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Regenerative Braking Using Switched Reluctance Generator

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***Abstract* — This paper proposes an effective method of energy regeneration during braking for a dc motor or internal combustion(IC) engine. During the braking period, instead of dissipating the kinetic energy in the brake shoes and poles in the form of heat, this energy is recovered using a switched reluctance generator that is mechanically coupled to the shaft of prime mover. Here the DC motor or the IC engine acts as a prime mover for the switched reluctance generator (SRG) which can be considered the dual of the switched reluctance motor (SRM). In the SRG the mechanical energy is converted into electrical energy by properly synchronizing the phase currents with rotor position. During generation, the SRG produces negative torque that is trying to oppose rotation, thereby extracting energy from the prime mover. Hereby the kinetic energy from the prime mover is converted into the electrical energy and used for battery charging applications. SRG generates energy as directed by the power controller.**

I. Introduction

SRM drives are simpler in construction compared to induction and synchronous machines. The SRM drives gives several advantages such as high efficiency, maximum operating speed, good performance of the motor in terms of torque/inertia ratio, together with four quadrant operation, making it attractive for variable speed application[2]. The absence of windings on the rotor helps to keep the majority of the losses within the stator, making the SRG relatively easy to cool. The switched nature of SRG makes it compatible with the engine that drives the SRG. SRG makes it compatible with any application that requires variable-speed operation, like in the case of aerospace and automotive applications. Disadvantages for the SRG are that they are difficult to control, that they require a shaft position sensor to operate, and they tend to be noisy [3]. The power extracted from the DC motor prime mover for various conduction angles are shown in this paper.

Figure.1 shows the relationship between the ideal inductance profile and phase currents for motoring and generating operation. For a 3φ-6/4 motor Number of phases φ=3(6/4). Number of stator poles Ns = 6, Number of rotor poles Nr = 4. Step angle=360/(φxNr)=360/(3x4)= 30°.The angle of rotation from one unaligned position of Phase A to next unaligned position of Phase A is 90 degree mechanical or 360 degree electrical. Phase A inductance profile will start with the unaligned position at 0 degree mechanical and reach unaligned position again at 90 degree mechanical. Phase B and C inductance profile will lag Phase A inductance profile by 30° mechanical and 60°mechanical respectively. Let the turn on angle be ά and turn off angle be β respectively. If ά and β are located at 45 and 75, the phase excitation current will be placed on the falling inductance slope. In this mode the SRM is operated in the generating mode converting mechanical energy from the prime mover to electrical energy.

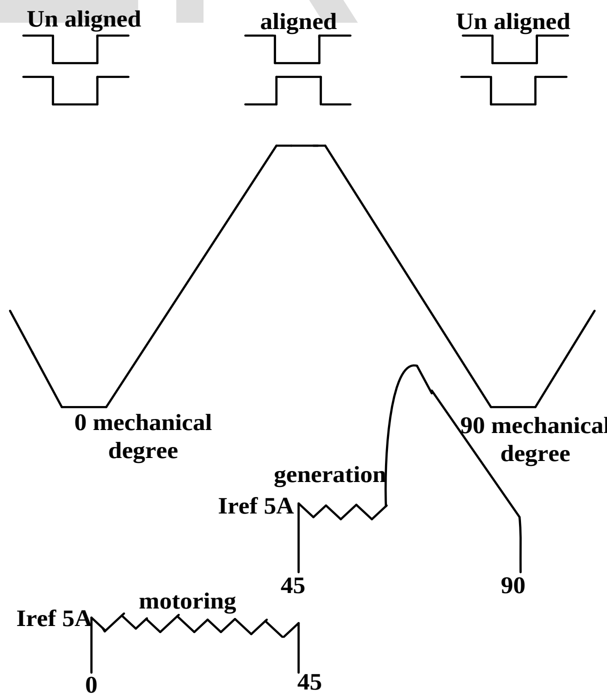

Fig. 1: Ideal inductance profile of SRM

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Referring Figure 2.a, phase winding A is connected to 12v DC supply through power semiconductor switches S1 and S2. For motoring mode, S1 and S2 are turned on when the rotor position causes a rising inductance slope for Phase A coils. S1 and S2 are turned off to de energize the Phase A stator coils. The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D1 and D2 to the supply. Thus the stored energy is fed back to the DC source[1]. Similarly Phase windings B and C are also switched on and switched off in a cyclic manner. This circuit requires two power switching devices and two diodes for each Phase winding. For high speed operation the stored energy can be fed back to the DC source within the available period. Usually the upper devices S1, S3, and S5 are turned on and off from the signals obtained from the rotor position sensor. The duration of conduction or angle of conduction can be controlled by using suitable control circuitry. The lower devices S2, S4, and S6 are controlled from the signals obtained by chopping frequency signal to control phase current. The current in the phase winding is the result of logical AND function of the rotor position sensor and chopping frequency [7] – [9].

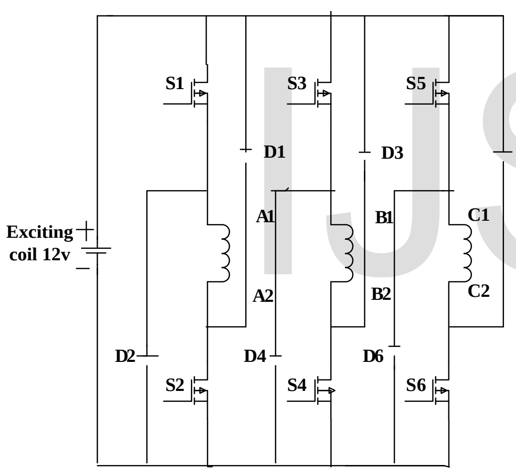

Fig.2a: power controller circuit for SRM

Referring to Figure 2.b phase winding A is connected to 12v DC supply through power semiconductor switches S1 and S2. During braking mode of the DC motor prime mover, the speed of the prime mover decreases. In this mode, the SRG extracts energy from the prime mover. Thus mechanical energy is converted to electrical energy by exciting the phase windings in the falling inductance profile. And the current through the winding increases more than the injected reference current. The generated current is extracted for charging a battery. Depending upon the rotor position, switches S1 and S2 are turned ON to energize Phase A winding. When the phase winding A is to be disconnected from the supply (this instant is also dependent on the position of the shaft) the devices S1 and S2 are turned off. The stored energy in the phase winding A tends to maintain the current in the same direction. The current passes from the winding through D1 and D2 to another auxiliary 12v battery supply for charging application. Similarly Phase winding B and C are also switched on to the supply and switched off from the supply in a cyclic manner.

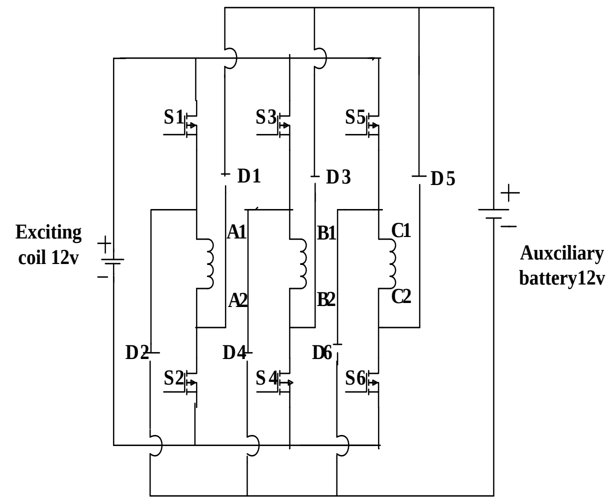

Fig.2b: Power controller circuit for SRG

II. MODEL FOR SRG

The MATLAB/SIMULINK model for SRG consists of rotor position sensor, and power controller circuit as shown in Fig.3. The power controller circuit used is the classic converter with two switches and two diodes per phase. This is used for giving the proper gating pulses to each phase of SRG according to the signals obtained from rotor position sensor block. The ά and β in rotor

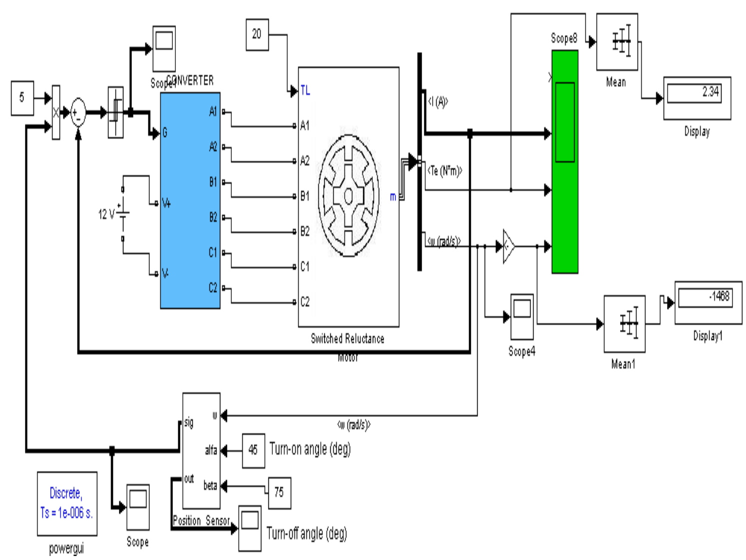

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Fig.3: Model for SRG

A. Converter circuit

The simulation model of converter block for one phase is shown in Fig.4 It has two power switches and two diodes .Step motion of SRG is realized by switching on or off of the phase windings. The choosing of conduction angle is crucial to the power and torque ripple of SRG.

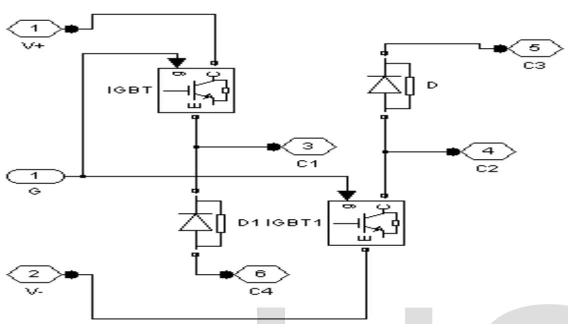

Fig.4: One phase of converter used for battery charging

The current due to generation is extracted to the battery through power diodes. Here the ports C3 and C4 have the connection of positive and negative terminals of battery. Fig.5 gives the 3 phase excitation of SRG For battery charging application. The display shows the average current entered into battery and display1 gives the average power generated and stored in the battery.

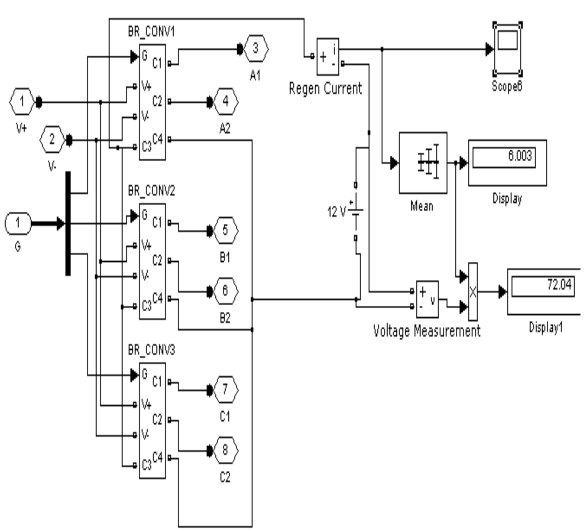

Fig.5: Multi phase excitation of SRG

B. Rotor Position mapped to phase angle

In the rotor position sensor uses a discrete time integrator KTs/(z-1) to generate an output vector of phase shifted inductance profiles for the three phases. Since the phases B and phase C lag by 30 deg and 60 deg, the initial condition for integration is given as 0, -30 and -60 so that the discrete time integrator outputs three vectors of angles that are rising in time. If Phase A is at 90 deg, then Phase B is at 60 and Phase C is at 30 deg. As speed increases this phase difference is maintained. w is the speed input in rpm in units of radians per second. K = 180/л is used to convert the speed in RPM into RPS. Fig.6 shows the output obtained from discrete time integrator block.

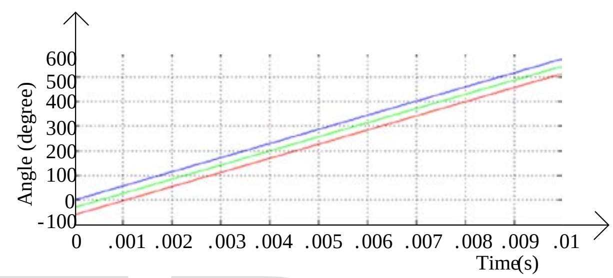

Fig.6: Simulation output from discrete time integrator block

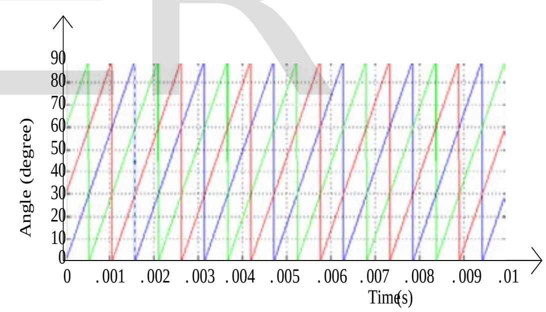

Fig.7: Simulation output from modulus block

The block kTs/(z-1) is used to integrate speed to give rotor angle since speed $\omega = \frac{d\theta}{dt}$. Mod function is used to divide the instantaneous rotor position by 90 and give the remainder. Any rotor position angle (0 to 360 degrees) coming from the position sensor is transformed so that it ranges from 0 to 90 and then it rolls over to 0 again so it maps in to the electrical angle for each phase. Fig.7 gives the simulation output obtained from modulus block.

III. SIMULATION RESULTS AND ANALYSIS

Multi phase excitation current waveforms

In single phase excitation any one of the phase A,B or C is energized. Here phase A and its corresponding two switches and two diodes are considered. The freewheeling diodes are connected to an auxiliary battery which has the capacity to absorb the generated power. For two phase excitation phase A and B are excited using the corresponding switches and diodes shown in Fig.2.b. The generated power fed into the battery is greater than the single phase excitation case and the braking effect on the prime mover is also increased. The three phase excitation operates the SRG at maximum capacity and is used for maximum braking of the prime mover and thereby increasing the stored energy in the auxiliary battery. Fig.8 shows waveforms for the SRG generated current that is extracted to the auxiliary battery used in single phase, two phase and three phase excitation respectively [6].

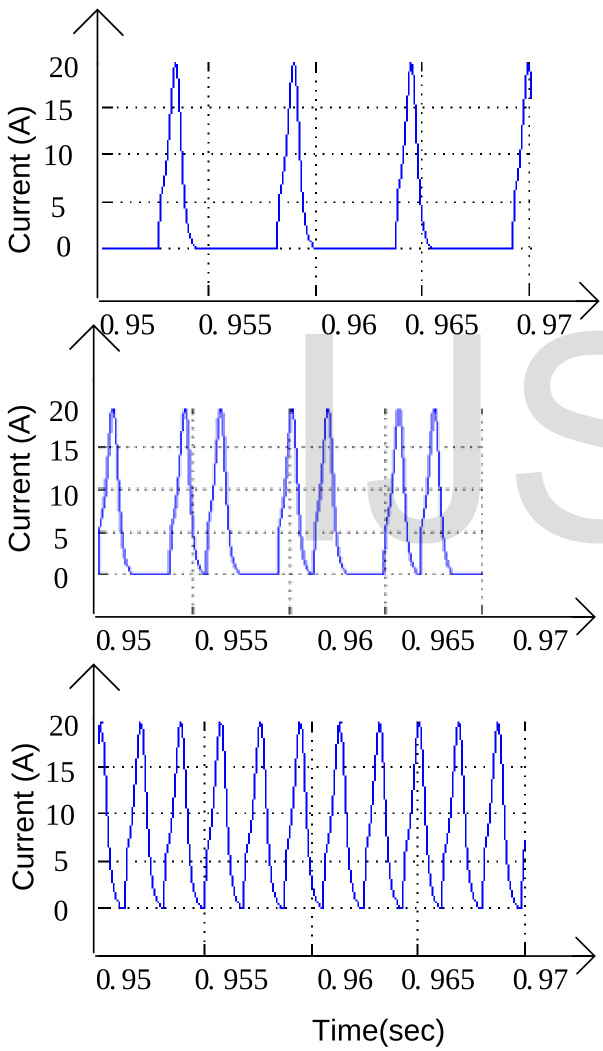

Fig.8: Generation current from single phase two phase and three phase excitation

The simulation output of SRG current, torque and braking speed of prime mover are shown in Fig.9 with TL=10, ά =45, β =75. Here three phase current with a peak of 20A is generated and fed to the battery. Torque is positive since the coils are triggered in the falling inductance region. Motor is running in the negative direction as seen by speed waveform. Applied load torque opposes the developed torque developed by DC motor during braking period. Here Te is positive and TL is positive but Te < TL so the motor is running in negative direction, and extracts the energy from the prime mover for continuous energy conversion using SRG.

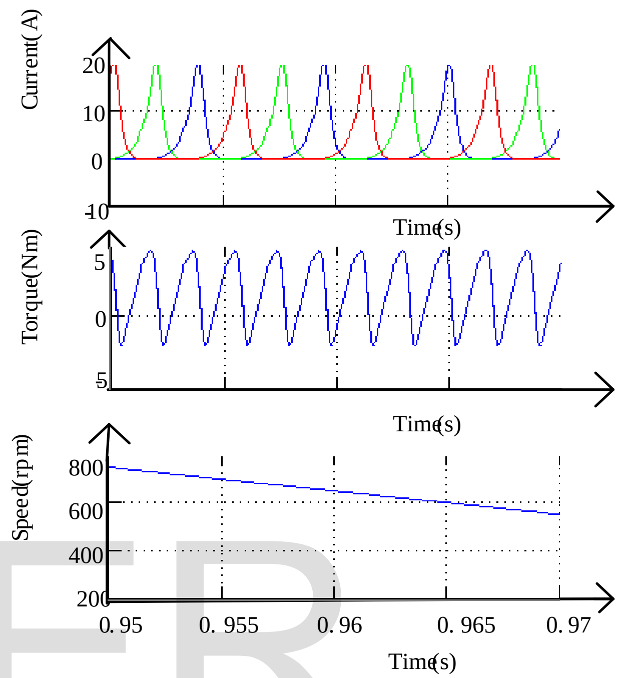

Fig.9: Multiphase excitation TL=10, ά =45, β =75

Referring to the graph shown in Fig.10 gives the peak power generated by SRG with TL=20, ά =45 under various conduction angles. The peak power of 240watts is obtained at 30 degree conduction angle for both single phase and multi phase excitation. But the average current generated is high in multi phase excitation when comparing with single phase excitation. For eg: TL=20, ά =45 β =60 the average power generated is 7.4 watts and 23 watts for single phase and multi phase excitation respectively. So the average power developed in three phase excitation is nearly three times than that of single phase excitation.

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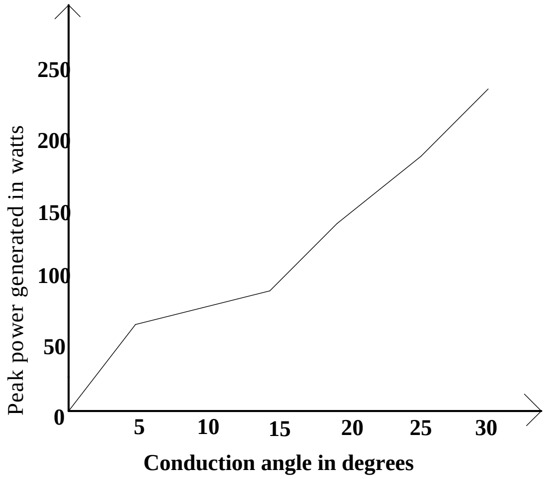

Fig. 10: Generation with single phase or multi phase excitation TL=20, ά =45

IV. EXPERIMENTAL SETUP

The operation of the proposed braking scheme is has been built using a DC motor mechanically coupled to a 3-phase SRM as shown in Fig.11. The two-switch per phase classic converter has implemented for giving proper excitation for the phase windings of SRG. The converter switches are current controlled using a PIC microcontroller (16F877A) with a 20kz PWM pin generated at RC2. Three other general purpose output pins are used to control the phase turn-on and turn-off instants. The circuit has been prototyped with IR2110 gate driver to drive the MOSFETs implemented using IRF630N for the converter. The rotor position for the SRG is detected using an inductance encoder that is a replica of the motor phase coils. The inductance encoder can be probed to provide the rising or falling inductance using additional control logic in coordination with the microcontroller software. Fig.12 shows the waveform of regenerated current being fed in to the auxiliary battery. Fig.13 shows the Regenerative Braking Using Switched Reluctance Generator. Speed is decreased from 800RPM into 300RPM.

Fig.11 Experimental system

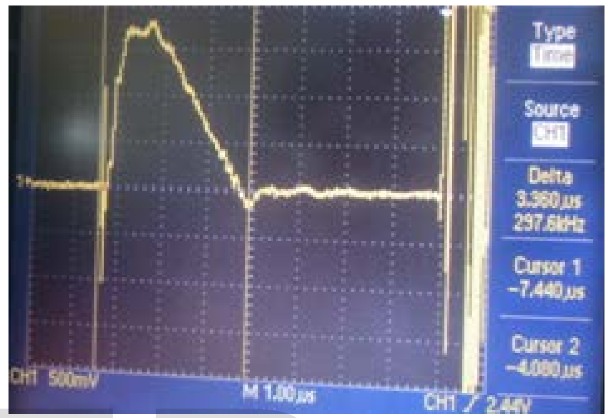

Fig.12 Regenerated current

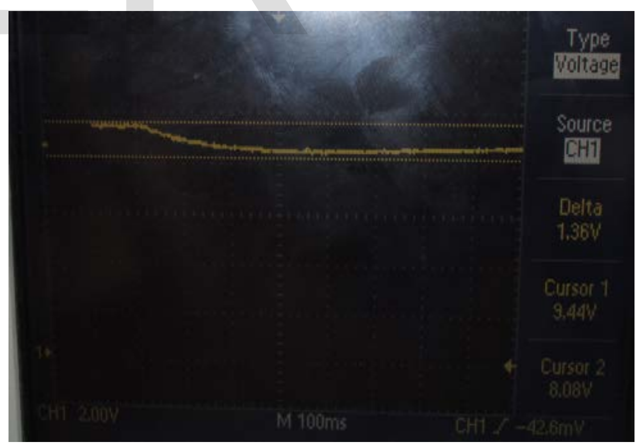

Fig.13 Regenerative Braking Using SRG

V. CONCLUSIONS

The generating modes of switched reluctance machine under single phase excitation and multi-

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phase excitation were compared. A simulation model was developed for the same with the energy generated being fed to an auxiliary battery. The braking effects on a prime mover such as a DC motor can be studied using this model. The generated power is seen to be dependent on the phase conduction angle and the number of coils used for the generating mode. The ability to predict the braking power on the prime mover and the mechanical energy that can be converted to stored energy in the battery is achieved using this model.

REFERENCES

[1] Sheng-Ming Yang and Jian-Yu Ch en, "Controlled dynamic braking of switched reluctance motor drives with a rectifier front end" IEEE Trans.Ind.Electron.,vol.60, no.11, nov.2013.

[2] David A. Torrey, "Switched reluctance generators and their control" IEEE Trans. Ind. Electron., vol.49, no.1, feb.2013.

[3] T.J.E Miller, "Switched reluctance motors and their control". London, U.K.: Oxford Univ. Press, 1993.

[4] Nisha Prasad and Shailendra Jain Simulation of switched reluctance motor for performance analysis using matlab/simulinkenvironment and use of FPGA for its control International journal of Electrical, Electronics and computer engineering 1910:91-98(2012).

[5] F. Soares and P.J.Costa Branco," Simulation of a 6/4 switched reluctance motor based on matlab/simulink environment" IEEE Trans. Aerospace and Electronic systems. Vol. 37, no. 3, July 2001, pp.989-1009

[6] Advantages of using a Switched Reluctance Generator (SRG) for wind energy applications "cmrt. Centralemarseille.fr/cpi/ever09/.../re6/EVER09-paper-199.pdf

[7] Ming-Ji Yang, Hong-Lin, Bin-Yen Ma, and Kuo-Kai Shyu, "A cost-effective method of electric brake with energy regeneration for electric vehicles" IEEE Trans. Ind. Electron., vol.56, no.6, june2009.

[8] X. D. Xue, K. Cheng, T. W. Ng, and N. C. Cheung, "Investigation on characteristics of braking operation of switched reluctance motor drives for electric vehicles," in Proc.AUPEC,2008, pp.1-6.

[9] J. Jiang and J. Holtz, "An efficient braking method for controlled ac drives with a diode rectifier end," IEEE Trans. Ind. Appl., vol. 37, no. 5, pp.1299-1037, Sep./Oct. 2001.