Design Optimization of 3hp, 4-Pole, 3-Phase, 50 Hz Induction Motor Employing Improved Genetic Algorithm

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***Abstract*— This paper deals with design optimization of asynchronous machine (3 HP, 4-POLE, 3-PHASE, 50 Hz) considering three objective functions torque (T), cost (C) and efficiency (η); using genetic algorithm (GA) / improved genetic algorithm (IGA) & non-linear programming.**

***Keywords*-Genetic Algorithm (GA); Improved Genetic Algorithm; Non-linear Programming.**

I. INTRODUCTION

Induction motors are being widely used for almost all practical purposes in industrial & domestic world, giving rise to the consumption of maximum share of the total electrical power generated. So, their efficiency, torque produced and cost becomes a major concern to be optimized. But the optimal design of I.M. is a problem due to the following reasons:

1. Induction motor involves so many variables, which non-linearly affects the performance of machine.
2. Due to involvement of various conflicting parameters, objectives and their non-linear behavior during design and operation of the machine, it becomes quite necessary to balance between many variables, sacrificing one for the other to obtain the best possible performance and optimized design depending on end user's application.

The effect of motor performance on surroundings and environment is of great concern also, e.g., the level of noise and acoustic comfort of train passengers and nearby residents has to be ensured. The motor starts making noise due to Maxwell's air gap forces, which causes in creating stator vibrations in audible range.

The problem of induction motor optimal design has received much attention since the beginning of computer sciences [4,13,16]. Many solutions and algorithms were designed based on following points.

Actually many conventions are made on the basis of practical experiences with manipulations of Induction motor design, e.g., a small air gap improves the efficiency, but increases the magnetic sound level and decreases the overload capacity of the motor; increasing the stator length of yoke to diameter ratio generally lowers magnetic vibrations [14]; but it increases the material cost; and with a fixed motor size, it decreases the available out-put torque with increased rotor temperature.

In literature so many single as well as multiple objective approaches for the electrical machine design has been proposed [13,17]; using various methods and techniques. These multiple objective approaches may be dealt with several NLP methods [8,9,10,11], as well as genetic algorithm [5,6,7,12,18] and improved genetic algorithm [15].

II. PROBLEM DEFINITION & DESIGN APPROACH

The standard single phase equivalent circuit model of a 3-phase induction motor on per phase basis is shown in figure-1. The model offers reasonably good prediction accuracy with modest computational efforts, despite its shortcomings. This model is basically a per phase representation of a balanced poly-phase induction motor in the frequency domain, comprising six model parameters. The six parameters have their usual meaning [5].

III. AN OVERVIEW OF OPTIMIZATION BY GENETIC ALGORITHM

In the most general sense, GA-based optimization is a stochastic search method that involves the random generation of potential design solutions and then systematically evaluates and refines the solutions until a stopping criterion is met. There are three fundamental operators involved in the search process of a genetic algorithm: selection, crossover, and mutation. The genetic algorithm implementation steps are shown as follows:

1. Define parameters and objective functions (Initializing).
2. Generate first population in a random manner from search space.

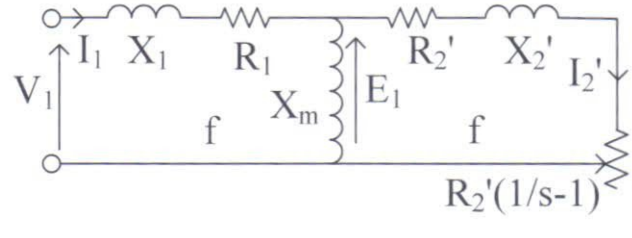

Fig. 1 Equivalent circuit model of an induction motor

3. Evaluate population by using objective functions and arrange in order of merit.

4. Test convergence. If satisfied then stop else continue.

5. Start reproduction process (Selection, Crossover, Mutation & elitism).

6. Form new generation of offspring and treat as new population. To continue the optimization, return to step 3.

To apply the GA approach, objective functions and constraints have to be defined to evaluate how good the motor design is obtained.

IV. Implementation of the Optimal Design Procedure

The formulation of the objective function [5] is as per the following process:

$$F(x) = \begin{cases} F(x) - P[g_i(x), r], & If\ F(x) - P[g_i(x), r] > 0 \\ 0, \quad If\ \ F(x) - P[g_i(x), r] \leq 0 \end{cases} \qquad (1)$$

Where, F(x) is the objective function, motor material cost/efficiency/torque, r is the penalty coefficient related to the value of objective function and x is design variable set. The penalty functions, P [g_j(x), r], are expressed with respect to the type of inequality used.

By means of exterior penalty function, constrained problems are converted to unconstrained problems by removing constraints. According to constraints, penalty function is defined as following [5]:

$$P\big(g_j(x), r\big) = \begin{cases} r\ [max\ (0, g_j)]^2, & j = 1, 2, ..m \\ r\ [min\ (0, g_j)]^2, & j = m, ...n \end{cases} \qquad (2)$$

When the constraint inequality is satisfied, the penalty function becomes inactive. The objective function emphasizes the larger constraint violations and the optimization search tries to reduce these violations to zero, in the feasible region. This would result in pushing the search into the feasible design region. All the constraints are satisfied within this region and the optimization approach attempts to move the design into its best optimum solution [5].

However, order of magnitudes of various constraints is much different from one another in case of electric motors. Therefore, constraint functions need to be normalized with respect to the specified objective function to have meaningful convergence criteria. It is to be ensured that constraints with higher values do not dominate over others. The normalized constraint functions in the penalty function are developed as shown in the following [5].

$$g_{j.norm}(x) = b_{j.ref} - b_j)/b_j, \ \ j = 1, 2, \ldots \ldots n \qquad (3)$$

Where $b_{j.ref}$ is the calculated value from the current generation / evaluation whereas b_j is the expert defined constraint as shown in Table 1. The main purpose for defining the constraint b_j is to have the final design for practically be feasible and acceptable. In general, the constraints are decided upon with great care taking into consideration the availability of materials, customer's requirements and manufacturing standards. Table 1 is also referred to as the motor specifications and their constraint values. Constraint values of variables can be expressed by following inequality [5] given below.

$$\begin{cases} g_1(x) = s - b_1 \leq 0, & g_6(x) = \frac{I_{sta}}{I - b} \\ g_2(x) = B_{sy} - b_2 \leq 0, & g_7(x) = Cos\Phi - b_7 \geq 0 \\ g_3(x) = B_{ry} - b_3 \leq 0, & g_8(x) = \dfrac{T_p}{T - b_8} \geq 0 \\ g_4(x) = B_{st} - b_4 \leq 0, & g_9(x) = \dfrac{T_{st}}{T - b_9} \geq 0 \\ g_5(x) = F_f - b_5 \leq 0, & g_{10}(x) = \eta - b_{10} \end{cases} \qquad (4)$$

In eqn.4, there are two different conditions of inequality constraint which are explained in following sections.

TABLE I INEQUALITY TABLE FOR MOTOR PARAMETERS

SR.NO.	NAME OF PARAMETER	INEQUALITY (b_j)
1	Slip, s	$\leq (b_1 = 0.05)$
2	Stator yoke flux density, B_{sy}	$\leq (b_2 = 0.6)$
3	Rotor yoke flux density, B_{ry}	$\leq (b_3 = 0.6)$
4	Stator teeth flux density, B_{st}	$\leq (b_4 = 1.7)$
5	Stator slot filling factor, F_f	$\leq (b_5 = 0.90)$
6	Starting current to rated current ratio, I_{start} / I	$\leq (b_6 = 7)$
7	Power factor, cosΦ	$\geq (b_7 = 0.8)$
8	Pull-out torque to rated torque, T_p / T	$\geq (b_8 = 1.5)$
9	Starting torque to rated torque ratio T_{st} / T	$\geq (b_9 = 0.6)$
10	Efficiency (η)	$\geq (b_{10} = 0.85)$

A. *First Condition*

It is not permitted that some constraints [as $g_j(x)$, j=7,…10] are below the expert defined level. For example, high value of power factor is desired for good performance in induction motors. If the expert-defined constraint for power factor as shown in Table 1 was 0.8, then anything less than that would be a violation.

B. *Second Condition*

It is not permitted that some constraints [as $g_j(x)$, j=1,..6] are above the expert defined level. For example, stator yoke flux density may not exceed certain values on account of iron losses. If the expert-defined constraints for stator yoke flux density as shown in Table 1 was 0.6, then anything more than that would be a violation.

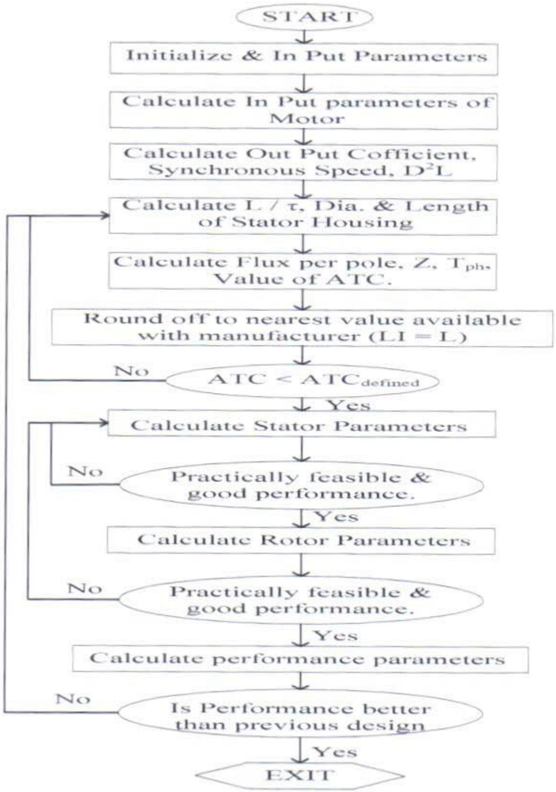

Fig. 2 Flow chart for 3-phase induction motor design using NLP

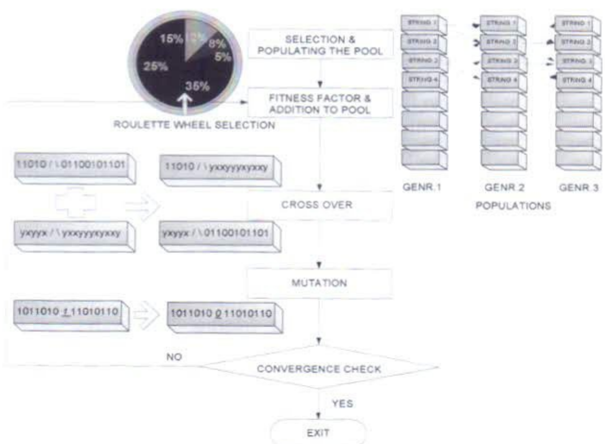

Fig. 3 flow chart for optimization using GA/ IGA

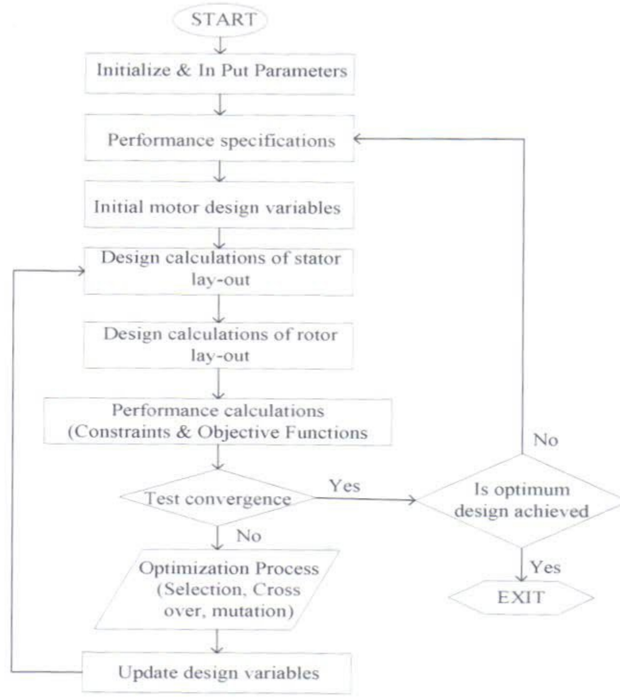

Fig. 4 Flow-chart for 3-phase induction design using GA/IGA

The software developed for the design optimization of the induction motor was prepared using "JAVA", which can analyze, optimize & evaluate design parameters and performance of motor. Parameters of the motor or materials used can be easily modified to investigate their effect on performance. Selection and optimization type (efficiency, torque, cost etc.) can be made depending on user.

The GA optimization algorithm was based on a roulette wheel selection, single point crossover, bit mutation and elitism. The flow chart for design optimization process using NLP is given in figure 2 and the flow chart for design optimization process using GA is given in Fig. 3 & 4. Each block consists of a number of subroutines.

V. Model for 3-Phase Induction Motor Design V. Optimization

The highly nonlinear constrained multivariable optimization problem is very difficult to be solved by the conventional methods. The optimization problem for 3-phase induction motor design can be formulated as [15]:

$$\begin{cases} \text{Min } f(x) \\ g_i(x) \geq 0, \quad i = 1,2,3,\ldots\ldots,n \\ h_i(x) \geq 0 \quad i = 1,2,3,\ldots\ldots,n \end{cases} \tag{5}$$

Where f(x) is the objective function of optimization, $g_i(x)$ and $h_i(x)$ are constraining functions, and x is the design variable set.

A. Objective Functions

In order to reduce the active (main) material cost and improve the efficiency of 3-phase induction motors, three different objective functions of optimization are defined separately as: [15]

$$\begin{cases} f_1(x) = C_{Fe.pu}W_{Fe} + C_{Cu.pu}W_{Cu.s} + C_{Al.pu}W_{Al.r}, \\ f_2(x) = \eta, \qquad f_3(x) = T \end{cases} \tag{6}$$

Where $C_{Fe.pu}$, $C_{Cu.pu}$, $C_{Al.pu}$ are the unit prices of magnetic material, copper wire and aluminum conductive bars respectively, W_{Fe}, W_{Cu}, and W_{Al} are the masses of the corresponding materials used in the construction of motor, η is the motor efficiency and T is full load torque produced.

$$\eta = \frac{Pout.put}{P_{out.put} + Losses} \tag{7}$$

Where, Losses = Stator iron loss + Stator copper loss + Rotor copper loss + mechanical loss,

$$\& \; P_{output} = P_{in.put} - Losses = \sqrt{3} V_L I_L \cos\Phi - Losses \tag{8}$$

B. Design Optimization Variables

There is a lot of design variables involved in the design of a 3-phase induction motor and it is required to choose critically the suitable parameters as the optimization design variables as per the following carefully [15]:

$$X = \begin{cases} [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}] \\ [L, D, l_g, Z, H_s, W_s, l_b, b_b, ATm, B_{av}, \delta_{Cu}, \delta_{Al}] \end{cases}$$

$$[L, D, l_g, Z, H_s, W_s, l_b, b_b, ATm, B_{av} \tag{9}$$

Where L stator core length, D stator core inner diameter, l_g length of air gap, Z number of stator conductors, H_s height of stator slot, W_s width of stator slot, l_b height of rotor slot, b_b width of rotor slot, ATm ampere conductors per meter, B_{av} average flux density, δ_{Cu} current density in stator winding conductor, δ_{Al} current density in rotor bars.

C. Constraining Functions

The Genetic Algorithm usually adopts the sequential unconstrained minimization technique (SUMT) to solve the problems defined by previous article [(V) B]. Experiences and simulations have shown that if the penalty factor is selected too large, the CGA may cause premature convergence. On the other hand, if the penalty factor is selected too small, the CGA may yield a highly computational burden. To overcome it, a new annealing penalty function, which adopts self-adaptive annealing penalty factors, is developed for Improved genetic algorithm (IGA) [15]:

$$f(x,\sigma) = f(x) + p(x,\sigma) \tag{10}$$

where,

$$p(x,\sigma) = \sigma[\Sigma i \, |min(0, gi(x)| + \Sigma i \, |hi(x)|]$$

σ is the penalty factor (σ=1/T, Ti+1=T_iα, , T is the value of the parameter under control, α is the proportionality constant within the range of 0-1), p(x, σ) the penalty function, and f(x, σ) the generalized objective function defined by the IGA.

To reflect the changing feature of the nature and imitate the parameter under control becoming more rigorous with the development of the generations, the fitness value of a string is defined as

$$fit = f_m - f(x,\sigma) \tag{11}$$

Where, f_m is a maximum objective function in a generation. To avoid prematurity, another technique known as the multi-turn evolution strategy was used.

D. Application of IGA to 3-Phase I.M. Design Optimization

The IGA is applied for design optimization of the 3-phase induction motor. In the process of optimization, the objective as well as constraining functions in previous articles [(IV), (V) C] are implemented as the following [15]:

$$\begin{cases} g_1(x) = L - L' \geq 0, \quad g_2(x) = D - D' \\ g_3(x) = l_g - l_g' \geq 0, \quad g_4(x) = Z - Z' \geq 0 \\ g_5(x) = H_s - H_s' \geq 0, \quad g_6(x) = W_s - W_s' \geq 0 \\ g_7(x) = l_b - l_b' \geq 0, \quad g_8(x) = b_b - b_b' \geq 0 \\ g_9(x) = ATm - ATm' \geq 0, g_{10}(x) = B_{av} - B_{av}' \geq 0 \\ g_{11}(x) = \delta_{Cu} - \delta_{Cu}' \geq 0, \quad g_{12}(x) = \delta_{Al} - \delta \end{cases} \tag{12}$$

Symbols have their meanings as given in eqn 9.

VI. OBJECTIVE FORMATIONS

The major performance parameters, which affects the machine performance typically, can be collected as: **1)** Cost of machine, **2)** Efficiency & Torque (FL) produced, **3)** Break down torque, **4)** Starting torque, **5)** Power factor of the machine, **6)** Full load slip of machine, **7)** Starting to rated current ratio, **8)** Pullout to rated torque ratio (over load capacity of the motor), **9)** Magnetic vibrations & noise.

A. Cost of Machine

It involves following parameters:

COST OF IRON:

$$C_{Fe} = L * OD^2 * k_s * P_{Fe} * C_{Fe.pu} \tag{13}$$

COST OF COPPER:

$$C_{Cu.s} = 3 * L_{swdg} * A_s * P_{Cu.d} * C_{Cu.pu} \tag{14}$$

COST OF ALUMINUM:

$$C_{Al.r} = L_e * A_b * S_2 * P_{Al} * C_{Al.pu} \tag{15}$$

COST OF INSULATION:

For a given voltage, Cost of Insulation material is proportional to Temperature rise of Machine & hence is proportional to total losses of the machine, and will be considered in efficiency maximization.

Total cost of the machine can be given by:

$$C_T = C_{Fe} + C_{Cu.s} + C_{Al.r} + C_{Insulation} + C_p \quad (16)$$

Where C_p is punching cost and can be taken as 20% of total cost.

B. Efficiency and Torque Produced at Full Load

The function for minimizing the losses can be used as function for maximizing the efficiency.

We know that,

$$Efficiency(\eta)\ \alpha \left[\frac{P_{out.put}}{P_{out.put}+Losses}\right] \quad (17)$$

And Losses in the motor can be given by:

$$Total\ Losses = W_i + W_{Cu} + F\ \&\ w\ loss \quad (18)$$

For maximum efficiency of the motor at full load, iron losses can be taken as equal to $P_{cu.stator.;}$ friction and windage loss can be taken as 10% of full load rotor copper loss ($P_{cu.rotor}$).

So, now total losses can be given by:

$$Total\ Losses = 2P_{Cu.stator} + 1. \quad (19)$$

$$Total\ Losses = 2 * 3I_{ph}^2 R_{swdg} + 1.1 I_b^2 (R_b S_2 + R_{ring}) \quad (20)$$

C. Breakdown (Pull-out) Torque

$$T_{BD}\ \alpha \left[\frac{1}{rotor\ reactance(X_r)}\right] \quad (21)$$

D. Starting Torque

We can obtain better starting torque with R / X ratio near to one at standstill, i.e.

$$T_{st}\ \alpha\ R_r; \quad If\ R_r/X_r = 1;\ T_{st} = T_{BD}$$

Better starting torque can also be obtained by deep bar or double cage rotor.

E. Starting Torque

We know very well that power factor of the motor is better with smaller air gap length (l_g).

$$Pf\ \alpha \left(\frac{1}{l_g}\right) \quad (22)$$

F. Full Load Slip

We know that slip, $$S = \frac{P_{Cu}}{P_g} \quad (23)$$

or, s α Copper Losses (24)

G. Starting to Rated Current Ratio

Starting Current is low with high rotor resistance, so it can be understood that if R / X ratio is near to one for better starting torque, the starting current will be low and ratio of starting current to rated current will be better for such a motor, but at the cost of efficiency.

H. Pull-out to Rated Torque Ratio

Pull-out to rated torque ratio

$$= \left(\frac{T_{Full\ out}}{T_{rated}}\right)\ \alpha \left(\frac{1}{X_r * efficiency}\right) \quad (25)$$

I. Magnetic Vibrations and Noise

We know that noise caused due to magnetic vibrations is a big problem, which is due to the zig-zag leakage reactance, which is inversely proportional to the air-gap length of the motor, i.e.

$$Noise\ \alpha\ (Zig - Zag\ leakage\ reactance) \quad (26)$$

But on the contrary larger air gap give rise to the magnetizing reactance which causes lower power factor and hence inferior performance of the motor. So, one has to make sacrifice between the noise and power factor of the motor.

VII. Performance Index

Now we can write performance index as:

$$J = k_1 CT + k_2\left(1-\frac{1}{\eta}\right) + k_3\left(\frac{R_r}{X_r}-1\right) + k_4\left(1-\frac{1}{l_g}\right) + k_5\left(1-\frac{1}{X_r * efficiency}\right) + k_5\left(\frac{1}{l_g}\right) \quad (27)$$

Where, k_1, k_2....k_6 are weight constants given to different functions, given in table 2.

TABLE II WEIGHTS FOR PERFORMANCE INDEX

SR.NO.	NAME OF FUNCTION	WEIGHT GIVEN TO THE FUNCTION
1	Cost of the motor	0.1
2	Total losses	0.5
3	Starting torque	0.1
4	PF (Length of air gap, lg)	0.15
5	Pull out to rated torque ratio	0.1
6	Magnetic Vibration and Noise Function	0.05
	Total Weight of Performance Index	1

These weights are decided for a motor running for a small *Atta-Chakki* under following conditions:

1. Continuous running for more than 20 hrs per day.

2. The motor should be economic but due to its continuous running and smaller size (lower capital cost) energy efficiency and performance is more important.

3. The motor is to be used in a silent environment (say residential area, or for house hold use). So, we have to consider weight for noise function also, but it is very less due to the fact that it conflicts with the power factor and hence the efficiency of the motor. One has to sacrifice between the noise and the efficiency and performance of the motor.

TABLE III PARAMETERS USED IN GA / IGA

SR.NO.	PARAMETER	VALUE / CRITERIA
1	Population Size	400
2	Cross over rate	0.8
3	Mutation rate	0.01
4	Elite count	2
5	Stopping criteria	|Performance Index| ≤ 0.15 && [1 / {| Performance Index_1 - Performance Index_0 |}] = null
6	Number of generations	10,000 (Max)
7	Cross over method	Single point crossover with fixed cross over rate (0.8)
8	Mutation method	Bit string mutation with fixed mutation rate (0.01)
9	Selection coefficient	Fitness
10	Fitness method	Genetic load

VIII. RESULTS

Results are summarized and analyzed in Table 4. These results are also depicted in Figs. 5, 6 & 7 given at the end.

IX. CONCLUSIONS

Result analysis of design, optimization and validation (by MATLAB/SIMULINK MODEL) gives the following conclusions:

1 The output of the GA program and its validation using SIMULINK / MATLAB shows that:

2 The cost of motor decreases with increase in efficiency.

3 Starting current of motor increases considerably but with better starting torque, which is required in the assumed case, as on load starting is required. Breakdown torque is also improved considerably and hence overload capacity also increases.

4 The optimized motor design using GA/IGA reaches full speed faster having lesser transient time, lower slip & higher efficiency at full load and lower cost, so the temperature rise of the windings and hence insulation during starting as well as running will be lower and the life of the motor will be longer due to longer life of the insulation material.

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TABLE IV. COMPARISION OF PERFORMANCE BY OUTPUT OF SIMULINK / MATLAB

SR.NO.	PARAMETER / MACHINE NO.	MANUAL	NLP		GA	
			AMOUNT	% IMPROV.	AMOUNT	% IMPROV.
1	Stator Voltage(Volt)	400.00	400.00	------	400.00	------
2	Stator starting current(Amp) (DOL)	28.00	42.07	50.25 (incr.)	44.90	6.73 (incr.)
3	Stator starting current(Amp) (Y-Δ)	9.33	14.02	50.25 (incr.)	14.96	6.70 (incr.)
4	Stator steady state current(Amp)	6.97	6.79	2.58 (decr.)	6.75	0.59 (decr.)
5	Rotor starting current(Amp)	26.87	41.97	56.19 (incr.)	43.70	4.12 (incr.)
6	Rotor steady state current(Amp)	3.96	3.61	8.83 (decr.)	3.66	1.38 (decr.)
7	Starting Torque(N-m) (DOL)	34.60	81.70	136.16 (incr.)	85.50	4.66 (incr.)
8	Starting Torque(N-m) (Y-Δ)	11.53	27.23	136.16 (incr.)	28.50	4.66 (incr.)
9	Break Down Torque(N-m)	35.20	59.20	68.18 (incr.)	62.00	4.73 (incr.)
10	Load Torque(N-m)	14.03	14.18	1.07 (incr.)	14.24	0.42 (incr.)
11	Time to reach full speed(Sec)	3.30	0.54	83.64 (decr.)	0.50	7.41 (decr.)
12	Rotor Speed(rpm)	1456.00	1466.00	0.69 (incr.)	1469.00	0.20 (incr.)
13	Slip(%)	2.93	2.27	22.52 (decr.)	2.06	9.25 (decr.)
14	Cost Function (α Cost in Rupees)	-------	754.06	-------	985.47	30.67 (incr.)

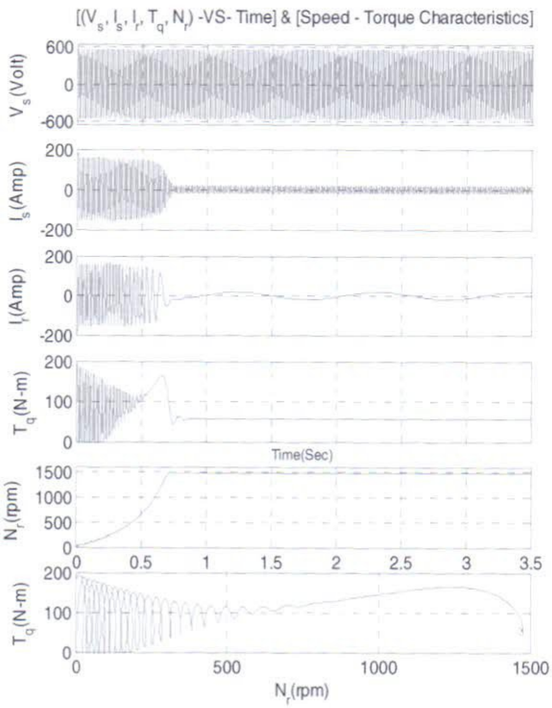

Fig. 5 Manual design

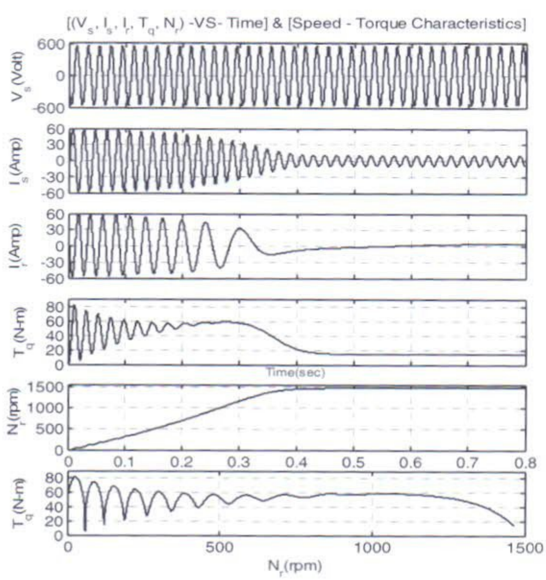

Fig. 6 NLP design

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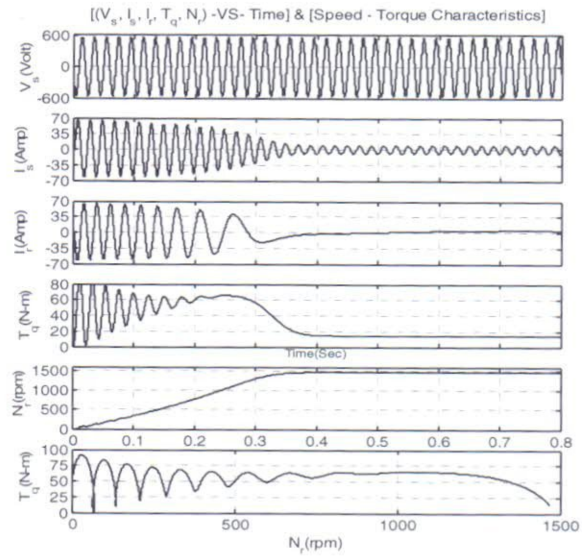

Fig. 5-7 Graphs showing results for designed Induction Motor. It depicts charateristics of 3 hp induction motor (transient response showing variation of stator voltage, Stator current, rotor current, torque, speed, speed – torque curve is also shown

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