Dual Mode Operation of 8/6 SRM with Optimum Angle Operation in Hybrid Electric Vehicles using FLC based Controller

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Abstract. An optimum operating period of an 8/6 Switched Reluctance Motor (SRM) based on different load condition is analysed in this paper. The system is designed to analyse the speed control of machine in motoring mode and voltage control mode is carried out in this paper. Dual Mode switched reluctance motor is tested with the fuzzy logic controller, Mamdani method is used in fuzzy based system. In this paper the main objective is to concentrate on modelling the machine to maximise the average torque with minimum torque ripple in the optimised operating region with different loading conditions in dual mode region. This method also found to have increased efficiency, with the closed loop controlling action the system is robust and simple in construction. The optimised designed system has less manufacturing cost due to simple construction. The simulation is carried out using MATLAB/Simulink.

1. Introduction

The development of SRM machines starts at the year of early 1920’s, as the conventional system. [2]. The major drawback of the machine is due to the further advancements due to the losses faced in electromechanical energy conversion and power electronic switches. After the significant change in the field of power electronics, the SRM machines were reintroduced during the year of 1960s. The switched reluctance motor has many commercial applications in adjustable speed drives recognized to its exclusive mechanical structure and also its simple power electronic structures. The intrinsic simplicity and ruggedness of the machine contributes to its superiority over other electric machines [3].

The numerous advantages posed by SRM in its performance, low cost, high speed and acceleration capability, is shadowed by its disadvantages caused by the non-linearity such as torque ripple, acoustic noise and position sensor. SRM machine can able to operate, when the machine is integrated with power converter, controller and rotor position sensor. The performance simulation of reluctance machine for different control strategies with the experimental data’s are validated. The designed SRM need to be detect the rotor position with respect to its stator using a position sensor connected to the motor shaft. A position sensor, such as an encoder, a resolver, or a Hall sensor is normally used which leads to increase in cost and size of machine with reduced reliability. As a result, several sensor-less drive techniques have been reported from the results [4]. SRM machines are
versatile with ordinary looking structure, and are hence easy to manufacture leading to their low cost [4]. This is mainly the result of the power electronic drives used here. The combination with the power electronic switches is one of the unique factors of this machine [5]. The modelling of 8/6 pole SRM machine here is done using the electro-mechanical and electromagnetic equations [6].

Trials have been done with different controllers to minimize the torque ripple, complexity in control, and non-linearity [8]. These controllers also determine the optimum turn on and turn off angle with other parameters like reference current and size of hysteresis band [9]. The optimising of the turn on and turn off angle not only reduces torque ripples but also increases average torque [10]. The turn on and turn off operation are each done by separate controllers. But, more importance is given to turn on controllers for as it minimises the torque ripple [11] and increase in the torque value is done by turn off angle control.

Sliding mode controller is also used for speed control in some cases [16] for eliminating the drive nonlinearity and it operates by setting up a state space [12]. Position sensing in SRM is a compulsion because the torque generation in SRM is subject to rotor position [13]. But, it has its own drawbacks with using external sensors like resolvers and optical sensors. Drawbacks like high cost, losses due to noise and problems with mechanical mounting usually minimises their importance in market for their accuracy and efficiency [14]. Using sensor-less control with optimised operating angle eliminates this disadvantage and increases the flexibility of SRM [12]. In this paper, the dual mode operation of this SRM eliminates the battery storage problem and increases the efficiency of the whole system with regenerative power. The closed loop controlling is done using fuzzy logic controller. The work is simulated using MATLAB/SIMULINK and results are obtained [7].

2. Modelling of SRM For Dual Mode Operation

The SRM has to be modelled to avoid discrepancies caused by non-linearity due to double saliency of the machine, leading to non-linear torque and current. Therefore, mathematical modelling is done relieving us of the tedious reference frame theory. To simplify it even more, leakage flux, magnetic saturation characteristics are neglected. The Fig 1 below shows the rotation of rotor with respect to stator for an angle of 15 degrees.

Voltage equation of motoring mode for SRM is given by

\[ V = I_a R_o + e + L \frac{di}{dt} \]  \hspace{1cm} (1)

Equating \( e \) to a function of inductance,

\[ e = \omega_m i \frac{dL}{d\theta} \] \hspace{1cm} (2)

Fig 1. 8/6 Switched Reluctance Motor
Power absorbed from the SRM is given by

\[ V = i_a R_a + \omega_m i \frac{dL}{d\theta} + L \frac{di}{dt} \]  

(3)

But, \( \frac{d}{dt} \left( \frac{1}{2} L i^2 \right) = \frac{1}{2} i^2 \frac{dL}{d\theta} + L i \frac{di}{dt} \)

Therefore, the torque equation is given by,

\[ T = \frac{1}{2} i^2 \frac{dL}{d\theta} \]  

(6)

Voltage equation for generating mode of the motor is given by

\[ V = i_a R_a + L \frac{di}{dt} - \omega_m i \frac{dL}{d\theta} \]  

(7)

And the torque produced will be

\[ T = -\left( \frac{1}{2} i^2 \frac{dL}{d\theta} \right) \]  

(8)

The equations (1) to (8) give the modelling equation for the switched reluctance motor. Where, the negative sign is contributed to the falling profile of inductance (negative region) with respect to the change in rotor position.

3. Dual Mode Operation of SRM

The raising region of the inductance profile of the SRM constitutes the motoring mode and the falling region constitutes the generating mode. In motoring mode, speed is the controlled parameter with the excitation given in the raising region. In generating mode, generally the output voltage is the controlled parameter with the excitation given in the falling region. If the excitation is in the optimum region, then the performance of the dual mode machine is better. Because of the non-linearity observed in the operating angle selection for different loading condition, the controller opted should be very rigid to obtain stable operation. The PID controller is replaced by fuzzy logic controller for rapid operation and faster simulation speed.

4. Optimum Angle Selection in Motoring Mode

The figure 2 shown below gives the current path in a single inductance curve showing the motoring mode operation. The optimum value of turn-on angle in the motoring mode is taken after eliminating the resistance due to the presence of inductive coils and fringing effect.

\[ \theta_{on}^M = \theta_{1u} - \theta_{01} = \theta_{1u} - \frac{\frac{1}{2} L i_t \omega_T}{V_{dc}} \]  

(9)
The optimal turn-off angle in motoring mode is given by

$$\theta_{c_{ff}}^M = \theta_{1u} + (2\theta_{ek} - \theta_{s2}) \left[ 1 - \frac{\theta_{s2}}{\theta_{s2}} \right]$$

(10)

Where the equation (9) and (10) gives the optimum turn on and turn off angle estimation for the motoring mode.

5. SRM Operation Dual Mode

The raising region of the inductance profile of the SRM constitutes the motoring mode and the falling region constitutes the generating mode. In motoring mode, speed is the controlled parameter with the excitation given in the raising region. In generating mode, generally the output voltage is the controlled parameter with the excitation given in the falling region. If the excitation is in the optimum region, then the performance of the dual mode machine is better. Because of the non-linearity observed in the operating angle selection for different resistance due to the presence of inductive coils and fringing effect

$$\theta_{c_{on}}^M = \theta_{1u} - \theta_{01}^M = \theta_{1u} - \frac{L_{w1}\tau_{rf}\omega_r}{V_{dc}}$$

(9)

The optimal turn-off angle in motoring mode is given by

$$\theta_{c_{ff}}^M = \theta_{1u} + (2\theta_{ek} - \theta_{s2}) \left[ 1 - \frac{\theta_{s2}}{\theta_{s2}} \right]$$

(10)

Where the equation (9) and (10) gives the optimum turn on and turn off angle estimation for the motoring mode.

6. Optimum Angle Selection in Generating Mode
Similarly in a switched reluctance motor, for generating mode, the optimum turn-on angle is given by

$$\theta_{\text{on}} = \theta - 2\left[\theta_{01} + \theta_{sk} \left(1 - \frac{\theta_{sk}}{\theta_{02}}\right)\right]$$  \hspace{1cm} (11)

And, turn-off angle given by

$$\theta_{\text{off}} = \theta - \theta_{01}$$  \hspace{1cm} (12)

Where the equation (11) and (12) gives the optimum turn on and turn off angle estimation for the generating mode. The figure 3 shows the current in the generating mode operation of a switched reluctance motor.

![Fig 3. Generating mode operation](image)

The operating angle of the SRM is equal to the stroke angle of the motor. This angle is always within the boundary limits. When it decreases below the given boundary limit, the torque obtained is reduced due to insufficient conduction period and when it crosses above the boundary limit, without producing torque winding losses only occurs. When it reaches the opposite slope then torque reversal occurs. It reduces the average torque and also stress occurs in the rotor shaft. To prevent this, the optimum region is always selected to be within the conduction region of 8/6 SRM.

7. Conduction Angle Estimation

From the figure 2 & 3, it is clear that the inductance changes for every change in rotor position with respect to stator. The stroke angle corresponds to the aligned position and average torque production is maximum here. When the conduction angle is less than the stroke angle, the torque production is minimised. The conduction angle decreases with increasing load. Care is taken to ensure optimum overlapping period where average torque increases and torque ripple decreases. Dual mode operation depends upon the inductance profile slope. The operating angle is advanced by an angle of
advance to obtain optimised results in the torque plot. Figure 4 shows the inductance profile of a dual mode region of switched reluctance motor.

![Fig 4. Inductance profile for 8/6 SRM](image)

**AB & DE - Minimum inductance region**

**BC1 - Raising inductance region**

**C1C2 – Maximum inductance region**

**C2D - falling inductance region**

\[
\text{Advance angle, } \theta_{adv} = \frac{L_{min-Ir}}{V} \quad (13)
\]

The advance angle given by equation (13) is given to the turn-on angle and the turn-off angle. The turn-on angle given to energise the winding is given before the rising profile of inductance and turn-off angle to de-energise the winding is given with a period interval of fifteen degrees from the turn-on angle. Similarly, the same is done for the generating mode. This turn-on and turn-off angles are selected for obtaining better Results.

**8. Main Constraints**

The main constraints to be introduced are that the turn off angle should be fifteen degrees from the turn on angle.

\[
\theta_{off} - \theta_{on} = \frac{N_s - N_p}{N_rN_s} \times 360 \text{ degree} \quad (14)
\]

Where,

\(T_{on} \geq 0 \text{ degree, } T_{off} \leq 30 \text{ degree}\)

**9. Fuzzy Logic Controller**
The main objective of controller is to achieve a high performance control, thereby maintain the output voltage of the system. In a fuzzy logic controller, the switching states are selected based on the predefined fuzzy variables. Here, speed control of the SR machine is done by taking into account the error in speed (input1) and the change in speed (input 2). Fuzzy logic controllers are advantageous compared to the conventional controllers when dealing with more complex processes. The difficulties in modelling non-linear models with uncertainties are generally a right choice for fuzzy controllers because of its high adaptive ness and robustness in performance under varying parameters and disturbed load.

The rules of the fuzzy system are given in the following table 01.

Table 01. Fuzzy rules

| Input 2 | NL | NM | NS | Z | PS | PM | PL |
|---------|----|----|----|---|----|----|----|
| Input 1 | NL | VB | VB | VB | B | SB | S | Z |
|         | NM | VB | VB | B | B | MB | S | VS |
|         | NS | VB | MB | B | VB | VS | S | VS |
|         | Z  | S  | SB | MB | Z | MB | SB | S |
|         | PS | VS | S  | VS | VB | B  | MB | VB |
|         | PM | VS | S  | MB | B | B | VB | VB |
|         | PL | Z  | S  | SB | B | VB | VB | VB |

The linguistic variables in table 01 are

NL- Negative Large  PS- Positive Small
NM- Negative Medium PM- Positive Medium
NS- Negative Small  PL- Positive Large
Z- Zero  VB- Very Big
MB- Medium Big  SB- Small Big
VS- Very Small  S- Small  B- Big
Triangular membership functions are used in the fuzzy interference system (FIS) file. The output speed from the fuzzy file is given as input to control the speed of the SRM.

10. Simulation Results

Figure 5 shows the speed variation in the generating mode while changing the load torque. Figure 6 and figure 10 shows the torque variation in the generating and motoring mode respectively during load change. Figure 7 gives the gate pulse given to the motor during the motoring mode.

![Fig 5. Speed under varying load torque for generating mode](image1)

![Fig 6. Generator torque under varying load torque](image2)
Fig 7. Gate pulse given to the SRM in motoring mode

Fig 8. Inductance profile under varying load torque for generating mode
Fig. 9. Inductance profile under varying load torque for motoring mode

Fig. 10. Motoring torque under varying load torque

Figure 8 and figure 9 shows the inductance profile of the SRM in generating and motoring mode respectively.

11. Conclusion

The dual mode operation of a Switched Reluctance Motor is implemented using MATLAB/SIMULINK platform. FLC controller is used for increased efficiency of the SRM machine. The average torque is obtained and is found to be of increased value, and the torque ripple content is obtained and found to be reduced. The results obtained from the simulation are plotted in both the mode of operations.

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