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OPTIMIZATION OF INDUCTION MOTOR DESIGN

Summary. The problem with electric machine optimization can be specified as searching for a compromise between requirements manufacturer's and user's. Optimum design depends on several parameters, therefore it is very difficult to find real optimum. The evolutionary methods seem to be a way to solve this problem. In this paper there is explained the basic principle of simple Genetic algorithm with binary coding and Simulated Annealing algorithm. Their application to design optimization of a maximum efficiency induction motor is presented as well.

Key words: Genetic algorithm (GA), evaluation function, fitness value, crossover, mutation, Simulated Annealing algorithm (SA)

1. INTRODUCTION

Squirrel cage induction motors are widely used in industry. These motors consume 35%-50% of the total electric energy [5]. Manufacturers should be motivated to manufacture motors of higher efficiency. This is practically executed in Canada. Manufacturers are granted if they make motors of higher efficiency [2]. Factories from Europe that want to export the motors to such a country, have to comply with strict standards. Production plan of high efficiency machines has SIEMENS s.r.o. in Frenštát p.R. (Czech Republic) at present time. The goal of my work is to design a squirrel double cage induction motor of maximum efficiency.

2. EFFICIENCY IMPROVEMENT

For optimization I have chosen the batch produced squirrel double cage induction motor with following parameters:

Number of poles	4	Number of stator slots	48
Nominal voltage	380 V	Number of rotor slots	40
Frequency	50 Hz	Outer stator diameter	0.28 m
Nominal power	18.5 kW		
Winding joint	D		
Efficiency	90.3 %		

This motor analysis shows the lay-out of the losses. The stator iron losses and stator winding losses are dominant, as we can see in Table 1 (the original motor). I would like to mention materials used in this motor. The magnetic core is made of laminations 0.5 mm width (p_{10}=2.3 W/kg). The stator winding is made of copper $\rho_{Cu}=1/56\ \Omega\text{-mm}^2/\text{m}$. The winding is of two layers with 5/6 short pitch. The rotor double cage is made of cast aluminium $\rho_{Al}=1/34\ \Omega\text{-mm}^2/\text{m}$.

The efficiency improvement of induction motors is discussed very often nowadays. The authors of [3] tested motors with modified parameters. The original construction was 4 kW, two poles, 400 V, Q_s=36, Q_r=28, D_δ=104 mm, D_r=103.2 mm, D_{ex}=180 mm. The design variables were: the core length, the use of semi magnetic slot wedge, the core material, the winding pitch full or 5/6 short, the rotor end ring material Copper or Copper+Fe (the original motor has Aluminum). The highest efficiency of the tested motor was reached by increasing the core length (0.12 m instead of 0.082 m), by using better magnetic material 0.5 mm CK-37 (1.45 W/kg, 50 Hz, 1 T) instead of 0.63 mm

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DK-70 (3.1 W/kg, 50 Hz, 1 T), by using end ring material Copper+Fe and by using full winding pitch. The efficiency increase was 6.5 % at nominal point (from 85.5% to 92%). See reference [3] for details.

The ways to improve the induction motor efficiency [5]:

1. decrease of the stator winding losses
    - greater stator winding section
2. decrease of the rotor winding losses
    - greater rotor winding section
    - fewer turns connected in series in one stator phase cause less rotor current
    - using copper
3. decrease of the core losses
    - longer magnetic core (decreasing of the magnetic flux density at constant magnetic flux and less number of turns connected in series in one stator phase)
    - better magnetic material
4. decrease of the additional losses
    - optimal air gap size
    - optimal shape and number of stator and rotor slots
    - using semi magnetic slot wedge
5. decrease of the mechanic losses
    - suitable ventilation
    - optimal motor frame in order to improve cooling
    - good bearings and lubrication
6. higher temperature category of insulating system – less amount of cooling media – smaller ventilator (but the temperature increase makes winding losses rise).

As mentioned in Table 1, the main losses arise in the stator winding (38.1 % of total losses) and in the core material (24.3 % of total losses). That is why there have been chosen the following parameters for design of a high efficiency motor with manufacturing possibility considerations:

1. number of turns connected in series in one phase........................N1 = 80-120
2. core length ....l = 0.19-0.30 m
3. diameter of stator wire (without insulation)...................................d = 0.8-0.95 mm

The core of the optimized motor is made up from laminations with p_{10}=1.8 W/kg instead of p_{10}=2.3 W/kg in original construction. The influence of these four design variables on the motor important parameters is discussed in Chapter 4.

Genetic algorithm and Simulated annealing algorithm were used to optimize this motor. In next chapters the basic principles of these two evolutionary methods will be described.

3. OPTIMIZING METHODS

In computational design optimization of an induction motor (generally a device) there are two tools that cooperate to yield the optimum result:

- **search tool** – this role is played by GA (SA) here. As every point in the search space represents a different design, for every chromosome (in GA case) that is decoded into a point in the search space, the algorithm submits that particular design to the other tool of the optimization, that is
- **analysis tool** – it is used to obtain a performance measure. The analysis tool task is to solve the equations for the submitted design and to return the relevant parameters back to the search tool.

The optimizing program uses the motor computation (the analysis tool) through the evaluation function. By means of this design the evaluation function is established and "fitness" value is computed. This is very important step in optimizing process. The evaluation function depends on the problem to be solved, and its form should be as follows:

$$F(x) = F_1(x) = \max(\min) \tag{1}$$

$$F(x) = \alpha \cdot F_1(x) + \beta \cdot \frac{1}{F_2(x)} = \max(\min) \tag{2}$$

$$F(x) = \frac{\alpha \cdot F_1(x)}{\beta \cdot F_2(x)} + \gamma \cdot F_3(x) + \ldots + \zeta \cdot F_n(x) = \max(\min) \tag{3}$$

$$F(x) = \sum_{i=0}^{n} \left(\mathrm{Value}_i(x) - \mathrm{Value}_{i,desired}\right)^2 = \min \tag{4}$$

x.....a set of design variables.

The symbols α, β, γ and ζ stand for biases. For example the equation (2) should be used to find maximum efficiency considering a minimum weight, the variable $F_1(x)$ is the efficiency and the variable F_2 is the component weight. The equation (4) should be used to minimize a deviation from a desired characteristic curve.

As mentioned earlier, my goal is to find maximum efficiency of the induction motor. The evaluation function is used in both algorithms. There have to be noticed the GAs search maximum and SAs look for minimum point of the explored space. Therefore the evaluation function has the forms

$$F(N1, l, d) = \mathrm{efficiency}(N1, l, d) \tag{5}$$

for GA, and

$$F(N1, l, d) = \frac{1}{\mathrm{efficiency}(N1, l, d)} \tag{6}$$

for SA algorithm.

The algorithms are available on the Internet, the Genetic algorithm on the ftp server, see [1], and the Simulated Annealing algorithm on the web page, see [6]. Both algorithms are in the programming language C. I implemented the electromagnetic design of the induction motor in the programming language C, and it stands for analysis tool.

3.1. Genetic algorithm

GA is inspired by mechanism of natural selection, a biological process in which stronger individuals are likely to be winners in a competing environment. Search space is tested stochastically without stringent mathematical formulation such as the traditional gradient-type of optimizing procedure. GA works with a population of potential solutions. The population consists of chromosomes. Each chromosome is made-up from genes. Design variables are regarded as the genes of a chromosome and it is structured by a string of values in binary form.

There is necessary criteria generally known as "fitness" value. It is used to reflect the degree of "goodness" of the chromosome for solving the problem, and this value is closely related to the evaluation value. Through genetic evolution, better chromosomes (a better solution of the problem) has higher chance to move up to the new population.

Creation of the new population:

- evaluation – calculating of each chromosome fitness value by evaluation function,
- selection – the population is divided into two parts, better and worse, by a fitness value,
- crossover – the new population is made from better part of former population by means of operator crossover. Worse part of the population is replaced by new chromosomes,
- mutation – some bits of the new population chromosomes are changed from 0 to 1 (or from 1 to 0).

We repeat these four points until the end condition is reached. This condition should be maximum number of populations (in this case), the amount of individual's variation between different generations, or a predefined fitness value.

The genetic algorithm structure including input values is shown in Fig. 1. The fitness (efficiency) improvement from initial generation to generation 200 is shown in Fig. 2.

The genetic algorithms, their modifications and applications are discussed in [1].

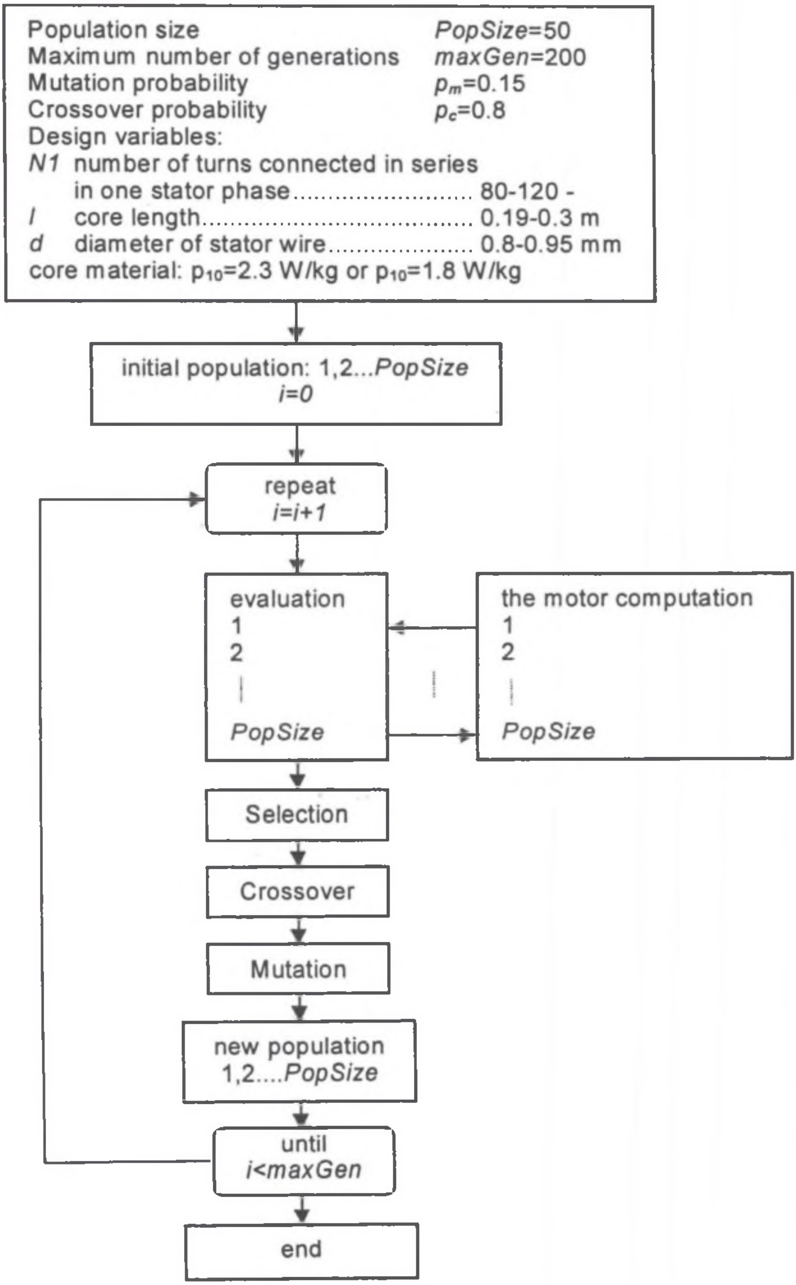

Fig. 1. The structure of the genetic algorithm

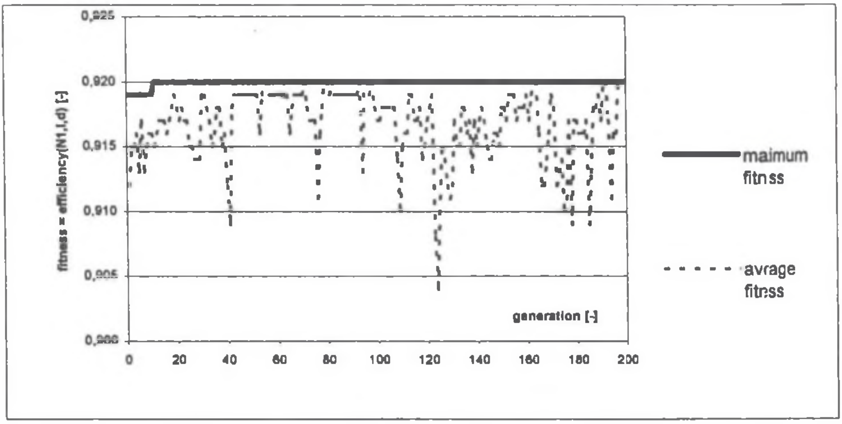

Fig. 2. The fitness value progress

3.2. Simulated annealing algorithm

The basic idea came up from thermodynamics. To grow a crystal, we start by heating a row of materials to a molten state. Then we reduce the temperature of this crystal melt until the crystal structure is done The material has minimum energy at the end of annealing process.

The searching space is exploring stochastically by the algorithm. In the beginning worse points in the neighbourhood of the current point are also accepted. This property is very important because the algorithm is able to escape from a local minimum. Than with decreasing temperature the probability of accepting these worse points is less than at high temperature. A worse or a better point is determined by evaluation function as mentioned above.

The basic evolutionary methods, the hill climbing, the tabu search and the simulated annealing algorithm are detailed discussed in [4].

4. RESULTS

The design variables, the original and the optimized motor parameters are shown in Table 1.

Table 1

The original and the optimized motor comparing

Subscripts: 1 – stator, 2 – rotor

Parameter		Original motor	Optimized motor
number of turns connected in series in one phase	N1 [-]	124	88
core length	l [m]	0.19	0.3
diameter of stator wire (without insulation)	d [mm]	0.8	0.85
core material (0.5 mm width)	p_{10} [W/kg]	2.3	1.8
Iron losses (hysteresis and eddy current)	ΔP_{Fe1} [W]	480.5	388.3
	ΔP_{Fe2} [W]	0 (neglected)	0 (neglected)
Surface losses	ΔP_1 [W]	2.3	2.5
	ΔP_2 [W]	41.5	44.3
Pulse losses	ΔP_{p1} [W]	4.7	3.8
	ΔP_{p2} [W]	15.1	11.8
Mechanical losses	ΔP_m [W]	100	100
Additional losses	ΔP_d [W]	101.8	101.8
Winding losses	ΔP_{J1} [W]	753	609
	ΔP_{J2} [W]	477	351
Total losses	ΔP [W]	1 976	1 612
efficiency	η [%]	**90.3**	**92.0**
rated torque	M [Nm]	120.8	120.0
rated power factor	$\cos\varphi$ [-]	0.86	0.85
rated speed	n [min^{-1}]	1463	1472
motor cost*	cost [units]	684.36	1 130.47

*The motor cost is calculated in units: the original motor - the core material cost_{Fe}=5 units/kg, the stator winding cost_{Cu}=30 units/kg, the rotor winding cost_{Al}=20 units/kg; the optimized motor - the core material cost_{Fe}=7.5 units/kg, the cost_{Cu} and the cost_{Al} remain the same.

As we can see in this table, the optimized motor is longer and it has better magnetic material (p_{10}=1.8 W/kg), the stator wire diameter increases thanks to less number of turns connected in series in one stator phase. It must be reminded that the motor diameter (the outer stator diameter D_2= 0.28 m) is the same in both cases. The iron losses (hysteresis and eddy current) as well as the winding losses decreased rapidly. The operating point parameters are listed in the last lines of the table. The torque-speed curves comparison is shown in Fig. 3.

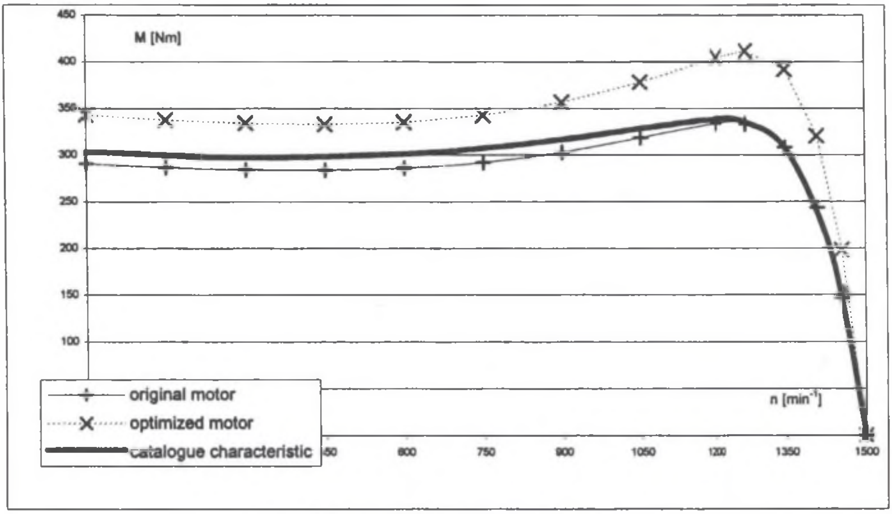

Fig.3. Torque-speed curves comparison

It is interesting to follow the motor cost price. The cost covers only main materials, the magnetic core and windings materials. The cost is calculated in units. The optimized motor cost increased almost twice. In practice we have to design a new stator frame and the motor cost keeps rising. But the total losses decreased by 364 W. The energy saving depends on the motor service.

The important advantage of this optimization result must be pointed out: the stator and the rotor shape laminations remain the same.

The motor shaft needs to be recalculated if its sag is in tolerance. If it is not satisfied there are two options: the first - using better shaft material (the rotor laminations shape remain the same), the second one – using new rotor laminations shape with larger hole for the bigger shaft. The second change makes the magnetic flux density in the rotor yoke increase, but the magnetic flux density decreased approximately by 10% in the optimized motor.

Using the magnetic slot wedge is very important for suppression of harmonics in the magnetic field. It is possible to increase the motor efficiency by several per cent [7].

5. CONCLUSIONS

In this paper there are presented two evolutionary methods, the Genetic algorithm and the Simulated annealing algorithm, used for to design of the induction motor of maximum efficiency. The optimized motor efficiency increased from 90.3 % to 92 % thanks to increasing the motor length, decreasing the number of turns connected in series in one phase, increasing the diameter of stator wire and using better magnetic material. The main advantage of this optimization is the same shape of the stator and rotor laminations (at compliance the conditions discussed in previous chapter). The optimization has the following disadvantages: the robust construction of optimized motor, the higher starting current and increasing the cost price (approximately twice). But the payback depends on the motor service and accruing the energy prices. Using the magnetic slot wedge is very useful and it can bring another significant improvement of the efficiency.

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