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A Novel Technique for Tuning PI-Controllers in Induction Motor Drive Systems for Electric Vehicle Applications

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ABSTRACT

In the last decade, the increasing restrictions imposed on the exhaust emissions from internal combustion engines and traffic limitations have increased the development of electrical propulsion systems for automotive applications. The goal of electrical and hybrid vehicles is the reduction of global emissions, which in turn leads to a decrease in fuel resource exploitation. This paper presents a novel approach for control of Induction Motors (IM) using the Particle Swarm Optimization (PSO) algorithm to optimize the parameters of the Proportional Integral Controller (PI-Controller). The overall system is simulated under various operating conditions. The use of PSO as an optimization algorithm makes the drive robust and insensitive to load variation with faster dynamic response and higher accuracy. The system is tested under variable operating conditions. The simulation results show a positive dynamic response with fast recovery time.

Keywords: Electric Vehicles, Particle Swarm Optimization, Field oriented control, Induction motor

1. Introduction

The major components of an electric vehicle system are the motor, controller, power source, charger and drive train. The majority of electric vehicles (EV) developed so far are based on dc machines, induction machines or permanent magnet machines. The disadvantages of dc machines forced the EV developers to look into various types of ac machines. The power density of permanent magnet machines together with the high cost of permanent magnets makes these machines less attractive for EV applications.

The main reasons for acceptance of the Induction motor are its ruggedness, reliability, and inexpensive cost, which are all desired for EVs and Hybrid Electric Vehicles (HEVs). However control of IM is complicated due to the fact that in obtaining decoupled control of the torque and flux producing components of the stator phase current, both the magnitude and phase of the stator quantities need to be controlled. In addition, there is no direct access to the rotor quantities, such as rotor fluxes and currents [1]. To overcome these difficulties, high performance vector control algorithms have been developed. These algorithms can decouple the stator phase currents by using only the measured stator current and flux, as well as the rotor speed [2-3]. This drive system has three PI-Controllers which are tuned using PSO instead of traditional tuning methods; the drive system plays an important role in meeting the other requirements. It should enable the drive to follow any reference speed taking into account the effects of load impact, saturation and parameter variation. The

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MATLAB SIMULINK software package is utilized to simulate each part of the system under study. The simulation of the overall system is composed of these simulated components when they are properly interconnected.

2. Induction Motor Control Strategies

Until recently induction motors have been plugged directly into the supply Direct Online (DOL) or operated using the relatively crude Open Loop Volts per Hertz (V/Hz) control strategy. Both techniques cause problems with efficiency, reliability and electromagnetic interference. Obviously DOL motors can only be operated at the supply frequency and are therefore incapable of variable speed control. Although the V/Hz strategy can provide speed variation it is unable to provide reliable control under transient conditions and can often cause circuit breakers to trip. Another problem with open loop control strategies is that they are only suitable when the motor can be operated at steady torque without speed regulation.

The need for more precise control over torque and speed led to the development of closed loop V/Hz controllers and other algorithms based on the induction motor model. The problem with using the machine model is that the electromagnetic characteristics are only valid in steady state so high peak voltages and currents still occur under transient conditions. These motor control strategies were also based on sinusoidal PWM which is not suited to closed loop PI regulation. Replacing the PI regulators with hysteresis controllers can slightly improve performance at the expense of high bandwidth noise that it hard to filter from the system. Another problem with early control strategies is that they were unable to consider phase interaction and could only be operated as synchronous or asynchronous, but not both simultaneously.

To overcome these limitations a new approach to motor control was required. This was provided in the early 1970s by Hasse and Blaschke who developed the theory of Field Oriented Control (FOC) and later in the mid 1980s by Takahaski and Dependbrock who created Direct Torque Control (DTC) [4]. These strategies are the foundation for every high performance control scheme used today.

3. Field Oriented Control

In a separately excited DC machine the axes of the armature and field currents are orthogonal to one another. This means that the magneto motive forces established by the currents in these windings are also orthogonal. If iron saturation is ignored the developed torque is equal to [5]:

$$T_{em} = K_a \phi(I_f) I_a \tag{1}$$

This means that the flux depends solely on the field winding current. If the flux is fixed then the torque is varied directly by the armature current. It is for this reason that DC machines are said to have decoupled or independent control over torque and flux.

Unfortunately the operation of induction machines is much more complicated. Induction motors are coupled, non linear, multivariable systems whose stator and rotor fields are not held orthogonal to one another. In order to achieve decoupled control over the torque and flux producing components of the stator currents, a technique known as Field Oriented Control is used.

4. The Structure of Field Oriented Control

A block diagram for a Field Oriented Controller can be seen in the following section. This design uses a more robust structure known as indirect FOC, meaning that the rotor angle is not determined directly by measuring the air gap flux with hall-effect sensors. These sensors are not particularly suited for use in large industrial motors as they can be fragile and sensitive to temperature change [5]. Instead the rotor flux angle is calculated from a mechanical speed sensor or encoder.

The key components of the FOC strategy are the Clarke and Park transform blocks. These transformation and induction motor equations exist in [6]. As can be seen in Figure (1) these map the three phase stator currents onto a direct and quadrature rotating reference frame that is aligned with the rotor flux. This decouples the torque and flux. Producing components of the stator currents allows the induction motor to be controlled in much the same way as a separately excited DC machine.

Three PI regulators are used to set the output reference voltages. The first PI regulator compares the speed set point with the measured mechanical speed of the rotor and produces the stator current quadrature axis reference, i_{sqref}. The stator current direct axis reference i_{sdref} is usually kept constant at the value required to produce the nominal rotor flux. To operate the motor above its nominal speed a technique known as Field Weakening is used to reduce the rotor flux. The reference currents are compared with the measured stator currents. The error is used by the PI regulators to generate the output stator voltages in the direct and quadrature axes. These are transformed back onto the α and β axes using the inverse Park transformer to allow the output voltage to be generated directly using SVPWM.

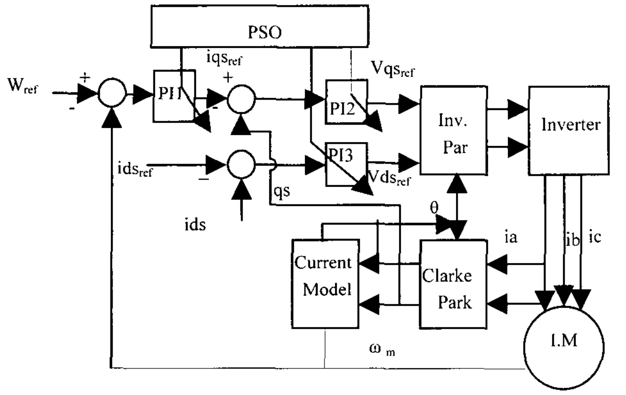


Fig. 1 Field oriented control of Induction Motor

5. Methods of Tuning the PI-Controller

PI-Controllers have been applied to control almost any process in current use, from aerospace to motion control, from slow to fast systems. Alongside this success, however the problem of tuning PI-controllers has remained an active research area. Furthermore, with changes in system dynamics and variations in operating points PI-Controllers should be returned on a regular basis. This has triggered extensive research on the possibilities and potential of the so-called adaptive PI-controllers. Loosely defined, adaptive PI-controllers avoid time-consuming manual tuning by providing optimal PI-controller settings automatically as the system dynamics or operating points change [7]. There are two methods of tuning the PI-Controller; they are the conventional Ziegler-Nichols method and the Intelligence methods such as the PSO method.

6. Ziegler-Nichols Method for Tuning the PI-Controller

Ziegler and Nichols developed PID tuning methods in the early 1940s based on open loop tests (less known than the Cohen-Coon formulas) and also based on a closed loop test, which may be their most widely known achievement.

The closed loop method prescribes the following procedure:

Step 1: Disable any D and I action of the controller (pure P-controller).

Step 2: Make a set point step test and observe the response.

Step 3: Repeat the SP test with increased / decreased controller gain until a stable oscillation is achieved. This gain is called the "ultimate gain" Ku.

Step 4: Read the oscillation period Pu.

Step 5: Calculate the parameters according to the following formulas:

PI: Proportional gain = 0.45 * Ku, integral time =Pu / 1.2

PID: Proportional gain = 0.6 * Ku, integral time =Pu / 2, derivative time = Tu / 8

This is shown in figure (2)

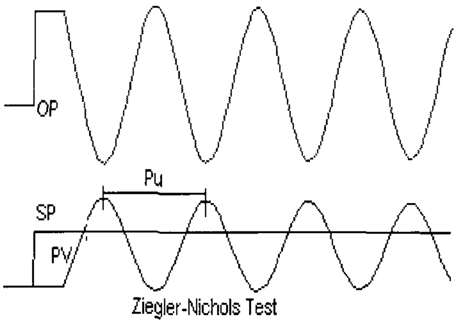


Fig. 2 Ziegler-Nichols for tuning PI-Controller

7. Design of the FOC Using PSO

The PSO was originally designed by Kennedy and Eberhart [8]. PSO begins with a swarm of particles as the initial population. Each particle has a position and a velocity. The position of the particle encodes the solution of the problem. The velocity of the particle represents the value added to the position of the particle to find its position in the next generation. The algorithm updates the position and velocity of all particles in each generation, until the algorithm finds an optimum. The velocity of all particles is initially zero and is updated according to the best local position (best fitness) the particle has come across in its lifetime (all generations so far) and the best position any particle in the whole swarm has ever come across. The original PSO formulae define each particle as a potential solution to a problem in D-dimensional space, with particle j represented as:

$X_j = (X_{j1} , X_{j2} , \ldots\ldots\ldots , X_{jD})$

Also, each particle maintains a memory of its previous best position as :

$P_j = (P_{j1} , P_{j2} , \ldots\ldots\ldots , P_{jD})$

Velocity along each dimension is represented as:

$V_j = (V_{j1} , V_{j2} , \ldots\ldots\ldots , V_{jD})$

PI-Controller is a good controller in the field of machine control, but the problem is the mathematical model of the plant must be known in order to solve the overall system. Several methods are introduced to tune the PI-Controller. Our proposed method is using PSO to optimize PI-controller parameters; the PSO algorithm is used on-line to update the PI parameters as shown in figure (1). In this figure there are three PI-controllers (PI1, PI2 and PI3) with six constants (Kp1 and Ki1, Kp2 and Ki2, Kp3 and Ki3) that are tuned using PSO. Each variable from the six variables has three vectors as previous (position vector, previous best position vector and velocity vector) vectors assumed of length 10 elements [9]. A higher value of $[w]$ favors global search while a lower value implies local search. We linearly decrease the value of w over generations to favor global search in initial generations and local search in the later generations.

At each iteration, the P vector of the particle with the best fitness in the local neighborhood, designated g, and the P vector of current particle are combined to adjust the velocity along each dimension. That velocity is then used to compute a new position for the particle as follow [10]:

$$V_{j,i} = wV_{j,i} + C_1 r_1(P_j - X_j) + C_2 r_2(P_{gj} - X_j) \tag{2}$$

$$X_j := X_j + V_j \tag{3}$$

8. Implementation of PSO

The PSO program is simple and takes few lines in the program. Reducing the time of implementation in the whole program, the steps of the PSO program is described as follows:

Step 1 Generation of initial conditions of each agent

Initial searching points (X_i^o) and velocities (V_i^o) of each agent are usually generated randomly within the allowable range. The current searching point is set to pbest for each agent. The best-evaluated value of pbest is set to gbest and the agent number with the best value is stored.

Step 2 Evaluation of searching point of each agent

The objective function value is calculated for each agent. If the value is better than the current pbest of the agent, the pbest value is replaced by the current value. If the best value of the pbest is better than the current gbest, gbest is replaced by the best value and the agent number with the best value is stored.

Step 3 Modification of each searching point

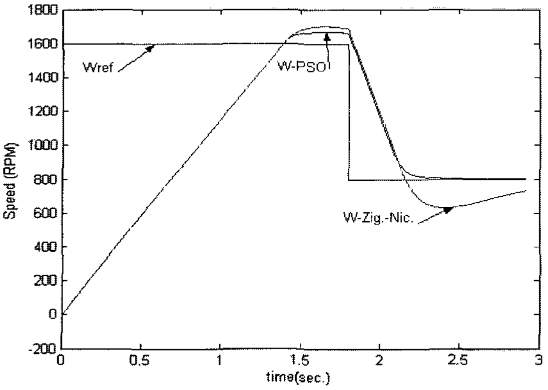
The current searching point of each agent is changing using (2) and (3).

Step 4 Checking the exit condition

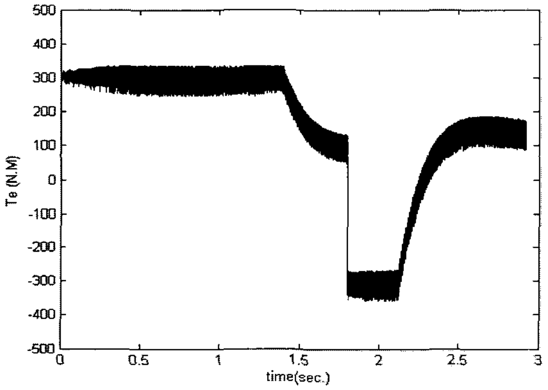
The current iteration number reaches the predetermined maximum iteration number and then is exited. Otherwise, the process goes to step 2.

The PI-controllers shown in figure (1) are tuned using both Ziegler-Nichols and PSO methods and the results are shown through figure (3) to figure (5).

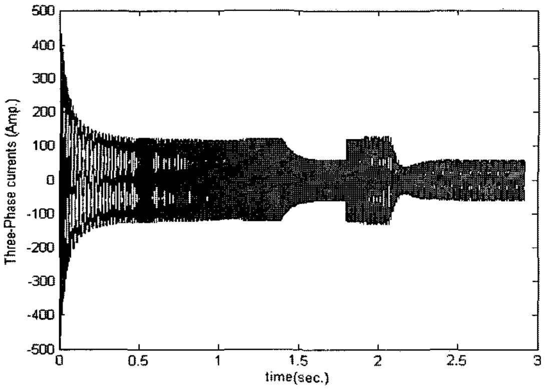
In figure (3) the system is tested under variations in speed reference and constant load and both conventional and PSO methods are used to tune PI-controller parameters. In figure (4) a standard driving cycle which contains both acceleration and deceleration is applied as a reference speed with a constant load. Also PI is tuned using both conventional and PSO methods; finally in figure (5) the system is tested under a variation in load and a constant reference speed.



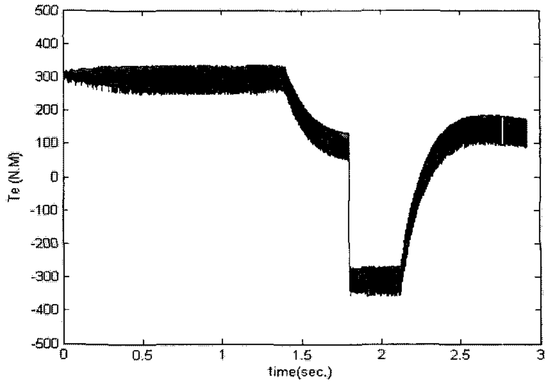
(a) Speed response



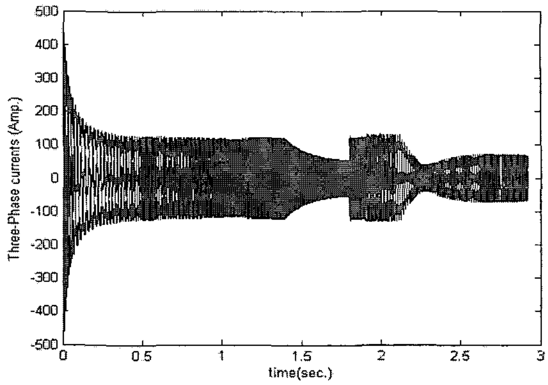
(b) Electromagnetic torque response with PSO



(c) Three-Phase currents with PSO

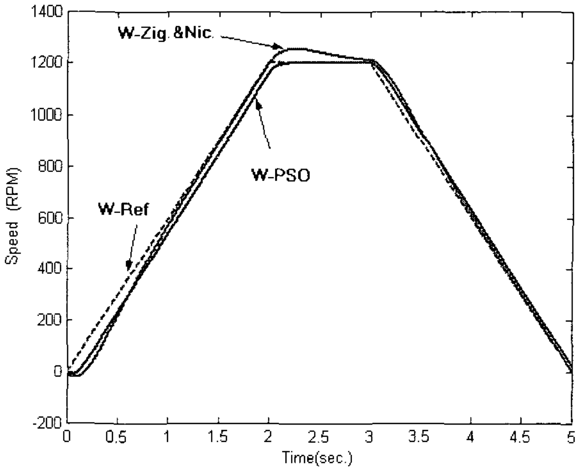


(d) Electromagnetic torque response with Z-N

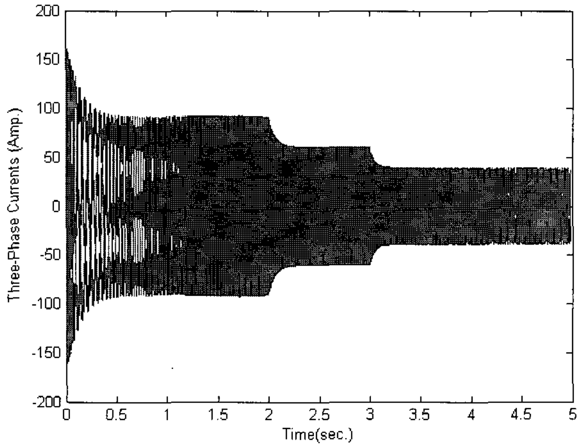


(e) Three-Phase currents with (Z-N)

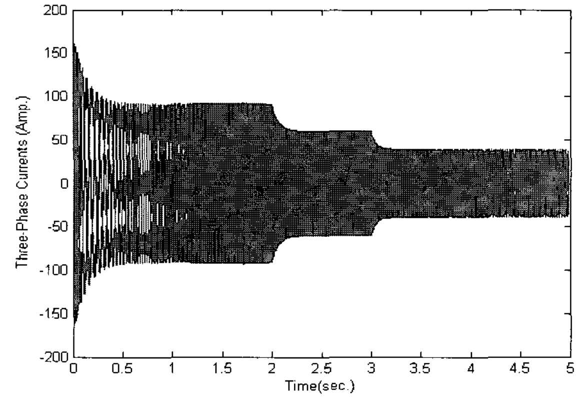
Fig. 3 transient response of the drive system under variation in speed reference (100 N.m) with both (Z-N) and PSO methods



(a) Speed response

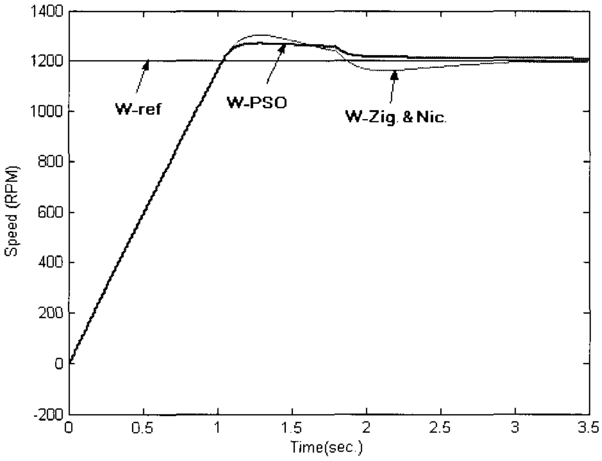


(b) Three-Phase currents with PSO

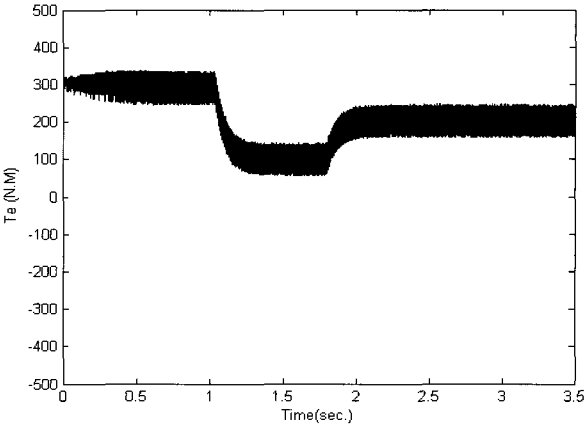


(c) Three-Phase currents with Z-N

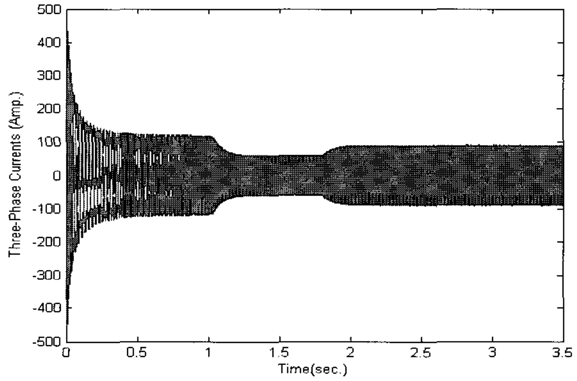
Fig. 4 transient response of the drive system under Ramp acceleration and Deceleration in speed reference (100 N.m) with both (Z-N) and PSO methods



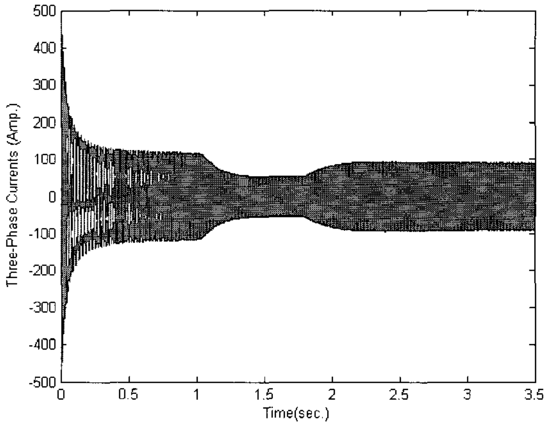
(a) Speed response



(b) Electromagnetic torque response with PSO



(c) Three-Phase currents with Z-N



(d) Three-Phase currents with PSO

Fig. 5 transient response of the drive system under sudden application of step change in speed reference and load change from 100-200 N.m with both (Z-N) and PSO methods

9. Conclusions

The overall system is simulated and tested when subjected to various operating conditions which are suitable for EV. The motor is controlled for both speed and currents using PI-controllers which are tuned using a PSO algorithm to optimize the PI parameters (Kp and Ki) for each controller instead of the traditional Z-N method.

The system is first tested for a step change in the speed of the motor under constant load. As shown in figure (3) the speed response of the tuned system using PSO is faster and has lower overshot than applying the Z-N method. The system is tested using a speed reference that includes acceleration and deceleration (more suitable than for EV) under constant load and the response is also is faster and has lower overshot with PSO. Finally the system is tested under a change in the load and a step change in the speed reference. From the response of the drive system shown in figure (5) it is obvious that the response of the system with PSO is faster, has lower overshot and has lower steady state error. From these results, the PSO succeeds in tuning on-line the PI-controller more efficiently than the traditional method, and shows a more dynamic response.

APPENDIX (A)

Motor Parameters
Power=37Kw
2P=2
$J=1.662\ Kg.m^2$
B=0.1 N.m.s
L_m=34.7mH
L_{ls}=0.8 mH
$L_{lr}^{-} = 0.8$ mH
R_s=0.087 Ω
$R_r^{'}$ =0.228Ω

APPENDIX (B)

LIST OF SYMBOLS
C1. C2 : Acceleration Coefficient
gbest : Global best value
I_a : Armature current
K_a : Torque constant
K_i : Integral Constant of PI-Controller
K_p : Proportional Constant of PI-Controller
pbest : personal best value
P_{gi} : Global best value
P_j : a personal best position in search space
r1 and r2 : are random numbers between 0 and 1
T_{em} : Electromagnetic torque of the motor
V_i : current velocity
V_k : current velocity
V_{k+1} : modified velocity
W : the inertia weight
X_j : current position in search space
X_k : current position in search space
X_{k+1} : modified searching point
$\phi(I_f)$: Flux

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References

[1] Vas, Peter, Sensorless Vector and Direct Torque Control" New York: Oxford University Press, 1998.

[2] R.W. De Doncker and D.W. Novotny, " The Universal Field Oriented Controller" IEEE Trans. On I.A., vol.30, Jan/Feb 1994, pp.92-100.

[3] T.G. Habetler, F.Projumo, M.Pastorelli, "Direct Torque Control of Induction Machine Over a Wide Speed Range" IEEE-IAS Conf. Rec., 1991, pp.600-606.

[4] J. Holtz, "The Representation of AC Machine Dynamics by Complex Signal Flow Graphs," IEEE Trans Ind. Elect., Vol 42, No. 3, June 1995, pp. 263 – 271.

[5] H Tajima, Y Hori, "Speed Sensorless Field Orientation Control of the Induction Machine," IEEE Trans. Industry Appl., Vol 29, No. 1, 1993 pp 175 – 180.

[6] S. E Lysherski, Electromechanical Systems, Electric Machines and Applied Mechatronics, CRC Press, Boca Raton, 2000.

[7] A.Besharati, W.Lo,K.M Tsang " Self-Tuning of PID Controller Using Newton-Raphson Search Method " IEEE, Trans. Om I.E., vol.44, No.5,pp.717-725.

[8] R.C.Eberhart, J.Kennedy " A New Optimizer Using Particle Swarm Theory" Proc. Of sixth International Symposium On Micro Machine and Human Science (Nagoya-Japan), IEEE Service center 1995, pp. 39-43.

[9] A.S.Elwer, S.Wahsh, O.Khalil and A.Nour eldin " Intelligent Fuzzy Controller Using Particle Swarm Optimization For Speed Control of PMSM " IECON 2003 conf. Proc. Roanoke, Virginia, USA, 2-6 Nov. 2003, pp.1762-1766.

[10] Y.H.Shi, and R.C.Eberhart " Parameter Selection in Particle Swarm Optimization " The 7th, annual Conf., on Evolutionary Programming, San Diego, USA, 1998.

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