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An Intelligent Control theory of IM for use in Electrical Vehicles: A Review

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Abstract:

This paper proposes an advance control strategy for an Induction motor driven Electrical vehicle. With emerging trend of Electrical Vehicle in today's world, the control of Electrical motors through power electronics devices and the controller has become an integral part of research. The control strategy proposed here is a vector control scheme in rotor flux oriented reference frame along with Hysteresis current controlled PWM technique. Two PI controllers are used for torque and flux control by controlling the d and q axis stator currents respectively. These PI controllers can be tuned and induction motor speed can be controlled at a desired speed. Later an ANN based controller can be designed trained in Levenberg Marquardt back propagation algorithm in lieu of PI controller for fast, intelligent and smooth control of speed of Induction motor hereby improving the performance of Electrical Vehicle. .

Keywords **—Electrical vehicle (EV), Neural Network, Vector control scheme, Induction motor, HCC-PWM**

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I. INTRODUCTION

As an alternative solution to growing energy and environmental problems, Electrical vehicle (EVs) is developing very fast to give very attractive solutions to our existing problems. The major Electrical Vehicle drive system consists of major Electrical motor, controller and inverter. Majorly two types of motors are used viz. the BLDC and Induction motor. Both the types of motors have their own advantages and disadvantages. Quick torque response and fast control of speed are the great advantages of EVs over internal combustion engine. The challenging part in the design of the Electrical vehicle is that the controller used depends upon some immeasurable parameters such as velocity of vehicle and slip angle.

Conventionally, in most EVs an AC motor is connected to the wheels by reduction gears and mechanical differential. In some vehicle drive system high-speed and low-torque wheel motors with gear reduction techniques are used.

For further simplification of the vehicle drive arrangement of EVs the gear is eliminated between the wheel and the motor and Electrical differential and motor controller unit is introduced. It simplifies the mechanical layout of the vehicle as the motors are mounted directly on the wheels. It also reduces the overall drive component thus improving the overall reliability and efficiency. As the mechanical differential and gears are not used weight of the vehicle is also optimized. However, one of the main issues in the design of these EVs (without mechanical differential) is how to ensure the vehicle stability. During normal driving conditions, all drive wheel systems require a symmetrical distribution of torque on both sides. This symmetrical distribution is not sufficient when the adherence coefficient of tires is changing; the wheels have different speeds, hence there is a need for traction controls systems. This is still an open problem as illustrated by the limited availability of literature.

This paper proposes a neural network based controller electrical differential system for an EV propelled by induction motor drives and power is transmitted uniformly to front two wheels. PI controller is used generally for the control of the motor drive. But with the emerging trend of the Artificial Intelligence technique, neural network based controllers provides a fast and smooth control of the power electronics and motor drives. Neural network based controllers can provide a wide range of control even for the non-linear models in a reliable manner.

The rotor speed of an induction motor in closed loop scheme is obtained using a feedback speed sensors. These sensors are usually expensive and bulky, the cost and size of the drive systems are increased. The vector control method of speed control of Induction motor is used.There are two control modes for the vector control system, including the vector control modes with and without speed sensor. In vector control scheme decouple control of speed and voltage can be done by controlling the rotor currents in d and q axis reference frame. The vector control scheme can be obtained by two methods. In rotor flux oriented reference frame and secondly stator flux oriented reference frame.

In this paper we will adopt the rotor flux oriented reference frame control for control of the Induction motor. The axis transformation theory is adopted for fast control of the motor. The position of rotor flux can be calculated by the corresponding calculating model in the control system. By detecting the stator current, the exciting current component and the torque current component of motor stator current can be obtained in the d-q reference frame through the coordinate transform from the three-phase to the two-phase synchronous rotating reference frame. The two current components of motor stator current are output by the PI controllers, respectively. Subsequently, they can be transformed into the two-phase stationary reference frame from the two-phase synchronous rotating reference frame, and then it is compared with the actual stator current components from the Induction motor and is fed into the hysteresis current control PWM Inverter circuit to generate controlled voltage waveform for the motor. The driving performance of the vehicle is usually evaluated by acceleration time, maximumspeed and grade ability. Therefore, a proper motor power rating and transmission parameters are theprimary consideration to fit the performance specification. Then, the design of all these parametersis depending on the speed-torque (power) characteristic of the traction motor. The inductionmotor is used as an electric motor in an electric vehicle because it has a good power factor, highefficiency, a high self-starting torque and a low cost. However, it suffers from weak transientperformance especially in applications where fast response to changes in speed or load is required.There are variety of control strategies applied to the induction motors in improving theirperformance such as cyclo-converter, synchro-converter, and others. Most of these control strategiesare only able to overcome speed performance, but are weak in the dynamic response. Therefore,more complex control strategies must be used in the control of induction motors. These complexcontrol strategies will be able to control the magnitude coordinate, frequency and phase of the statorflux such that to minimised flux pulsation. Thus, there must be control strategies that are able toimprove the dynamic performance of the induction motors. One of the most popular is a vectorcontrol. A vector control will make the induction motor behaves like a fully compensated separatelyexcitation direct current motor. This occurs when the stator currents are expressed withreference to the frame of coordinates which rotate in synchronism either with a stator or with a rotormmf vector. Then, stator currents will be operated into two components namely a componentproviding the air-gap flux and the other producing the torque. If the operation can be maintainedconsistently, this will be similar to the direct current motor where the torque and flux are controlledby the armature and field current, independently. This statement was approved that an inductionmotor is able to exhibit direct current motor characteristic if the motor is controlled in asynchronously rotating frame where the sinusoidal machines variable appear as direct currentquantities in the steady state.

I. VECTOR CONTROL PRINCIPLE OF INDUCTION MOTOR

An inverter-fed induction motor three phase current in stationary reference frame is converter to two phase current i.e I_{ds} and I_{qs} in a synchronously rotating reference frame. I_{ds} is the direct-axis component of the stator current while I_{qs} is the quadrant-axis component of the stator current. In vector control scheme this two currents are equivalent as the field and armature currents as in DC motors.

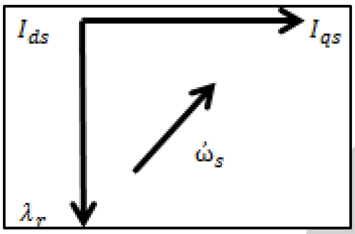

Figure 1: Space-vector diagram for vector control

I_{ds} is in a line with the rotor Flux $\emptyset_r$ and I_{qs} is leading $\emptyset_r$ by 90 degree. This space-vector is rotating synchronously at a frequency of w_s. Hence, this vector control will ensure that the position of the space-vector is accurate in order to generate input control signal. Hence decoupled control of the Speed and voltage is possible as in dc motor by controlling the q axis stator current and the flux.

We now

$$T_e = K_t * I_a * I_f$$
$$T_e = K_t * \emptyset * I_{qs}$$

T_e=Electromagnetic torque of Induction motor
I_a=Armature current and I_f= Field current

II. MODELLING OF THE INDUCTION MOTOR

Induction machines are one of the top motors for driving electric vehicles and they are widely used now days in modern electric vehicles. Many research carried out in this era concludes that the induction machine provides a better overall torque speed performance compared to other machines. It has the advantages such as low-cost, high-efficiency, high reliability, maintenance-free easy for cooling and firm structure, etc. making it especially competitive in EV driving.

For the sake of convenience in analysis and study, we propose four assumptions as follows:

i. The magneto motive force is distributed symmetrically around the air gap in all the three phases with 120 degree electrical degree between them.
ii. Magnetic saturation is neglected, and the self- and mutual inductance of every phase windings are constant.
iii. 3. Iron loss is neglected.
iv. 4. The effects of the frequency change and the temperature change on the winding resistance are not considered.

With the assumptions above, the mathematical model of induction motor in the synchronization reference frame is given. The relationship between voltage and current in given by-

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s P & -\acute{\omega}_s L_s & L_m P & -\acute{\omega}_s L_m \\ \acute{\omega}_s L_s & R_s + L_s P & \acute{\omega}_s L_m & L_m P \\ L_m P & 0 & R_r + L_r P & 0 \\ \acute{\omega}_e L_m & 0 & \acute{\omega}_e L_r & R_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} \quad (1)$$

V_{ds} is stator Voltage in direct axis, V_{qs} is stator voltage in quadrature axis,V_{dr} is rotor voltage in direct axis and V_{qr} is rotor voltage in quadrature axis. Similarly, I_{ds} is stator Voltage in direct axis, I_{qs} is stator voltage in quadrature axis,I_{dr} is rotor voltage in direct axis and I_{qr} is rotor voltage in quadrature axis.

R_s and R_r are stator and rotor winding resistances and L_s , L_r and L_m are stator, rotor and mutual inductances respectively. $\acute{\omega}_s$ is the synchronous speed and $\acute{\omega}_e = \acute{\omega}_s - \acute{\omega}_r$

$\acute{\omega}_r$=Rotor speed.

The flux equations are-

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} \quad (2)$$

Where $\lambda_{ds}$the stator flux of the d-axis is, λ_{qs} is the stator flux of the q-axis, λ_{dr} is the rotor flux of the d-axis, andλ_{qr} is the rotor flux of the q-axis.

The elecromagnetic torque equation is given by-

$$T_e = PL_m(I_{qs}I_{dr} - I_{ds}I_{qr}) \quad (3)$$

The three phase current is transformed into two phase model for decouple control like a dc motor.

The stator current is decomposed into two dc components aligned with rotor magnetic field, I_d and I_q with I_d corresponding to excitation current and control of flux and I_q corresponding to torque current and thus control torque. These two currents can be controlled separately like separately excited dc motor, and then different control strategies can be easily applied on the control of EV driven by induction motor. This technique makes the control of AC motor fast and easy.

Modifying the electromagnetic torque further in terms of rotor flux and q axis stator current, we get-

$T_e = p\frac{L_m}{L_r} I_{qs}\lambda_r$ (4)

$$P = \frac{d}{dt}$$

The torque equation is given by-

$T_e - T_L - B\dot{\omega} = J\frac{d\dot{\omega}}{dt}$(5)

T_L=Load Torque

B= Damping Coefficient

J= moment of Inertia

$\dot{\omega}$=motor speed

III. CONTROL STRATEGY OF INDUCTION MOTOR

The most important part of the Electrical Vehicle are-

i. Electrical motor
ii. Controller
iii. PWM unit

The design strategies of all the three parts are discussed in this paper.

An innovative scheme for control of the Induction motor is proposed. One of the fast methods of control of motor is vector control in which the q axis rotor current is control to control the speed of the motor. An advance strategy is to convert the rotor and stator parameters in their natural reference frame and then control. The stator being stationary part, the parameters are controlled in Stationary reference frame and the rotor being rotating part, the rotor parameters are controlled in rotor rotating reference frame. The vector control strategy is done in stator flux oriented reference frame. Furthermore, vector control is also used together with pulse width modulation to control the output voltage and speed of the Induction motor.

In Fig. 2, T_e*is the desired torque; $\lambda^*$is the desired rotor flux modulus value. The reference torque and flux is compared with the actual flux and torque of the motor and the error is fed in to the torque and flux PI controller. I_{ds} and I_{qs} are the reference current output from the PI controllers. The two axes current in transformed to αβ reference frame using angleΘ_r with Parks transformation equation (7) and then transformed to three phase current using Clarks transformation equation (6).

Clark's equation is given by-

$$I_\alpha = I_a$$

$$I_\beta = \frac{1}{\sqrt{3}}I_a + \frac{2}{\sqrt{3}}I_b \qquad (6)$$

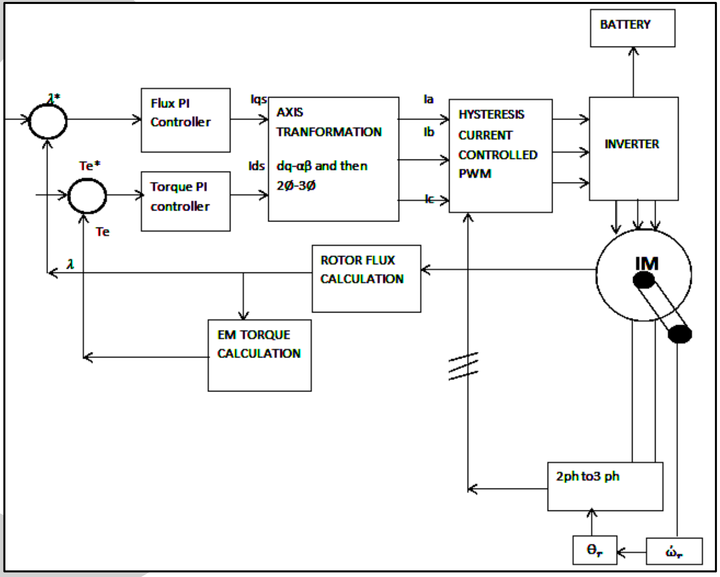

Figure 2: Vector control Scheme for Induction motor

To transform the parameter from stationary reference frame to rotor rotating reference frame by Parks' equation is given by-

$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} cos\Theta_r & -sin\Theta_r \\ sin\Theta_r & cos\Theta_r \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}$(7)

Inverse transformation equation is given by-

$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} cos\Theta_r & sin\Theta_r \\ -sin\Theta_r & cos\Theta_r \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$ (8)

The three phase reference currents are then compared with three phase actual currents and are fed into the hysteresis current controlled PWM technique for generation of controlled rotor voltage waveform using inverter equations. The controlled voltage output from the inverter is then fed into the motor for controlled speed as desired. This closed loop vector control scheme for motor speed control is very efficient and fast.

Two PI controllers are used in the outer loop. The flux PI controller and Torque PI controller, which controls the excitation and torque of the motor respectively. Here in this strategy the use of voltage controller in the inner loop is avoided by using hysteresis current controlled PWM modulation technique.

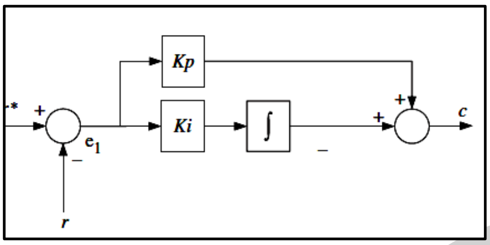

Figure 3: PI controller

The control principle of the PI controllers' are-

$$I_{ds}^{*} = K_{pd}(T_e^{*} - T_e) + K_{id}\int (T_e^{*} - T_e)dt (9)$$

$$I_{qs}^{*} = K_{pq}(\lambda_e^{*} - \lambda_e) + K_{iq}\int (\lambda_e^{*} - \lambda_e)dt (10)$$

Hysteresis band current control PWM technique along with the inverter circuit is used to generate the controlled voltage waveform to feed to the rotor of the Induction motor.

A. Design of the Hysteresis band current controlled PWM Technique

Hysteresis band PWM technique is an instantaneous feedback current controlled PWM technique where the actual current continually tracks the reference or command current within the hysteresis band. A control circuit is designed to generate a sinusoidal reference current waveform of desired magnitude and frequency and it is compared with the actual phase current waveform generated from the circuit network. As the current exceeds a certain prescribed hysteresis band or limit (say 0.001) the upper switch in the three phases half bridge inverter circuit is turned off and the lower switch is turned on. As a result, the output voltage from the inverter transits from +0.5*Vd to-0.5*Vd and consequently the current starts to decay. As the current crosses the lower band limit (-0.001), the lower switch is turned off and the upper switch is turned on. By back and forth switching of the upper and lower switches the actual current wave is made to track the sine reference wave within the hysteresis band

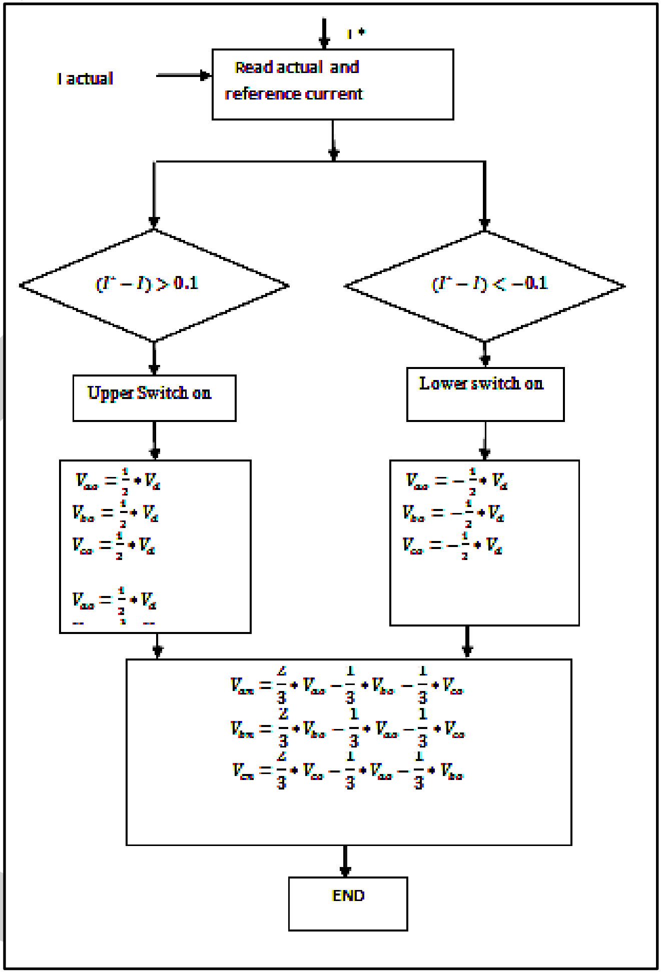

Figure 4: Flowchart for Hysteresis Current Controlled PWM Technique

V. DESIGN OF ANN CONTROLLER

With the booming of Artificial Intelligent techniques the artificial neural-network techniques are becoming quite fast and easy control strategies for control of power electronics and drives circuits. The Levenberg Marquart back propagation algorithm which is a supervised type of learning algorithm can be used for designing the controller. The ANN controller can be trained using the data obtained from PI controller used for controlling the Induction motor.

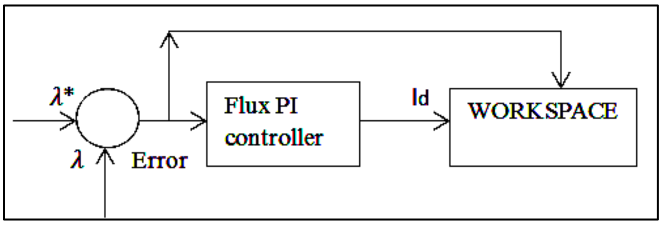

Figure 5: Training data for ANN Flux controller

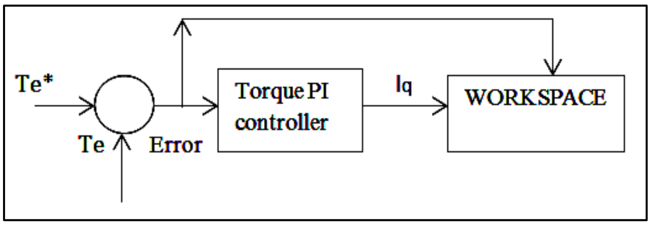

Figure 6: Training data for ANN torque controller

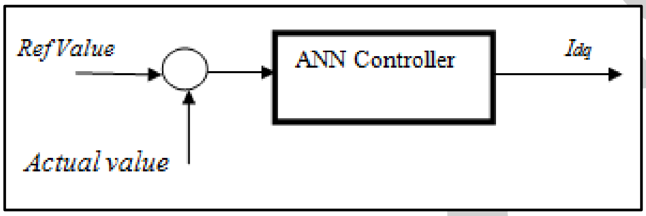

Figure 7: ANN Controller

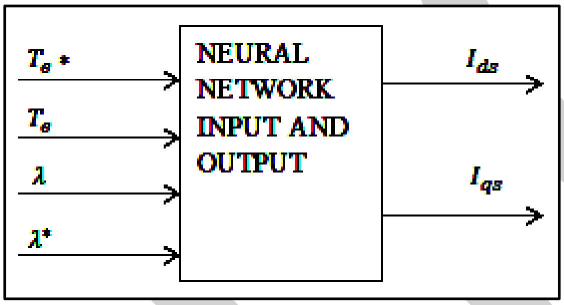

Figure 8: ANN Controller Input and Output

Design of ANN controller involves two major steps:

i. Choosing the number of inputs and outputs neurons
ii. The number of hidden neurons and layers.

As the ANN controller will be trained from the data available from the system using PI controller (Figure 5 and 6) it can be seen that the no. of Inputs are 4 and outputs are 2. Number of hidden layers selected can be either 1 or 2. The number of hidden layers is selected based on the "rule of thumb" wherein the number of hidden layer is in between 1 and the number of input variables. The number of hidden neurons can also be selected based on cross validation or mean square error (MSE) technique. A feed forward network can be taken.

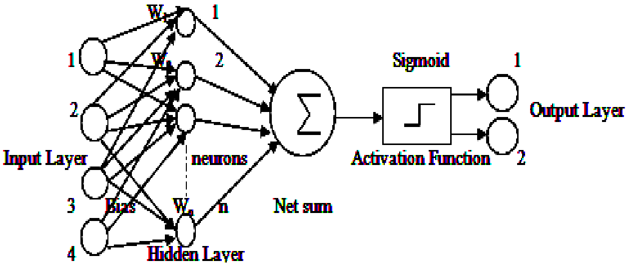

Figure 9: Feed Forward Network

A. *Back Propagation Algorithm*

Algorithms for Back Propagation Learning Method are:

i. Initialize random weight and choose learning rate η.
ii. Forward Pass for each input patterns and target outputs. Assuming j hidden layer nodes and N input for a 2 Layer MLP $Y_k = f(\sum_{j=0} w_{jk} O_j)$.Where O_j is output from each hidden node j:$O_j = f(\sum_{j=0} w_{ij} x_i)$.
iii. For each output unit k, compute : $\delta_K = (y_{target} - y_k)y_k(1 - y_k)$.
iv. For hidden units j (from last to first hidden layer, for the case of more than 1 hidden layer) compute delta: : $\delta_j = O_j(1 - O_j)\sum_k w_{jk}\delta_k$.
v. For all weights change weight by gradient descent $\Delta w_{ji}(n) = \eta\delta_j(n)y_j(n))$.
vi. For weight from input layer unit i to hidden layer unit j the weight changes by :$\Delta w_{ji}(n) = \eta\delta_j x_j$
vii. For weight from hidden layer unit j to output layer unit k weight changes: $\Delta w_{jk}(n) = \eta\delta_k O_j$.

B. *Levenberg-Marquardt Algorithm*

To solve second order training patterns without computing Hessian Matrix another algorithm The Levenberg Marquardt algorithm designed. For performance function in the form of a least squares, the Hessian matrix can be calculated as:
H = J^TJ, and the gradient can be computed asg = J^Te
Where J is the Jacobian matrix that contains first derivatives of the network errors with respect to the biases and weights, and e is the error vector. Error back propagation algorithm is used to calculate the Jacobian matrix which is easier than computing Hessian Matrix
The approximation to Hessian Matrix in the Levenberg-Marquardt is done by the following method:

$$x_{k+1} = x_k - [J^TJ + \mu I]^{-1} J^Te$$

When the constant μ is zero, it is similar to Newton's method.. When μ is larger, then it is similar to gradient descent algorithm with smaller step size. Newton's method is usually faster and gives better accuracy near error minimum, so it is better to shift toward Newton's method quickly for fast convergence. Thus, constant μ is gradually decreased after each successful step and is increased only when a tentative step would increase the performance function. The performance function is thus reduced at every steps of iteration of the algorithm.

VI. CONCLUSION

This paper presents a review on the use of vector control scheme and Hysteresis current controlled PWM technique along with torque and flux PI controller for the control of speed of Induction motor. This technique reduces the total number of controller used in the system. The use of additional voltage controller is abolished. Also the paper presents a discussion on the use of Artificial Neural Network based controller tuned in Levenberg Marquardt algorithm for fast and intelligent control of the speed of Induction motor to improve the performance of Electrical Vehicles.

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