DEVELOPMENT OF AN ELECTRIC VEHICLE SYNCHRONOUS RELUCTANCE MOTOR DRIVE

Mr. Thakur Chandrajit N.[1], Prof. Jogdand M.C.[2] , Dr. B.M.Patil [3]

[1] M.tech. Student, Dept. of PG (Control System), COLLEGE OF ENGINEERING AMBAJOGAI.

[2] Professor, Dept. of PG , COLLEGE OF ENGINEERING AMBAJOGAI.

[3] Dean , Dept. of PG, College of Engineering , Ambajogai.

Abstract: *This paper presents the development and control of an electric vehicle (EV) synchronous reluctance motor (SynRM) drive. A bilateral DC/DC converter is used as an interface between the battery and the motor drive. The boostable and well-regulated DC-link voltage with robust regulation control can enhance the motor driving performance in wide speed range. And the regenerative braking energy can be successfully recovered to the battery. In SynRM drive, the robust current PWM switching control considering inherent slotting effects and robust speed model reference control are made. Moreover, an adaptive commutation scheme (ACS) is developed to automatically set the commutation instant for achieving the motor total loss minimization. The dynamic and static driving characteristics of the established EV SynRM drive in various conditions are verified experimentally.*

Keywords: ***Electric vehicle, synchronous reluctance motor, battery, interface converter, commutation, current control, robust control, adaptive control etc.***

I. INTRODUCTION

During the past few decades, AC motor drives have gradually replaced the DC drives because of high performance and low cost in variable speed applications. During this transition period, the squirrel cage induction motor drive has emerged as the AC motor of choice for most applications due to its simple structure and good performance. However, the induction motor is not an ideal machine for many applications due to its relatively low efficiency and difficulties associated with controlling torque. In particular, modern field oriented control of such machines requires the use of a position sensor in the torque loop. It acts, in effect, as the equivalent of the brush /commutator ring of a DC machine. Even if eliminating this problem has been actively pursued using position sensing schemes, a universally satisfactory solution has yet to appear, prompting to examine alternate AC motor possibilities.[1]-[4]

The machine which has been proposed for variable speed drives is the Variable Reluctance Motor (VRM). Despite the fact, its concept has only been pursued for variable speed drives for about last 20 years. This machine mainly relies upon the "reluctance torque" rather than the more conventional "reaction torque" of wound field synchronous, surface magnet, permanent magnet and induction machines. In this machine both stator and rotor have projecting poles along the air-gap. The torque is produced by the tendency of the rotor to line up along a minimum reluctance position established by the alignment of a particular stator and rotor saliency. Continuous rotation is produced by sequentially switching the stator current from one phase to the next, as the rotor pole moves into alignment with a stator pole. It has gradually been shown that the variable reluctance machine can compete favorably with induction machines, particularly in small sizes below a few kilowatts where the decreasing magnetizing inductance of the induction motor causes performance degradation.[5]

The variable reluctance machine unfortunately has its own set of problems such as high torque pulsation at low speed, considerable noise, cost penalties due to small mechanical tolerances, substantial switch volt-ampere rating, and relatively high losses during the field weakening condition. While much work has been done on addressing these problems, it is extremely difficult to find a solution which solves all of them simultaneously. Variable reluctance will certainly find its rightful place in the application spectrum, such that these machines will have much of an impact across the board.[6]-[7]

Synchronous Reluctance Motor (SRM) is another machine, which has been relatively ignored for the past several decades. The synchronous reluctance motor is a singly salient machine in which the rotor is constructed so as to again employ the principle of reluctance torque to produce electromechanical energy conversion. In this case, however, only the rotor is constructed with salient poles, while the stator inner surface is cylindrical and typically wound in an identical manner to an induction machine. Thus the machine typically retains many of the benefits of variable reluctance motors, while at the same time eliminating several of its disadvantages. For example, this machine can also be operated with unipolar currents in much the same manner as variable reluctance machines. In addition, the noise and torque pulsation problems became so difficult to overcome with VRM. These can be easily overcome in a SRM by simply winding the stator in the conventional manner so as to produce a sinusoidal uniformly rotating air- gap magneto motive force (MMF).

II. LITERATURE REVIEW

- With the development of new technology in the field of digital electronics and power semiconductor devices, the performance of synchronous drives has drastically improved. The introduction of current controlled PWM inverters that works with the field oriented (vector) control (Bose 1986) Murphy et al 1988; Leonhard 1985) has significantly contributed to the increased use of SRM over the last few years. Improvements in the drive performance and stable synchronous operation for very low speeds including standstill has been possible by the use of vector control.[1]-[2]

- (Xu et al 1991) Fratta & Vagati 1992; Xu & Yao 1992; Boldea et al 1994; Uezato et al 1994).Driving the machine at low speed has been difficult by the use of conventional voltage/frequency control (Lipo et al 1967; Lawrenson & Bowes 1971). [3]
- In order to achieve a high performance SRM drive that can compete with the other brushless drives, design and optimum refinement of the rotor geometry is required. As was presented, so much effort has been put on the development of SRM rotor geometry in order to have a more efficient SRM drive (Menzies et al 1972). [4]-[5]
- More refinements in the design of the SRM rotor geometry have been possible through the numerical magnetic analysis by the use of finite element softwares (Vagati et al 2000 a; Martins et al 2003; Schmidt & Brandl 2001). The use of other materials, such as composite powder metal rather than iron, has been considered as an alternative for the rotor manufacturing (Reiter & Stuart 2003). [6]-[8]
- By using this type of materials, the geometry of the rotor can be more flexible and thus manufacturing becomes easier. Inserting magnet in the rotor flux barriers of the rotor improves the performance of the motor and this changes the motor from SRM to PMSRM (Lee et al 1999; Morimoto et al 2001; Boldea et al 2004). [9]-[10]
- With the development of the better design of the motor, the enhancement of the overall drive is possible by the introduction of more advanced control algorithms (Niazi et al 2007).
- Due to the availability of the high speed microprocessors, it has been possible to implement the advanced control procedures. Most of the modern control algorithms are model based and are parameter dependent. The major drawback of most of the researches on the optimal control of SRM is the use of an ideal model in order to perform theoretical analysis and practical implementation (Lagerquist et al 1992). [11]-[14]
- However, in a real machine, the effects of iron loss and saturation result in deviation of the current angle from the optimal operating point. Relevant knowledge of the motor parameters and also the use of a more realistic model are crucial in order to implement an optimal control.[15]-[16]
- In the literature most of the early designs presented in the period of 1950 to 1970 were based on a simple salient pole rotor shown in Figure 2.1. Their performances were investigated with reference to the fixed frequency operation in the presence of rotor cage. A detailed review on these works are found in the literature (Lawrenson & Agu 1964; Cruickshank et al 1971; Hosinger 1971). [17]-[18]
- These machines were commonly used in the line start singlespeed applications (Chalmers & Mulki 1970; Chalmers & Mulki 1972; Fong & Htsui 1970) and two-speed applications (Lawrenson 1965; Fong 1967). These

machines had the advantages of simple and rigid structure. Their manufacturing cost was also low. Poor performance of these machines was due to low saliency ratio. [19]-[21]

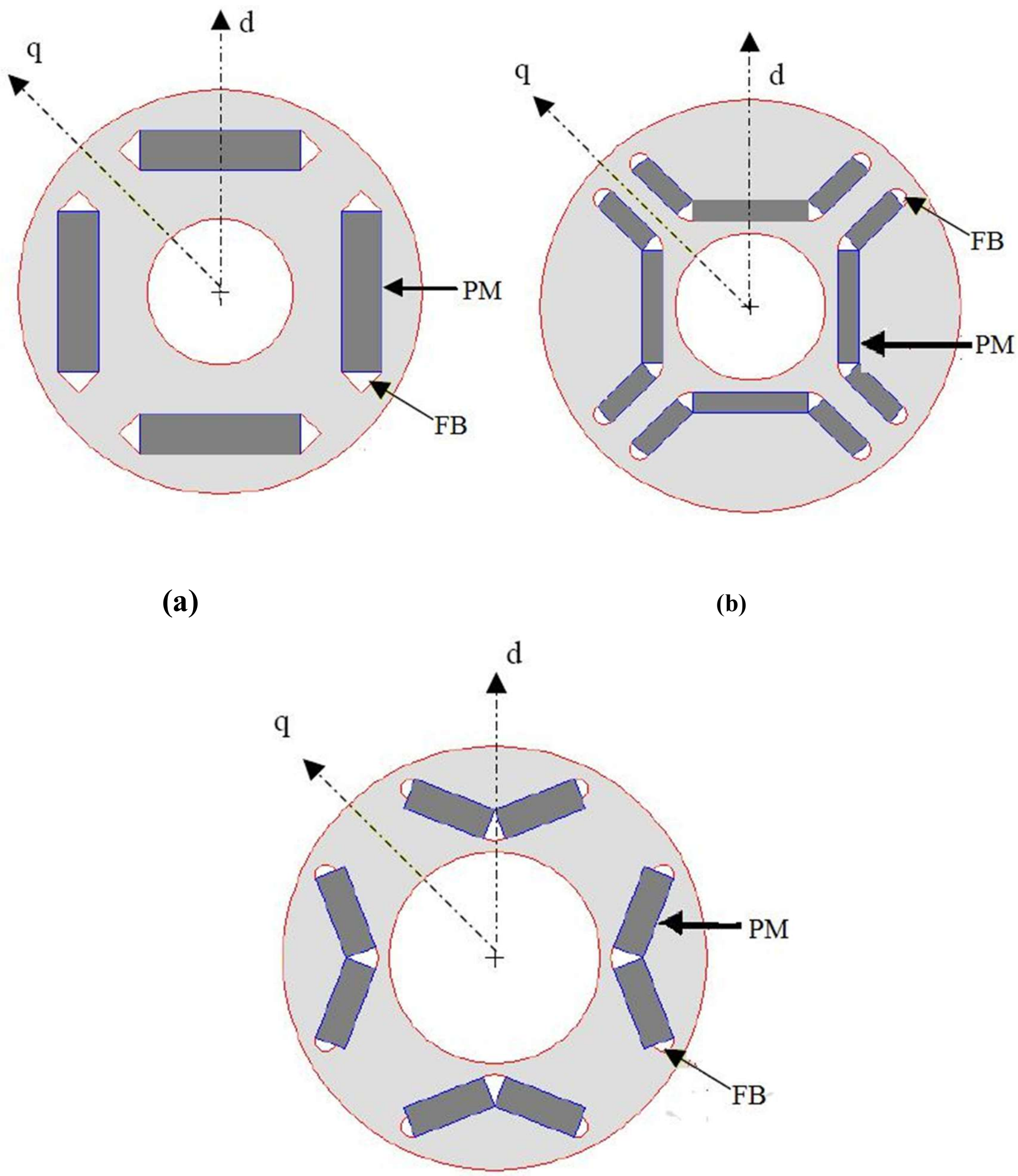
- Two applications were reported in the literature during the period of 1980 to 1990 (Hassan et al 1980; Mohamadein et al 1990). The main reason for inferior performance was the absence of vector controllers and its inferior performance with respect to the conventional machines.[22]-[25]

III. PERMANENT MAGNET SYNCHRONOUS RELUCTANCE MOTOR (PMSRM)

The next type of permanent magnet machines are the permanent magnet synchronous reluctance motor which is introduced with the permanentmagnets located in the flux barriers of the rotors. These motors are preferred due to the main characteristic of generating its output torque by both permanent magnet alignment and reluctance. It has the following useful properties when compared to SMPMSRM:

- Under-excited operation for most load conditions
- Field weakening capability with high inductance
- Ability to withstand high temperature
- High resistance from demagnetization

There are several types PM motors, and each type has its own advantages and specific applications. Figure 2.10 shows rotors with PM inserted in the flux barrier. In the absence of permanent magnets in each rotor configuration, the motor behaves like a pure reluctance synchronous motor. The rotor of PMSRM has some empty spaces, called flux barriers, for increasing its reluctance torque. In the past, much research has been conducted to determine the amount of PM in the flux barriers of different rotor structure. Also, it has been identified that by addition of more PM, it increases the torque and efficiency increases but it decreases the constant power region (Morimoto et al 1997; Morimoto et al 2001).



(a) (b) (c)

Figure 3.1 Rotors with PM inserted in the flux barrier

The rotor shown in Figure 2.10 (a) is the simplest design where the magnets are inserted in the flux barrier. The torque generated by this type of design is comparatively lesser than SMPMSRM. The arrangement of Figure 2.10 (b) is known as a 'flux-concentrating design. It has the advantage of the magnet pole area at the air-gap producing an air-gap flux density higherthan that in the magnet, but presents increased torque ripple and cogging torque. Also, it has been proved that by using V-shaped magnets as shown in Figure 2.10 (c), the torque can be increased with a wider efficiency operating range than the single layer, but it cannot avoid the increased PM cost. The polarity of magnets is chosen in such a way that counteracts the *q*-axis flux of the SRM at rated load. Regardless of the different choice of the *d*, *q* axis, in working principle, the PMSRM are similar to the interior permanent magnet motor .

However, a substantial difference is the high anisotropy rotor structure of PMSRM and, as a result, the low value of the PM flux. The value of PM flux is quite lower than the amount of rated flux. In contrast, in the normal IPM, most flux comes from the magnets and the flux produced by stator currents is considered as an unwanted reaction flux. In practice, becauseof the difference mentioned above between PMSRM and IPM machines, they have different suitability to the large flux-weakening ranges.

IV. CONTROL SCHEME OF SYRM DRIVE FOR EV

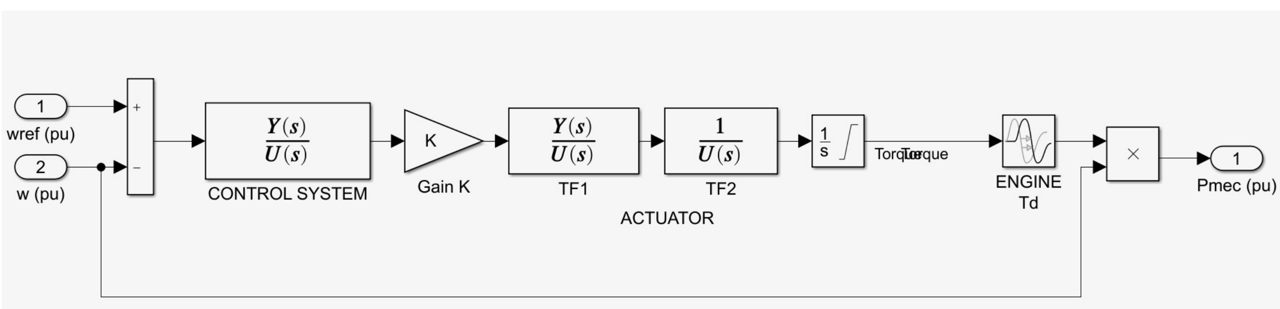


Figure 4.1 Simulink Diagram for control scheme SYRM drive for EV

The cascaded control structure in Fig. 2(b) consists of outer voltage loop and inner current loop. Since the battery interface converter is mostly operated under boost mode for discharging, the designs of all controllers are conducted in this mode. And their suitability in buck converter mode will then be verified. The designs of current and voltage controllers based on the dynamic models established using the state-averaging approach are described below.:

(a) Current controller

The current feedback controller is chosen to be PI type:

$$G_{ci}(s) = K_{Pi} + \frac{K_{Ii}}{s}$$

During the initial transient period after the occurrence of disturbance, one can let KIi □ .0 The equivalent circuit of the interface converter in boost mode during the PWM OFF period (TA= OFF, D4 = ON) and the control scheme are depicted in Fig. 3. The upper limit of P-gain is determined by applying the large-signal stability criterion for a ramp comparison CCPWM (RC-CCPWM) switching scheme, i.e., $(dv_c / dt) < (dv_{tri} / dt)$ to be:

$$K_{Pi} < (\frac{L_b}{(V_{dc} - V_b)K_i} \frac{dv_{tri}}{dt} = \frac{0.0015 \times 30 \times 10^3}{390 \times 0.01} = 11.54)$$

Accordingly $KPi = 3$ is chosen. Then through computer aided design, $KIi = 10$ is determined to yield the current loop-gain cross-over frequency of fc = 2.62 kHz (fc<< 0.5(fs)).

$$G_{ci}(s) = K_{Pi} + \frac{K_{Ii}}{s} = 3 + \frac{10}{s}$$

(b) Voltage controller

(i) Feedback Controller

The voltage controller is also chosen to be PI type:

$$G_{cv}(s) = K_{Pv} + \frac{K_{Iv}}{s}$$

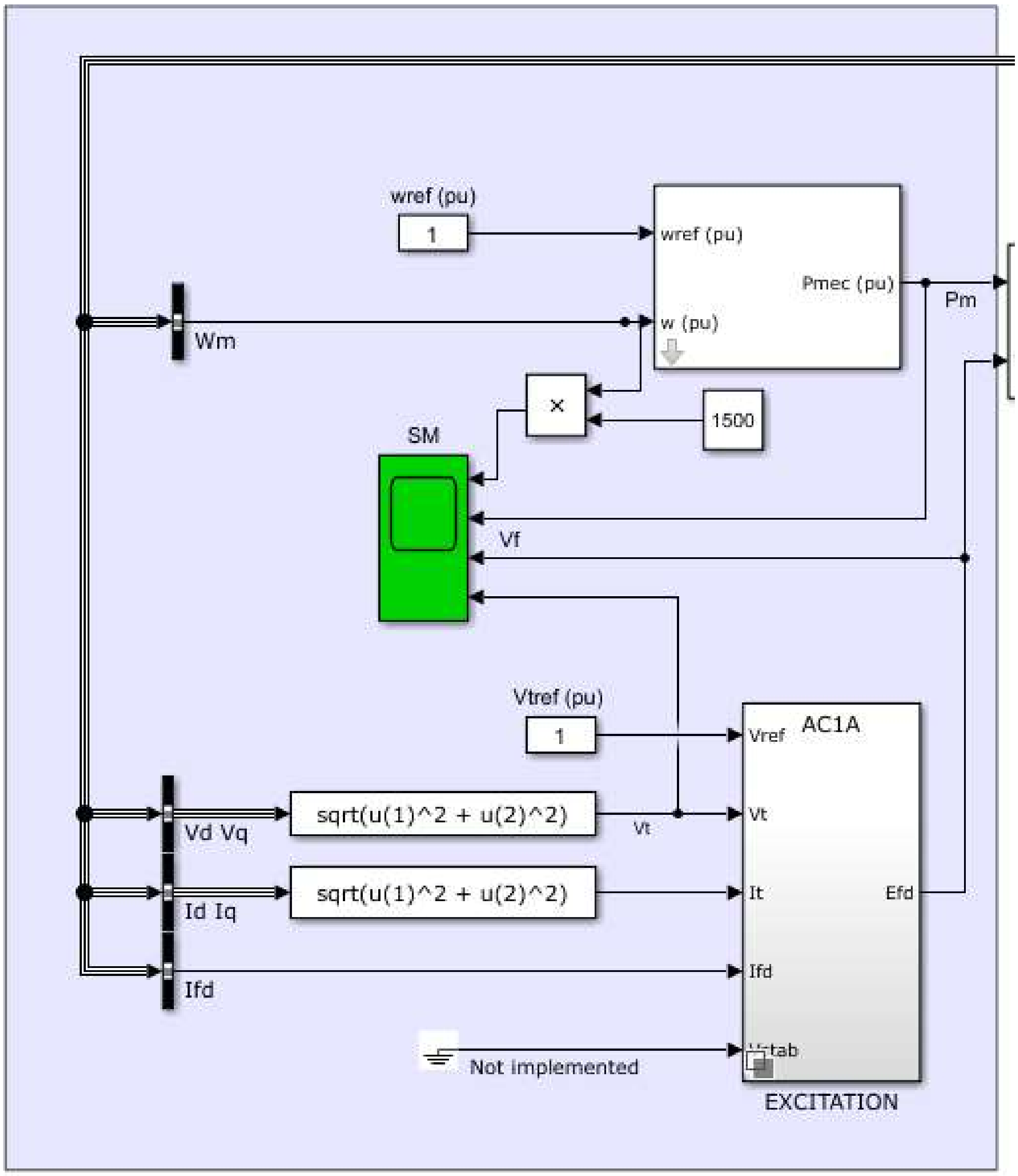
The controller design is treated as followed:

(1) A resistive load with *Rdc* is placed across the DC-link. By applying the step load regulation response method, the converter voltage loop dynamic model parameters are estimated.

(2) The controller *cv sG* is designed to have the desired voltage response due to a step load power change of Δ*Pdc* : (i) without overshoot; (ii) maximum voltage dip Δ*vdcm*; and (iii) restore time *tr* , which is defined as *dc r* Δ=Δ *vtv dm*.1.0)(By specifying *vdcm* =Δ V5 and *tr* = s2.0 due to a step load power change of *Pdc* =Δ 201.67W (*Rdc* 200 →Ω= 176.47Ω), through careful derivation one can

obtain the designed controller:

$$G_{cv}(s) = 1.0558 + \frac{15.6903}{s}$$



SYRM DRIVE CONTROL SCHEME

V. RESULT ANALYSIS

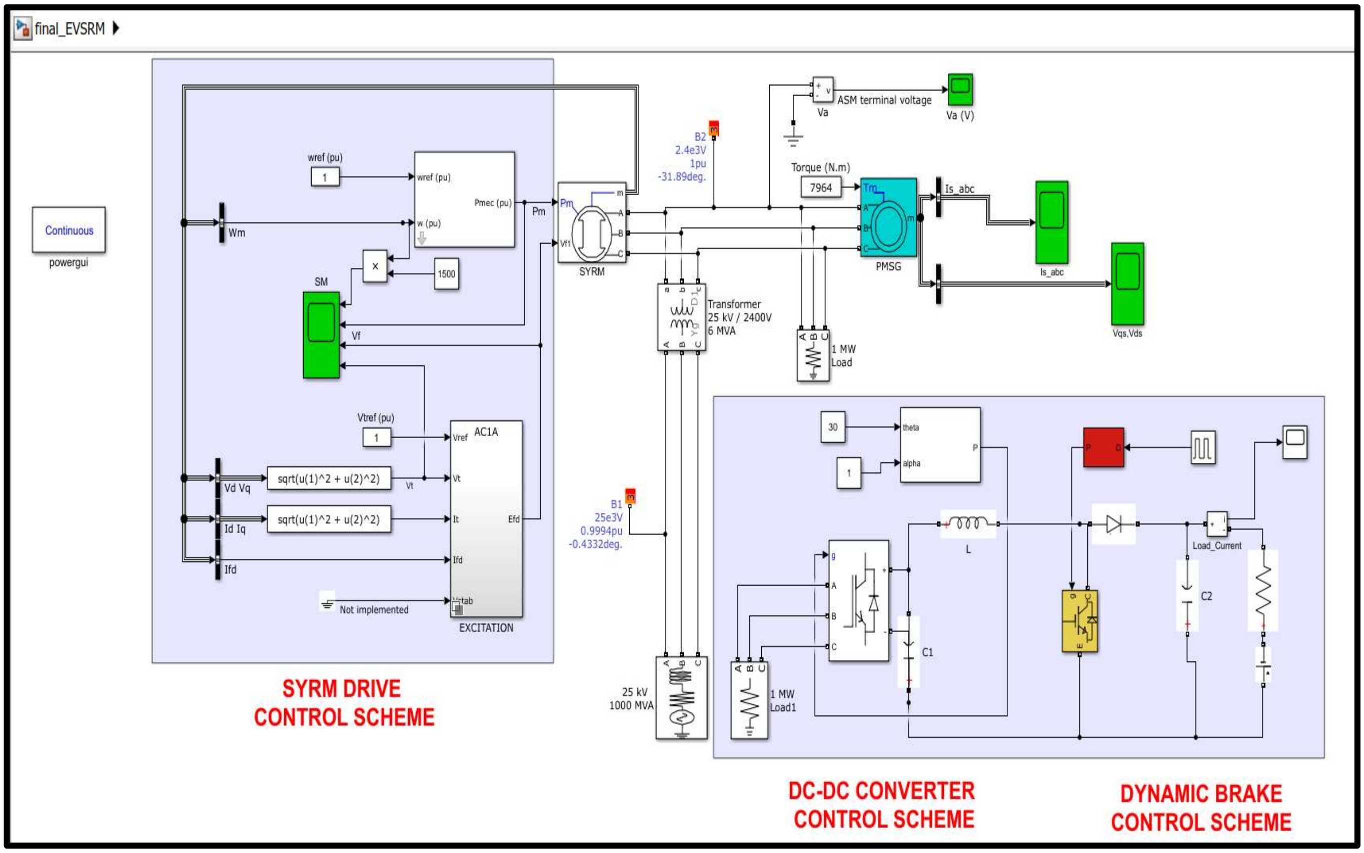


Figure 5.1 Simulink Diagram for development SYRM drive for EV

The established battery powered EV SynRM drive is shown in Fig. 1. A bidirectional DC/DC interface converter is used to establish a 550V DC-link from the battery bank (160V) in boost converter mode by AA LDT),,(. And a three-phase inverter is used to drive the SynRM coupled with a PMSG dynamic load. A flywheel is added on the shaft of M-G set to increase the kinetic stored energy for facilitating the regenerative braking test. The photo of the constructed M-G set is also depicted in Fig. 5.1 . The proper commutation is arranged to yield the improved driving characteristics. In addition, a dynamic brake leg is equipped to avoid the DC-link overvoltage due to the failure of regenerative braking.

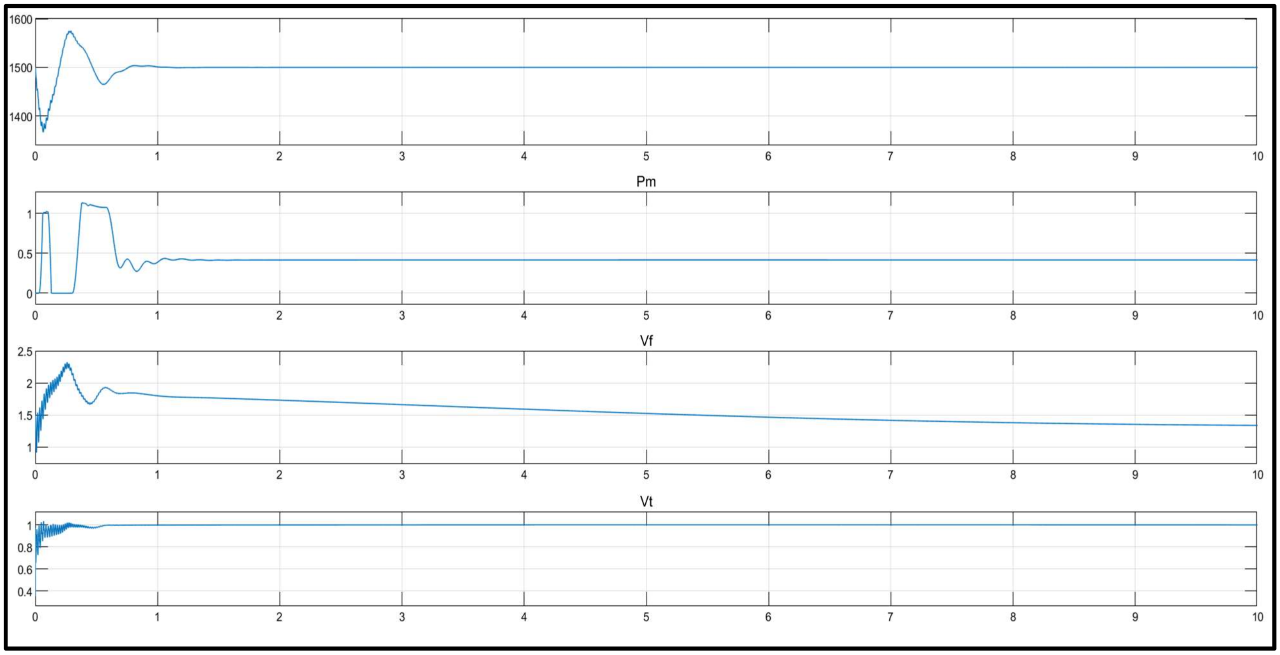


Figure 5.2 Speed for SYRM, Terminal Voltage, Field Voltage, Reference Voltage

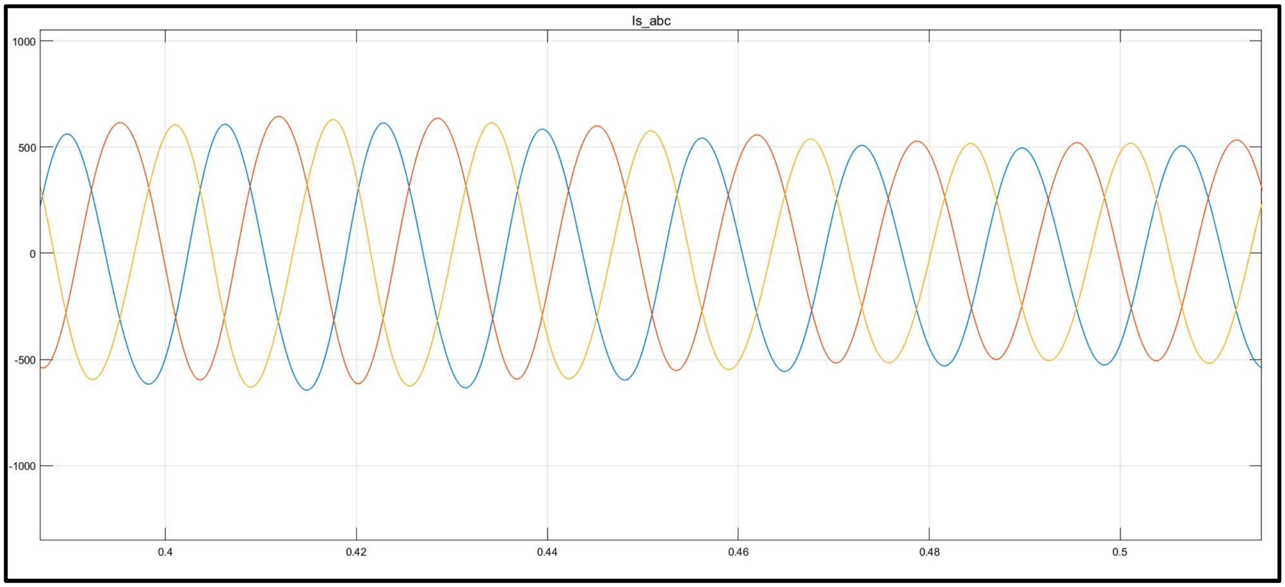


Figure 5.3 Grid Voltage receive from Synchronous Generator

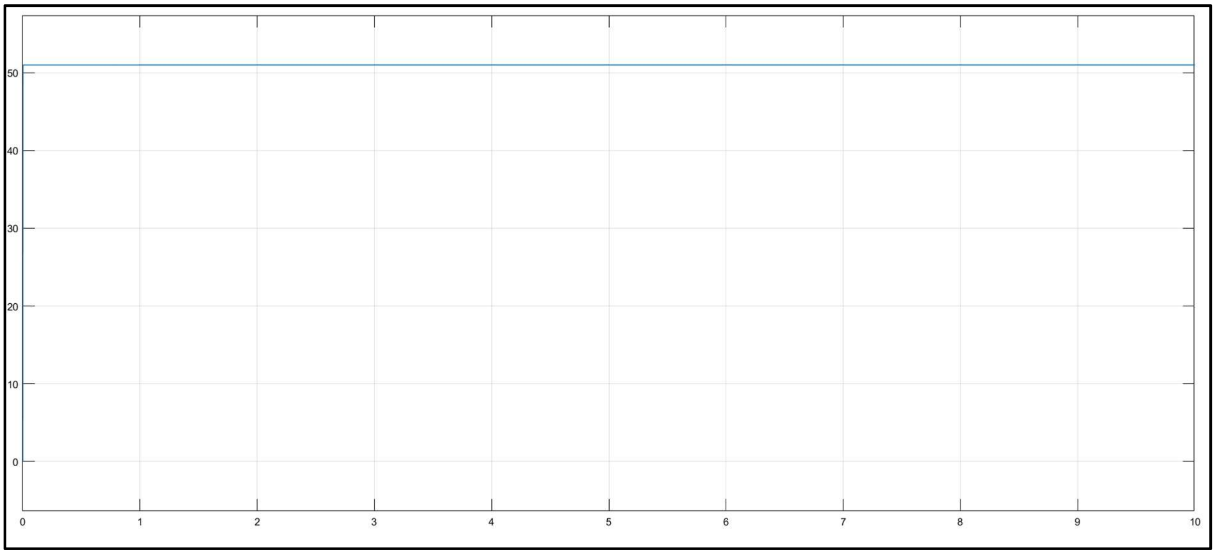


Fig. 5.4 Load Current flows through the Bidirectional DC-DC Boost Converter

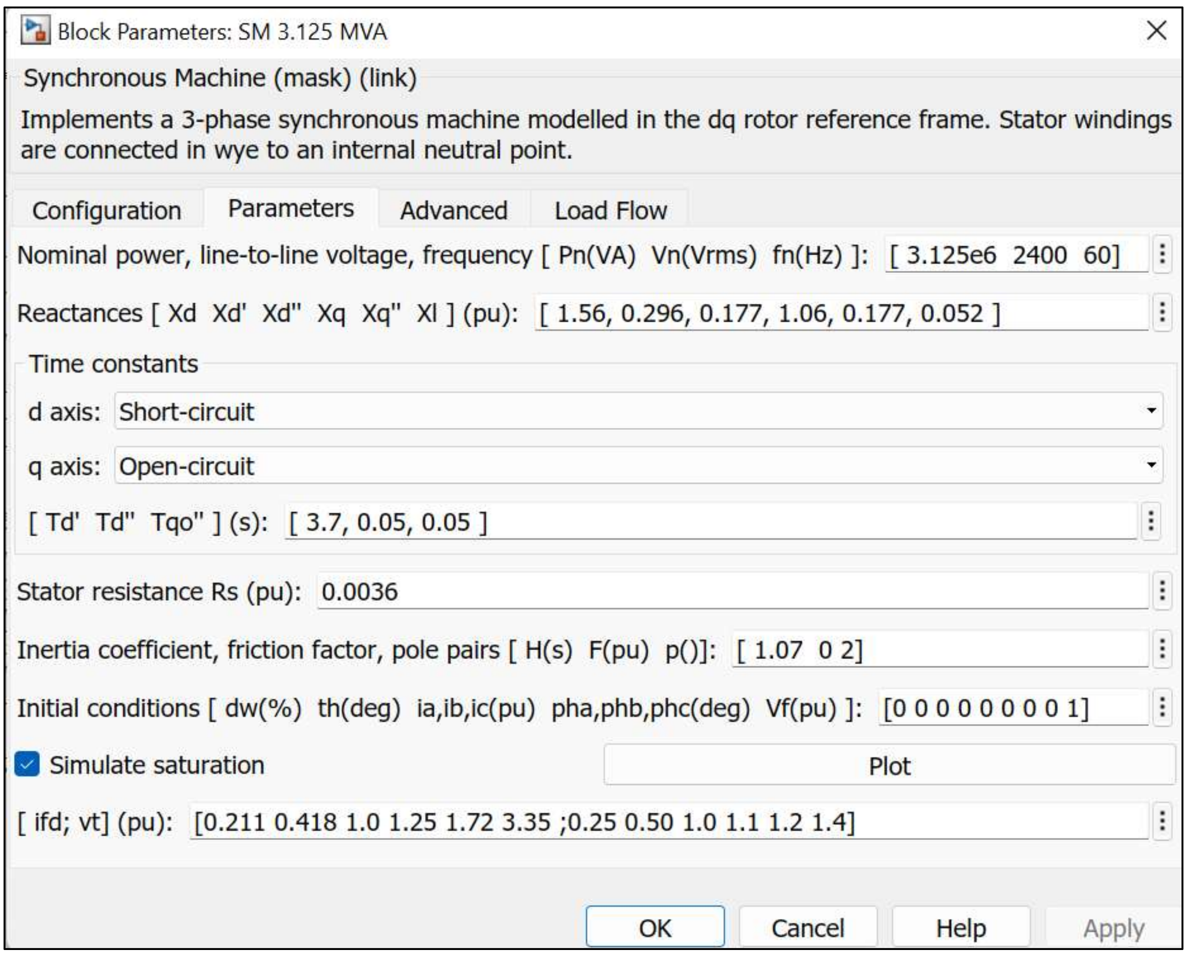


Fig. 5.5 Parameters of Synchronous Reluctance Motor Drive

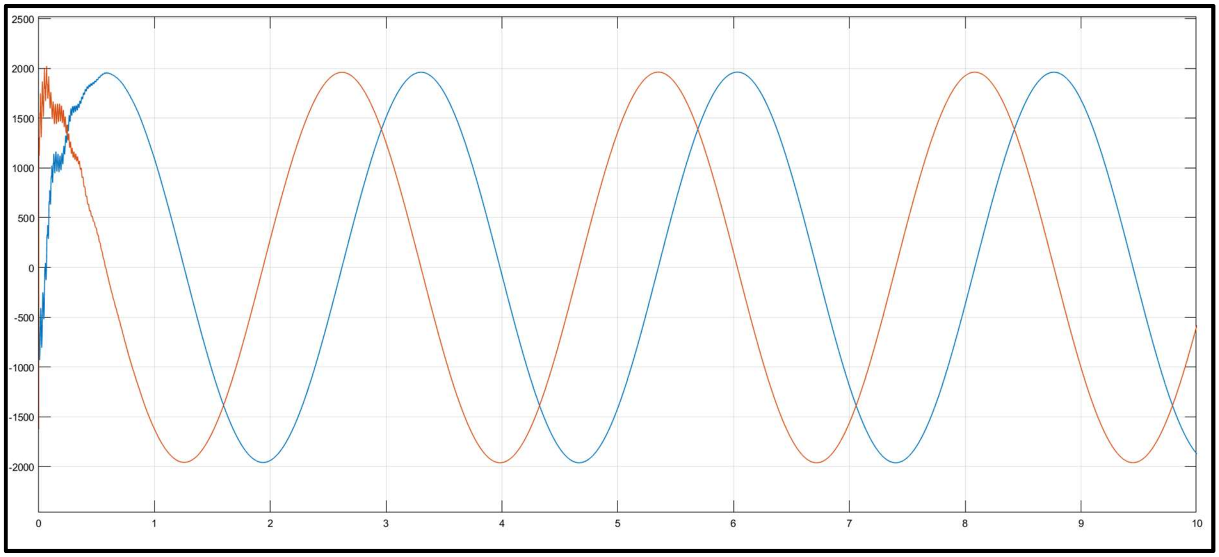


Fig.5.6 D-axis, Q-axis Current for the Excitation

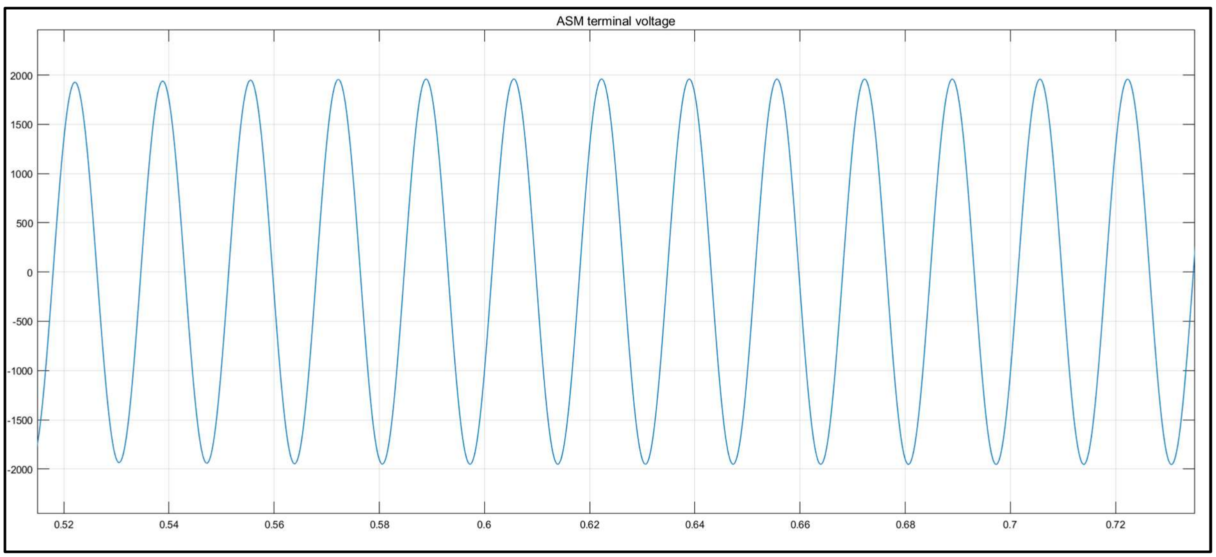


Fig. 5.7 Asychronous Motor Terminal Voltage

For an EV AC motor drive, the battery voltage must be determined considering the speed range and load level. To increase the battery voltage choice flexibility, one can add a bidirectional DC/DC converter [33-36] between the battery and motor inverter. The variable and well-regulated DClink voltage can yield the improved motor driving characteristics within wide speed range. And the regenerative braking is also applicable.

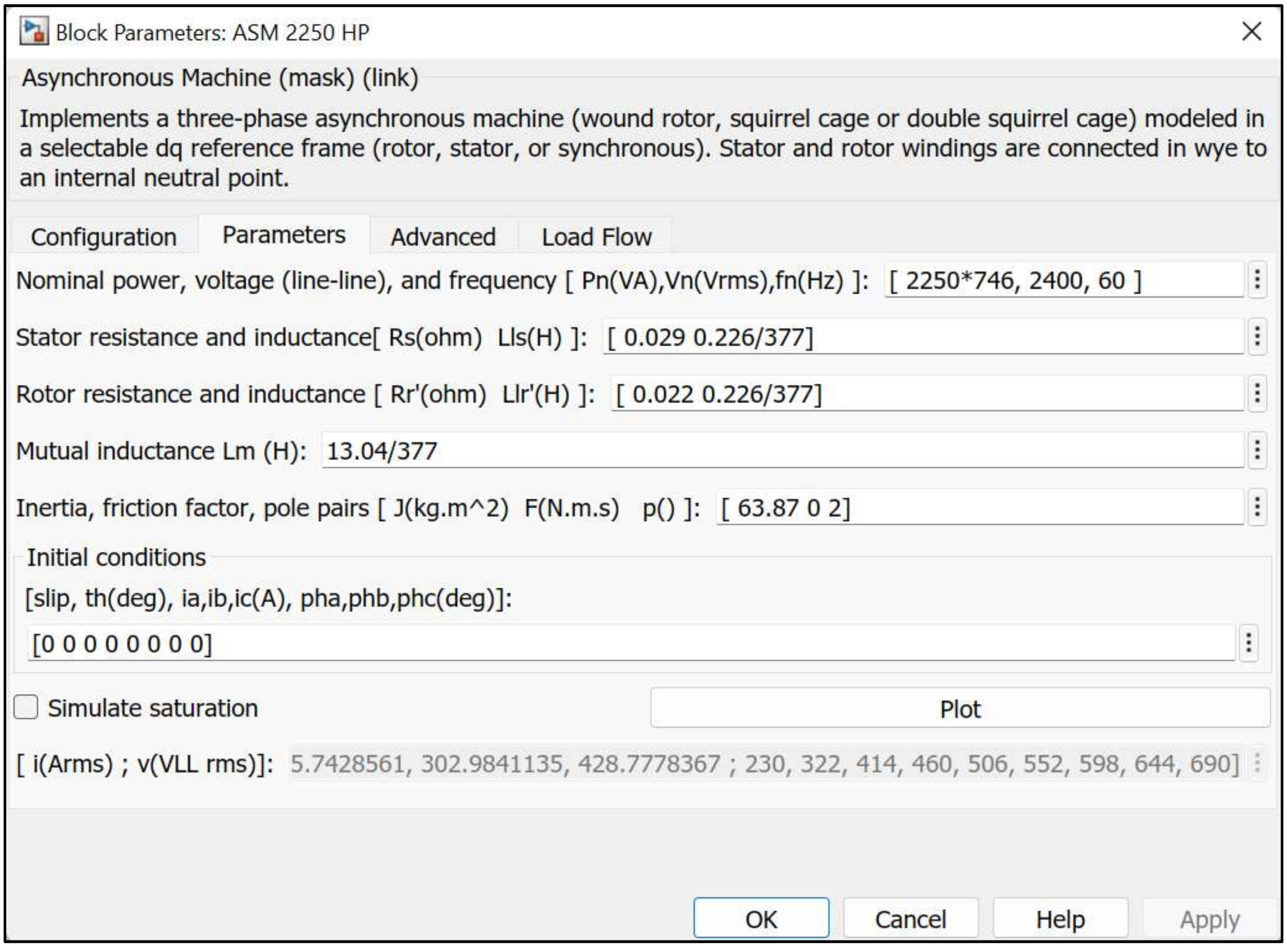


Fig. 5.8 Parameters of Permanent Magnet Synchronous Generator Drive

A bilateral DC/DC converter is used as an interface between the battery and the motor drive. The boostable and well-regulated DC-link voltage with robust regulation control can enhance the motor driving performance in wide speed range. And the regenerative braking energy can be successfully recovered to the battery. In SynRM drive, the robust current PWM switching control considering inherent slotting effects and robust speed model reference control are made. Moreover, an adaptive commutation scheme (ACS) is developed to automatically set the commutation instant for achieving the motor total loss minimization.

4.3 CONCLUSION

An EV SYRM drive and the performance Enhancement control technologies. The battery bidirectional Interface DC/DC converter with robust voltage control is First established to provide boostable and well-regulated Motor drive DC-link voltage. The regenerative braking can Also be successfully operated. As to the synrm drive, the Back-EMF cancellation feedforward control and the robust Tracking error cancellation control are added to the feedback Control to counteract the slotting effects. Then the robust Speed model reference control is made. In addition, the Adaptive commutation scheme is proposed to achieve the Motor total loss minimization..

4.4 FUTUE SCOPE

Permanent magnet machines are increasingly attracting the researchers due to their enhanced performance and easier controllability. The new design of PMSRM proposed in this research work is analyzed using 2D finite element method for estimating the motor parameters. 2D analysis is performed due to easier modeling and lesser calculating time. Though the modeling is complex in FEM, the effect of saturation and cross magnetization could be analyzed more accurately. Implementation of the 3D FEM based design through the same procedure is recommended for the future work for more accurate results. In the presented work, effect of each parameter was studied independent of the other existing parameters. Use of a design procedure which includes the mutual effects of different parameters is suggested in order to achieve global optimized rotor geometry.

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