FLOWER POLLINATION ALGORITHM BASED PI CONTROLLER DESIGN FOR INDUCTION MOTOR SCHEME OF SOFT-STARTING

P. S. R. Nayak
NIT Trichy
India,
psnayak@nitt.edu

T. A. Rufzal
NIT Trichy
India
307115002@nitt.edu

Abstract—Metaheuristic optimization algorithms are largely employed to solve engineering problems. Flower pollination Algorithm is implemented in MATLAB to design feedback control for soft-starting of the induction motor. The motor is constrained to start at the rated current using the parameters of the PI controller obtained from Flower Pollination Algorithm. The algorithm converges faster to provide near-optimal global parameters. The satisfactory limiting of rated current during starting of the motor is observed.

Keywords—Induction Motor Starter, Flower Pollination Algorithm (FPA), Metaheuristic Optimization, Soft-starting.

I. INTRODUCTION

Starting of induction motors while limiting the inrush current within the rated current of the motor requires certain electrical or electromechanical devices, named as soft-starters. These devices are highly employed in industries to limit the start induction motors motor [1]. Induction motors can produce rotational starting torque when a polyphase induction machine is powered by balanced polyphase supply. In such conditions where there is no device to limit the current and torque of the motor, the starting transients are highly dangerous. The high inrush current creates a pronounced voltage drop in the system and the equipment connected to the same line are disrupted [2]. Also, the fluctuating starting torque, twice or thrice the rated torque, gradually makes wear and tear in the machine. Hence, the lifespan of the connected instruments and devices, as well as the induction machine, is drastically affected. To reduce the effects of induction motor starting, electromechanical reduced-voltage starting mechanisms are the mostly applied starting systems employed for the motors. These starting methods consist of reactor starting, reactor starting, star/delta starting and autotransformer starting. Among the starter types mentioned above, star/delta starters are widely adopted due to its simplicity and economic advantages. Application of different power electronics based soft-starters are detailed in [2], [3]. A closed loop soft-starter design implementing an algorithm based on ACO algorithm is discussed in [4].

The soft-starters are adopted wherever induction motors are started frequently. Variable frequency drives are used instead of soft-starters where further speed control of the motor is required [6]. If the motor does not require speed control, implementation of variable frequency drive cannot be economically justified. Design of PID controllers for induction motor soft-starters has gained better literature support [7]. Five sets of non-linear equations mathematically define the induction motor. Hence, the motor drive system becomes more complex to model. The feedback controller for the closed loop soft-starter design, therefore, should be elaborated in detail. This paper incorporates a dynamic model of the induction motor drive taken from [6]. The design of the feedback controller is achieved by formulating the starting dynamics of the motor as an optimization problem and thereby finding the best solution.

Employing metaheuristic algorithm to tackle highly non-linear engineering problems have been proven to be a better method. The control of closed loop PI controlled induction motor is non-intuitive. Also, conventional PID tuning methods rarely work effectively. In the paper, one of the recent metaheuristic algorithm, Flower Pollination Algorithm (FPA), is used to tune the PI controller constants, namely K_p and K_i, to provide the best performance of the drive.

Nature inspired metaheuristic algorithms follows a set of rules which are defined by observing the behavior of any biological organism or natural processes. The Flower Pollination Algorithm (FPA) is a population-based metaheuristic optimization algorithm and is introduced in 2012 [7]. This optimization algorithm is inspired by the reproduction strategy of flowering species of plants. This chapter explains the application of Flower Pollination Algorithm for estimation of the controller PI constants, such as K_p and K_i, for constant rated current starting of induction motors. FPA offers certain advantages such as simple computational steps, incorporation of levy flights and assures near global optima. PID controller design using FPA for a buck converter is discussed in [8]. Tuning of PI constants is for heater control using various metaheuristic algorithm including flower pollination algorithm is detailed in [9]. FPA has proven to be highly efficient to find the parameter of motor models [10]. In this paper development of the method for finding the optimal controller PI constants such as K_P and K_I, are well documented, and computed results are incorporated to confirm the validity of the approach.

![Figure 1. Circuit diagram of induction motor fed from anti-parallel thyristors with open loop control.](image-url)

978-1-5386-6159-8/18/$31.00 ©2018 IEEE
The soft-starter regulates motor current by comparing the motor current to the full load current of the motor and generating control action based on the error difference. The soft starter presented in this paper employs anti-parallel SCRs acting as a voltage regulator in a closed loop with a Proportional-Integral (PI) controller. The antiparallel pairs of thyristor, say T1-T2, T3-T4, and T4-T5, controls the terminal voltage of the motor according to the pulse generated by the feedback loop. The best parameters of PI feedback controller is estimated using FPA. The parameters are validated by substituting it in a induction motor soft-start drive model and observing the starting performance of the drive. The drive should be able to constrain the current so the motor is not badly affected with the starting transients.

II. DYNAMIC MODELING OF THE INDUCTION MOTOR

The basic schematic of the induction motor soft starting scheme used in this paper is depicted in Figure 1. The three-phase supply voltage is given to the motor through SCR based AC voltage regulator for stator voltage control during starting. Here, motor model is described [6] by the fifth order differential equation and is given below:

The rotating reference frame representation helps in eliminating spatially varying inductance of the induction motor. The stator voltages in rotating reference frame, \( V_{ds} \) and \( V_{qs} \) are given by,

\[
\begin{align*}
V_{ds} &= \frac{1}{\sqrt{2}} \left[ \begin{array}{c}
\frac{1}{2} \frac{1}{2} \frac{-1}{2}
\end{array} \right] V_{rs} \\
V_{qs} &= \frac{1}{\sqrt{3}} \left[ \begin{array}{c}
\frac{1}{2} \frac{-1}{2} \frac{-1}{2}
\end{array} \right] V_{ys} \\
V_{bs} &= \frac{1}{\sqrt{3}} \left[ \begin{array}{c}
\frac{-1}{2} \frac{1}{2} \frac{1}{2}
\end{array} \right] V_{bs}
\end{align*}
\tag{1}
\]

the state space model of the induction motor is given below:

\[
\begin{align*}
\frac{d}{dt} \left[ \begin{array}{c}
i_{ds} \\
i_{qs} \\
i_{dr} \\
i_{qr}
\end{array} \right] &= \frac{1}{\sigma} \left[ \begin{array}{cccc}
\frac{-r_s}{l_s} & \omega l_m & r_l & \omega l_m \\
\omega l_m & \frac{-r_s}{l_s} & l_m & \omega l_m \\
l_m & \omega l_m & \frac{-r_s}{l_s} & l_m \\
l_m & \omega l_m & l_m & \frac{-r_s}{l_s}
\end{array} \right] \left[ \begin{array}{c}
i_{ds} \\
i_{qs} \\
i_{dr} \\
i_{qr}
\end{array} \right] \\
&+ \frac{1}{\sigma} \left[ \begin{array}{cc}
\frac{1}{l_s} & 0 & 0 & 0 \\
0 & \frac{1}{l_s} & 0 & 0 \\
0 & 0 & \frac{1}{l_s} & 0 \\
0 & 0 & 0 & \frac{1}{l_s}
\end{array} \right] \left[ \begin{array}{c}
V_{ds} \\
V_{qs} \\
V_{ds} \\
V_{qs}
\end{array} \right]
\tag{2}
\end{align*}
\]

Where, \( \sigma = 1 - \frac{l_{sh}}{l_{s}} \)

The electromagnetic torque is given by,

\[
T_e = \frac{2}{\sqrt{2}} \rho L_m (i_{dr} i_{qs} - i_{qr} i_{ds}) \tag{3}
\]

The speed of the motor shaft is generally measured in rad./sec. The change in speed is affected by difference between load torque and electromagnetic torque of the motor and the total moment of inertia of the rotating parts,

\[
\frac{d\omega}{dt} = \frac{2}{J} \left( T_e - T_L \right) \tag{4}
\]

The \( d - q \) axis \( \psi_{dr} \) and \( \psi_{qr} \), the rotor flux linkages are given by,

\[
\begin{align*}
\psi_{dr} &= L_{dr} i_{dr} + \omega L_{m} \psi_{qr} \\
\psi_{qr} &= L_{qr} i_{qr} + \omega L_{m} \psi_{dr}
\end{align*}
\tag{5}
\]

The back emfs in \( d - q \) axis of the motor are given by,

\[
\begin{align*}
e_{dr} &= \omega r L_{dr} i_{dr} + \psi_{dq}
\end{align*}
\tag{6}
\]

where,

\[
\begin{align*}
\psi_{dq} &= \left[ \begin{array}{c}
\psi_{dr} - L_{dr} i_{dr} \\
\psi_{qr} - L_{qr} i_{qr}
\end{array} \right]
\end{align*}
\tag{7}
\]

The induced emfs in each phase are given below:

\[
\begin{align*}
e_{r} &= \sqrt{3} \left[ \begin{array}{c}
\frac{1}{2} \\
\frac{-1}{2} \\
\frac{-1}{2}
\end{array} \right] e_{dr} \\
e_{q} &= \sqrt{3} \left[ \begin{array}{c}
\frac{1}{2} \\
\frac{-1}{2} \\
\frac{-1}{2}
\end{array} \right] e_{qr}
\end{align*}
\tag{8}
\]

The phase currents are obtained as

\[
\begin{align*}
i_{r} &= \sqrt{3} \left[ \begin{array}{c}
\frac{1}{2} \\
\frac{-1}{2} \\
\frac{-1}{2}
\end{array} \right] i_{ds} \\
i_{q} &= \sqrt{3} \left[ \begin{array}{c}
\frac{1}{2} \\
\frac{-1}{2} \\
\frac{-1}{2}
\end{array} \right] i_{ds}
\end{align*}
\tag{9}
\]

The power electronics component to control the supply voltage to the motor is now introduced, Assume the instantaneous phase voltages as

\[
\begin{align*}
V_{b} &= V_m \sin (\omega t) \\
V_{r} &= V_m \sin \left( \omega t - \frac{2\pi}{3} \right) \\
V_{b} &= V_m \sin \left( \omega t + \frac{2\pi}{3} \right)
\end{align*}
\tag{10}
\]

The motor phase voltage is given by

\[
\begin{align*}
V_{r} &= V_m \sin (\omega t) \text{, when } i_r = 0 \text{ and } \omega t < \alpha, \\
&= e_r, \text{ when } i_r = 0 \text{ and } \omega t < \alpha, \\
&= V_m \sin (\omega t) \text{, when } i_r \neq 0 \text{ and } \omega t \geq \alpha
\end{align*}
\tag{11}
\]

Similarly the voltage for other branches can be derived based on equation (11), Equation (12) and (13) are derived with the assumption that the supply voltages to the voltage controller is balanced with a phase shift of 120 degrees with respect to each other.

\[
\begin{align*}
V_{r} &= V_m \sin \left( \omega t - \frac{2\pi}{3} \right) \text{, when } i_y = 0 \text{ and } \omega t < \alpha, \\
&= e_y, \text{ when } i_y = 0 \text{ and } \omega t < \alpha, \\
&= V_m \sin \left( \omega t - \frac{2\pi}{3} \right) \text{, when } i_y \neq 0 \text{ and } \omega t \geq \alpha
\end{align*}
\tag{12}
\]
required change in the firing angle based on the difference current from one of the phase is sensed and compared with the sum of the phase voltages and convert it into a digital pulse. The Detection (ZCD) function is created which steps it down one synchronization of the pulse. Hence, a Zero Crossing

\[
\alpha(t) = K_p e(t) + K_I \int e(t) dt
\]  

(16)

Differentiating the above equation, the neutral shift voltage existing for thyristor voltage controller with three wire system is given by:

\[
V_{sn} = \frac{1}{3} (V_A + V_B + V_C)
\]

(14)

Thus, the three-phase forcing voltages at the machine terminals are given by:

\[
V_{ra} = V_A - V_{sn} \quad V_{rb} = V_B - V_{sn} \quad V_{rc} = V_C - V_{sn}
\]

(15)

Equations (1) to (15) comprehensively describe the dynamics of AC voltage controller fed induction motor drive, where SCR firing angle, \(\alpha\), and load torque, \(T_L\), are taken as the independent variables.

A. Modeling of PI controller for the drive

Figure 2 shows the schematic of the three-phase AC voltage controller fed induction motor. The induction motor is made to work in a closed loop with feedback PI controller. Here, the AC voltage controller fed induction motor drive model is represented through equations (1) to (15). The motor is operated at no load, hence, the load torque, \(T_L\), is taken as zero. The initial firing angle, \(\alpha_0\), in each iteration of the algorithm is taken as 100 degrees. The point at which the supply voltage crosses zero point is important in synchronization of the pulse. Hence, a Zero Crossing Detection (ZCD) function is created which steps it down one of the phase voltages and convert it into a digital pulse. The function variable from zero crossing detection function acts as a timer to generate six firing pulses required for operation of the thyristors with a delay angle, \(\alpha\) computed by the PI controller. To generate the error signal for the PI controller, current from one of the phase is sensed and compared with the help of a comparator function. The PI controller provides the required change in the firing angle based on the difference between the currents.

\[
\frac{\Delta \alpha(t)}{\Delta t} = K_p e(t) + K_I \int e(t) dt
\]

(17)

For a programmable implementation in MATLAB at the \(n^{th}\) iteration with a step time of \(\Delta t\), we have

\[
\frac{\alpha(n) - \alpha(n-1)}{\Delta t} = K_p (e(n) - e(n-1)) + K_I e(n) \Delta t
\]

(18)

i.e., \(\Delta \alpha(n) = K_p [e(n) - e(n-1)] + K_I e(n)\Delta t\)

The step time for the simulation of the motor current, \(\Delta t\) is fixed at one cycle period of the supply voltage which is assumed to be constant at 50 Hz such that SCR firing angle is updated at the beginning of each supply cycle. It is important to mention that the SCR firing angle, \(\alpha\) is constrained between zero and \(\frac{2\pi}{3}\) radians, which is the effective range for a three-phase AC voltage controller.

B. Formulation of the Optimization Problem

FPA is employed to find the optimal parameter for the feedback controller of the induction motor. The feedback PI controller has the parameters namely \(K_p\) and \(K_I\). The mathematical value assigned to these constants affect the performance of the induction motor. The drive system will become unstable just by varying these parameter’s values. Since the induction motor drive system is non-intuitive and is governed by several differential equation, conventional tuning of these parameters does not work effectively or are highly complicated. Hence the problem is stated as a minimization function and algorithm is employed to determine the best suitable values. The aim of the algorithm is to find the optimal value for the controller PI constants so that the induction motor can maintain rated current throughout the starting period. The controller is also responsible to constrain the current overshoot during the starting transients. Let \(I^*\) be the rms value of rated current of motor and \(I\) be the actual motor current. Let \(e = (I^* - I)\) be the error and the minimization of the sum of square of the error, ie; sum-squared-error. Thus optimization problem can be stated as follows:

Minimize,

\[
F(\phi) = \sum_{i=0}^{n_0} (e(t_i))^2
\]

(20)

Subject to \(\phi_{(lower)} \leq \phi \leq \phi_{(upper)}\)

In the above,

\(ts\) = Starting interval and

\(\phi = (K_p, K_I)\) is the controller parameters.

In this paper, a recently developed biologically inspired optimization method, namely Flower Pollination Algorithm are used to design the PI controller and the above equation is used as the objective function for the optimization task. The algorithm continuously computes the resultant value of equation (20) and ranks the parameters which gives the minimal value.

III. PI CONTROLLER DESIGN THROUGH FPA

Pollination is the reproductive strategy practiced by flowering species of plants. Flower pollination mimics the reproductive strategy of flowers and was introduced by Xin-Sheng Yang in 2012 [6]. There are two types of pollination based on the pollen carriers; biotic pollination and abiotic pollination. In biotic cross-pollination the pollens are carried...
from one plant to another plant by means of animals or birds. On the other hand, in abiotic self-pollination, the pollens are transferred among different branches of the same plan by means of elements like winds. The biotic pollination strategy serves as exploration capability of the FPA whereas abiotic pollination serves as exploitation of the search space for the local search. The bees or other insects participating in biotic pollination exhibit patterns of Levy flights in fly distances. The FPA has been simplified with the following rules created by Yang for the ease of application in engineering domains.

1. Biotic cross-pollination is considered as processes of global pollination, and pollen-carrying pollinators obey Lévy flights for their movement.
2. For local exploitation, abiotic self-pollination is used.
3. Flower constancy, may be developed between pollen and carrier which tends to pollinate on specific species irrespective of availability of resources.
4. The switching probability \( p \in (0,1) \), controls the switching of local pollination and global pollination. A slight emphasis is given to global pollination for tuning switching probability.

For solving an optimization problem with the help of computer programming, it is obligatory to recast the rules in to mathematical equations. The mathematical equations also sets the rules for inter commutation among various pollen gametes. New controller constants are obtained based on these rules. The global pollination can be written as in equation (21)

\[
y_{i}^{k+1} = y_{i}^{k} + yL(\lambda) (b_{i} - y_{i}^{k})
\]

Where, \( y_{i}^{k} \) is the pollen at \( k \)th iteration. \( y \) is the scaling factor to control step length and \( b_{i} \) is the best solution among all the pollen at \( k \)th iteration.

\( L(\lambda) \) is levy flight-based step length vector. Levy flights can mimic the behavior of flying characteristics of pollen insects. Insects and several other species occasionally tends to travel long distance in search of food [9]. The levy flight equation is given by equation (18).

\[
L = \frac{2^{\Gamma(\lambda)}}{\Gamma(\lambda)} \frac{2^{1/\lambda}}{1} \frac{\Gamma(\lambda)\sin\left(\frac{\pi \lambda}{2}\right)}{\pi^2} x
\]

\( \Gamma \) is a gamma function. Mantegna Algorithm [6] is used to create Levy flight pattern from which step size \( s \) is drawn by using two Gaussian distributions \( P \) and \( Q \) by the subsequent transformation.

\[
s = \frac{p}{Q^{1/\lambda}} \text{ and } P \sim N(0, \sigma^2) \text{, } Q \sim N(0,1)
\]

Here \( P \sim (0, \sigma^2) \) implies Gaussian normal distribution is used to take the samples where the distribution have a variance of \( \sigma^2 \) and mean is equal to zero. For local exploitation, through abiotic pollination, the equation (21) is used

\[
y_{i}^{k+1} = y_{i}^{k} + \epsilon(y_{j}^{k} - y_{i}^{k})
\]

where \( y_{j}^{k} \) and \( y_{i}^{k} \) are pollen of the same plants but from different branches. This essentially mimics the flower constancy in a limited neighborhood. The steps for employing Flower Pollination Algorithm for the design of feedback controller is given as follows:

Step1: Initiate pollens with random positions. Here the position of pollen gametes is the \( K_{p} \) and \( K_{I} \) parameter of the PI controller. Evaluate fitness function, which is the sum squared error which is defined in equation (20), with these positions. Find the best solution among initial population. Evaluating fitness functions.

Step2: Define a switching probability, \( p \). The switching probability is used to switch between exploration and exploitation of the search space. In the paper switching probability of 0.7 gives a satisfactory convergence of all the pollens.

Step3: Select a random number and compare with switching probability. The random number is drawn from a uniform distribution to ensure randomness of the process. If random number is less than the switching probability, a step vector is drawn from levy distribution. Pollination is carried out by global pollination formula from equation (21)

Step4: If the random number selected in step three is greater than the switching probability, local pollination is carried out using equation (25).

Step5: Evaluate the fitness function based on the solutions after carrying out the pollination. If the value of fitness function is improved; update the solution else keep the old solution. Find the current best position of the pollen.

Step6: If the tolerance condition is met, the global best of that iteration is taken as the optimal solution. Else go to step 3. The program is designed to take the first fifty iteration of flower pollination algorithm as termination criteria.

During every generation of new \( K_{p} \) and \( K_{I} \) values during running of the algorithm, the program keep a check on boundary conditions of the search space. If the parameters are moving out of the bound, the program constraints the parameters within the search space. Once the motor reaches the rated speed, the firing angle of motor is set to zero so that rated voltage is continuously supplied at the motor terminals. The algorithm evaluates the sum-squared error of the objective function only till the motor reaches it no load current. Hence the program has lesser computational requirements.

IV. CONVERGENCE GRAPH

The Matlab program developed to implement Flower Pollination Algorithm for induction motor starting provides the optimal values of controller parameters. Fifty iterations of the program is run and convergence graphs are plotted. The convergence graph of best pollen is depicted in Figure 3. The convergence graph of each pollen is given in Figure 4. Figure 4 clearly illustrate that the efficient pollination of plant and successfully identifies optimum values of the controller constants. The parameters of the FPA used to obtain the convergence graph in figure 4 is given below in table 1. The optimal controller PI constants obtained using FPA are

\[
K_{p} = 11.11, \quad K_{I} = 9.9
\]
V. RESULTS

The machine variables used to program the closed loop model of the induction motor fed from the ac voltage regulator is taken from the datasheet of 3-ph, 415 V 1.27 kW star connected induction motor. The rated speed of the motor is given as 1435 rpm with rated frequency of 50 Hz. The parameters which are optimal for the soft-starting is obtained from running Flower Pollination Algorithm for 50 iterations. The effectiveness of the parameter, $K_p$ and $K_i$, are tested by substituting the procured values into the closed loop model that has been programmed in the MATLAB. The program simulated the starting of the motor and results are plotted. The motor is run for a time of 8 seconds and various measurements are computed. The rms voltage and current waveforms are plotted and depicted in Figure 5. As can be observed in the figure, the current drawn during the starting period of the motor is made to constrain to the rated current of the motor, 2.7 A. The ratings of the motor is given in Appendix. In Figure 5 the rms voltage applied to the motor is seen varying in accordance with the rms current waveform.

The SCR pairs control the current by varying the supply voltage to the motor. Instantaneous values of the voltage and current is plotted in Figure 6. The initial portions of the instantaneous voltage seemed to clamp off is due to the fact that the peak of the supply power is restricted by adjusting the firing angle of the thyristors. The change in firing angle with respect to change in current can be observed from Figure 7. The firing angle, $\alpha$, makes a jump from the given initial firing angle to restrict the voltage and thereby reducing the starting current. As the motor gains no load speed, the firing angle is reduced with respect to reduction in the motor current. The speed of the motor is plotted in Figure 8. The motor gains it’s no load speed at 4.2 seconds from the initiation of power supply to the motor. The analysis of all the waveforms in this section of the chapter implies that the feedback controller designed by employing Flower Pollination Algorithm has proved to be effective in limiting the starting current of the motor. The algorithm was able to reach near global optima for the design of closed-loop feedback controller for the soft-starting of the induction motor.

CONCLUSION

This paper systematically describes the steps to be followed to employ Flower Pollination Algorithm towards the design of parameters for the feedback controller. The induction motor is modelled dynamically in $d$-$q$ axis and the supply for the motor is fed from a 3-ph ac voltage regulator. The motor is started in closed loop with controller constants substituted in the feedback PI controller and satisfactory results are obtained. With the optimal parameters obtained by using FPA the starting of the motor was smooth and the motor current was restricted to its rated value.

REFERENCES


