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.

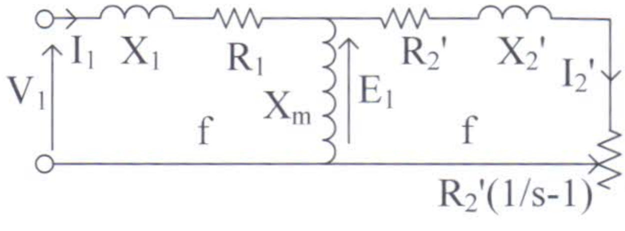

Fig. 1 Equivalent circuit model of an induction motor

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:

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

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]:

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

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].

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

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.

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

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.

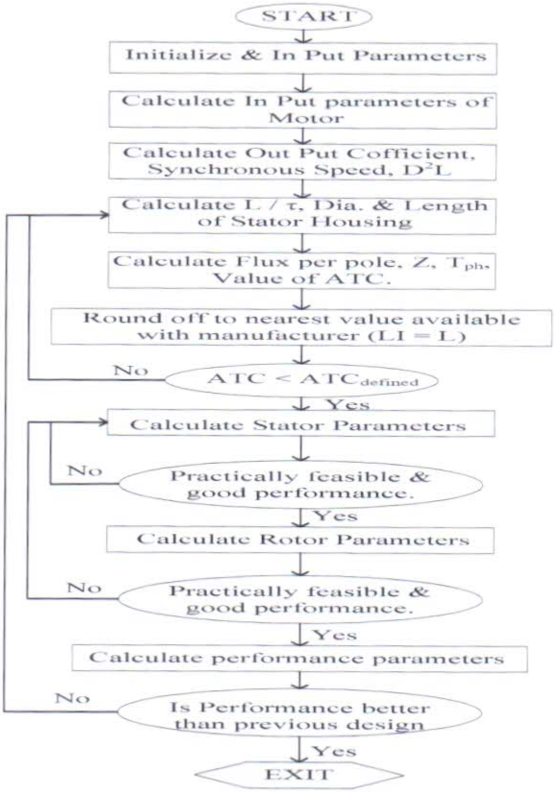

Fig. 2 Flow chart for 3-phase induction motor design using NLP

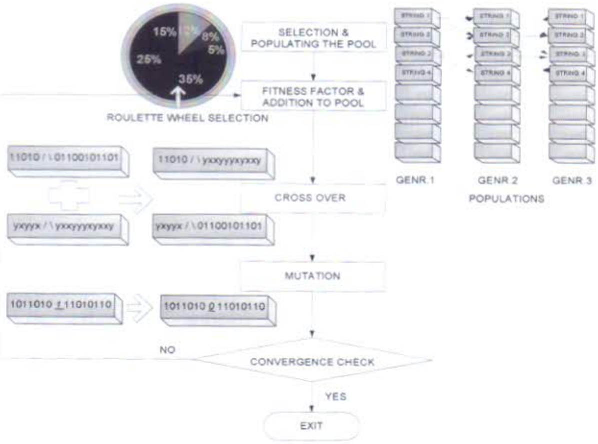

Fig. 3 flow chart for optimization using GA/ IGA

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.

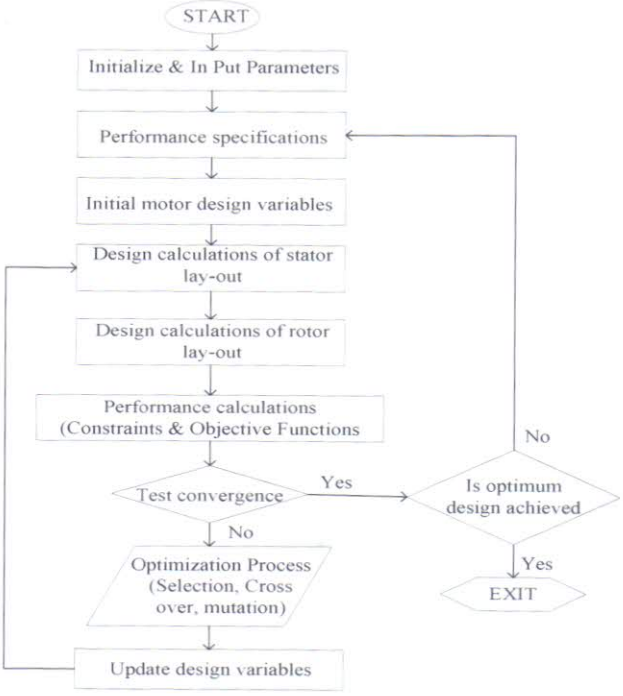

Fig. 4 Flow-chart for 3-phase induction design using GA/IGA

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]

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