MultiScience - XXX. microCAD International Multidisciplinary Scientific Conference
University of Miskolc, Hungary, 21-22 April 2016, ISBN 978-963-358-113-1

# OPTIMIZATION OF A THREE-PHASE INDUCTION MACHINE USING GENETIC ALGORITHM

***György Tamás[1], Popp Áron Attila[1], Bíró Károly-Ágoston[2]***
PhD. Student, Professor
*Technical University of Cluj-Napoca*

*Abstract: Evolutionary algorithms (EA) have been systematically developed to solve mono-objective, multi-objective and many-objective optimization problems. In recent works connected with the Genetic Algorithms (GAs) in the design optimization of Electrical Machinery, it has been observed that GAs locate the global optimum region faster than the conventional direct search optimization techniques. In this paper a study of the NSGA-II algorithm is presented alongside with the optimized design results, obtained in the research work.*

**Keywords:** *induction machine, Genetic Algorithm, multi-objective optimization, cross over methods.*

## INTRODUCTION

In the last years the increase of the energy costs is leading to an increased attention to the energy saving in any energy transformation, whichever the energy sources are. Among these ones, the electrical machines represent an important category to focus on and develop further for getting important results in improving the motor efficiency [1]. Between the electrical machines the widely used one is the induction machine due to its robustness, low cost, flexibility and simplicity. The common needs of different size companies to reduce the electricity consume and the costs lead to the use of higher efficiency induction motors. Other consequences like the reduction of $CO_2$ emission are taken into account too [2, 3]. The electrical machines are the main consumers in the industrial sector with an electrical consumption up to 70% of the total consumed energy.

In the last years several studies demonstrated the potential energy saving in the electrical machines can be estimated at about 20% - 25%. [4] For this reason the International Electrotechnical Commission (IEC) promulgated the new set of rules IEC 60034-30 in 2007 [2]. The aim of this set of rules is to lead to an unification of the efficiency energetic classes with the scope to make clear the difference among the rules active in the different EU countries [3].

Optimization of induction motor design is one of the important aspects in electrical engineering design. The induction motor design is considered a nonlinear programming problem, where one or more objective cost functions of the design are minimized. The equation system, which defines the motor design procedure, consist a set of non-linear equations regarding to the motor mechanical characteristics, the motor performance, magnetic stresses inside the machine and thermal limits [4]. The research in this study has applied multiple objective optimizations in the design of a three phase induction motor. The design has been carried out using Genetic

DOI: 10.26649/musci.2016.066

Algorithm (*GA*) optimization method and the results obtained are discussed in this paper.

## OVERVIEW OF GENETIC ALGORITHMS

During the past two decades, evolutionary multi-objective optimization (EMO) algorithms have demonstrated their usefulness in solving optimization problems having multiple objective functions [5]. For this research the NSGA-II was implemented in MATLAB environment. The pseudo code for a standard GA can be represented as shown in Figure 1.

Before GA can be run, a suitable representation of the problem must be created. The GA also requires a fitness function, which assigns a merit to each coded solution. During the compilation, parents must be selected for reproduction and recombination to generate new offspring.

A fitness function is defined for each problem which was solved. Given for a particular chromosome, the fitness function returns a single numerical "fitness", which is supposed to be proportional to the utility of the individual result which that chromosome represents.

```
BEGIN /* genetic algorithm */
        generate initial population
        compute fitness of each individual

        WHILE NOT finished DO
        BEGIN /* produce new generation */

                FOR population_size / 2 DO
                BEGIN /* reproductive cycle */
                        select two individuals from old generation for mating
                                /* biassed in favour of the fitter ones */
                        recombine the two individuals to give two offspring
                        compute fitness of the two offspring
                        insert offspring in new generation
                END

                IF population has covered THEN
                        finished := TRUE

        END

END
```

Figure 1. Pseudo Code of a Traditional Genetic Algorithm

During the reproduction phase of a GA, individuals are selected from the population and recombined, producing offspring which will create the next generation of the GA population. Parents are selected randomly from the population using an equation which favors the individuals with higher fitness values.

Having selected to parents, their child's are created using recombination, typically using the mechanism of *crossover* and *mutation*.

*Crossover* takes two individuals and cuts their chromosome string at some randomly chosen position to produce two head and two tail segments. The tail segments are swapped and two new full length chromosomes are created. The two offspring inherit some genes from each parent. (Figure 2.a) In most of the cases the crossover is randomly applied in a threshold between 0.6 and 1. This gives each individual a chance of passing on its genes without the disruption of crossover.

*Mutation* is applied to each child individually after crossover (Figure 2.b). It randomly alters each gene with a small probability (in most of the cases 0.001).

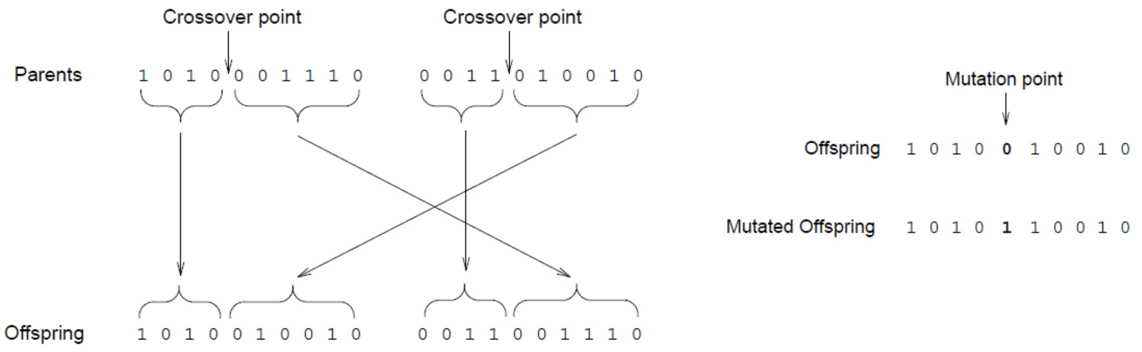


Figure 2. a).Single point crossover b). mutation.

It is considered that crossover is the more important technique for rapid exploration of the search space, mutation provides a small random search, which ensure that every point in the search space has a high probability of being examined.

## PROBLEM DEFINITION AND MATHEMATICAL MODEL

The equivalent circuit model of the induction machine is shown in Figure 3. This model is widely used by engineers and despite its shortcomings, offers good prediction accuracy with low computational effort. The model is a per phase representation of the poly-phase induction machine comprising six model parameters. These parameters are the stator resistance $R_S$, rotor leakage reactance $X_{\sigma S}$, magnetizing reactance $X_{\sigma m}$, core-loss resistance $R_m$, rotor leakage reactance $X_{\sigma R}$ and rotor resistance $R_R$ [6].

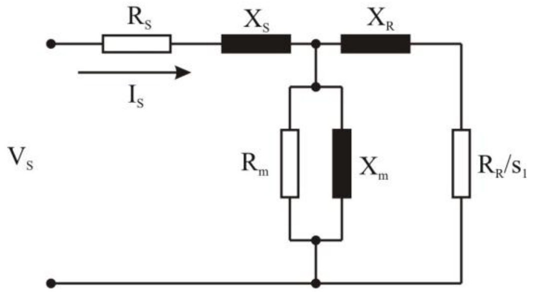


Figure 3. Induction machine equivalent circuit.

According to the equivalent circuit, motor input power, electrical losses, iron losses and mechanical losses are calculated as follows:

$$P_u = m\frac{U^2 * \frac{R_R}{s_1}}{\left(R_S + C_S * \frac{R_R}{s_1}\right)^2 + (X_{SS} + C_s * X_{SR})^2} - p_R \qquad (1)$$

$$p_{el} = m_f(R_S I_{Sn}^2 + R_R C_S I_R^2) \qquad (2)$$

$$p_{fe} = p_{jS} + p_{dS} + p_{jR} + p_{dR} \qquad (3)$$

$$p_m = p_{fa} + p_{lag} \qquad (4)$$

$$p_R = p_{elR} - p_m - p_{feR} \tag{5}$$

where $m_f$ is the number of phases, $I_{Sn}$ is the stator current, $I_R$ is the rotor current projected to the stator, $p_j$ are the yoke losses on stator and rotor, $p_d$ are the tooth losses of the stator and rotor, $p_{lag}$ are the losses on bearing and $p_{fa}$ is the air friction.

The total losses of the machine are given by the equation below:

$$p_{tot} = p_{el} + p_{fe} + p_m \tag{6}$$

In order to improve the overall design of the three-phase induction machine, two different objective functions were determined, based on efficiency and power factor.

*First objective function:* The efficiency of the machine needs to be maximized and the objective function is defined as:

$$f_1(x) = 1 - P_u/(P_u + p_{tot}) \tag{7}$$

*Second objective function:* The power factor of the machine will be maximized; the objective function is given as:

$$f_2(x) = 1 - (P_u + p_{tot})/(m_f U I_{Sn}) \tag{8}$$

*Second objective function:* The weight of the motor without the windings, are minimized to decrease the material cost and the total cost of the machine:

$$f_3(x) = G_{feS} + G_{feR} \tag{9}$$

where $G_{feS}$ is the weight of the stator and $G_{feR}$ is the rotor weight.

The constraints of this optimization are presented as:

- Breakdown torque, $T_M \geq 5$ Nm;
- Locked-rotor torque, $T_{st} \geq 2.5$ Nm;
- Rated torque, $T_N \geq 2$ Nm;
- Fill factor of stator slot, $k_{ucr} \leq 0.35$;
- Slip, $s_N \leq 0.12$.

It isn't preferable to use the constraints directly because their magnitude order is different and also the sensitivity of the functions is different too. The constraints having high sensitivity will reach the constraint border first and the other constraint functions wouldn't work [7]. To avoid this case, the constraints should be changed into:

$$\begin{cases} g_1(x) = \dfrac{T_M - T_{M0}}{T_{M0}} \geq 0 \\ g_2(x) = \dfrac{T_N - T_{N0}}{T_{N0}} \geq 0 \\ g_3(x) = \dfrac{k_{ucr} - k_{ucr0}}{k_{ucr0}} \leq 0 \\ g_4(x) = \dfrac{s_N - s_{N0}}{s_{N0}} \leq 0 \\ g_5(x) = \dfrac{T_{st} - T_{st0}}{T_{st0}} \geq 0 \end{cases} \tag{10}$$

The optimization process of an induction machine is highly nonlinear with the presence of equality constraints. However, this can be transformed into an unstrained optimization problem by adding the constraint violation (a penalty function) to the objective function [8]. Using the constraint violation, an augmented objective function F is formulated as:

$$F(x) = f(x) + \sum_{i=1}^{n} \{\min[0, g_j(x)]\}^2 \omega_j \qquad (11)$$

where $\omega_j$ is the penalty factor [9].

The design parameters and their limit values were given, the stator and rotor slot area, the diameter of the conductor, the number of turns and the inner diameter of the machine can be modified. The parameters are presented in Table 1.

To simplify the optimization process, the area of stator and rotor slot was included in the optimization process and a set of equations and constrains were determined for the calculus of the geometric dimensions of the stator and rotor slots, as The variation of induction on stator and rotor tooth surface shown in Figure 4. This excludes the slot geometry designs which are not feasible for realization.

The selection of the winding cross-section and number of windings are defined using a helper function implemented for the GA, which helps to choose numbers from a lookup table.

## THE RESULTS GIVEN BY THE GA

The induction machine model and the optimization algorithm were realized in MATLAB environment by the author, without using any implemented toolboxes. For the optimization an 8-core Intel Core I7-4770 processor was used with 12 GB RAM. The running time of the algorithm was extracted for further analysis.

Table 1

Optimization parameters and constrains of the GA algorithm.

| **Design parameter** | **Description** | **Lower limit** | **Upper limit** |
|---|---|---|---|
| $S_{cS}$ | Stator slot surface [$m^2$] | $92*10^{-6}$ | $104*10^{-6}$ |
| $S_{cR}$ | Armature slot surface [$m^2$] | $36*10^{-6}$ | $46*10^{-6}$ |
| $d_i$ | Inner diameter [mm] | 103 | 106 |
| $A_c$ | Conductor cross-section [$m^2$] | $1.77*10^{-7}$ | $1.96*10^{-7}$ |
| $w_b$ | Windings | 164, 185 | 183, 210 |

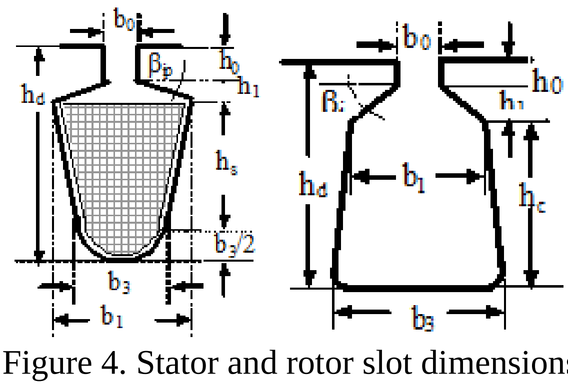

Figure 4. Stator and rotor slot dimensions.

The GA parameters used in this paper are presented in Table 2. The values of parameters are chosen by means of parameter tuning by analogy, namely using past experience that provide successful results for similar problems [4, 10].

Table 2

Set-up parameters of the GA.

| | |
|---|---|
| Population size | 400 |
| Selection function | tournament |
| Tournament size | 5 |
| Mutation function | Adaptive feasible |
| Crossover function | 185 |
| Crossover fraction | 0.75 |
| Pareto front population fraction | 0.35 |

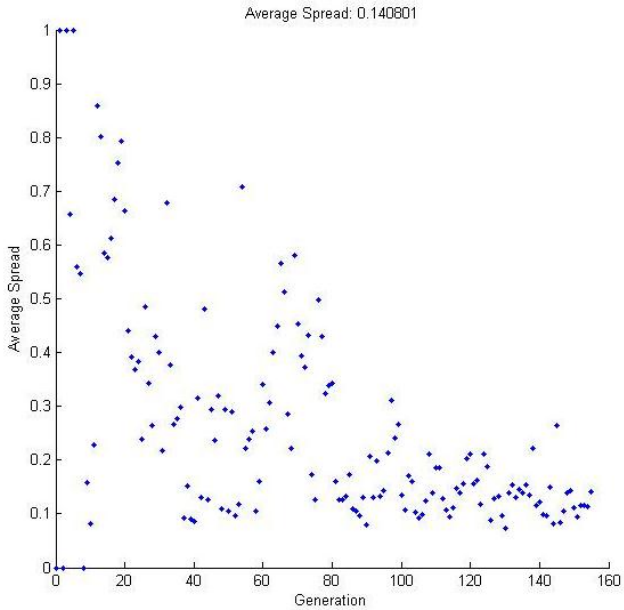


Figure 5. Average spread of the results.

Figure 5 presents the average spread of the generated individuals for every population. It can be stated, that with the algorithm reaching the optimum, this spread is greatly decreased.

The Figure 6 presents the results estimated by the GA in the form of a Pareto-front, which is a surface, where every point is an optimal solution. These points are considered optimal because the fitness function referring to every point is equal and maximum. For the research the Pareto-front is useful for choosing the proper optimal result from this dataset.

Because the purpose of the research was to find the highest efficiency with the lowest total weight, the power factor is considered a secondary result. The chosen motor parameters are presented in Table 3.

As it was expected, the initial calculus of the machine, done by the researchers, was far from the optimum, are worse than the results estimated by the

GA. The GA revealed the full potential of the initial design, with a significant increase of the efficiency, the power factor for the same torque values. The weight loss of the design was smaller than expected (aprox. 2%), however in the mass production this can be significant.

Table 3
Result chosen from the Pareto-front.

| **Parameter** | **Description** | **Initial model** | **GA model** |
|---|---|---|---|
| $S_{cS}$ | Stator slot surface [$m^2$] | $96*10^{-6}$ | $101.802*10^{-6}$ |
| $S_{cR}$ | Armature slot surface [$m^2$] | $36*10^{-6}$ | $38.5*10^{-6}$ |
| $d_i$ | Inner diameter [mm] | 106.1 | 104.613 |
| $A_c$ | Conductor cross-section [$m^2$] | $1.77*10^{-7}$ | $1.77*10^{-7}$ |
| $w_b$ | Number of spires | 184 | 207 |
| η | Efficiency | 72.87 | 80.589 |
| cosφ | Power factor | 62.31 | 0.79565 |
| $G_{fe}$ | Machine weight | 5.42 | 5.326 |

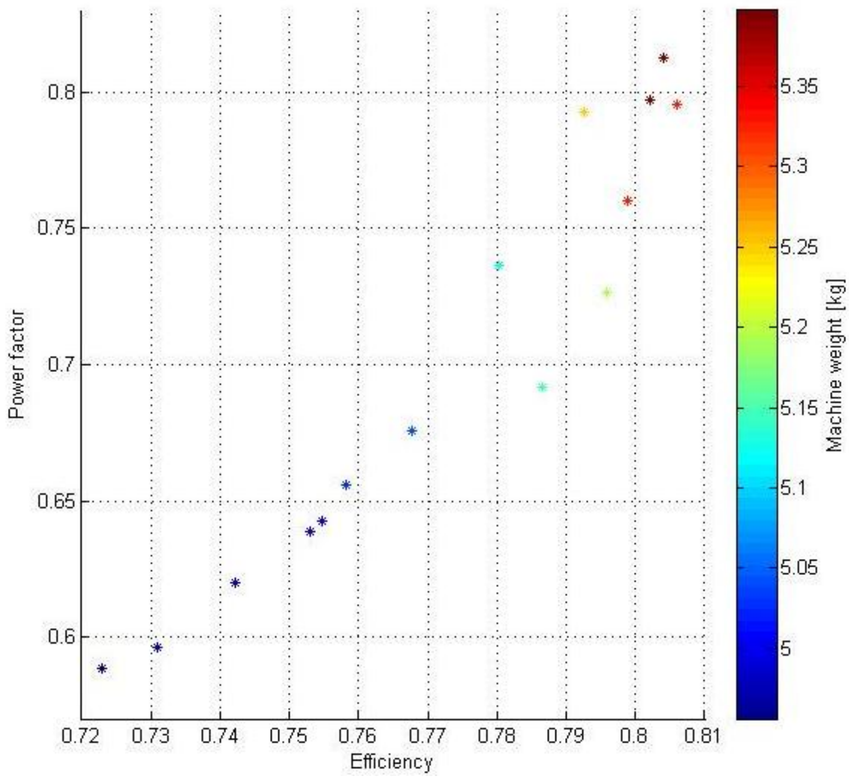

Figure 6. Pareto-front given by the GA algorithm.

## CONCLUSION

A GA-based design approach has been successfully applied to an induction machine in order to improve the efficiency, weight and the power factor of the machine. A software application has been developed for analyzing and optimizing the performance of the induction machine with external rotor according to a set of predefined parameters and constraints. The results demonstrate that the proposed method can lead to a significant improvement in the efficiency and power factor of an induction machine. However, further studies are necessary to prove the effectiveness and the accuracy of the presented method, including the FEM model of the optimized induction machine with external rotor.

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