Using Separately Excited DC Motor in Railway Vehicles Systems

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Abstract— Like most road running vehicles, a railway traction power system provides mechanical power that can be converted into kinetic and potential energy and can be used to overcome resistance to motion.For every successful train traction system, there are certain general requirements which should be met such as The capability to start and haul a prescribed load over its specified routes whilst maintaining the timetable and a sufficiently long service lifetime with minimal non-availability due to maintenance and standby. Three typical railway traction systems are used in railway system: electric, diesel electric and hybrid. DC and AC electric traction systems are commonly deployed in the railway industry. A separately excited DC motor is adopted in this paper. The electric vehicle power train system and the components are modelled in details and all the simulation models has been done designed and evaluated with Matlab programming environment.

Keywords: Railway System, SEDM, Electric Vehicle, Driveline, Powertrain.

I. Introduction

The first railways were powered by steam engines. Although the first electric railway motor came on the scene halfway through the 19th century, the high infrastructure costs meant that its use was very limited. The first Diesel engines for railway usage were not developed until halfway through the 20th century. The evolution of electric motors for railways and the development of electrification from the middle of the 20th century meant that this kind of motor was suitable for railways. Nowadays, practically all commercial locomotives are powered by electric motors (Faure, 2004; Iwnicki, 2006)[1,2].Figure(1) illustrates a flow diagram for the different types of rail engines and motors most widely used throughout their history. The first Diesel locomotives with a mechanical or hydraulic drive immediately gave way to Diesel locomotives with electrical transmission[3,4]. These locomotives are really hybrids equipped with a Diesel engine that supplies mechanical energy to a generator, which, in turn, supplies the electrical energy to power the electric motors that actually move the drive shafts. Although this may appear to be a contradiction in terms, it actually leads to a better regulation of the motors and greater overall energy efficiency.

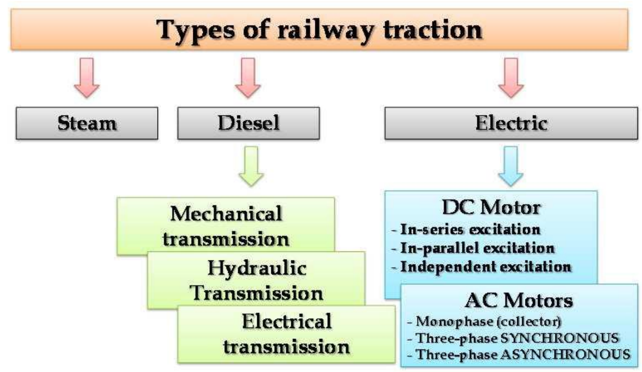


Figure.1. Railway engine and motor types.

The major drawback of electrical traction is the high cost of the infrastructure required to carry the electrical energy to the point of usage[5,6]. This requires constructing long electrical supply lines called *"catenary"*, (Figure 2).

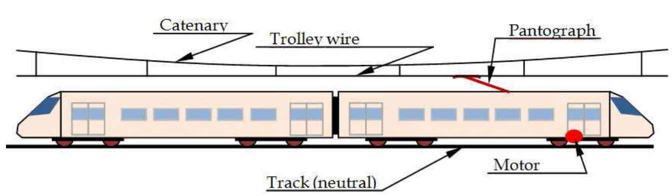


Figure. 2. Electric railway traction: General outline, catenary and pantograph.

In addition, the locomotives need devices that enable the motor to be connected to the catenary: the most common being "pantographs" or the so-called "floaters". In its favour, electrical traction can be said to be clean, respectful of the environment and efficient, as an optimum regulation of the motors can be achieved. In this work, we will only focus on the functioning and regulation of the most widely used types of electric motors.

The most widely used electric motors for railway traction are currently of three basic types:

1. Direct current electric motors with in-series excitation.
2. Direct current electric motors with independent excitation.
3. Alternating current electric motors.

The induction motor has long been regarded as a suitable final drive for railway traction systems due to its inherent capability for regeneration and steep speed and torque characteristics[7,8]. However, the widespread introduction of induction motors could only be realised after modern power electronics became available [9]. The two reasons for this are as follows:

- Speed control of the induction motor is achieved by changing the input frequency and voltage of the input power supply;
-The difficulty of obtaining the proper three-phase supply from a DC or single phase AC traction line should be solved by power electronics techniques.

The development of power electronics relies on advancement of semiconductor devices [10,11]. In the 1960s, the development of the power thyristor gave rise to trials of several experimental inverter-fed induction motor locomotive drives. The main drawback of this type of device is the lower current and voltage level which it could withstand which limits its application in high power fields. In the 1970s, the development of a high-power force-commutated thyristor led to the deployment of the Current Source Inverter (CSI) in DC-fed metro traction drives. Later, the large power Gate-Turn-O_ (GTO) thyristor realised the Voltage Source Inverter (VSI) in railway applications. Until very recently, the Insulated Gate Bi-polar Transistor (IGBT), which has a lower operation current and higher switching speed has taken the place of the GTO. In the 1980s, the pulse converter was developed, which is a four-quadrant AC-DC line converter that enables three-phase VSI-Induction Motor drives on single-phase AC supplied railways. There are two commonly applied types of AC motor: induction and asynchronous motor[12].

Direct current electric motors usually work under a 3 kV supply and alternating current motors under 25 kV[13]. Direct current motors are gradually becoming obsolescent in favour of alternating current motors. This is mainly due to maintenance problems with the direct current motor collectors and the better technological progress of alternating current motors.

The most common DC traction motors used in the railway industry are series and separately-excited machines[14,15]. In series motor, the field winding is connected in series with the armature, resulting in the field being determined by the armature current. The series field forms a protection to ensure that no current flows in the motor without a corresponding field having already been established. The field becomes non-linear when iron saturation occurs at a higher current. For any series traction motor with a steady terminal voltage, "wheel-slip correction" can be inherently realised with a high starting torque followed by a constant power operation regime with increasing speed. This is a very attractive feature for stable operation. Speed control for a series DC machine can be achieved by varying the terminal voltage at the starting stage and the field through the diverter resistor at a greater speed which is usually referred to as a "field weakening operation". However, the insertion of a series resistor into the motor circuit is regarded as wasteful of power and of limited use. In a camshaft controlled train, the series resistance is varied to give the overall characteristic shown in Figure.3. At the beginning, both armature and field current are both maintained constant to generate a constant torque. With the increase of rotating speed, the output power is increased until the base speed. Subsequently, field current is reduced and bring down the output toque. This operation called field weakening operation. After the rotating speed is over the transition speed, the armature current begins to drop and further bring down the torque. The motor then goes into a weak field operation.

For the separately-excited motor, the field excitation circuit is independent from the field circuit. Speed control is also realised through varying the armature voltage or the field current. This type of motor with its separately excited field can be used for regenerative braking. In Figure.3, three control regimes have been identified with different characteristics in terms of torque, current, speed and power [16,17].

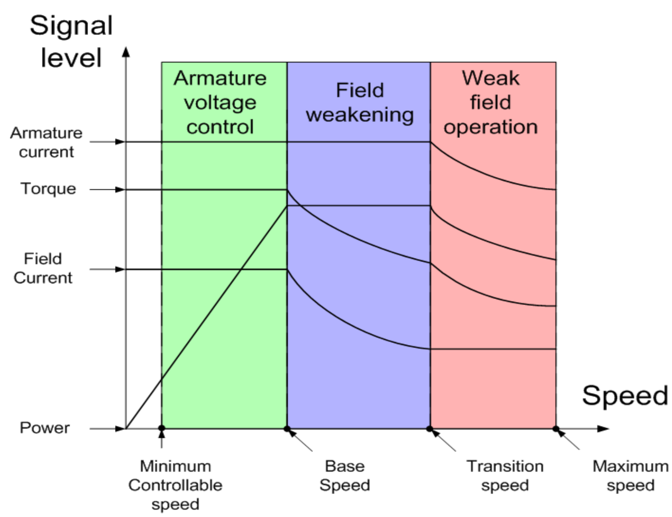


Figure3. Characteristics curve of separately excited DC motor

II. SEPARTELY EXCITED DC MOTOR MODELLING

The equivalent circuit of separately excited DC motor shown in figure(4) [18,19]. The armature voltage equation is given by:

$$V_a = I_a R_a + L_a \frac{dI_a}{dt} + E_b \qquad (1)$$

Where (V_a) is the armature voltage, (I_a) is the armature current, (R_a) is the armature resistance, L_a is the armature inductance, (E_b) is the back emf.

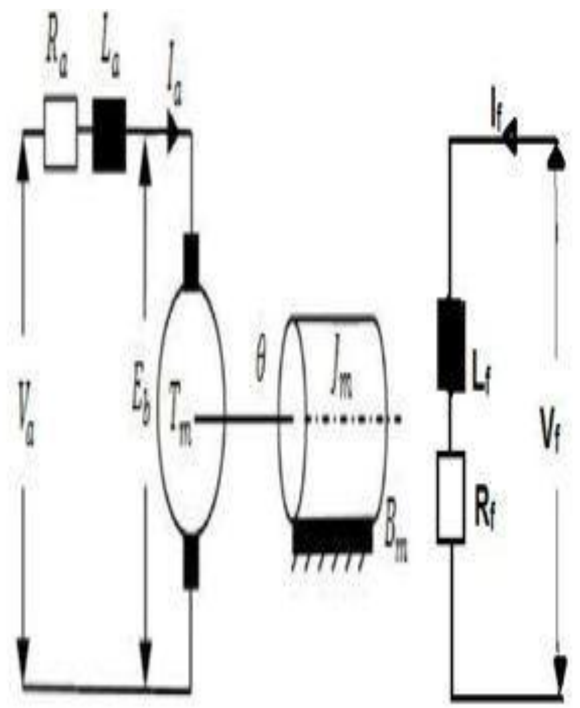


Figure4. Equivalent circuit of separately excited DC motor.

When the armature conductors carry current, forces are exerted on them due to the interaction of this current with the steady air gap flux (Φ), which consists of the field current component(Φ_f).The resulting instantaneous electromechanical torque(*Te*) developed by D.C motor is given by:

$$T_e(t) = K_t \Phi I_a \qquad (2)$$

Rotation of the armature conductors in the flux field causes an electro motive force. to be induced in the armature circuit of such polarity as to oppose the flow of armature current. This induced e.m.f. is usually known as the reverse e.m.f. or back e.m.f., which in terms of instantaneous variables is given by:

$$E_b = K_E \Phi \omega \qquad (3)$$

Where (ω) is the instantaneous speed. In the international system units, the torque and voltage constants (K_t) and (K_E)are equal and have the dimensions of Newton meters per Weber ampere and volt second per Weber radian.

The electromechanical torque developed by the drive has to supply the torque demand of the externally applied load (T_L), overcome the friction, windage effects and accelerate the inertial mass of the rotor during speed increases. If the polar moment of the inertia of the load and drive machine is (*Jm*) and the friction consists of a coulomb friction torque (T_f) plus a viscous friction term(*Bm*) then the dynamic mechanical part is implemented by the following equation for an adjustable speed drive is given by :

$$T_e = J_m \frac{d\omega}{dt} + T_f + B_m \omega + T_L \qquad (4)$$

Mathematical model for the dynamic simulation of the dc motor has been developed. This model has been verified by simulation using Matlab. Looking at the DC motor output shaft position(θ), and choosing the state variable to be the motor shaft output position (θ), velocity (ω) and armature current (I_a).

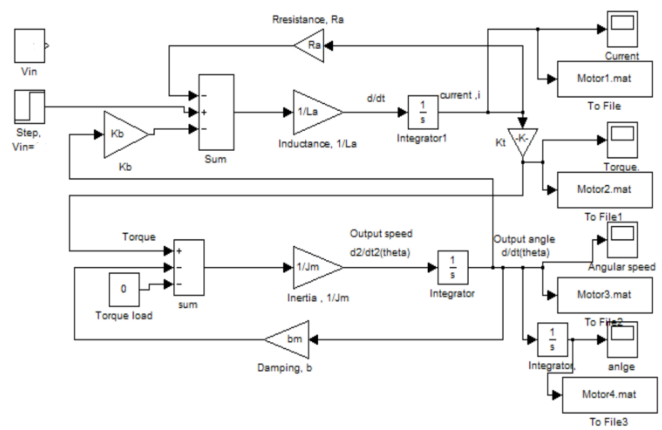


Figure5.Dynamic model of separately excited DC motor

III.DRIVELINE MODELLING

A typical driveline model consists of motor, spring-damper, gearbox and the wheel in series. The purpose of using a torsional damper is to keep engine torque peaks as well as operational irregularities away from the powertrain and connected units. If the forces operating in the powertrain area were not countered, driving comfort would be noticeably reduced and the powertrain components would also show considerably higher levels of wear.For the system the equations of motion can be derived as:

$$J_m \ddot{\theta}_m = T_m - K(\theta_m - n\theta_\omega) - c(\dot{\theta}_m - n\dot{\theta}_\omega) \qquad (5)$$

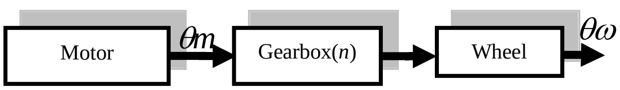
Where $\theta_m, \dot{\theta}_m, \ddot{\theta}_m$ are the angular ,angular speed and angular acceleration of the motor respectively, and $\theta_\omega, \dot{\theta}_\omega, \ddot{\theta}_\omega$ are the angular ,angular speed and angular acceleration of the wheel respectively . (*K*) and(c) are coefficient and coefficient of viscous friction of spring damper (*n*) is the gear ratio.

$$\ddot{\theta}_\omega = \frac{nK}{j_e}(\theta_m - n\theta_\omega) + \frac{nc}{J_e}(\dot{\theta}_m - n\dot{\theta}_\omega) - \frac{FR}{J_e}\dot{\theta}_\omega + \frac{FV_S}{J_e} \qquad (6)$$

$$J_e = J_\omega + n^2 J_g \qquad (7)$$

$$\dot{V}_s = \frac{FR^2}{M_v}\dot{\theta}_\omega - \frac{FR}{M_v}V_s - \frac{B}{M_v}V_s \quad (8)$$

Where:
(V_s), $(\dot{V}_s)$ are the vehicle speed and acceleration respectively. (J_ω) is the Wheel inertia, and (J_g) is Transmission gear inertia refer to motor.*(F)* is vehicle running resistance, (M_v) is the vehicle mass and *(R)* is the wheel radius.



Figure(7).Driveline model

IV.SIMULATION RESULTS AND DISCUSION

To analyze the performance of the separately excited DC motor when it is used in powertrain system, the following modeling parameters are adopted:

Motor &driveline system	
Armature resistance (Ra)	0.04 Ω
Armature inductance (La)	0.4mH
DC supply	1500V
Nominal armature current	75A
Motor constant (Kt)	4.28
Power	112.5KW
Armature inertia(Jm)	11Nm/rad.s^2
Torque max	317N.m
Damping ratio of motor shaft(Dm)	0.003
Transmission gear inertia(Jg) refer to motor	0.6
Motor windage &viscous friction(Bm)	0.12
Corner speed of the motor	350rad/sec
Wheel inertia(Jw)	250Nm/rad.s^2
Wheel radius(R)	0.45m
Gear ratio(n)	5.68
Spring coefficient (K)	10000KNm/rad
Coefficient of viscous friction(C)	100KNms/rad
Vehicle running resistance(f)	10000KN
Train &track parameters	
Vehicle Mass(Mv)	6000000Kg
Rolling resistance coefficient,(Fr)	0.001
Air density, (ρ)	1.2Kg/m^3
Aero dynamic drag coefficient,(CD)	0.653
Front area, (Af)	2m^2
Track gradient,(i)	1%
Vehicle acceleration(a)	0.5m/s^2
Average electrical accessory load	30KW

The current demand input to the system is shown in figure 8.With the help of MATLAB programming , the performance of separately excited DC motor connected to drive line system in time domain was obtained and the results are shown in figure 9,10,11.

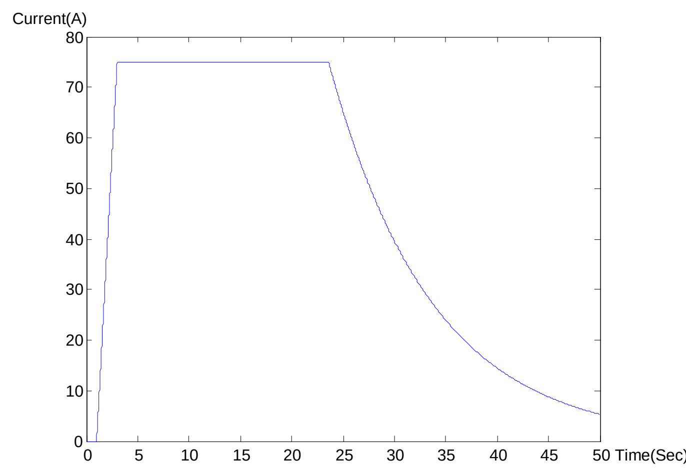
It is clear that the relation between the vehicle acceleration is equal to the wheel acceleration multiplied by the wheel radius(R=0.45m) .

The characteristic curve of the motor can be divided into three regions:

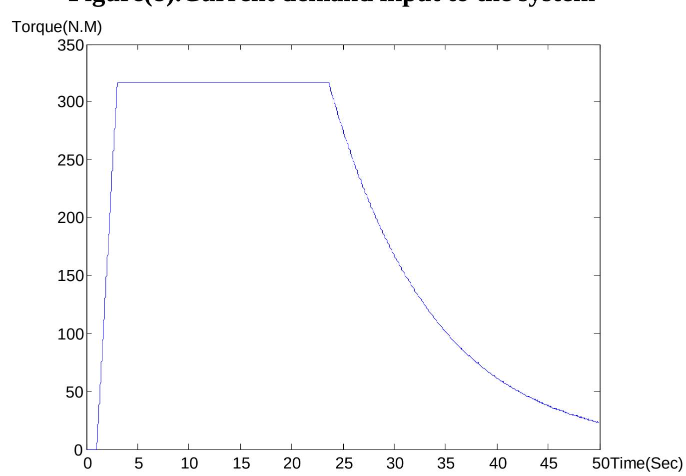
First region (0-1sec):In this region the motor starts from zero position until the current reaches 75A,and the torque at this point is equal to 317Nm.

Constant torque re region (1-23.6sec): In this region the armature and the current torque are constants, while the speed is increasing until reaching the corner speed(ω_c =350rad/sec) at the time of 23.6sec.

Constant power region($\omega > \omega_c$):It can be seen that in this region the armature torque and current are decreasing with the increasing of the motor speed. So the power (P=Tω)remain constant, and the motor works naturally.

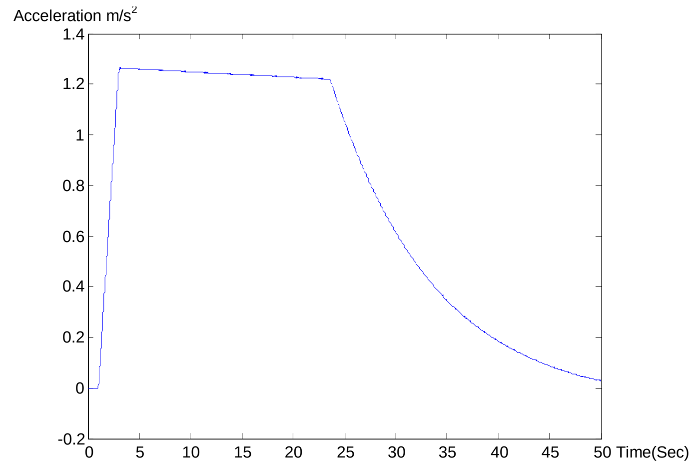


Figure(8).Current demand input to the system

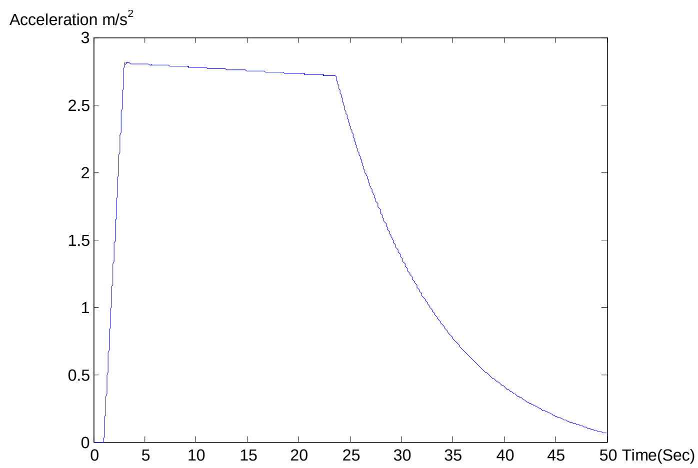


Figure(9).Torque versus time of the motor

The motor torque during starting is very high and gradually decreases as the angular velocity of the motor increases. Consequently, during starting, the current intensity needs to be limited to avoid the circuits burning out and to limit the motor torque, thereby preventing the adhesion limits being exceeded in the wheel-rail contact.



Figure(10). Vehicle acceleration versus time



Figure(11). Wheel acceleration versus time

V. CONCLUSTION

There are different types of electric motors which are commonly used in the drive train. Choice of the electric motor depends on several factors such as speed and torque characteristics, physical size ,weight differences, material cost and efficiency. Because of its high starting torque, and it can operate in stable conditions with any field excitation, separately excited DC motor is adopted in this paper. The electric vehicle power train system and the components are modelled in details and all the simulation models has been done designed and evaluated with Matlab programming environment. The results show that the performance of separately excited DC motor when it is used in powertrain systems was confirmed to be satisfactory because its wide range of speed control.

REFERENCES

[1] R. Liu and L. M. Golovitcher, “Energy-efficient operation of rail vehicles,”Transportation Research Part A: Policy and Practice, vol. 37, no. 10, pp. 917–932, 2003.

[2] T. K. Ho and T. H. Yeung, “Railway junction control by heuristic methods,” IEEE Proceedings- Electric Power Applications, vol. 148, no. 1, pp. 77–84, 2001.

[3] Y.-H. Chou, Distributed approach for rescheduling railway traffic in the event of disturbances. PhD, School of Electronic, Electrical and Computer Engineering, The University of Birmingham, 2009.

[4] G. J. Hull, “Simulation of energy efficiency improvements on commuter railways, ”Master of Philosophy, School of Electronic, Electrical and Computer Engineering, the University of Birmingham, Dec. 2009.

[5] H.-S. Hwang, “Control strategy for optimal compromise between trip time using genetic algorithms,” IEE Proceeding -Electric Power Applications, vol. 144, no. 1, pp. 65–73, 1997.

[6] Y. V. Bocharnikov, A. M. Tobias, C. Roberts, S. Hillmansen, and C. J. Goodman,“Optimal driving strategy for traction energy saving on DC suburban railways,” Electric Power Applications, IET, vol. 1, no. 5, pp. 675–682, 2007.

[7] H.-J. Chuang, C.-S. Chen, C.-H. Lin, C.-H. Hsieh, and C.-Y. Ho, “Design of optimal coasting speed for saving social cost in mass rapid transit systems,” in Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp. 2833–2839, 2008.

[8] T. Albrecht, Railway timetable & traffic: analysis, modeling and simulation. Energy-Efficient Train Operation, pp. 83–105. Eurailpress | DVV Rail Media (DVV Media Group GmbH), 2008.

[9] P. Howlett, “The optimal control of a train,” Annals of Operation Research, vol. 98, pp. 65–87, 2000.

[10] E. Khmelnitsky, “On an optimal control problem of train operation,” IEEE transactions on automatic control, vol. 45, no. 7, pp. 1257–1266, 2000.

[11] M. Alaküla, Hybrid Drive Systems for Vehicles: System Design and Traction Concepts, Lund: Lund University of Technology, 2006.

[12] M. Leksell, Electrical Machines and Drives, Stockholm: KTH, 2004.

[13] R. Ottersten, Hybrid Vehicle Drives: Power Electronics, Göteborg: Chalmers University of Technology, 2004.

[14] B. S Fan, "Modeling and Siumulation of a Hybrid Electric Vehicle Using MATLAB/Simulink and ADAMS," University of Waterloo, Waterloo, ON, MASc Thesis 20

[15] Li-Cun Fang and Shi-Yin Qin, "Concurrent Optimization for Parameters of Powertrain and Control System of Hybrid Electric Vehicle Based on Multi-Objective Genetic Algorithm," in *SICE-ICASE International Joint Conference*, Busan, Korea, 2006, pp. 2424-2429. 2006.

[16] Y. Ding, F.-m. Zhou, Y. Bai, T.-k. Ho, and Y.-f. Fung, "Parallel computing for multi-train movement simulation on electrified railway," in Second International Conference on Information and Computing Science, vol. 4, pp. 280–283, 21-22, 2009.

[17] Y. Cai, M. R. Irving, and S. H. Case, "Iterative techniques for the solution of complex DC-rail-traction systems including regenerative braking," IEEE Proceedings-Generation Transmission and Distribution, vol. 142, no. 5, pp. 445–452, 1995.

[18] A.K. Mishra, V.K. Tiwari, R. Kumar, "Speed control of dc motor using artificial bee colony optimization technique," IEEE International Conference on Control, Automation, Robotics and Embedded Systems (CARE 2013), Jabalpur, 2013.

[19] J. Sriram, K. Sureshkumar, "Speed Control of BLDC Motor Using Fuzzy Logic Controller Based on Sensorless Technique," IEEE International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), Coimbatore, 2014.