

Black Hole Algorithm Optimization Based Design for Improving Starting Torque of Induction Motor

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ABSTRACT: This paper presents a Black Hole Algorithm Optimization based design methodology for maximizing the starting torque of Induction Motor (IM) . The BHA based design methodology is tailored to optimize the chosen primary variables with a view to obtain the global best design. The developed methodology is applied in solving two IM design problems and the results are presented with a view of exhibiting the superiority of the developed algorithm. The optimal design obtained by the proposed methodology for two IMs are presented with a view of illustrating the superiority.

KEYWORDS: Induction Motor, *Black Hole Algorithm Optimization*

Nomenclature

ED_i equivalent decimal value of i th sub-string
 $h(x)$ Objective function to be maximized
 LI fitness function of i th star
 $g(x)$ a set of inequality constraints
 I_{ph} phase current, A
IM induction motor
 I_r equivalent rotor current, A
 I_{sc} short circuit current per phase, A
"min"& "max" minimum and maximum limits of the respective variables
 nd number of decision variables
ODIM optimal design of IM
PM proposed method
 PS population size
 SFL slip at full load, per unit
 T_{st} starting torque, per unit
 V_{ph} phase voltage, V
 w weight constant of the penalty terms
 x_i i th decision variable
 Z impedance per phase

I. INTRODUCTION

Although squirrel-cage induction machines are widely used in the industry for their easy manufacturing and robustness, their applications in electrical transport systems such as subways and trains are limited due to inferior starting torque than those of permanent-magnet motors. In the light of the fact that the resistance of a squirrel-cage motor is fixed and

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small as compared to its reactance that is very large especially at the start, the frequency of the rotor currents equals the supply frequency, the starting current of the rotor is very large in magnitude and lags by a very large angle, resulting a poor starting torque per ampere. It is roughly 1.5 times the full-load torque, although the starting current is 5 to 7 times the full load current. Hence, such motors are not useful where the motor has to start against heavy loads. Therefore it becomes imperative that the best architecture and the corresponding dimensioning have to be determined in order to maximize the starting torque with respect to several constraints in applications requiring high starting torque such as in traction systems. The resulting mathematical optimization problem is usually difficult since the design variables contain continuous variables related to the real dimensioning parameters and combinatorial variables associated with architecture characteristics and discrete dimensioning parameters; and their relationship with motor specifications are in general nonlinear (Kentli 2009).. The optimal design of IM (ODIM) is so complicated that it is still a combination of art and science. There are many geometrical parameters and their relationships connected with motor specifications, which are in general nonlinear. Mehmet Cunkas 2010.

Over the years, in addition to statistical methods (Han and Shapiro 1967 and the Monte Carlo technique Anderson 1967, several mathematical programming techniques, which provides a means for finding the minimum or maximum of a function of several variables under a prescribed set of constraints, have been applied in solving the IM design problems. These techniques such as nonlinear programming, Ramarathnam et al 1971, Lagrangian relaxation method Gyeorye Lee et al 2013 direct and indirect search methods Nagrial et al 1979, Hooks and Jeeves method Faiz et al 2001, Rosenbrock's method -Bharadwaj et al 1979-a, Powell's method Ramarathnam et al 1973, finite element method T. S. Parkin et al 1993 and sequential unconstrained minimization technique Bharadwaj et al 1979-b are most cumbersome and time consuming. Besides a few of them requires derivatives and exhibits poor convergence properties due to approximations in the derivative calculations.

Apart from the above methods, another class of numerical techniques called evolutionary search algorithms such as simulated annealing Bhuvanewari et al 2005 Kannan et al 2010), genetic algorithm (GA) Satyajit Samaddar et al 2013: Sivaraju et al 2011, evolutionary algorithm Jan Pawel Wiecezorek et al 1998), evolutionary strategy Kim MK et al 1998), and particle swarm optimization (PSO),Thanga Raj et al Sakthivel et al 2011, have been widely applied in solving the IM design problems. Having in common processes of natural evolution, these algorithms share many similarities; each maintains a population of solutions that are evolved through random alterations and selection. The differences between these procedures lie in the techniques they utilize to encode candidates, the type of alterations they use to create new solutions, and the mechanism they employ for selecting the new parents. These algorithms have yielded satisfactory results across a great variety of engineering optimization problems.

Recently, Block Hole Algorithms Optimization (BHA) has been suggested for solving optimization problems. It is inspired by The stars are accelerated to move towards black hole as best solutions with random numbers based on current locations in every iterations.. In this approach, each problem solution is represented by a stars, population of stars are randomly created in the search space with the help of objective functions. It has been applied to a variety of power system problems and found to yield satisfactory results.

The aim of this paper is to develop a BHA based method for optimally designing IMs with a view of effectively exploring the solution space and obtaining the global best solution. The developed methodology has been applied in designing two IMs and the performances have been studied. The paper is divided into six sections. Section I provides the introduction, section II overviews BHA, section III formulates the IM design problem and elucidates the proposed method (PM), section IV discusses the results and section V concludes.

II. THE BLACK HOLE PHENOMENA

The concept of black hole was familiarized by John Michell and Pierre Laplace in the century, with the absence of stars in the space identified by integrating Newton's law. On those days the absence of stars in the space is

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not known as a black hole. Later in the century, an American physicist, John Wheeler who first named the phenomenon that mass collapsing or absence of stars is known as black hole. At the space region, the black hole has a strong gravitational field that even light cannot escape from it once the light enters through it. th 18 th 20

The radius of black hole is mathematically as defined as surface of event horizon also known as Schwarzschild radius [26].

The Schwarzschild radius is mathematically formulated by the equation (1):

$$R = \frac{2GM}{C^2} \quad (1)$$

Where,

- G is the gravitational constant
- M is the mass of the black hole
- C is the velocity of light

If any particle moves closer to the event horizon or crosses over surface of event horizon that will be absorbed by black hole and swallowed by it. The existence of black hole is distinguished by the effects of surrounding over it, like when light hits the horizon that will be absorbed completely without any reflection and vanish permanently. The schematic view of black hole in the space shown in figure (1)

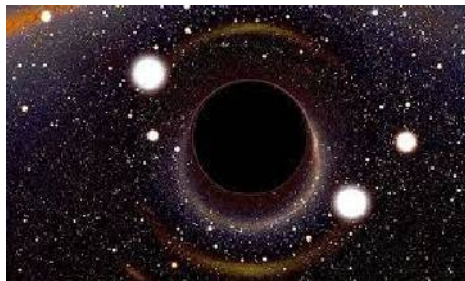


Fig. 1: Black Hole in the Space

2.1 Black Hole Algorithm

The BHA is a recently developed population based metaheuristic algorithm, which is used for optimization problems like genetic algorithm (GA) and particle swarm optimization (PSO) with some similar working mechanism. In BHA, the stars are used as a candidate solutions in a random search space. Where as in Genetic algorithm operators like cross cover, mutation, and reproduction are used for obtaining global best solution. Particle swarm optimization mimics the food foraging behaviour of birds, in which velocity and best positions are used to obtain gbest solutions. In the suggested algorithm, population of stars are randomly created in the search space with the help of objective functions. The candidate of stars are accelerated to move towards black hole as best solutions with random numbers based on current locations in every iterations. The absorbing power of stars is mathematically formulated for initializing of stars with objective functions is as follows:

$$X_i(t+1) = x_i(t) + rand(0,1)(x_{BH} - x_i(t)) \quad (2)$$

Where

$x_i(t)$ location of the star at iteration ;

$X_i(t-1)$ location of the star at iteration ;

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x_{BH} location of the black hole in the search space;

$rand$ random number in the interval [0, 1].

During the search process towards the black hole, a star can reach the black hole with lower cost, in that occasion the black hole should move to the locations of stars and vice versa. Thereafter, in BHA the black hole will start from its new location and searching will continue towards the new locations. In addition to the above said mechanism, there is a probability that stars will be moving towards the black hole that it may crosses the event of horizon. If the crossing stage happens, at that time stars will be sucked by the black hole, another new star will be created to maintain population size constant. The radius for the event of horizon in black hole algorithm is determined by mathematically as

$$R = \frac{f_{BH}}{\sum_{i=1}^N f_i} \quad (3)$$

Where,

f_{BH} is the fitness for the black hole and f_i is the fitness value for the i^{th} star. N is the number of candidate solutions (stars). The stars will be collapsed, when the distance of stars and black hole is less than the radius R and at randomly new stars will generated in the search space. Based on the above explanation the key steps in the BH algorithm are given in pseudo code as follows:

- Step1 Initialize a random population of stars at arbitrary locations in the search space. Step2 Calculate the fitness value of every star as a candidate of solution.
- Step2 Select the best star with lower cost as the fitness value.
- Step3 Modify the position of every star according to Eq. (2).
- Step4 if star reaches a position with lower cost than the black hole, then interchange their locations.
- Step5 When star crosses the event horizon of the black hole, create a new star randomly in search space.
- Step6 Distance between black hole and star is less than the R, generate a new star in search space.
- Step7 Stop criterion with global best solution

III. PROPOSED METHOD

The proposed BHA based solution method for ODIM involves formulation of the problem, representation of stars through the chosen design variables and stars are accelerated to move towards black hole as best solutions.

3.1 Problem Formulation

The ODIM problem involves large number of design variables. Many of these variables fortunately have a little influence either on the objective function or on the specified constraints. However, to ease the curse of high dimensionality, the following seven variables are identified as primary design variables.

$$X = [x_1, x_2, \dots, x_7] = \begin{bmatrix} \text{Core length to polepitch} \\ \text{Average value of air gap flux density} \\ \text{Ampereconductor} \\ \text{Length of air gap} \\ \text{Stator current density} \\ \text{Rotor current density} \\ \text{Flux density in the core} \end{bmatrix}^T \quad (4)$$

The ODIM problem is formulated by defining an objective function and a set of constraints as

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Maximize

$$h(x) = T_{st} = \left(\frac{I_{st}}{I_r} \right)^2 \times SFL \quad (5)$$

Subject to

$$g(x) \leq 0 \Leftrightarrow \left\{ \begin{array}{l} \text{maximum flux density of stator teeth} \leq 2 \\ \text{maximum flux density of rotor teeth} \leq 2.0 \\ \text{slip at full load} \leq 0.05 \\ \text{starting to full load torque ratio} \geq 1.5 \\ \text{stator temperature rise} \leq 70 \\ \text{per unit no load current} \leq 0.5 \end{array} \right\} \quad (6)$$

$$x_i^{\min} \leq x_i \leq x_i^{\max} \quad i = 1, 2, \dots, nd \quad (7)$$

Where

$$I_r = 0.85 \times I_{ph} \quad (8)$$

$$I_{sc} = \frac{I_{ph}}{Z} \quad (9)$$

3.2 Representation of Design Variables

The star s , is represented to denote the chosen primary design variables, defined by Eq. (4), in vector form as:

$$s_i = [s_i^1, s_i^2, \dots, s_i^7] = [x_1, x_2, \dots, x_7] \quad (10)$$

3.3 Fitness Function

The algorithm searches for optimal solution by maximizing a fitness of star LI , which is formulated from the objective function of Eq. (5) and the penalty terms representing the limit violation of the explicit constraints of Eq. (6). The LI function is written as

$$\text{Maximize} \quad LI = \frac{h(x)}{1 + w \sum_{i \in \eta} [g_i(x)]^2} \quad (11)$$

IV. NUMERICAL RESULTS

The proposed BHA based method is used to obtain the optimal design of two IMs. The first machine under study is rated for 7.5 kW, 400 V, 4 pole, 50 Hz and the second one for 30 kW, 400 V, 6 pole, 50 Hz. The effectiveness of the PM is demonstrated through comparing the performances with that of the GA based design approach. In this regard, the same set of primary design variables, fitness function and design equations, involved in the PM, are used to develop the GA based design approach. The software packages are developed in Matlab platform and executed in a 2.67 GHz Intel core-i5 personal computer. There is no guarantee that different executions of the developed design programs converge to the same design due to the stochastic nature of the GA and BHA, and hence the algorithms are run 20 times for each motor and the best ones are presented. The optimal design representing the values of the primary design variables and their performances are presented for both the motors in Table-1 and 2 respectively.

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Table 1 Comparison of Results for Motor-1

		GA	PM
Primary Variables x	Design		
	x_1	1.84829	1.96528
	x_2	0.43291	0.41167
	x_3	6973.12	6547.07
	x_4	0.29346	0.26089
	x_5	3.91240	3.63145
	x_6	7.92705	7.03718
	x_7	1.16720	1.26820
Constraints $g(x)$	$g_1 \leq 2$	1.375	1.267
	$g_2 \leq 2$	0.929	0.877
	$g_3 \leq 0.05$	0.033	0.031
	$g_4 \geq 1.5$	18.865	20.202
	$g_5 \leq 70$	26.302	25.463
	$g_6 \leq 0.5$	0.496	0.497
	$g_7 \geq 0.75$	0.895	0.899
Objective function $h(x)$	Starting Torque (Per unit)	10.063	10.435

Table 2 Comparison of Results for Motor-2

		GA	PM
Primary Variables x	Design		
	x_1	1.48782	1.78348
	x_2	0.50262	0.56613
	x_3	5978.26	5578.95
	x_4	0.28605	0.31653
	x_5	2.81751	2.87318
	x_6	7.25236	7.26332
	x_7	1.24152	1.14394
Constraints $g(x)$	$g_1 \leq 2$	1.599	1.638
	$g_2 \leq 2$	1.143	1.124
	$g_3 \leq 0.05$	0.019	0.020
	$g_4 \geq 1.5$	31.105	30.704
	$g_5 \leq 70$	28.754	26.552
	$g_6 \leq 0.5$	0.484	0.500
	$g_7 \geq 0.75$	0.893	0.886
Objective function $h(x)$	Starting Torque (Per unit)	16.142	16.218

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It is seen from these tables that the PM offers a starting torque of 10.435 and 16.218 per units, which are higher than that of SA based approach, for motor-1 and -2 respectively. These tables also include the values of the constraints of Eq. (4) along with their limits. It can also be observed from these tables that both the methods bring the constraints such as maximum flux density, slip at full load, starting to full load torque ratio, etc., of Eq. (6) to lie within the respective limit, as the constraints are added as penalty terms in the fitness function of Eq. (11).

V. CONCLUSION

Indeed the BHA is a powerful population based method for solving complex optimization problems. A new methodology involving BHA for solving ODIM problem has been developed and applied on two IM design problems. It determines the optimal values for primary design variables. The ability of the PM to produce the global best design parameters that maximizes the starting torque of the motor has been projected. It has been chartered that the new approach fosters the continued use of BHA and will go a long way in serving as a useful tool in design problems.

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