STARTING CURRENT REGULATION OF INDUCTION MOTOR THROUGH (NPSO)

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Abstract

The proposal in this research paper is starting current regulation for 3-φ induction motor through feedback controller. The challenging task in induction motor is starting current regulation. To ensure smooth starting of induction motor we need a device that can control the current inrush. The innovation in this paper is probabilistic based Particle Swarm Optimization for the PI controller. A standard PSO is modified by appropriate unification of probabilistic method, Elitism, and population adjustment taken from existing biological enhancement approaches like Genetic Algorithm (GA), Bees GA, Artificial immune system (AIS) etc. In the updated version of PSO, the randomly generation of particles will be based on the probability, so that with less iteration we can achieve the optimized values of PI controller. Some standard test functions are used to test
the updated PSO. Once the algorithm is successful in the test cases, then it is used for the soft starting of induction motor. Another crux of this paper is well tuned Proportional integral (PI) controller for closed loop operation. These testing results show cased at the time of smooth starting. The experimental results also depicted along with simulation.

**Keywords:** Induction motor, updated Particle swarm optimization technique (MPSO), Probabilistic technique, Elitism technique, population technique, Genetic Algorithm, Bees (GA), Artificial Immune System (AIS).

**NOMENCLATURE:**

\[ V_{ds} = \text{stator voltage along direct axis.} \]
\[ V_{qs} = \text{stator voltage along quadrature axis.} \]
\[ i_{ds} = \text{stator current along direct axis.} \]
\[ i_{qs} = \text{stator current along quadrature.} \]
\[ i_{dr} = \text{rotor current along quadrature axis.} \]
\[ i_{qr} = \text{Quadrature axis vector component of rotor current.} \]
\[ i_r, i_y, i_b = \text{Per phase current of induction motor.} \]
\[ r_s = \text{stator resistance} \]
\[ r_r = \text{rotor resistance} \]
\[ L_m = \text{Magnetizing inductance} \]
\[ L_s = \text{stator inductance} \]
\[ L_r = \text{rotor inductance} \]
\[ \omega_r = \text{Angular speed} \]
\[ \omega = \text{supply voltage angular frequency} \]
\[ T_e = \text{Electromagnetic torque} \]
\[ T_L = \text{Load torque} \]
\[ P = \text{Number of poles} \]
\[ J = \text{motor moment of inertia} \]
\[ \alpha = \text{firing angle representation} \]
\[ I = \text{hot line current} \]
\[ I^* = \text{reference rated current} \]
\[ e = \text{Feedback error from motor} \]
\[ \alpha_o = \text{Initial triggering angle} \]
\[ K_p = \text{Induction motor constant proportional gain} \]
\[ K_I = \text{Induction motor constant integral gain} \]
\[ C_1, C_2 = \text{Updated PSO positive constants} \]
1 INTRODUCTION

The basic methods for starting an induction motor is DOL starting, Electromechanical reduced voltage starting, solid state reduced voltage starting and variable frequency drive (VFD) starting. Direct online starting is the most economical way, but the poking for technology is drawing of high starting current. Another way of starting of an induction motor is electromechanical reduced voltage, which is being skeleton into auto transformer starting, star/delta starting and resistor/reactor starting. Comparatively star/delta starting is the most preferable one as it is economical, less space consuming and having low power losses. But this method can be used only for normally delta- connected star provided with six leads.

Generally starting methods need a mechanical switch or contact and have several disadvantages like, need a time to time examination and maintenance, non-synchronous switching of motor phases(RYB) to the mains. Large amount of switching further leads to breakdown of moving parts, etc.

Nowadays sophisticated electrical technology has been evolved. The availability of these high-power devices demands sophisticated operation of drives. There by the innovation heading towards bio-inspired algorithms like Particle swarm optimization (PSO). The testing results ensure PSO is the most useful techniques for solving the global developmental problems. This method was primarily designed by J. Kennedy as an optimization method in 1995 and later on this technique has been proved to be one of the valuable techniques for solving the global optimization problems.

With SCR based voltage regulator operating in closed loop mechanism, makes the smooth starting of induction motor by varying the firing angle. the major essence in the ac voltage regulator with induction motor in closed loop is that we can vary

W = Updated PSO inertial weight
P_{rg} = random generation of particle by probability.
the voltage across the thyristor. Whereas at past works were grounded to current limit starting, the starting torque profile of induction motor for the better improvement was addressed later. By taking the voltage and power factor as feedback for a soft starter there is a development in the starting torque of the machine and artificial neural network (ANN) is also used for the generation of thyristor firing angles for smooth starting of the machine. Soft starters are also useful for saving of power.

The mitigation of starting current spikes resulted in extensive usage of soft starter even in large industries. But the differentiation proposed in this paper is soft starter works in closed loop mechanism. Closed loop control methods are normally obtained by iteratively simulating the induction motor model.

Innovation in this paper is induction motor smooth starting is employed by applying small signal model. Basically induction motor smooth starting is a dynamic process and we cant be explained that with steady state equivalent circuit. New technique is proposed updated PSO technique in which it searches the finest values of PI controller for induction motor smooth starting.

The main function of updated particle swarm optimization is when the set of particles are taken in order to depict the tuned particle. When the number of particles iterates for certain number of times then after some iterations the best particle would occupy the first place and remaining particles occupies with their respective position based upon their functionality behavior. Again those particles which have come from the first operation are again goes to operation and in that finds out the best particle and those particles are applied to the system for better performance. When those particles (poles and zeros) are plotted on the system stability graph, the main concentration is on the particles which are nearer to the origin because those particles only effects the system performance compared to the particles far away from the origin.

Due to some of the limitations PSO was having some drawbacks and they can be overcome by Time varying acceleration
coefficients (TVAC), particle swarm optimizer with mutation and Time varying acceleration coefficients (MPSO-TVAC) and self-organizing hierarchal particle swarm optimization with time varying acceleration coefficients (HPSO-TVAC). A collegial approach to standard PSO can be achieved by the improved particle swarm optimization methods. The updated version of pso signifies the smooth performance which is depicted in simulation and hardware results. This paper mainly represents updated structure of PSO, whereas the concepts of probability, Elitism and population are taken from some of the biologically inspired algorithms like genetic algorithm (GA) Ant colony optimization (ACO), Artificial immune system (AIS) etc. whereas ACO deals with probabilistic approaches. Genetic algorithm uses one or two best chromosomes in elitism and they will retain without undergoing to some selection, crossover and mutation.

Due to this advanced techniques availability the new PSO could produce its result in less number of iterations. On this process the new PSO is tested in different test functions and find out the best one and verified it. Due to this characteristic functions the novel algorithm is used for smooth starting of induction motor.

2 DEVELOPMENT OF MODIFIED PARTICLE SWARM OPTIMIZATION

The primitive equations which control the movement of the particle in standard in particle swarm optimization are given below: the predicted position of $i^{th}$ particle of the swarm and speed of the particle at $(k+1)^{th}$ iteration are defined as:

\[
\begin{align*}
V_{ij}^{k+1} &= w \cdot V_{ij}^k + C_1 \cdot \text{rand}() \times [pbest_{ij}^k - X_{ij}^k] + C_2 \cdot \text{rand}() \times [gbest_j^k - X_{ij}^k] \ldots \ldots (1) \\
X_{ij}^{k+1} &= X_{ij}^k + V_{ij}^{k+1} \ldots \ldots (2)
\end{align*}
\]

Where $i = 1, 2, 3, \ldots p$ is the particle index, $w$ is the inertial weight, and $c1$ and $c2$ are positive constant, called the acceleration
constants \( r() \) and is a random number, systematically allocated within the interval \([0, 1]\). \( j \) is the size (dimension) of the problem.

In PSO, after certain iterative operations the newly produced particle is within the direction of vector sum of the position of the particle which best fits within that position and its previous best position of the particle.

In PSO, the importance of random function is it gives a result of probabilistic particle movement. But, the quantum of probabilistic approach is limited because the speed of the particle is limited which is defined on equation (1) is a resultant of particle best and global best. Due to these limitations conventional approach of PSO is not suitable for finding the solution space quickly and efficiently. These can also results in reduced rate of convergence and performance of PSO.

In the modified method, the particles of population size, \( p \) is selected in a random manner and in those pbest and gbest are identified easily. In conventional approach the velocity and position of an each particle is updated for every iteration in PSO. But, in modified version of PSO a random number, \( p_i \), \( 0 \leq p_i \leq 1 \) is generated each time and compared with the randomly generated particle \( p_{rg} \). For the condition \( p_i = p_{rg} \), in this the best particle is retained to first place and remaining (\( p-1 \)) particles are replaced with randomly produced particles. For another condition, this is when \( p_i \neq p_{rg} \), for this the originally generated population is retained and the loop will continuously iterate.

The pseudo code for updated PSO is given below:

Firstly the three parameters, like Max iteration, population size \( P \) and probability of random generation \( P_{rg} \) would be initialized.

\( P \) particles which are taken randomly are allowed into the solution space.

In those randomly generated particles, figure out the objective function value, for each particle at the end of the problem.
While after randomly generating the particles. For each particle initialize the present location as Pbest (particle best).
Find out the gbest.
Upgrade the current position and speed of each particle by using equations (1) and (2).
For (i<sub>Max iteration</sub>) Generate a random number,
The particle which is retained that particle having the gbest and remaining particles all are deleted; generate (P-1) particles randomly.
Else
Go to step 8
Upgrade (Renovate) Pbest and gbest of each particle.
i = i+1
End
In order to calculate the capability of the suggested algorithm, considerable simulations were carried out on a number of test functions. By applying these test functions the performance also included in the figure. The curves which we got are taken by doing, after averaging of 20 trail ru.

For each train run what we had used for initial population is used for each technique for easiness of comparison. Whatever the results that had been obtained after trailing each test function is listed in the table. From the above listed table and from the performance graph we can get in to one conclusion that, the proposed algorithm is the best standard PSO compared to previous methods. By using this technique we get quality output.
results and we get output in less number of iterations. This clearly determines the excellence of standard PSO.

The parameters what we had obtained from standard PSO is tabulated in table 2.

The results obtained by using standard PSO are shown in the figurative graph. In the improved version of PSO it is easy to calculate the test functions and performance graphs of these modified techniques.

3 APPLICATION OF NEW PSO FOR FEEDBACK CONTROLLER DESIGN

Designing of induction soft starting

The representational diagram of induction motor soft starting is shown in the figure. Here motor design is explained by the fifth order differential equation and it’s written as:

\[
\begin{pmatrix}
V_{qs} \\
V_{ds}
\end{pmatrix} =
\begin{pmatrix}
\frac{r_s L_m}{L_r} & 0 & L_m P & 0 & 0 \\
0 & \frac{r_s L_m}{L_r} & 0 & L_m P & 0 \\
0 & 0 & \frac{L_m P - \omega_r L_m}{r_r L_r} & \frac{r_r - L_r P - \omega_r L_r}{r_r L_r} & \frac{r_r + L_r L_r}{r_r L_r}
\end{pmatrix}
\begin{pmatrix}
i_{qs} \\
i_{ds} \\
i_{qr}
\end{pmatrix}
\]

Where \( p = \frac{d}{dt} \)

The electromagnetic torque is given by:

\[
T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qr} i_{qs} - i_{qr} i_{ds}) \ldots \ldots (4)
\]

The speed of the rotor is given by:
\[ P_{\omega r} = \frac{T_e - T_h}{J} \] ........(5)

The voltages at stator are \( V_{qs} \) and \( V_{ds} \) in equation(3) are given by

\[
\begin{bmatrix}
V_{qs} \\
V_{ds}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}
\end{bmatrix}
\begin{bmatrix}
V_{rs} \\
V_{bs} \\
V_{ys}
\end{bmatrix}
\]

Where \( V_{rs} \), \( V_{bs} \) and \( V_{ys} \) are motor terminal voltages and are derived below:

We can vary the speed of the induction motor by varying the stator side voltage. It can be done by using an AC voltage regulator, by changing the parameter \( \alpha \) called as firing angle, which is connected in between the induction motor and supply.

Voltage components of stator side and with its instantaneous phase voltages can be written as:

\[ V_r = V_m \sin(\omega t) \] .......(7)
\[ V_y = V_m \sin(\omega t - 2\pi/3) \] .......(8)
\[ V_b = V_m \sin(\omega t + 2\pi/3) \] .......(9)

Here \( \omega \) is the angular frequency in rad/s of sinusoidal supply voltage.

The motor phase voltage between the SCR voltage controller and supply phase voltage is given by:

\[ V_r = V_m \sin(\omega t), \text{ when } i_r \neq \text{ zero and } \omega t < \alpha \]
\[ = e_r \text{ when } i_r \neq \text{ zero and } \omega t < \alpha \] .......(10)

\[ = V_m(\sin \omega t), \text{ when } i_r \neq \text{ zero and } \omega t \geq \alpha \]

Similarly:

\[ V_y = V_m(\sin \omega t - 2\pi/3), \text{ when } i_y \neq \text{ zero and } \omega t < \alpha \]
\[ = e_y \text{ when } i_y = \text{ zero and } \omega t < \alpha \] .......(11)

\[ = V_m(\sin \omega t - 2\pi/3), \text{ when } i_y \neq \text{ zero and } \omega t \geq \alpha \]

\[ V_b = V_m(\sin \omega t + 2\pi3), \text{ when } i_b \neq \text{ zero and } \omega t < \alpha \]
\( e_b \text{ when } i_b = \text{ zero and } \omega t < \alpha \ldots \ldots \ldots (12) \)

\( = (\sin \omega t + 2\pi/3), \text{ when } i_b \neq \text{ zero and } \omega t \geq \alpha \)

While controlling the SCR voltage controller with three phases R, Y, B

There is another parameter called neutral shit voltage and is given by:

\[ V_{sn} = \frac{1}{3}(V_r + V_y + V_b) \ldots \ldots \ldots (13) \]

Thus the three phase forcing voltages at the induction motor terminal are given by:

\[ V_{rs} = (V_r - V_{sn}) \]
\[ V_{ys} = (V_y - V_{sn}) \ldots \ldots \ldots (14) \]
\[ V_{bs} = (V_b - V_{sn}) \]

The emf induced in each phase is written as:

\[
\begin{bmatrix}
  i_r \\
  i_y \\
  i_b \\
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
  1 & 0 \\
  \frac{-1}{2} & \frac{\sqrt{3}}{2} \\
  \frac{-1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
  i_{ds} \\
  i_{qs}
\end{bmatrix} \ldots \ldots (15)
\]

At the d-q axis the back emf induced in the motor terminals are:

\[
\begin{bmatrix}
  e_{dr} \\
  e_{qr}
\end{bmatrix} = \omega_r \begin{bmatrix}
  l_{rl} i_{qr} \\
  l_{rl} i_{dr}
\end{bmatrix} \begin{bmatrix}
  \psi_d \\
  \psi_q
\end{bmatrix} \ldots \ldots (16)
\]

Where;

\[
\begin{bmatrix}
  \psi_d \\
  \psi_q
\end{bmatrix} = \begin{bmatrix}
  \psi_{dr} - l_{rl} i_{qr} \\
  \psi_{qr} - l_{rl} i_{dr}
\end{bmatrix} \ldots \ldots (17)
\]

The rotor flux linkages in the direct and quadrant axis \( \psi_{dr}, \psi_{qr} \) are:
\[
\begin{bmatrix}
\psi_{dr} \\
\psi_{qr}
\end{bmatrix} =
\begin{bmatrix}
L_r & L_m & 0 & 0 \\
0 & 0 & L_r & L_m
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\
i_{qs} \\
i_{dr} \\
i_{qr}
\end{bmatrix}
\] ....(18)

The controlling of induction motor design is by using SCR firing angle \(\alpha\) and load torque \(T_L\). At the initial stage motor is started at no-load i.e. \(T_L = 0\) and motor current \(I\) is calculated through the model and that current is compared with the motor rotor current \(I^*\).

The main function here is to we can vary the motor current up to its rated value during the initial time. For this controlling action normally proportional integral (PI) controller is suggested. Thus we can see the controlling action by the variation of parameter \(\Delta \alpha\). The value of \(\alpha_0\) Tells us the starting SCR firing angle and is acceptably chosen.

4 PROBLEM DESIGNING

The input given to the motor smooth starting is \(K_p\) and \(K_t\) value. The motor current is made constant throughout the starting. The error \(ie = I - I^*\) is minimized by optimization, this is started as optimized problem and is given as minimized error

\[F(\phi) = \sum_{0}^{ts} (e(t))^2\]

This is subjected

\(Ts\) is starting internal

\(\phi = \{K_p, K_t\}\) Is the controller structure

The performance graph:

A Specific program in mat lab is designed for controller identification for newer PSO. The inputs to the proposed PSO are \(C1, C2,\) inertia factor, and probability of movement, population size and no of iterations. These all inputs are normally
The convergence graph for the conventional PSO and newer PSO are obtained. The graph can be plotted after giving 20 trail runs. The each trail is perfectly scrutinized for the better output.

The convergence graph clearly shows the comparison between the Conventional and newer PSO. The better result obtained can easily identified. The result obtained after the 30th iteration with the control constants are:

\[ K_p = 7.27 \text{ and } K_i = 15.8851 \]

The controller constants obtained from standard PSO are

\[ K_p = 9.92 \text{ and } K_i = 6.68 \]

**Simulated and measured results:**

This section will clearly describe about the experimental result carried out on a laboratory motor with advanced PSO with conventional and new PSO. The soft starting of motor is first simulated with help of motor dynamic equation and thus, verified with prototype motor which is available in laboratory. The soft starting dynamic model of motor is shown in figure 3 and the experimental setup shown in figure 5.

A 3-phase AC voltage regulator is employed to a power converter. In order to adjust the stator voltage more the firing angle is varied. The AC voltage controller consists of six SCR’s labeled as T1, T1’, T2, T2’, T3 and T3’. At a delay angle of \( \alpha \) and \( \pi + \alpha \) SCRs T1 and T1’ are triggered respectively with reference to the zero crossing of R-phase voltage. At delay angles of \( (2\pi/3) + \alpha \) and \( (2\pi/3) + (\pi + \alpha) \) the SCRs T2 and T2’ are triggered respectively. In the same way at the delay angles of \( (4\pi/3) + \alpha \) and \( (4\pi/3) + (\pi + \alpha) \) the SCRs T3 and T3’ are triggered respectively.

Microcontroller is the heart of any closed loop system and
microcontroller works as PI controller and also as a firing pulse
generator. The reference voltage of R- phase VRN is stepped
down and by using zero crossing detection (ZCD) it is converted
into digital pulse and then this pulse is connected to the pin RC0
of the microcontroller. The status of this pin is sensed by the
microcontroller at every second, it starts producing six firing
pulses through RB0 TO RB5 with a delay angle, which is
computed by PI controller which is realized by using the
microcontroller once the zero crossing signal will get appeared.

Extensive simulations and experimentations are being carried out
in order to validate soft starting scheme. The motor current
transient during starting is shown in figure 6(a). The soft starting
with the new PSO based PI current regulator is excellent with
zero overshoot and least ripple is suggested by the nature of
variation of motor current. The soft starting is also performed
using PI controller tuned through standard PSO for comparison.
Figure 6(b) shows the current transient with this scheme.

The motor current will have least ripple but it will have large
overshoot. The figure 4 shows the convergence graph which
describes difference in transient nature of motor current can be
gauged.

The objective function value is 48.36 at the end of 30 iterations
with a new PSO. The value is 98.30 with conventional PSO. The
difference in the quality gives raise to different transient motor
current variation with the new PSO and conventional PSO.

Circuit of Closed loop control of induction motor
Schematic diagram of the microcontroller based soft starter for induction motor
## Table 1: Standard Test Function Results

<table>
<thead>
<tr>
<th>Test Function</th>
<th>Interval</th>
<th>Global Optimal</th>
<th>Global Optimal obtained through</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex. 1</td>
<td>[0.10]</td>
<td>0.20</td>
<td>((2.0, 3.8))</td>
</tr>
<tr>
<td>Sphere</td>
<td>[5.11, 5.11]</td>
<td>(0.0, 0.0)</td>
<td>((0.004, 0.000, 0.00183))</td>
</tr>
<tr>
<td>Rosenbrock</td>
<td>[1.10, 1.10]</td>
<td>(1.1, 1)</td>
<td>((0.99591, 0.997126))</td>
</tr>
<tr>
<td>Kowalik</td>
<td>[3.5]</td>
<td>0.00</td>
<td>((0.00009, 0.09986))</td>
</tr>
<tr>
<td>Rastppin</td>
<td>[3.15, 3.15]</td>
<td>0.00</td>
<td>((0.00025))</td>
</tr>
<tr>
<td>Brainina</td>
<td>[3.10]</td>
<td>0.199726</td>
<td>((3.14159, 2.278324))</td>
</tr>
</tbody>
</table>

## Table 2: Parameters of Algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Standard</th>
<th>PSO TVAC</th>
<th>MPSO TVAC</th>
<th>HPSO TVAC</th>
<th>NEW PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1)</td>
<td>1.3</td>
<td>2.3-0.4</td>
<td>2.3-0.4</td>
<td>2.3-0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>(C_2)</td>
<td>1.3</td>
<td>0.4-2.3</td>
<td>0.4-2.3</td>
<td>0.4-2.3</td>
<td>1.2</td>
</tr>
<tr>
<td>(w_{max})</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>----</td>
<td>0.8</td>
</tr>
<tr>
<td>(w_{min})</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>----</td>
<td>0.2</td>
</tr>
<tr>
<td>Probability of random generation (p_g)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.3</td>
</tr>
<tr>
<td>Mutation probability (p_m)</td>
<td>---</td>
<td>---</td>
<td>0.4</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Population size</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
### TABLE III
**UPDATED PSO PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_x )</td>
<td>1.3</td>
</tr>
<tr>
<td>( C_y )</td>
<td>1.3</td>
</tr>
<tr>
<td>( w_{max} )</td>
<td>0.8</td>
</tr>
<tr>
<td>( w_{min} )</td>
<td>0.3</td>
</tr>
<tr>
<td>Probability of random generation ( P_{rg} )</td>
<td>0.3</td>
</tr>
<tr>
<td>Population size</td>
<td>9</td>
</tr>
<tr>
<td>Number of iterations</td>
<td>28</td>
</tr>
</tbody>
</table>

### TABLE IV
**MEASURED VALUE OF KEY PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard PSO</th>
<th>New PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current over shoot</td>
<td>3.5A</td>
<td>0.012A</td>
</tr>
<tr>
<td>Objective function, ( F(0) )</td>
<td>98.26</td>
<td>48.34</td>
</tr>
</tbody>
</table>

### 5 SIMULATED AND HARDWARE RESULTS

Fig:1(speed RMS current)
Fig:2 (instantaneous voltage current)

Fig:3 (instantaneous voltage current after soft starting completion)
6 CONCLUSION

Closed loop mechanism for a induction motor drive named smooth starter is the focused area.

The soft starter fed 3-φ induction motor drive with closed loop operation is first designed in MATLAB software.

Using updated version PSO results of the feedback controller constants identification for enhanced starting dynamics. The convergence values of the new PSO are tested on standard functions and then used for estimating optimal structure of motor current regulator. The complete equipment is first of all tested in the MATLAB and then finally implemented in the laboratory.

The main essence of this paper is tuned PI controller constants obtained through Probalistic PSO and hard ware implementation through low cost pic microcontroller(16f876) feedback controller validation through hardware.
References


