DEVELOPMENT OF AN ELECTRICAL VEHICLE SYNCHRONOUS RELUCTANCE MOTER DRIVE

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ABSTRACT

In this project 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 evaluated using simulation results

1. INTRODUCTION

1.1 About the project

Recently, electric vehicles have been gradually employed to replace the internal combustion engine vehicles to reduce the fossil consumption. Unlike the general industrial drives, the motor drive to be the actuator of an EV must satisfy more stringent driving requirements. Till now, induction motor and permanent-magnet synchronous motor (PMSM) are still the mainstream machines in EV propulsion. However, SynRM also possesses the application potential as the comparative explorations made in. SynRM has drawn significant attention recently due to its merits of simple and rigid rotor structure, no permanent magnet and without cogging torque, having no rotor copper loss, low cost, reliable and high efficiency, etc. Thus, it possesses high potential to replace the induction motor in various speed driving applications including EVs. The energy conversion efficiencies of SynRM can reach the IE4 class, higher than Ims and slightly lower than PMSMs. However, it also has some drawbacks, the critical ones are lower power factor, higher core loss, higher torque ripple and difficult to properly set the PWM commutation instant. The existing researches concerning the performance enhancement for SynRM drive include: (i) Motor designs: emphasized on EV applications, rotor structure optimization, low torque ripple, etc.; (ii) Switching controls and loss minimization: Basically, the existing ones can be classified into searching and loss model-based methods. The former approaches minimize the power consumption by determining the d-axis current on-line. As to the loss model-based approaches, they are based on the motor mathematical model, resulting parameter sensitive control characteristics, particularly the d- axis inductance, which is significantly changed with the armature current level due to magnetic saturation. To reduce the effects of d-axis inductance, some efficiency maximization control approaches based on the estimated inductance have been developed. In the developed SynRM drive, the commutation angle is set by an ACS using on-line updated motor parameters, including core loss resistance, d-axis and q-axis inductances, to minimize motor total loss; and (iii) Current control and direct torque controls, etc. The torque ripple is mainly caused by its inherent slotting effects. To alleviate this, the current control must first be made considering the nonlinear winding inductances and the harmonics caused by slotting effects. 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 between the battery and motor inverter. The variable and well-regulated DC link voltage can yield the improved motor driving characteristics within wide speed range. And the regenerative braking is also applicable. In the recent researches, the review of modular multilevel converters for electric transportation applications can be found in, and a new bidirectional buck-boost converter for EV is presented in. This paper presents the development of an EV SynRM drive. A one-leg bidirectional boost-buck battery interface DC/DC converter is equipped to enhance the motor driving performance. After comprehending the key issues of a SynRM, the robust current PWM switching control scheme considering slotting effects is developed. And the robust speed model reference control is made. Then an adaptive commutation scheme is proposed to determine the proper commutation instant with total loss minimization. The fitted core loss resistance and d- and q-axis inductances are all used for determining the commutation angle. The driving characteristics of the established EV SynRM drive are verified experimentally, including acceleration

2. Literature Survey

[1] T. A. Lipo, Although design of the variable reluctance (switched reluctance) type of synchronous machine has experienced intense activity in recent years, relatively little effort has been expended on improving the torque capability of the synchronous reluctance type of motor drive. Based on the analysis presented in this paper, it appears that substantial improvements can be made in the design

of such motor drives resulting in performance characteristics which match or, indeed, perhaps even exceed that of the induction machine.

[2] P. Krause, O. Wasynczuk, an updated approach to reference frame analysis of electric machines and drive systems since the first edition of Analysis of Electric Machinery was published, the reference frame theory that was detailed in the book has become the universally accepted approach for the analysis of both electric machines and electric drive systems. Now in its second edition, Analysis of Electric Machinery and Drive Systems presents, in one resource, the application of this theory to the analysis, simulation, and design of the complete drive system including the machine, converter, and control.

[3] I. Boldea; L. N. Tutelea; L. Parsa and D. Dorrell, Hybrid and electric vehicle technology has seen rapid development in recent years. The motor and the generator are at the heart of the vehicle drive and energy system and often utilize expensive rare-earth permanent magnet (PM) material. This paper reviews and addresses the research work that has been carried out to reduce the amount of rare-earth material that is used while maintaining the high efficiency and performance that rare-earth PM machines offer. These new machines can use either less rare-earth PM material, weaker ferrite magnets, or no magnets; and they need to meet the high performance that the more usual interior PM synchronous motor with sintered neodymium-ironboron magnets provides. These machines can take the form of PM-assisted synchronous reluctance machines, induction machines, switched reluctance machines, wound rotor synchronous machines (claw pole or biaxial excited), double-saliency machines with ac or dc stator current control, or brushless dc multiple-phase reluctance machines.

[4] S. Estenlund, M. Alakula and A. Reinap, This literature review presents a summary of recent research about PM-less machines for electrical vehicles. Recently, IPM machines has proven to be very popular among electrical vehicle manufacturers. However, the neodymium permanent magnets being used are expensive and have a risk of rocketing the production cost of a machine if the price increases more. With this in mind, five PM-less machine topologies have been studied in recent literature. The topologies in question are synchronous reluctance machines, switched reluctance machines, double stator switched reluctance machines, electrically excited synchronous machines and induction machines. Their pros, cons and potential in the EV market are reviewed, coming to the conclusion that they have a potential for the EV market, depending on how demands and techniques are developed. It is concluded that SynRM are cheap and easy to control, while design and material choices are the greatest challenges for it meet the requirements. SRMs are robust and simple to manufacture, but noise and torque ripple reduction as well as design and materials needs more

research. EESMs have a wide operation area with high efficiency, but larger losses for higher load, which makes cooling a challenge. Ims is mature and reliable, but control can be improved and some trade-offs in the design choices has to be dealt with.

[5] D. Cabezuelo, E. Ibarra, E. Planas, I. Kortabarria and J. I. Garate, Nowadays, permanent magnet synchronous machine technologies are being widely used in electric and hybrid electric vehicle applications due to their features and high-power densities. However, and considering rareearth material cost fluctuations and supply concerns, the manufacturers and academia are working towards the introduction of rare-earth free alternatives. The main drawback of these alternatives is their lower power density. In this context, this paper reviews the recent advances achieved to provide competitive operational features for these alternative candidates, i.e., synchronous reluctance, permanent magnet assisted synchronous reluctance, induction and switched reluctance machines.

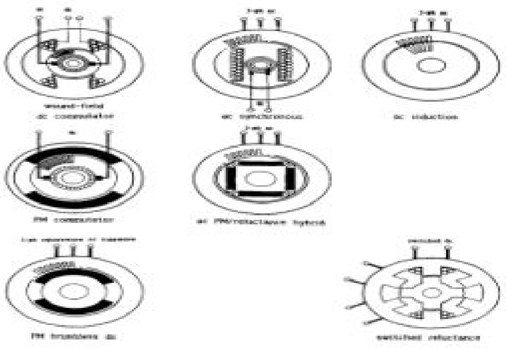
3. Methodology

INTRODUCTION

This machine developed particularly in the 1960’s as a line-start (cagetype) synchronous ac motor for applications where several motors are operated synchronously from a single voltage-source inverter. In some cases, it has been replaced by cage-type ac permanent-magnet (PM) motors that, although more expensive, have better performance and permit more motors to run from the same inverter 171. More recently, there has been increasing use of variable-frequency ac induction motor drives with one motor per inverter. At first, the six-step inverter was used, usually with constant voltage/frequency ratio and often without speed feedback. The development of pulse-width-modulated (PWM) inverters *followed with slip-control, and today, field-oriented or “vector” control is the most advanced form of ac drive, with performance characteristics that match those of the best dc drives. Although the induction motor is the most common in ac drives, synchronous PM motors are also used. With one motor per inverter, there is no need for a rotor cage because the motor does not have to start across the line. It is perhaps surprising that there has been so little development of the cage less synchronous reluctance motor instead of the induction motor or PM ac motor for variable-frequency operation. One reason is probably its reputation for poor efficiency and low power factor, but the removal of the rotor cage and the use of field-oriented control Paper IPCSD 91-17, approved by the Electric Machines Committee of the IEEE Industry Applications Society for presentation at the 1989 Industry Applications Society Annual Meeting, San Diego, CA, and October 1-5. Manuscript released for publication February 5, 1991. This work was supported by the UK Science and Engineering Research Council, a grant from the General Electric Company, and the member companies of the Scottish Power Electronics and Electrical Drives (SPEED) Consortium.

The main features of the synchronous reluctance motor are as follows: The rotor is potentially less expensive than the PM rotor. Because it requires no cage winding, it is lighter and possibly cheaper than an induction-motor rotor. The torque per ampere is independent of rotor temperature, unlike that of the PM or induction motors. The stator and the inverter power circuit are identical to those of the induction motor or PM synchronous motor drives. The control is simpler than that of the field-oriented induction motor drive, although shaft position feedback is necessary. Because of scaling effects, the poor efficiency and high slip of small induction motors prevent the extension of ac drive technology down to low power levels. The AC motor or brushless DC motor can be used instead, but PM motors are more expensive. They are temperature sensitive, susceptible to demagnetization, and may require additional inverter protection. The synchronous reluctance motor offers an alternative means of obtaining the advantages of a synchronous motor but at lower cost

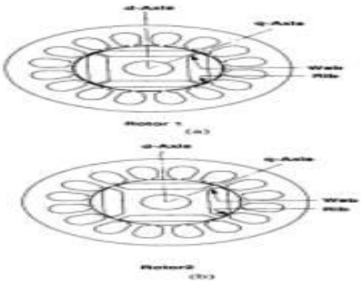
The synchronous reluctance motor's smoothly rotating field distinguishes it from the switched reluctance motor. It therefore fits in the "family of ac drives," which is represented by the motors along the diagonal of Fig. 4.1. This family enjoys a high degree of uniformity of motor and controller component parts while offering a wide range of performance characteristics [9] obtained by changing only the motor rotor and the control strategy. The rotating field permits smooth torque and good operation down to low speeds, both of which are difficult to achieve in the switched reluctance motor. Unlike the switched reluctance motor, the synchronous motor is completely compatible with the stators and controllers of other ac motor drives. To provide a shorter name and to distinguish it from the switched reluctance motor, the term SYNCHREL is used in this paper. The design of a small SYNCHREL motor drive is described, and the performance is compared with those of a switched reluctance drive, an induction motor drive, and a brushless dc (BLDC) PM motor drive. The results presented are confined to the preliminary experimental findings of a study whose scope includes larger drives than the ones.



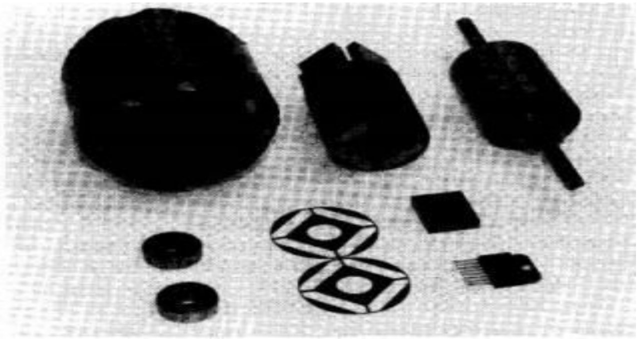
Family of motor types showing ac motors along the diagonal:
the SYNCHREL motor is the center motor with magnets removed [9]. described here, as well as the optimization of lamination geometry and control parameters. It is palmed that those results will be published later. Particular points of interest in the present paper are the comparison of motors of different types, all with essentially the same frame size and tested under identical conditions.

EVOLUTION OF THE DESIGN

Three rotors have been built, and the cross sections of two of these are shown in The pole pieces are held by two



Transversely laminated single-barrier SYNCHREL rotors: (a) Rotor 1; (b) rotor 2.



Components of hybrid synchronous reluctance/PM motor showing optional permanent magnets.

Thin ribs that attach to the q axis webs in the same way as in the interior magnet motor described by Jahns. Fig. 4.4 shows the components of the disassembled motor. To minimize Ld, the ribs (Fig. 4) must saturate at a low level of current. This requires them to be radially thin. L, is not sensitive to the air gap length because of the large reluctance in the flux barrier. L, must be maximized; therefore, saturation is undesirable in any part of the q-axis flux path. Therefore, the pole piece needs to have adequate radial depth, and the web needs to be sufficiently wide as well. Rotor 1 (Fig. 4.4(a)) was designed to accommodate 5.4-mmthick magnets, and for operation as a SYNCHREL motor, the webs are too narrow; therefore, they were widened in rotor 2. With 16 slots, this ensures that the web does not saturate when aligned with the axis of the phase winding. The parameters of the two rotors are summarized in Table I and [12]. The inductances quoted in Table I were measured and calculated at 3.0 A. The synchronous inductance ratios quoted in Table I are all well below the theoretical limit of 25 mentioned earlier. This is because saturation decreases the q-axis inductance, whereas leakage through the ribs increases the d-axis inductance. It is the price paid for the convenience of a lamination that has a simple punching geometry and the ability to accommodate magnets when required. However, as stated earlier, an object of the investigation is to determine whether acceptable performance is obtainable while retaining these natures. Fig. 4.6(a) and (b) show typical dand q-axis finite-element flux plots. The calculation of magnetization curves is a straightforward exercise of the finite-element method 181 once the magnetization characteristics of the core steel are accurately known. Fig. 4.6 shows measured magnetization curves for rotor 1, clearly showing the effect of saturation on the inductance ratio. Fig. 4.7 shows the running torque of both rotors as a function of rms phase current. The calculated curves were obtained from equation (1) and L, and L, taken from the appropriate magnetization curves at the appropriate current level. This calculation is approximate, but it reflects the general trend and underlines the superiority of rotor 2 with its higher inductance ratio. The torques in Fig. 8 were measured at a low speed in order to minimize the effects of windage and core losses and provide data for the comparison described in Section

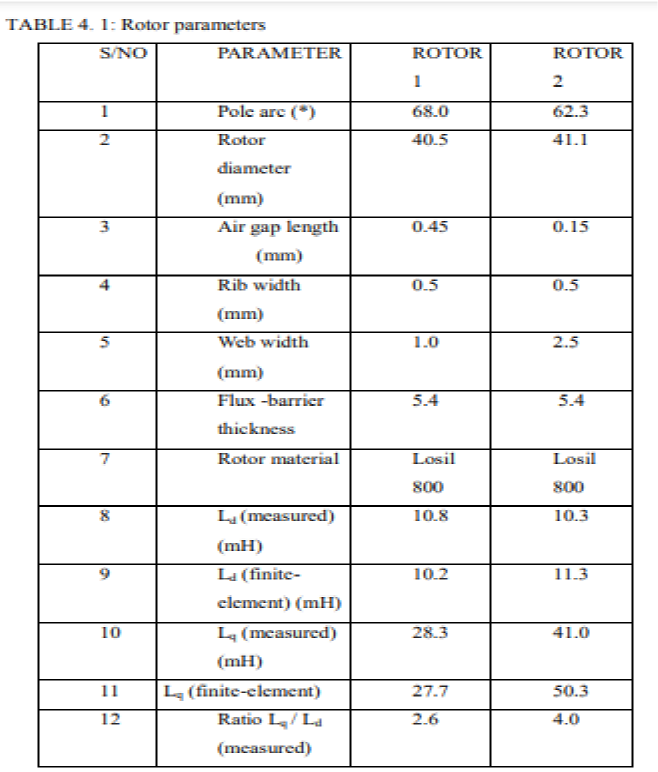
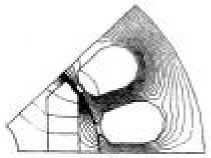


TABLE 4. 1: Rotor parameters

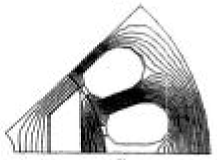
S/NO	PARAMETER	ROTOR 1	ROTOR 2
1	Pole arc (*)	68.0	62.3
2	Rotor diameter (mm)	40.5	41.1
3	Air gap length (mm)	0.45	0.15
4	Rib width (mm)	0.5	0.5
5	Web width (mm)	1.0	2.5
6	Flux -barrier thickness	5.4	5.4
7	Rotor material	Losil 800	Losil 800
8	L_d (measured) (mH)	10.8	10.3
9	L_d (finite-element) (mH)	10.2	11.3
10	L_q (measured) (mH)	28.3	41.0
11	L_q (finite-element)	27.7	50.3
12	Ratio L_q / L_d (measured)	2.6	4.0

ELECTRONIC CONTROL

The configuration of the electronic control for two-phase motor is shown in Fig. 4.8 A 360-pulse magneto resistive encoder mounted on the motor shaft generates an indexed pulse count representing the rotor position. This count is used to address two EPROM's: one for the d- axis and one for the q axis. The EPROM's contain sine and cosine values multiplied in MDAC's by the reference or command value of the phase current. These analog signals are used as references for two full H-bridge hysteresis-type current-regulators, one for each phase. Power integrated circuits operating at 40 V are used for the H bridges. In the simplest mode of operation, the current phase angle is set at a fixed value of 45 electrical degrees, and the motor is controlled entirely by its current reference with torque approximately proportional to current

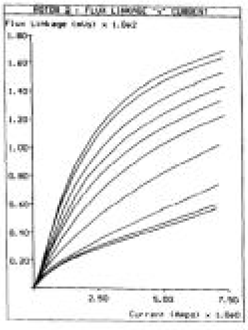


(a)



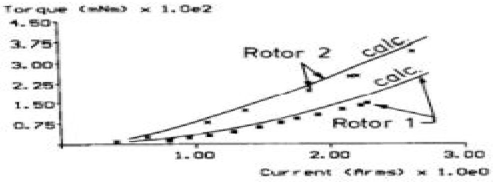
(b)

. (a) D-axis flux plot showing operation of flux barrier and leakage through the ribs that hold the pole pieces in position. D-axis current = 3.0 A; (b) Q-axis flux plot. Q-axis current = 3.0 A.

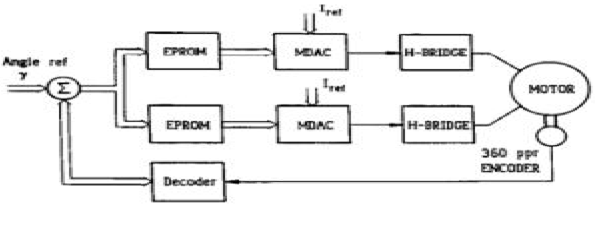


Phase flux linkage versus current over a range of rotor positions between the d axis and the q axis; rotor 2.

Two full H-bridge hysteresis-type current-regulators, one for each phase. Power integrated circuits operating at 40 V are used for the H bridges. In the simplest mode of operation, the current phase angle is set at a fixed value of 45 electrical degrees, and the motor is controlled entirely by its current reference with torque approximately proportional to current.



Running torque versus phase current. The points are measured; the lines are calculated (by (l), with inductances read from Fig. 6).

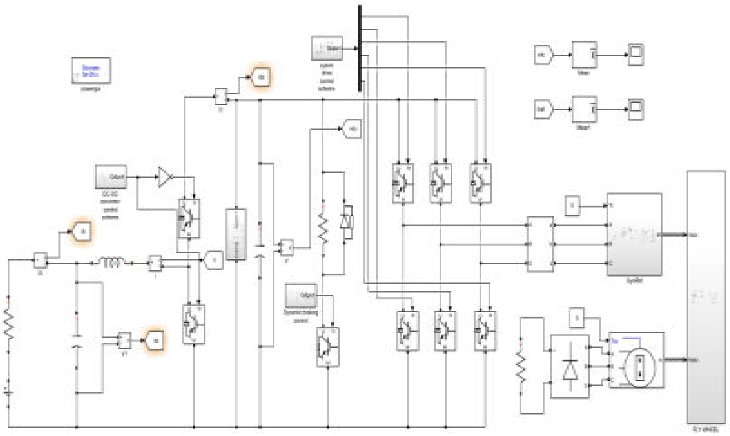


Electronic controller block diagram

An electronic sensor installed at the measurement of the location continuously sends an input signal to the controller. At set intervals the controller compares this signal to a predefined set point. If the input signal deviates from the set point, the controller sends the corrective output signal to the control element. This electric signal must be converted to a pneumatic signal when used with an air operated value. Such as a Terrace series 910 or 940 control value. The conversion can be made using a Terrace TA901 1/p Transducer, which converts a 4 to 20mA electric signal to a 3 to 5 psi air signal.

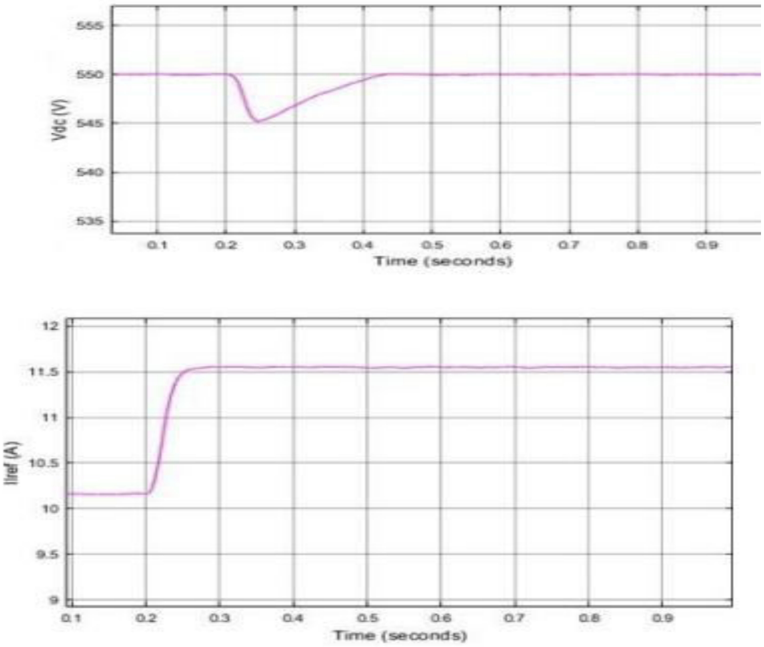
4. SIMULATION RESULTS

Development of an Electric Vehicle Synchronous Reluctance Motor Drive



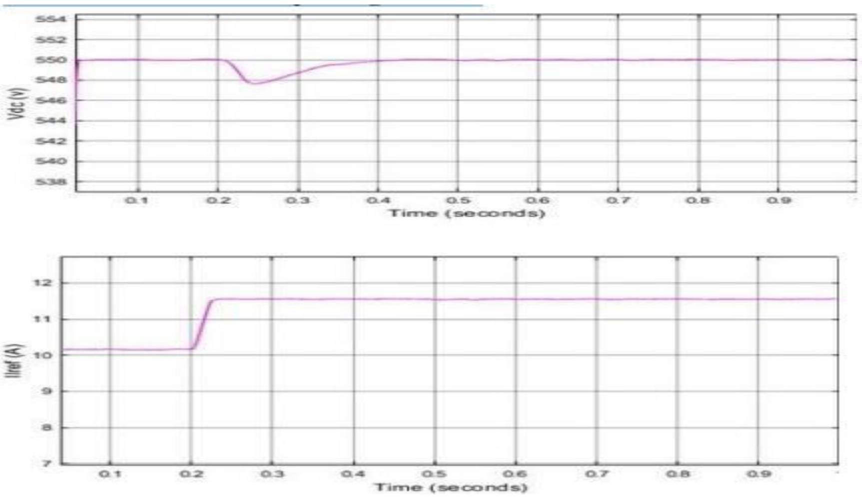
Simulink Model of proposed system

Boost converter due to step change in load



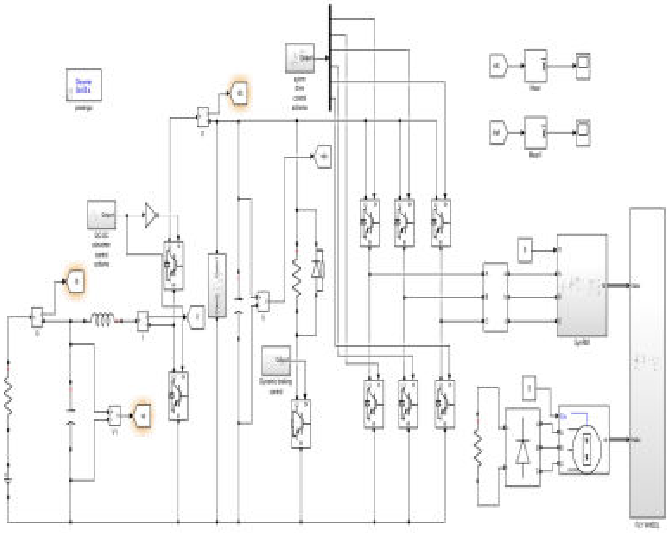
DC-link voltage vdc of the boost converter due to a step 176.47ohm (deltaPdc = 201.67W)◊load resistance change Rdc= 200ohm under (Vdc = 550V, Rdc = 200ohm) by the designed controller: (b) simulated result.

Boost converter due to step change in load:

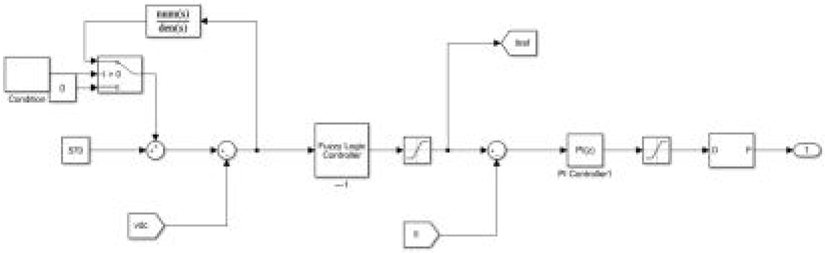


Measured dc V and *L i of the boost converter due to a load 176.47ohm under (Vdc = 550V, Rdc =◊resistance change of Rdc=200ohm 200 ohm) without and with robust controller (Wv =0.5).

EXTENSION SIMULATION RESULTS



Simulink diagram of proposed model



Simulink diagram of fuzzy logic controller

5. CONCLUSIONS

Although till now, IM and PMSM are the major EV actuators, SynRM also possesses this application potential. However, except for the motor design, the proper driving control is the critical issue. This paper has presented the development of an EV SynRM 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.

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