Modelling and Control of Switched Reluctance Motor for Hybrid Electric Vehicle

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Abstract – This paper presents the modelling and control of switched reluctance motor (SRM) for hybrid electric vehicle (HEV) application. Nonlinear characteristics of SRM are obtained using finite element analysis. The fuzzy logic controller is used to minimize the torque ripple which improves the average torque capability of SRM. Obtained results from the drive using fuzzy logic controller are compared with PI controller for four different converter topologies. Asymmetric converter with simple structure is preferred since its fast energy recovery operation helps to improve the average torque. Ttractive effort modelling and optimal vehicle control strategy for defined driving cycle is implemented in MATLAB. Simulation results show the better operating performance of HEV with fuzzy logic controller and optimal vehicle control strategy at different load commands.

Keywords - Switched reluctance motor, Finite element analysis, Ttractive effort, Fuzzy logic controller, Torque ripple reduction.

I. INTRODUCTION

Switched reluctance motor (SRM) works on reluctance principle with the tendency of rotor pole to attain the position where stator winding inductance is low. It is rugged in construction and cheap. Rotor is winding free without any permanent magnet. As compared to permanent magnet synchronous motor and induction motor it has more constant power to base speed ratio which is suitable for HEV [5]. The breakdown torque capability of SRM can be increased by pumping more current into the stator winding against back emf [4].

SRM has some disadvantages like torque ripple, acoustic noise and heating problem. Proper designing of the motor minimizes torque ripple. Further, it can be reduced by proper control techniques like fuzzy logic based speed controller [10], artificial neural based torque controller [1, 2], torque sharing mechanism [3] and Indirect torque control techniques [10].

In this paper, the SRM designed by Khwaja M. Rehman et.al [4] for HEV application is considered for modelling of both 6/4 and 8/6 SRM. The inductance of stator winding is a function of current and rotor position which is obtained by finite element analysis.

Current through the stator winding must be constant up to the base speed for obtaining constant torque, which is achieved by the hysteresis band current controller. Above base speed (field weakening region) the back emf increases with the speed of motor and it opposes the rising stator current. Hence advanced excitation control is required for obtaining sufficient torque in the constant power region.

Due to the salient structure of stator and rotor pole and nonlinear inductance and torque nature, the motor develops more torque ripple [7]. The fuzzy logic based speed controller is implemented in this paper to minimize the torque ripple. It gives better and smooth response as compared to PI controller which is required for HEV.

Designing of the motor and engine requires ttractive effort demand data which is modelled in the simulation by considering all resistive forces. Effective control strategy for optimal vehicle driving is made in the MATLAB.

II. MODELLING OF SRM

The voltage applied across stator winding is given by,

\[ V_a = i_a R_a + L_a(i_a, \theta) \frac{di_a}{dt} + E_b \]

(1)

where \( V_a \) is the applied voltage, \( i_a \) is stator winding current, \( R_a \) is the winding resistance, \( L_a \) is stator winding inductance and \( E_b \) is the back emf.

Flux developed in the stator winding is given by,

\[ \phi_a = L_a(i_a, \theta) i_a \]

(2)

Torque developed by the motor is given by,

\[ T_c(i_a, \theta) = i_a^2 \frac{dL_a(i_a, \theta)}{d\theta} \]

(3)

Torque of the SRM is a function of the current and rotor position. For motor to develop positive torque, the excitation must be in the positive inductance region. If excitation persists in the negative inductance region, the effective torque decreases because of the negative torque development.

Dynamic torque equation of the motor is given by
\[ T_e - T_L = J \frac{d\omega}{dt} + B_m \cdot \omega \]  \hspace{1cm} (4)

Where, \( T_e \) is the load torque, \( J \) is the rotor inertia and \( B_m \) is the viscous friction of the motor. Finite element analysis is used for the magnetic and torque analysis.

### III. FINITE ELEMENT ANALYSIS OF SRM

SRM model for the MATLAB simulation is obtained by electromagnetic analysis using FEMM 4.2. (Finite Element Method Magnetics)[8]. The inductance and torque for different excitations and rotor angles are stored as a lookup table.

Fig.1 shows the per phase nonlinear inductance characteristics of the 6/4 SRM at different current values and rotor positions. Stator to rotor pole arc ratio of this configuration is 30:32. Inductance of stator winding is low (0.23 mH) at unaligned rotor position (0° to 15° and 75° to 90°) and it is high (5.3 mH) at totally aligned rotor position (44° to 46°). Inductance profile of stator winding will repeat after every 90° interval.

![Fig.1. Nonlinear inductance characteristics of 6/4 SRM.](image1)

Torque of SRM is a function of stator current and rotor position. Fig.2 shows the per phase nonlinear torque characteristics of 6/4 SRM. Torque is zero during totally aligned (44° to 46°) and totally unaligned (0° to 15° and 75° to 90°) stator-rotor position and positive during rising inductance region (15° to 44°) and negative during falling inductance region (46° to 75°). Maximum torque obtained is 102.3 Nm.

![Fig.2. Nonlinear torque characteristics of 6/4 SRM.](image2)

Fig.3. shows nonlinear inductance characteristics of 8/6 SRM. Stator to rotor pole arc ratio is 21:23. Inductance at unaligned rotor positions (0° to 8° and 52° to 60°) is 0.15 mH and 2.23 mH at totally aligned rotor position (29° to 31°). Inductance values will repeat after 60° interval in 8/6 SRM.

![Fig.3. Nonlinear inductance characteristics of 8/6 SRM.](image3)

Both the motor configurations use the same material (M19 steel) and have same stator and rotor outer diameter, stator and rotor core thickness, shaft diameters, stack length and air gap length [4].

From the result analysis, we conclude that 8/6 SRM has much better power rating than 6/4 SRM since motor saturation for 6/4 SRM and 8/6 SRM remains same with the current excitation of 168.3A and 225A respectively. Due to higher phase overlapping in 8/6 SRM, it delivers more average torque (shown in Fig.6) as compared to 6/4 SRM (shown in Fig.5). Due to wider rotor arc, 6/4 SRM has more overload capability, but poor transient response (more acceleration time) compared to 8/6 SRM. Hence 8/6 SRM is a better candidate for HEV.
Split capacitor phase converter has the advantage of single switch per phase for excitation but it causes voltage unbalancing problem due to the split power supply and at starting percentage torque ripple is more. In case of R dump converter, recovered energy from the winding is wasted as heat across the resistor which reduces the overall efficiency. In C dump, buck converter is required for defluxing which makes the converter very bulky. Also because of incomplete discharging it will induce more torque ripple while exciting the upcoming phase [6].

Asymmetric converter needs two switches and two diodes per phase for fluxing and defluxing operation. Recovered energy from the winding supplies the filter capacitor. Its simple structure and easy operation makes it favourable for HEV application.

V. TRACTIVE EFFORT

Pressure applied on the accelerator pedal indicates the total driving effort requirement for the vehicle driving. To propel the vehicle, the total drive train supplies the power to overcome road resistive forces. Tractive effort development depends upon the vehicle parameters, road structure and outer environmental conditions. Some resistive forces which oppose the vehicle motion are described in the following section [5].

A. Rolling resistance force

This type of force occurs due to the friction between vehicle tyres and road. Rolling resistance coefficient depends upon the type of tyre and road conditions.

Rolling resistance force,

\[ F_r = M \cdot g \cdot f_r \]  \hspace{1cm} (5)

where \( M \) is the mass of vehicle is, \( g \) is the earth gravity and \( f_r \) is the rolling resistance coefficient.

B. Aerodynamic resistance force

Aerodynamic resistive force is a function of vehicle frontal area, air density and vehicle speed. The expression for aerodynamic resistive force is

\[ F_{ad} = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V^2 \]  \hspace{1cm} (6)

where \( \rho \) is the air density, \( C_d \) is the aerodynamic drag coefficient, \( A \) is the frontal area and \( V \) is the speed of vehicle.

C. Hill climbing resistance force

This type of force depends upon mass of the vehicle and the percentage road gradient (are given in (7)). This force is positive when vehicle moves up the gradient, and negative during moving down the gradient. When it becomes negative, regeneration is possible.

\[ F_{hc} = M \cdot g \cdot \sin \alpha \]  \hspace{1cm} (7)

where \( \alpha \) is slope of the road gradient.

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>Torque Ripple (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PI controller</td>
</tr>
<tr>
<td>Asymmetric</td>
<td>39.01 %</td>
</tr>
<tr>
<td>C dump</td>
<td>37.44 %</td>
</tr>
<tr>
<td>Split capacitor phase</td>
<td>38.64 %</td>
</tr>
<tr>
<td>R dump</td>
<td>46.29 %</td>
</tr>
</tbody>
</table>
D. Linear acceleration force

Acceleration force depends upon the force acting on the vehicle and mass of the vehicle.

\[ F_{la} = M.a \]  

(8)

where \( a \) is the acceleration and \( F_{la} \) is the linear acceleration force on the vehicle. Vehicle runs at constant speed when the difference between applied force and resistive force is zero.

E. Angular acceleration force

It is the force required by the wheel to make angular acceleration. This type of force mainly depends upon the moment of inertia, gear ratio and radius of the tyre.

\[ F_{wa} = I \cdot \frac{g^2}{r^2} \cdot a \]  

(9)

where \( I \) is the moment of inertia, \( G \) is the gear ratio and \( r \) is the radius of the wheel.

VI. DESIGN OF ENGINE AND MOTOR FOR HEV

The engine capacity for HEV should be such that, it can handle the steady load. The engine should be able to supply the average power which is greater than the average load power. The engine and motor together handles higher torque demand corresponding to the gradient road condition [5].

The parameters of the passenger car used for the simulation are vehicle mass 1500 kg, rolling resistance coefficient 0.01, air density 1.205 kg/m³, front area 2 m², aerodynamic drag coefficient 0.3, radius of wheel 0.2794 m and efficiency of motor and engine transmission is 0.95 and 0.9 respectively [5].

From the calculation of all tractive forces, the engine capacity is selected as 42.5 kW and the motor capacity is 54 kW. The motor handles dynamic load i.e. acceleration and hill climbing load. If the load torque requirement is greater than the rated torque of engine, the surplus torque is supplied by the motor.

VII. OPTIMUM CONTROL STRATEGY FOR HEV

For optimal vehicle driving, performance of the engine and motor should be better in their respective operating region. Below the bottom line of specified vehicle speed, the engine cannot operate steadily and hence the motor alone propelling mode is preferred due to its good speed torque characteristics with single gear transmission. If the load torque requirement is more than the engine capacity, hybrid mode of operation is preferred [5].

VIII. SIMULATION OF HYBRID ELECTRIC VEHICLE

The block diagram of closed loop simulation of hybrid electric vehicle is as shown in Fig.7. Road situations define the speed command for the vehicle. In real time simulation urban and highway driving cycles are considered for a large time duration. For the MATLAB simulation in this work, the predefined load cycle of lesser duration covering different road conditions like traffic, highway and gradient road are taken into consideration. The load torque corresponding to the different speed commands for the given load cycle is given in TABLE II. The mode of operation is selected on the basis of efficient control strategy as discussed in section VII. Only motor is considered for low speed drive (below 20 km/h). Maximum torque capability of the engine at base speed of 950 rpm is 430 Nm which drives the average load demand. Peak load demand above 430 Nm is shared by the motor.

IX. RESULT ANALYSIS

In heavy traffic, the vehicle needs to stop and start frequently where the engine is not preferred due to its poor efficiency. At low speed normally below 20 km/h where tractive load demand is less, the motor operating mode is preferred compared to the engine due to its better performance. Engine operating mode gives good driving efficiency on highway since the speed is high, generally above 100 km/h and tractive load is within the range of engine capacity. At average speed on gradient road, hybrid mode of operation is required for achieving the high tractive effort demand.

TABLE II. LOAD TORQUE DEMAND AT DIFFERENT SPEEDS AND VEHICLE MODE OF OPERATIONS.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Speed command (Km/h)</th>
<th>Total load Demand (Nm)</th>
<th>Mode of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125</td>
<td>216.7</td>
<td>Engine</td>
</tr>
<tr>
<td>0.75</td>
<td>45</td>
<td>508.05</td>
<td>Hybrid</td>
</tr>
<tr>
<td>1.15</td>
<td>85</td>
<td>183.52</td>
<td>Engine</td>
</tr>
<tr>
<td>1.35</td>
<td>45</td>
<td>236.23</td>
<td>Engine</td>
</tr>
<tr>
<td>1.6</td>
<td>65</td>
<td>503.79</td>
<td>Hybrid</td>
</tr>
</tbody>
</table>

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Table 1

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Torque Demand (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>115</td>
</tr>
<tr>
<td>2.05</td>
<td>95</td>
</tr>
</tbody>
</table>

Fig. 8 shows the vehicle speed response at different speed commands for a total simulation time of 2.3 sec. The corresponding torque demands are shown in Fig.10. According to the optimal control strategy discussed in section VII, the load sharing by the motor and engine is given in Fig.11 and Fig.12 respectively. From the observation of the motor mode and hybrid mode (TABLE II) in Fig.8 it is clear that the motor tracks the reference speed with less transients using fuzzy logic controller. Fig.9 shows the speed response with only motor for various speed commands. Initial transients (Fig.8) during the engine alone and hybrid mode operation are more due to the step change in speed commands given. In practical case the driver will be modulating the speed command by pressing the accelerator smoothly. The initial peaks in the torque developed by the motor (Fig.11) is due to the accelerating torque demanded by the speed reference.

Fig. 9. Speed response with only SRM for various speed commands.

Corresponding to the speed reference of 125 km/h, the load demand is 216.7 Nm which is handled by the engine alone. PI controller is used for throttle control of the engine and it is observed that the performance is better near the engine base speed. Engine load torque demand in this case is lesser than its rated torque capacity, hence the remaining torque can be utilized for charging the battery by operating the same machine as a generator.

Fig. 10. Torque developed by vehicle during hybrid mode of operation.

When the load torque demand on gradient road is higher than the rated torque of the engine, hybrid mode is selected and the load share of the motor and engine are shown in Fig.11 and Fig.12 respectively.

Fig. 11. Motor developed torque.

Fig. 12. Torque developed by the Engine.

X. CONCLUSION

Due to the salient structure, SRM is having highly nonlinear magnetic characteristics which makes its analysis complex. Using FEMM 4.2, two SRM topologies (6x4 and 8x6 configuration) were analysed and the results are taken for modelling of SRM in the MATLAB simulation. Higher power rating, more average torque delivering capability and lesser time for acceleration makes 8x6 SRM favourable for hybrid vehicle application. Fuzzy logic based controller is used in this paper for torque ripple reduction and smooth speed response. The obtained results are compared with the PI controller which is given in TABLE.I. Four different converter topologies are considered for the analysis. Flexible control, fault tolerance operation and
fast energy recovering ability of asymmetric converter makes it suitable for motor excitation. This paper describes the tractive effort demand modelling by considering all dynamic and steady state loads for hybrid electric vehicle propulsion. Discussed optimal control strategy for the vehicle in TABLE. II is implemented in MATLAB. Simulation results indicate the proper controlling of motor and engine in their respective mode of operation.

XI. REFERENCES


