A New Control Algorithm for Doubly Fed Induction Motor with Wide Torque-Speed Range for EV/HEV Application

Sheenu V S[1] Jomole Joseph P[2]
[1]P.G. Student [2]Assistant Professor
[1,2]Department of Electrical & Electronic Engineering
[1,2]Mar Baselios College of Engineering and Technology, Trivandrum

Abstract— A new control algorithm which enables the Doubly Fed Induction Motor (DFIM) to operate in both the extended torque and extended power region is proposed here. This algorithm is employed for EV/HEV application. Torque and air-gap flux of a DFIM can be controlled directly. Flux weakening region operation is made possible by controlling current phase shift angle.

Key words: Doubly fed induction motor (DFIM), electric vehicle/hybrid electric vehicle (EV/HEV)

I. INTRODUCTION

Nowadays, EVs and HEVs have got better acceptance due to their high fuel efficiency and low emissions. Selection of motors for EV/HEV application is a major step that requires special attention. The automotive industry is still searching for the most suitable electric propulsion system for EVs. The EV/HEV traction motors should be designed to meet the requirements like high efficiency over wide torque-speed ranges, reliability and cost. Permanent magnet (PM) motor and cage induction motor (IM) are the two choices that we can adopt for EV/HEV traction motors. But these are singly fed motors. Moreover, the dual mechanical port machine is also recommended for EV/HEV applications. Dual port machine includes both motor as well as generator.

Doubly fed induction machine (motor) is treated as a better choice for EV/HEV application due to its excellent & extended constant power and constant torque operating region.

A systematic difference between doubly fed induction machine traction system and singly fed machine traction system is that DFIM traction system has got two inverters-one for stator side and another for rotor side. A controller is provided and controlling the two inverters actively.

A vector control algorithm of the Doubly Fed Induction Motor (DFIM) is proposed in [4].In this control algorithm, magnetizing & torque components are obtained by decoupling stator and rotor currents. For this purpose, a magnetizing current decoupling controller is provided in the proposed algorithm. A torque current decoupling controller is also employed for the stator torque current and the stator/rotor turns ratio is used to couple the rotor. For the independent control of magnetizing & torque currents of the stator & rotor, four current regulators are required. Experimental results of four quadrant operation are explained, but there is no explanation about the determination of torque and magnetizing current references.

For the current reference optimization two methods are recommended for DFIM that are power distribution control algorithm and minimum copper loss technique[9].In this algorithm, speed of the motor is treated as objective for the control and then independent control of four currents are taking place. So in addition to speed control, other three controls are taking as part of it. Among three, one is used to control rotor flux, second one for the distribution of power to the stator & rotor and the remaining one for the minimum copper loss implementation. Experimental results are provided. But the only requirement is the clear knowledge of accurate motor parameters.

In [6], there is an introduction of direct torque control (DTC) algorithm without using a current controller. In this method, by using two hysteresis controllers the torque of doubly fed Induction Motor is controlled through stator & rotor fluxes. The aim is to control the torque angle by maintaining nominal values for stator& rotor fluxes. Under some assumptions a flux model is developed. The assumptions are

1) For a given operating frequency, neglect the resistive effect in the winding.
2) Neglect the coupling terms.

A problem that was faced with this method is that the above said assumptions may degrade the accuracy of torque control. When low operating frequency is reached and the winding resistance may also not negligible. Moreover, the requirement of DTC algorithm is that the time constants of both the stator & rotor must always larger than inverter switching time. Experimental result is provided, but the problems associated with flux weakening region operation are not specified in this paper.

From the above said control algorithms, we can understand that suitable control technique is still in need with regard to using Doubly Fed Induction Motor in EV/HEV applications.

In [7], there is an efficiency comparison of doubly fed & singly fed induction motor used in variable speed drives.

In this paper, a dual current loop algorithm is proposed & a detailed investigation with this new algorithm is done. With this algorithm DFIM can offer high performance in both the extended constant torque & extended constant power region. This high performance can be achieved by controlling torque & air-gap flux. Along with an attempt is carried out for the confirmation of two things.

1) Parameter insensitiveness of the proposed algorithm.
2) No need of decoupling magnetizing and torque currents.

II. DOUBLY FED INDUCTION MACHINE

Doubly Fed Induction Machine includes the motor as well as generator. For EV/HEV application Doubly Fed Induction Motor is used.

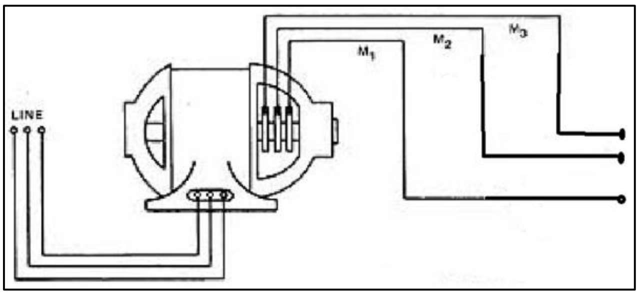

Fig. 1: Doubly-fed wound-rotor induction motor connected to two 3-phase sources

In wound-rotor induction machine, the stator and rotor connected to separate ac sources having different frequencies. They are said to be doubly fed machines. This type of machines, when operating as motors, can be used to drive variable-speed pumps.

A. Doubly-Fed Wound-Rotor Motor (Speed Relationships)

In DFIM, stator is connected to a power supply with frequency (f) 60Hz and rotor is connected to another source having frequency (f2) 14Hz.Suppose we are considering a 3 phase, 4 pole machine. A flux is produced by the stator rotating at a synchronous speed $n_s = 120\frac{f}{p} = 120 \times \frac{60}{4} = 1800\, r/min$. Let us further suppose that the flux rotates clockwise. But for an outside observer, the stator flux rotates clockwise at a speed of 1800r/min.

Now, the rotor is connected to a 14Hz supply. So the rotor flux will rotate at a speed $n_2 = 120\frac{f}{p} = 120 \times \frac{14}{4} = 420\, r/min$.with respect to the rotor. Suppose it rotates clockwise with respect to the rotor.

For the interlocking of N poles of the stator and S poles of the rotor, they must rotate at the same speed as far as an outside observer is concerned. That means, to an outside observer the rotor flux must turn clockwise at 1800r/min. For this, the rotor itself should turn clockwise at a speed of 1800-420=1380r/min.If the rotor runs at any other speed, the rotor poles would slip past the stator poles and the average torque will be zero & the motor stops.

The machine can operate as a motor, if and only if its speed is exactly 1380r/min.Then the machine is said to be running at sub synchronous speed.

If we are interchanging any two leads connected to the slip-rings, we can observe that the rotor flux to turn counter clockwise with respect to the rotor. Under this time, the N poles of the stator can only lock with the S poles of the rotor & the rotor turns clockwise at a speed of 1800+420=2220r/min.Under this conditions, the motor is said to be running at super synchronous speed.

B. Dynamic Equations

The motor dynamic model is represented in synchronously rotating frame d-q.

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \qquad (1.1)$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} - \omega_s \lambda_{ds} \qquad (1.2)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \qquad (1.3)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \qquad (1.4)$$

$$V_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - \omega_r \lambda_{qr} \qquad (1.5)$$

$$V_{qr} = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + \omega_r \lambda_{dr} \qquad (1.6)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \qquad (1.7)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \qquad (1.8)$$

$$T_e = 1.5p\frac{L_m}{L_s}(\lambda_{qs} i_{dr} - \lambda_{ds} i_{qr}) \qquad (1.9)$$

$$\omega_{mr} = \frac{1}{p}\omega_{er} = \frac{1}{p}(\omega_s + \omega_r) \qquad (1.10)$$

The subscripts “s” and “r” refer to the stator & rotor windings variable, respectively.v_s and v_r are the stator and rotor voltages;i_s and i_r denotes stator and rotor currents;R_s and R_r are the stator and rotor resistance;L_m, L_s, L_r are the magnetizing, stator and rotor inductances, respectively;λ_s and λ_r are the stator and rotor flux linkages;ω_s is the stator winding electrical angular velocity and ω_r is the rotor winding electrical angular velocity;$\omega_{mr}$is the rotor mechanical angular velocity and ω_{er} is the rotor electrical angular velocity in radians per second; and p is the pole pair number.

III. DFIM DRIVE SYSTEM IN EV/HEV APPLICATION

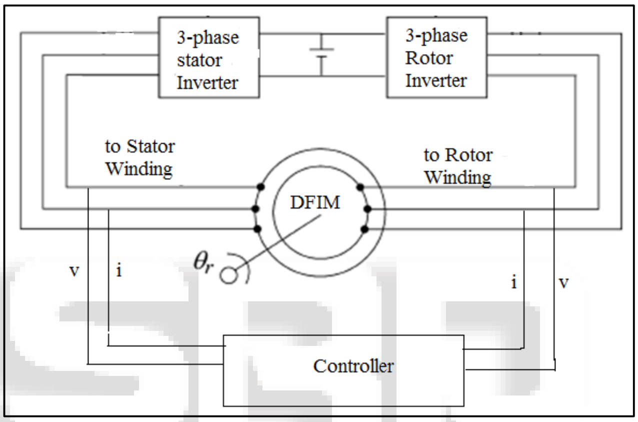

Fig. 2: DFIM drive system

A drive system for DFIM in EV application is shown in fig.2. There are two inverters: one for stator side and other for rotor side. These two inverters are actively controlled. The two inverters have the same KVA rating. There is a battery pack and both the inverters on stator and rotor side will share the battery pack with a common d.c. bus voltage. The KVA rating of each inverter is a half of total system KVA rating. Inverter used is a Space Vector Pulse Width Modulated (SVPWM) one.

For high (maximum) performance in Electric Vehicle/Hybrid Electric Vehicle traction applications, the selected traction motor has to be matched by a well-designed controller. Several control algorithm of the Doubly Fed Induction Motor is discussed in [4], [6] and [9].

A. Implementation of the Proposed Algorithm

In the constant power region, the aim is to control level of flux weakening. If it is not controlled, stability problems may occur. By controlling magnetizing current, the air-gap flux can be controlled directly. The air-gap flux weakening control of the DFIM is obtained by reducing magnetizing current. Reduction of magnetizing current can be achieved by controlling angle difference δ, where δ is the current phase shift angle. δcan be calculated by the following equation.

$$\delta = \cos^{-1}\left(\frac{i_m^2 - i_s^2 - i_r^{s'2}}{2 i_s i_r^{s'}}\right) \qquad (1.11)$$

In the constant power region, the main goal is to provide sufficient torque and fast dynamic response.

IV. SIMULATION RESULTS

A. *Simulation*

Simulation diagram for DFIM with each inverter on stator and rotor side is shown in Fig.4.1.

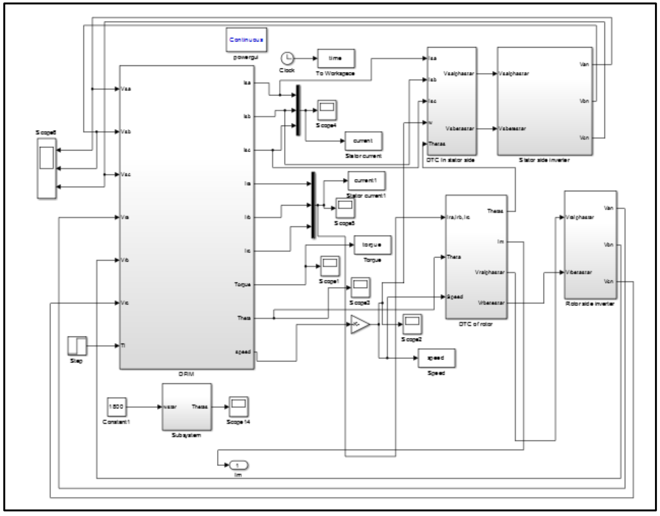

Fig. 3: Simulation Diagram

B. *Results*

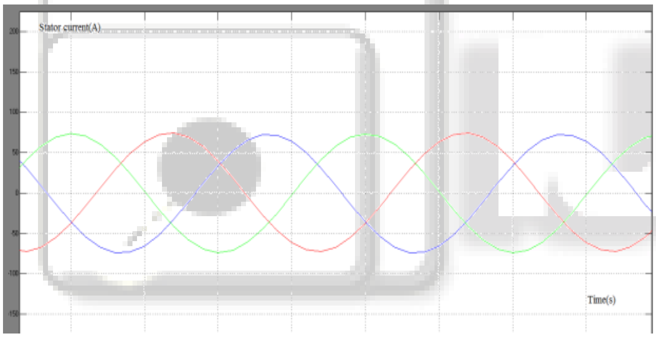

Fig. 4: Stator current of DFIM (X-axis: stator current (A), Y-axis: Time(s))

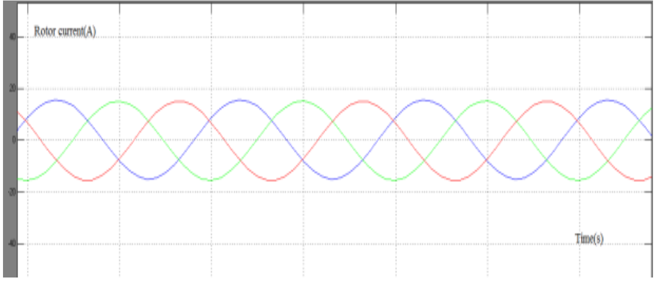

Fig. 5: Rotor current of DFIM (X-axis: Rotor current (A), Y-axis: Time(s))

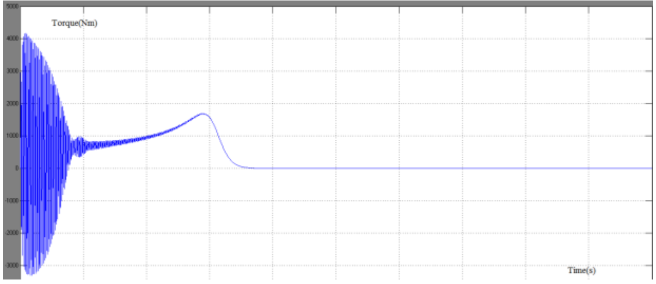

Fig. 6: Torque characteristics of DFIM (X-axis: Torque (Nm), Y-axis: Time(s))

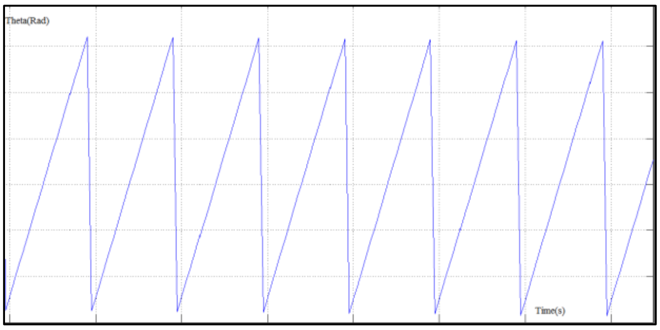

Fig. 7: Rotor angle(X-axis: Theta(Radian),Y-axis: Time(s))

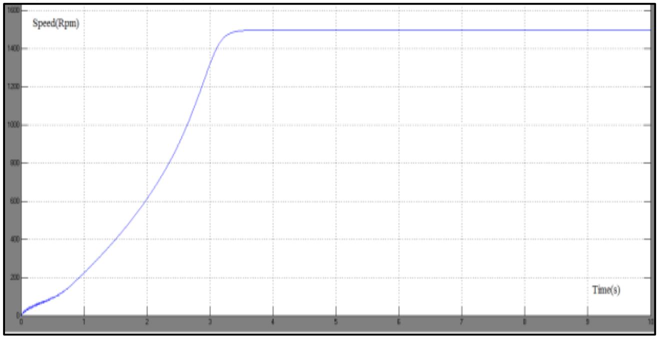

Fig. 8: Speed Characteristics of DFIM (X-axis: speed (rpm), Y-axis: Time(s))

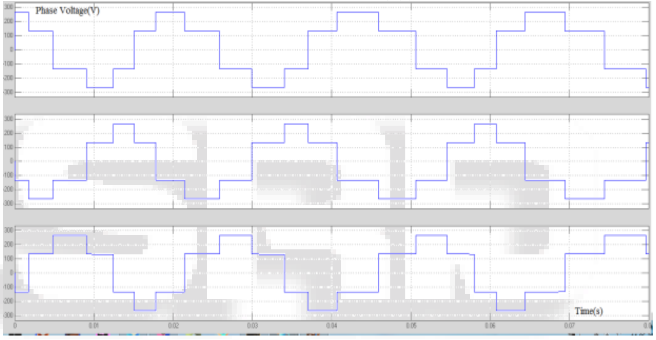

Fig. 9: Phase voltage from the stator side Inverter (X-axis: phase voltage (V), Y-axis(Time(s))

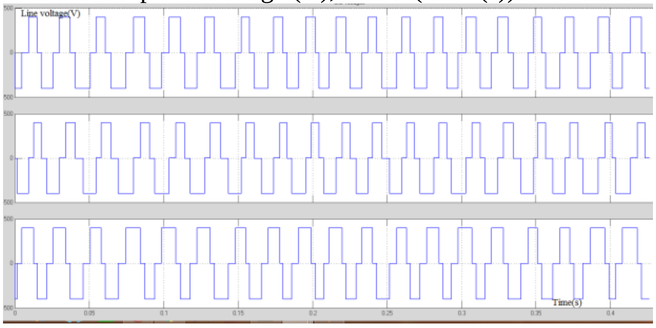

Fig. 10: Line voltage from the stator side Inverter (X-axis: Line voltage (V), Y-axis: Time(s))

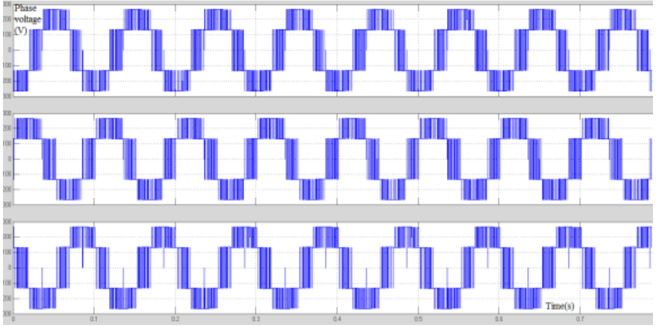

Fig. 11: Phase Voltage from the rotor side inverter (X-axis: phase voltage (V), Y-axis: Time(s))

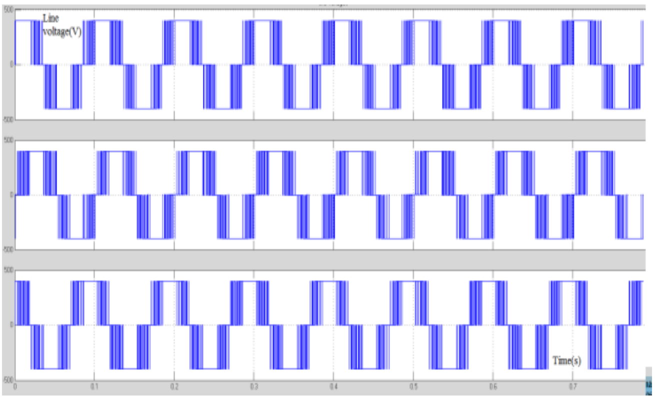

Fig. 12: Line voltage from the rotor side inverter (X-axis: Line voltage (V), Time(s))

V. CONCLUSION

This paper introduces a new control algorithm for the proper control of doubly fed induction motor for Electric Vehicle/Hybrid Electric Vehicle applications. There are some advantages for this algorithm.

1) Torque and air-gap flux of the DFIM can be controlled directly in both constant torque and constant power region. This is made possible by controlling two current vectors.
2) Efficiency of DFIM is controlled here.
3) When this algorithm is applied in a DFIM, the total system has less dependence on motor parameters than other type of control algorithms.

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