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Regenerative Braking in Induction Motor Drives in Applications to Electric Vehicles

Amrit Anand Mahapatra
Dept. of Electrical Engineering,
National Institute of Technology, Rourkela
Rourkela, India
amrit.mahapatra@gmail.com

S. Gopalakrishna
Dept. of Electrical Engineering,
National Institute of Technology, Rourkela
Rourkela, India
vandithagopal@gmail.com

***Abstract*—Electric traction is a promising technology that can bring out significant improvement in vehicle performance, fuel efficiency and energy utilization. The energy management in the traction system can be well improved through regeneration. In this paper, a method for regenerative braking has been proposed in which the induction machine is operated with negative slip to obtain braking torque. Regeneration during deceleration of electric vehicle is demonstrated by controlling supply frequency and voltage.**

Keywords—electric traction; induction machine; regenerative braking; torque-speed characterictics; state of charge;

I. INTRODUCTION

With the growing concerns towards the environmental protection and energy conservation, the development of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) has been the acceptable challenges for research and development. Traditionally, DC machine drives were mainly used due to their simple speed control and well suited torque speed characteristics for traction purpose. It is well known since many years, that IM has advantages like robustness, ruggedness and low cost. But the complexity involved in controlling the speed and torque of IM hampered their application in electric vehicles. With the advent of new control techniques like direct torque control, IM drives are well controlled and hence being widely used now a days [1] - [5].

Regenerative braking is an important aspect to improve the efficiency of EV and HEV. Regenerative braking used in addition with the traditional mechanical braking is more apt to the driver's braking requirement while improving the operating range of the vehicle. During regenerative braking, the electrical traction motor provides negative torque to the driven wheels and converts the kinetic energy into electrical energy for recharging the battery.

The powertrain configuration of the EV and HEV is inherently a nonlinear system including many uncertainties with the composition of electrical, mechanical, thermodynamic and chemical devices combined together to form the power circuit [6]. Therefore the design of the efficient braking algorithm involves the proper and efficient coordination of all the devices. As stated in [7], the braking operation in a drive can be envisaged through plug, dissipative and regenerative braking. The plug braking although enables quick stop but produces high peak currents and high transient torques [8]. The energy is being dissipated in the former two types of braking whereas in the regenerative braking the energy is recovered back into the system. Thus many researchers have coined new strategies and designed numerous control algorithms so as to reduce the complicacy in the development of regenerative braking. An Energy Regeneration System (ERS) proposed in [9] designed a boost equivalent Main Power Circuit (MPC) which implements the nonlinear model directly considering the small signal and large signal analysis. Most of the control algorithms developed is based on Parallel Hybrid Electric Vehicle (PHEV) which implements regenerative braking as well as hydraulic braking thereby assuring shortest braking distance with a controlled and stable travelling direction. The control concepts are mathematically defined [9] and for the drivetrain configuration with dependence on the various condition of the road, thus making the algorithm quite complex and variable according to the path of travel. The platforms of MATRIX [6] and ADVISOR [10] have been utilized to study and analyze the developed control strategy. However, these analysis tools are expensive and are not readily available.

In this paper, a method to extract maximum energy from wheels to the battery by operating in negative slip region is proposed. The aim is to operate the induction machine at maximum power generation by operating at different frequencies. A simulation study is performed on a squirrel cage IM using MATLAB/ Simulink and method of regeneration is demonstrated during the braking process applicable in Electric Vehicles.

II. PRINCIPLE OF OPERATION

Fig.1 shows torque-slip characteristics of IM for steady state operation. There are three regions of operation of the induction machine namely motoring ($0 < s < 1$), generating (slip $s < 0$) and braking ($1 < s < 2$). Fig. 2 shows the power-slip characteristics of IM. These characteristics curves show that the maximum torque and the maximum power generated in the braking region are quite less in comparison to that of in the generating region. Operating in generating region provide quick transfer of energy from the wheel to the battery but the complexity lies in tracking the maximum power transfer point (MPTP) during deceleration of IM. Based on the speed of IM, the supply frequency and voltage are controlled so that the slip is maintained at MPTP (s_{max}) and flux at rated value, efficient regeneration is possible.

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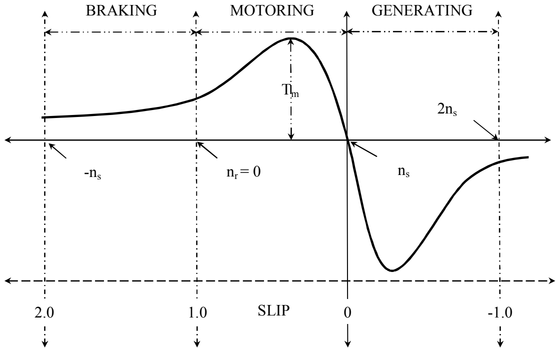

Fig. 1. Torque Slip Characteristics

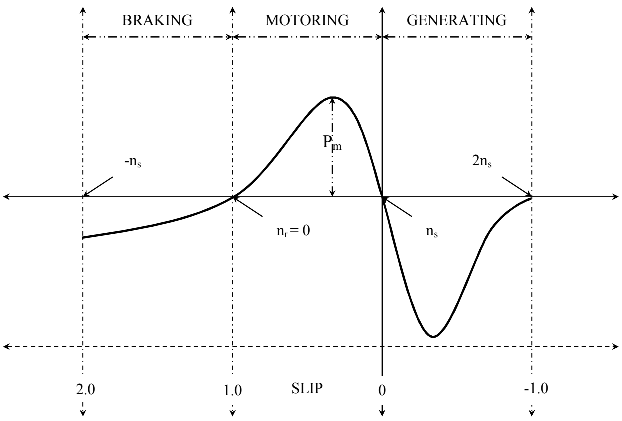

Fig. 2. Power Slip Characteristics

The proposed algorithm is to generate the desired braking torque (braking mode) and in the process of braking, do re-generate a substantial amount of power (generating mode).

III. Regeneration During Constant Vehicle Speed

A three phase induction motor with the parameters listed in Table. I is used to demonstrate the method of regeneration. A model shown in Fig. 3 is simulated using MATLAB/Simulink. A simple analysis is carried out by considering optimum frequency (f_0) that gives maximum regeneration for a given steady state speed of the machine. The optimum frequency can be obtained either by maintaining constant speed of the motor and sweeping the frequency or by maintaining a constant frequency and sweeping the motor speed.

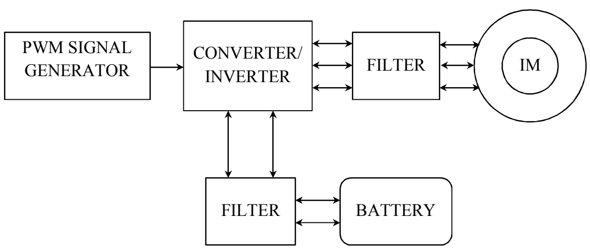

Fig. 3. MATLAB/Simulink Model for the proposed Model

TABLE I. Machine Parameters

Sl. No.	Parameters	Symbols Used	Value
1	Voltage	V_l	460 V
2	Power	P	100 Hp
3	Base frequency	ω_b	50 Hz
4	Number of poles	p	4
5	Stator resistance	r_1	0.04232 Ω
6	Rotor resistance	r_2	0.04232 Ω
7	Magnetizing reactance	x_m	7.406 Ω
8	Stator reactance	x_1	0.19044 Ω
9	Rotor reactance	x_2	0.19044 Ω

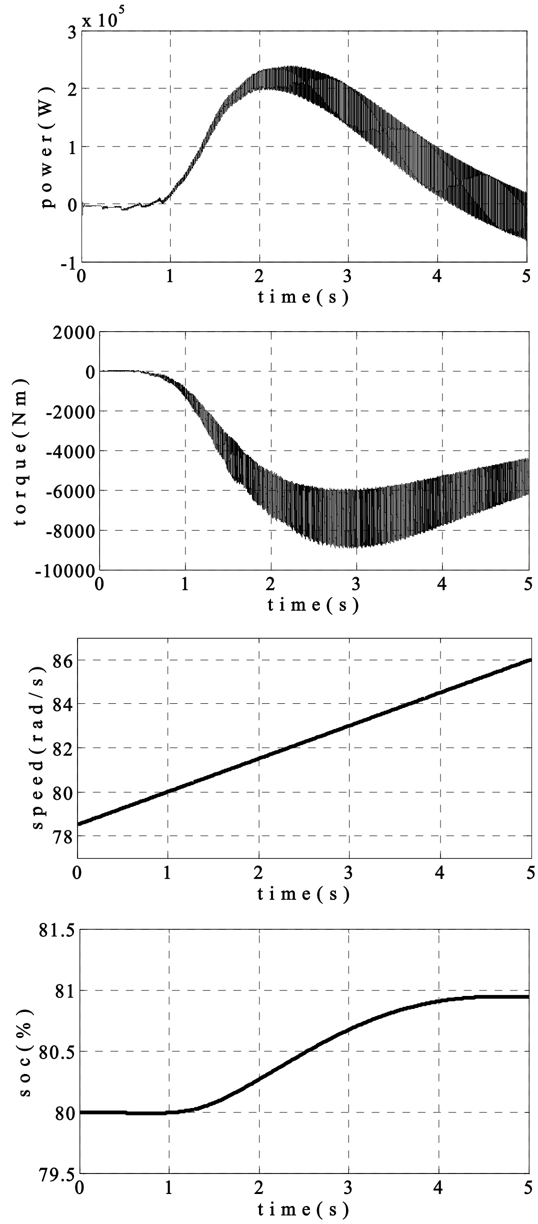

Fig. 4. Variation of Power ,Torque, SOC at Battery Terminals with Speed.

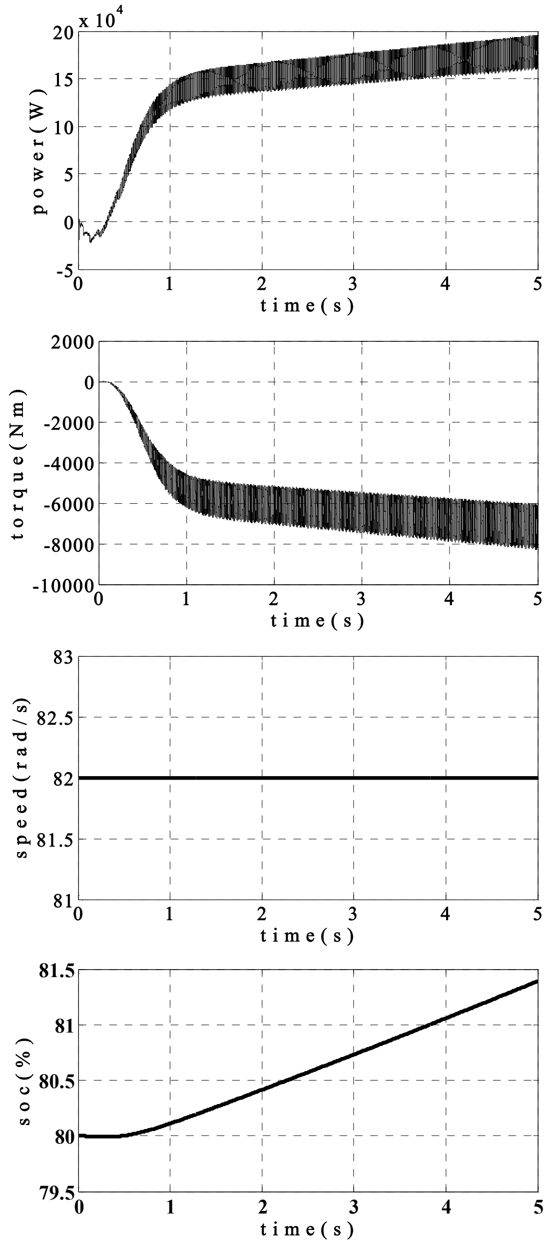

Fig. 5. Variation of Power ,Torque, SOC with Speed. (N_r = *82 rad/s*)

Since, the Simulink provides an option to take the speed of the motor as an independent quantity; the latter case is implemented here. Fig. 4 shows the electromagnetic torque and power delivered to the battery during a linear increase in speed. The speed is taken such that the slip of the IM changes linearly from 0 to -0.1. In this case, the reference frequency is taken as 25 Hz and supply voltage half of its rated value i.e. 230 V line to line. Here the ratio of V/f is kept constant to maintain mmf constant. As the supply frequency is half, the rotating magnetic field rotates with half the rated synchronous speed, nearly 78.5 rad/s. Hence the motor speed is varied from 78.5 rad/s to 85 rad/s so as to maintain the machine in the generating mode of operation. It is clear from the Fig. 4 that at 82 rad/s, maximum power is delivered to the battery and maximum braking torque is obtained. Hence, it can be concluded that when the motor speed is at 82 rad/s, a supply with 25 Hz frequency charges the battery faster than any other frequency as in this region

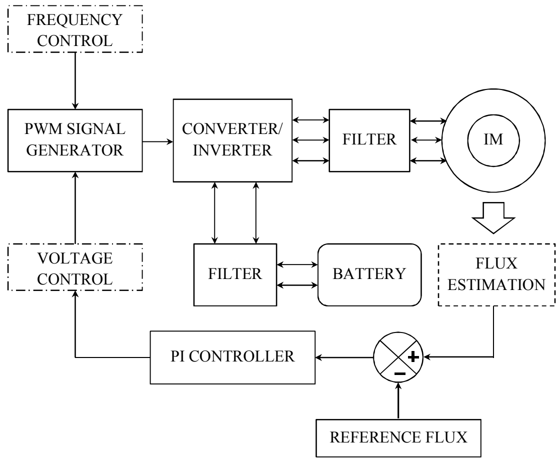

Fig. 6. Block Diagram for Proposed Model in MATLAB/Simulink

the SOC is seen to be constantly increasing as being observed from SOC characteristics shown in Fig. 4. Fig. 5 shows State of Charge (SOC) of the battery along with power and torque when the motor is maintained at a constant speed of 82 rad/s where in the SOC is seen to be increasing during the process of regeneration. It is assumed that the state of charge of the battery is initially 80% which further increases in the process of regeneration. The high frequency contained in the power can be reduced by the use of well-tuned low pass filter.

IV. Regeneration During Deceleration of Vehicle

In the previous section, simple regeneration process is demonstrated by considering a constant speed of the vehicle with constant supply frequency. But deceleration is the phenomenon during braking. Thus the supply frequency should also be decreased in such a manner so as to operate the IM in the generating region to achieve regeneration.

The IM is initially operated at rated voltage and rated frequency and is running with rated speed. After reaching a steady state, braking is applied so that speed falls linearly from 145 rad/s to 115 rad/s as shown in Fig. 7. As the speed falls, the supply frequency should be decreased to achieve regeneration. The control techniques as discussed in Section (3) are carefully designed by using a mathematical linear relationship between the frequency and the feedback rotor speed (vehicle speed) such that the input supply voltage and frequency gives required braking torque simultaneously providing maximum optimized charging to the battery in accordance to the traditional V/f algorithm such that the slip remains negative. The braking mode is justified through the decreasing speed in Fig. 8. From the slip relationship from Fig. 7 and Fig. 8 it can be concluded that the slip remains negative making it operating in the generating mode. Therefore the braking power and torque has been improved as shown in Fig. 1 and Fig. 2. Here, it is shown that braking torque and charging of battery is possible by considering the frequency change as shown in Fig. 8. A constant flux is maintained by voltage control using PI controller by estimating the flux using the formulas in [5] as shown in Fig. 6. The state of charge (SOC) of the battery and the variation of power, voltage, and current at the battery terminals are shown in Fig. 10 – Fig. 13 respectively. The rising part of SOC from 78.96 % to 79.01 % clearly indicates the regeneration of battery power during the braking process. The voltage and current measurements are considered at the battery terminals. A high value of battery voltage has been selected so as to compensate for the losses in the inverter and the filter circuit (Fig. 6) thereby maintaining the rated supply voltage at the machine terminals. A positive value of current is taken as the reference for voltage being supplied to the battery. Fig. 12 and Fig. 13 clearly indicates the positive values of voltage and current respectively. The power as shown in Fig. 11 is obtained through direct multiplication of the voltage and current at the battery terminals. Fig. 14 shows the variation of voltage at the machine terminals during regeneration. To have current controlled phenomenon for the machine the flux is maintained constant through a designed PI controller. The per unit value of d- axis flux is shown in Fig. 15 which depicts that a constant flux in maintained throughout the regeneration process thus allowing the machine to be controlled by current alone. The d-axis verses q-axis flux in pu is shown in Fig. 16. The outer unstable loops in Fig.16 are produced due to the initial machine transients during regeneration as shown in Fig. 14.The decrease in the rise of SOC after t = 2.5 can be inferred to the fact that the machine is saturating due to its non-linear characteristics in the Simulink platform.

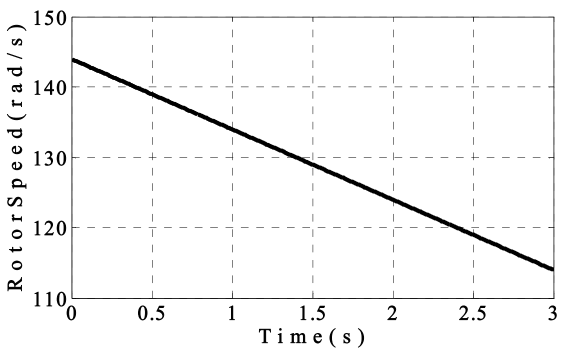

Fig. 7. Variation of Speed.

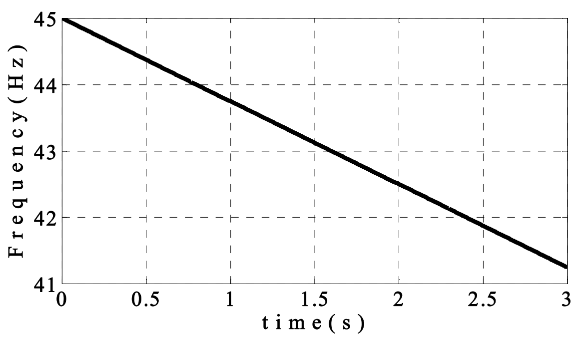

Fig. 8. Variation of Frequency.

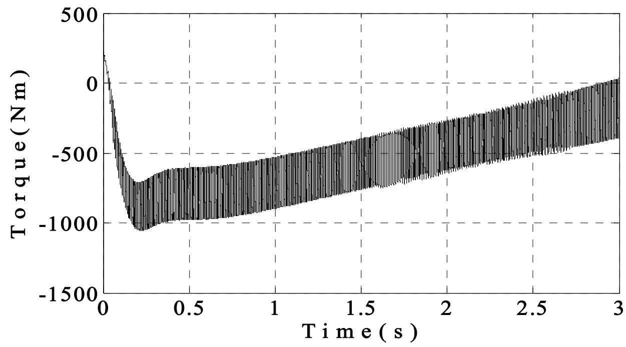

Fig. 9. Variation of Torque.

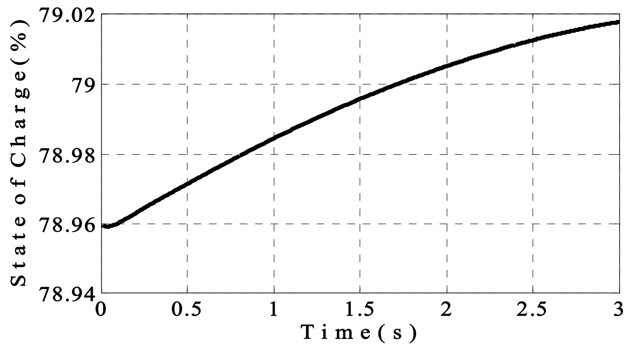

Fig. 10. Variation of SOC.

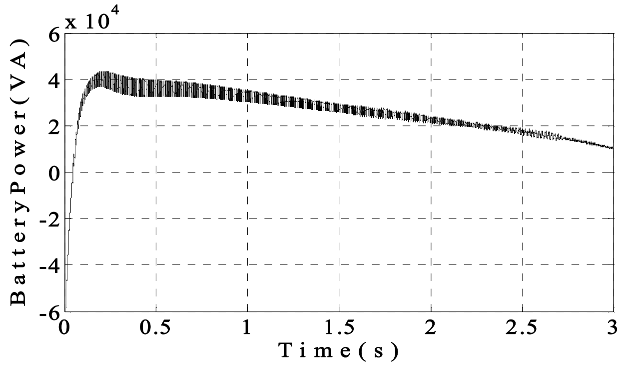

Fig. 11. Variation of Battery Power.

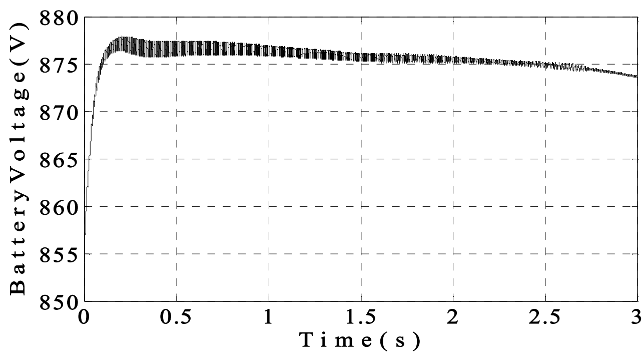

Fig. 12. Variation of Battery Voltage.

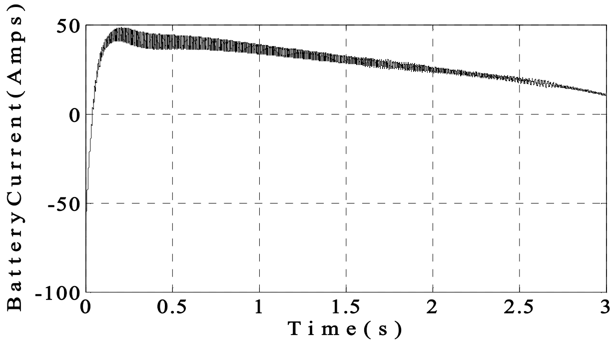

Fig. 13. Variation of Battery Current.

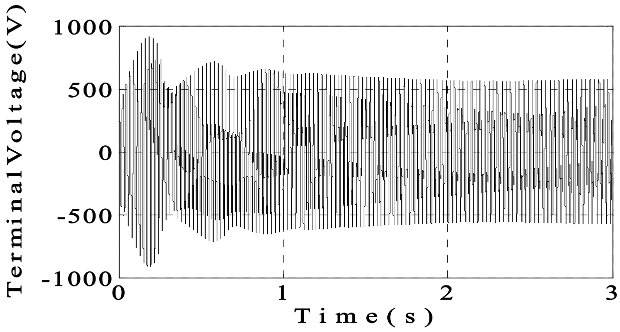

Fig. 14. Variation of Machine Voltage.

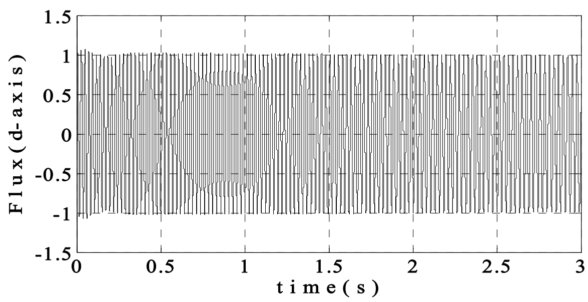

Fig. 15. Variation of Flux in d- axis.

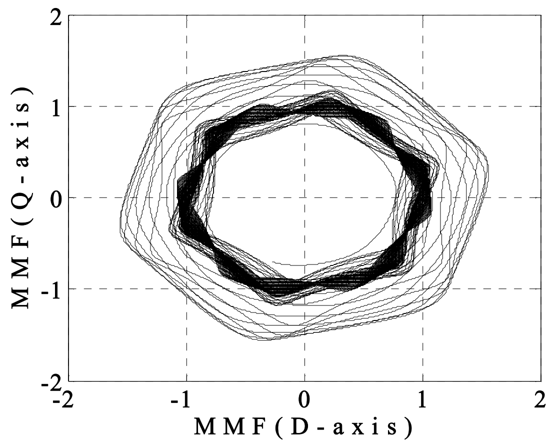

Fig. 16. Variation of MMF of d & q axis.

V. CONCLUSION

The regeneration methods used in induction machine drives to involve convertors at the rotor side and stator side. In this paper a regeneration method that consists of convertors only on stator side is proposed. Input voltage magnitude and frequency are used as control parameters. Simulation results show that by proper control technique desired braking torque with maximum regeneration is possible.

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