where the measured speed of the SRM serves as an index to retrieve the necessary torque. Subsequently, this torque is applied as a load torque to the SRM model. As a result, the load torque exerted on the SRM becomes a function of the speed.

The second section examines the SRM combined with the vehicle, treated as a single entity in the shape of a cylindrical lump with a weight equal to that of the vehicle and a radius equal to that of the wheel. The inertia of the SRM model is assumed to be equivalent to that of the lumped cylinder.

$$J = mr^2 = 6.615 \quad (4)$$

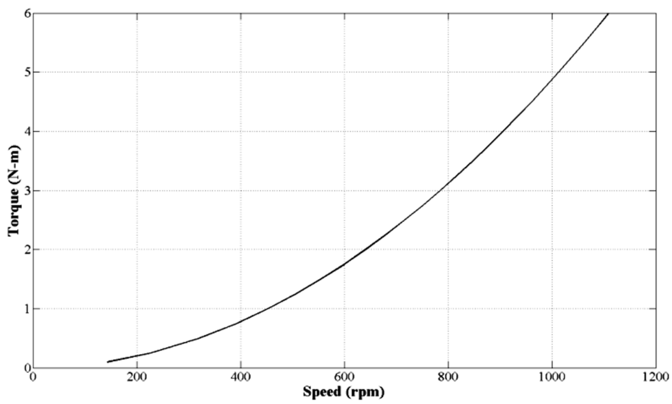


Fig..3 Speed-torque curve of the vehicle

where 'm' is mass of the vehicle and 'r ' is radius of the wheel and 'J' is the inertia in $K_g m^2$. Thus, the SRM model having inertia of the lumped cylinder and loaded with the vehicle speed-torque characteristics, acts as the equivalent model of the in-wheel electrical vehicle system.

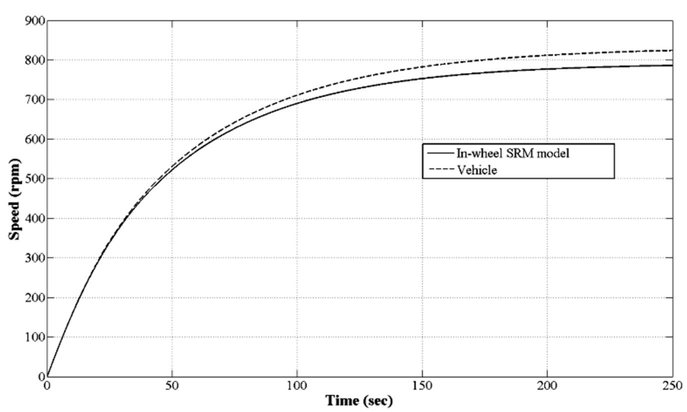


Fig. 4 Speed response of the in-wheel vehicle

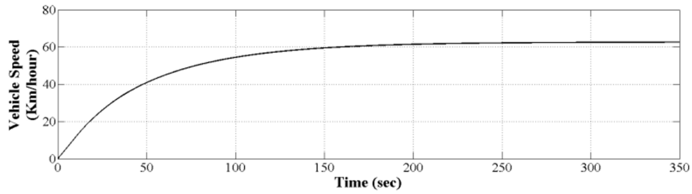


Fig. 5 Plot of vehicle speed

To validate the proposed scheme, measured torque of the SRM is supplied to the vehicle model, and the speed response of the designed in-wheel SRM model and actual vehicle model are compared. The in-wheel SRM is supplied with the full voltage. The speed response curves shown in Fig. 4 confirm that the speed response of both the cases matches very closely. It validates that the designed SRM model represents the in-wheel electric vehicle system.

Fig. 5 shows the speed response of the vehicle in Km/hour. It shows that the maximum possible speed of the vehicle is 63 Km/hour, while it takes 150sec to accelerate form 0 to 60 km/hour.

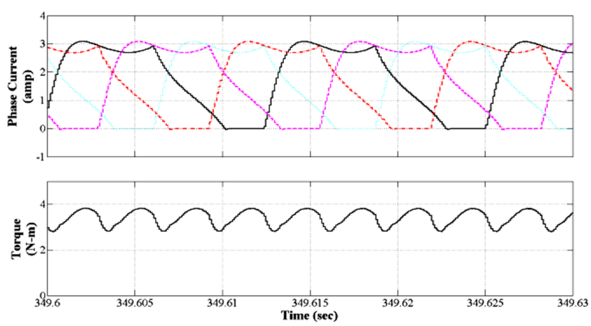
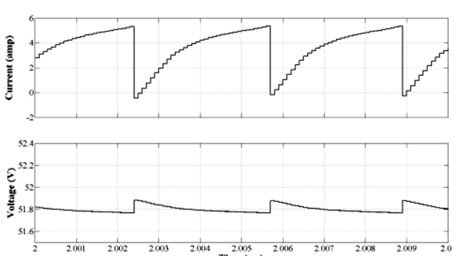


Fig. 6 Waveform of phase current and motor torque at full speed

Waveform of phase current and torque are shown in Fig. 6. It shows that the peak current is less than 3.5 Ampere and ripple in torque is very low (0.3 unit) to produce significant effect on the performance of the electric vehicle.



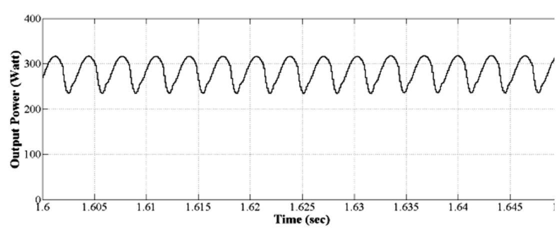


Fig. 7 Battery voltage and current at full speed

Fig. 8 Power output at full speed

Fig. 7 shows the battery voltage and current which dictates that the peak current of the battery is less than 6 Ampere. However, current reaches 18 Ampere during starting. Assuming average battery current of 10 Ampere, the fully charged battery will serve approximately for the next 2.5 hour. Considering constant speed of 40 Km/h, the vehicle will run for 75 Km with one charge.

Fig. 8 shows the mechanical output power of the motor at full speed. The average output power is 282W while the peak value is 317W.

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3. Fixed turn-off angle method

It is more convenient to incorporate an electrical regeneration braking with the SRM as compared to conventional motors. Simplest way to produced regenerative braking for SRM based electrical vehicle system has been proposed and investigates.

The SRM offers easiest way to change the operation mode from motoring to generator. It is required to change the commutation angles (turn ON and turn OFF) such that the phase energizes during the falling inductance profile instead of rising. The scheme is proposed to implement the braking with the low cost fixed angle controller. It uses a simple mechanical switch which interchanges the commutation pulse of each phase as-

Phase-1 to Phase-3

Phase-2 to Phase-4

Phase-3 to Phase-1

Phase-4 to Phase-2

The simple mechanism changes the turn-ON angle to the 57° and turn-OFF angle to the 87°. It produces the negative torque as the falling inductance region of the 8/6 pole, four phase SRM is from 60° to 90°. The simulation results of the electrical braking applied to an in-wheel vehicle system are as follow.

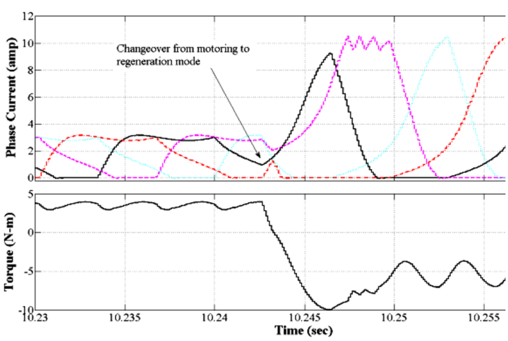

Fig. 9 Waveform of phase current and torque during regenerative breaking

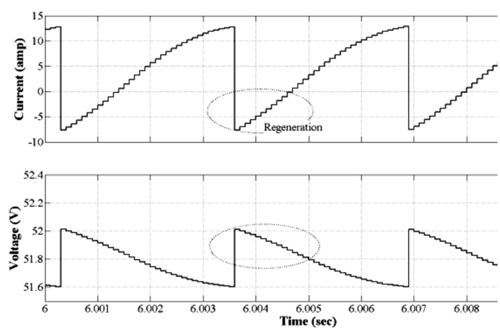

Fig. 10 Battery voltage and current during regeneration operation

Fig. 9 shows the waveform of phase current and torque while braking is applied with the full voltage. Fig. 10 shows the battery voltage and current during regeneration operation. However, kinetic energy of the vehicle is not fully utilized because even with regeneration, it consumes the energy in braking. An angle control scheme can offer a more efficient regeneration by ensuring the prevention of phase excitation during rising inductance period. Efficiency of the regeneration can also be increased by reducing the dwell angle to allow the more regeneration time. But, at the same time it reduces the amount of braking torque. The phenomenon is comparable with the motoring operation, where torque can be increased by increasing the dwell angle but at the cost of efficiency. Fig. 11 shows the battery current and voltage with reduced dwell angle (15°). The regeneration allows recharging of battery during braking and improves the range.

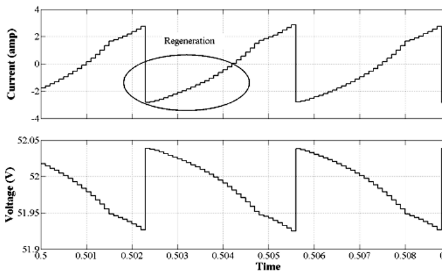

Fig. 11 Battery voltage and current with reduced dwell angle

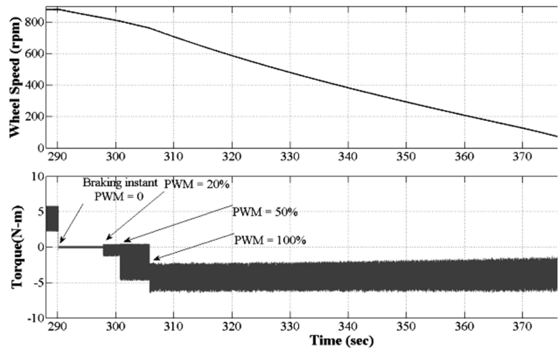

Fig. 12 Braking torque control

The braking torque can also be controlled by the PWM duty cycle. Fig. 12 shows the control of braking torque by the PWM duty cycle. It seems that electric braking system can be used along with the mechanical braking system. The motor that develops more acceleration can also provide fast braking operation.

4. Conclusion

Result shows that SRM offers reasonably good result for the in-wheel electrical vehicle. Passive loading scheme based developed model of In-wheel vehicle drive reduces the complexity of modelling and can also be used with other types of motor to investigate the performance of in-wheel electrical vehicle. Vehicle achieves maximum speed of 65km/hour which is quite good compared to available BLDC based electrical two wheelers of same rating. It takes 150 second to accelerate from 0 to 60 km/hour speed. Considering 48V, 25Amp-hour battery, vehicle runs approx 75 km per charge. It can further increase by applying regenerative braking as described. It shows that implementing regenerative braking with SRM is quite easy as compared to conventional motor. Also, it becomes simple to control the braking torque with the same PWM controller used for controlling the speed of motor. It shows that ripple in torque is very low (0.3 unit) to produce significant effect on the performance of the electric vehicle. Performance investigation shows that SRM offers numbers of advantages compared to BLDC motor for the in-wheel vehicle system. It also includes low-cost, smaller size, less weight, higher starting torque and higher efficiency drives. On the other hand, cost of BLDC is high as it requires permanent magnets.

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