Optimal Design of a Single-Phase Two-Value Capacitor Induction Motor With Fan Load

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***Abstract*— Nowadays, due to increase in price of electrical energy, the efficiency is especially important in the design of electrical motors. Since the different types of electrical motors are used in various fields including industry, agriculture, households, etc., increasing the efficiency of electrical motors significantly reduce the consumption of electrical energy. The losses of electrical motors include stator and rotor ohmic losses, core loss, mechanical loss and stray load loss. In this paper, to increase the efficiency, the design parameters of a single-phase two-value capacitor induction motor are optimized by Genetic Algorithm (GA). In order to reduce the copper losses, the copper bars are used for rotor cage. Since for manufacturers the production costs are very important, this factor is also included in objective function. The accuracy of design process and optimization approach are verified by simulation results.**

Keywords- Single-Phase Two-Value Capacitor Induction Motor; Stator and rotor slots; Stator winding, Rotor copper bars; Finite Element Analysis (FEA); Genetic Algorithm (GA); Efficiency

I. INTRODUCTION

Due to the widespread use of single-phase induction motors in home appliances and also in some industrial applications, the need to pay particular attention to increase the efficiency is very important. The use of high performance motors, in addition to significant reduction in energy consumption, contribute to environmental improvement [1]. The factors including the optimal design of the rotor and stator slots, the stator and rotor windings, the cooling fan, the core material and etc. reduce the electrical motors losses. In the single-phase motors due to the backward field, the both copper and rotor core losses are higher than the three-phase motors. The low starting average torque and the high torque fluctuation in the both high speeds and running state, are two basically problems of the single-phase induction motors [2]. In the capacitor-start, capacitor-run induction motors, the start capacitor is used to improve the starting performance (increasing the starting torque) [3]. Also, by using the run capacitor, both efficiency and power factor are increased. In this paper, to increase the efficiency of a 100W two-value capacitor induction motor, in addition to optimal design of the parameters, the copper bars are used for rotor cage.

II. DESIGN PROSEDURE

In this section, the design of various parts of motor is discussed.

A. Number of Stator and Rotor Slots

The proper selection of stator and rotor slots has a significant effect on the proper performance of the motor. Therefore, to determine these values, the certain constraints should be considered for achieving the both mechanical and magnetic considerations [4]. In this paper, the appropriate combination for the stator and rotor slots have been considered 24 and 18, respectively. To avoid crawling and rotor blocking effect, the rotor slots are arranged diagonally.

B. Stator Design

In this section, the core length, the inner and outer diameter of core, the shape of teeth and slot and, etc. are calculated. According to the space required to locate the wire in the slot and also the allowed range of flux density in the teeth and yoke, the dimension of the teeth and slot of stator are determined. The dimension of the stator slot has been shown in Fig. 1. In the low power motors, the stator slots are semi-closed and they are designed in such a way that teethes are parallel to each other. According to the preliminary design, the dimension of the slot and teeth are presented in the Table 1.

In the initial design, the flux density in the stator core and stator teeth are 1.41 T and 1.281T, respectively. These values are within the permissible rang. By using design formulas, the stator parameters are calculated (Table (2)).

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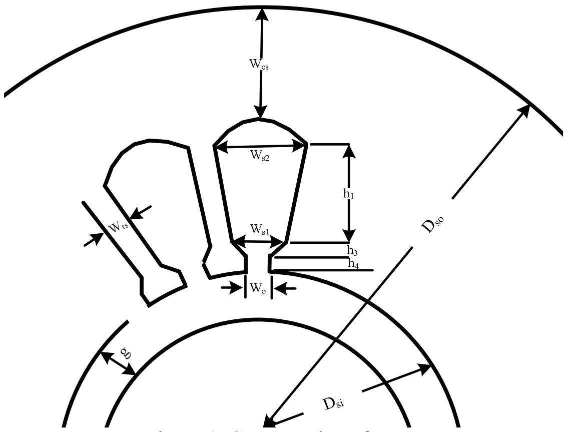


Figure 1. Cross-section of stator

TABLE 1: GEOMETERIC DIMENSION OF STATOR SLOT AND TEETH

Parameter	Value (mm)
W_0	1.5
W_{s1}	3.90
W_{s2}	7.33
W_{cs}	7.75
h_1	13
h_3	1.80
h_4	0.5
W_{ts}	3.25

The following empirical expression can be used to calculate the air-gap in small motors. Of course, by considering the manufacturing process and some considerations, the designer may make a better decision.

$$g = 0.2 + 2\sqrt{D.L} \tag{1}$$

Where D is inner diameter of the stator, L is stator core length and g is air-gap. All of these parameters are in meter.

In the following, the initial design results will be verified by the Finite Element Analysis (FEA). In the optimal design of the single-phase induction motor, the total volume of the main winding is greater than the auxiliary winding. Also, the auxiliary winding cross-section is smaller, but its turn number is greater than the main winding. In order to reduce the intrusive harmonics, increasing the efficiency and the better cooling, a double-layer fractional-pitch winding has been used. Its diagram is shown in Fig. 2.

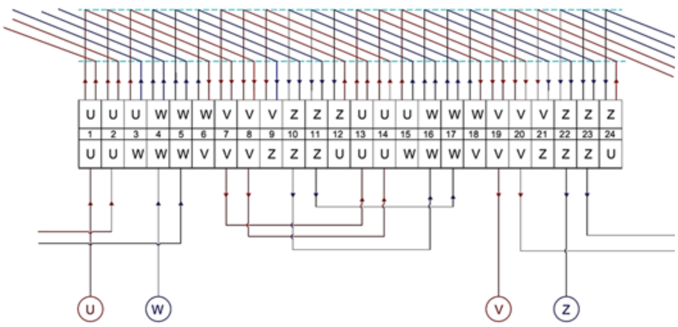


Figure 2. Double-layer fractional-pitch winding arrangement for a 4-pole stator

TABLE 2. PARAMETERS DESIGNED FOR STATOR

Parameter	Symbol	Value
Apparent power (VA)	S	168.55
Stator current (A)	I_s	0.733
Main winding current (A)	I_m	0.583
Auxiliary winding current (A)	I_a	0.444
Average flux density in air-gap (T)	$\bar{B}$	0.55
Flux per pole (mwb)	φ	0.801
Number of stator slots	Z_s	24
Stator inner diameter (mm)	D_{is}	50
Stator outer diameter (mm)	D_{os}	101
Pole pitch (mm)	Y_p	39.26
Number of turns of the main winding	N_m	1320
Number of turns of the auxiliary winding	N_a	1728
Main conductor diameter (mm)	d_m	0.45
Auxiliary conductor diameter (mm)	d_a	0.40
Core length (mm)	L	55
Average flux density in stator teeth (T)	$\bar{B}_{ts}$	1.281
Average flux density in stator core (T)	$\bar{B}_{cs}$	1.41
Length of air-gap (mm)	g	0.3

C. *Calculate the Run and Start Capacitors*

The two-value capacitor motors have the benefits of both capacitor start motor and capacitor run motor. For minimum nominal current, this motor can be designed for maximum efficiency. Therefore, at the same operating conditions, this motor works at a lower temperature than other single-phase motors. The simultaneous use of the run capacitor and the start capacitor have advantages such as higher torque and power factor, lower noise during continuous operation and better efficiency. In the following, the process of selecting the run and start capacitors is expressed.

In (2), the relationship between the source current and the main and auxiliary winding currents is written:

$$\vec{I}_s = \vec{I}_m + \vec{I}_a \Rightarrow I_s = \sqrt{I_m^2 + I_a^2} \tag{2}$$

By considering turn ratio (turns of main winding to auxiliary winding ($a = \frac{I_m}{I_a}$)):

$$I_m^2 = I_s^2 - \left(\frac{I_m}{a}\right)^2 \Rightarrow I_m = \frac{I_s}{\sqrt{1 + \left(\frac{1}{a}\right)^2}} \tag{3}$$

So, the capacitor voltage is obtained as follows ($V_a = aV_m = aV_s$):

$$\vec{V}_c = \vec{V}_m - \vec{V}_a = \vec{V}_s - \vec{V}_a \Rightarrow |V_c| = \sqrt{V_s^2 + (aV_s)^2} = V_s\sqrt{1 + a^2} \tag{4}$$

According to (3) and (4), the value of run capacitor is determined:

$$V_{c,run} = X_c.I_a = \frac{I_a}{\omega.c_{run}} \Rightarrow c_{run} = \frac{I_a}{\omega.V_{c,run}} \tag{5}$$

Based on the (5), the value of the run capacitor is 3.75 µF. The value of start capacitor is also selected 2 times the run capacitor, 7.5 µF. It should be noted that the start capacitor is disconnected when the rotor speed reaches 1100 rpm.

D. Rotor Design

In design of the rotor, the conductor volume in rotor slot has been calculated based on copper conductor. Accordingly, for initial design, the geometric dimensions of rotor core are obtained (Table (3)). Also, the shape of the slot designed for rotor is shown in Fig. 3. In order to reduce cogging torque, vibration or noise and disturbance of sinusoidal distribution of air-gap flux density, the rotor bars are skewed by 1.5 times rotor slot pitch. The diagonal rotor slot increases the rotor resistance, starting torque, magnetizing reactance and leakage reactance. This issue also reduces the power factor and starting current which should be considered in design. The geometric dimensions designed for the rotor slot are presented in Table 4. In order to confirm the initial design, the FEA has been used. The values obtained from initial design and FEA are compared in Table 5.

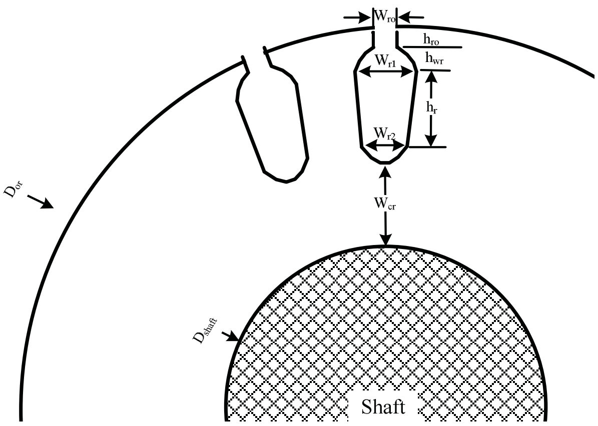


Figure 3. Cross-section of rotor

TABLE 3. PARAMETERS DESIGNED FOR ROTOR

Parameter	Symbol	Value
Number of rotor slots	Z_r	18
Rotor inner diameter (mm)	D_{ir}	18
Rotor outer diameter (mm)	D_{or}	49.4
Rotor slot pitch (mm)	$Y_{slot,r}$	8.622
Average flux density in rotor teeth (T)	$\bar{B}_{tr}$	1.647
Average flux density in rotor core (T)	$\bar{B}_{cr}$	1.475
Core length (mm)	L	55

TABLE 4. GEOMETERIC DIMENSION OF ROTOR SLOT

Parameter	Value (mm)
W_{r0}	0.5
W_{r1}	4.2
W_{r2}	1.9
h_{r0}	0.5
h_{wr}	1.8
h_r	7.215
W_{cr}	5.35
W_{tr}	3.5

TABLE 5. COMPARISON OF THE VALUES OBTAINED FROM INITIAL DESIGN AND FEA

Parameter	Initial design	FEA	Designer comment
Stator current (A)	0.733	0.695	Accepted
Main winding current (A)	0.583	0.413	Accepted
Auxiliary winding current (A)	0.444	0.496	Accepted
Average flux density in air-gap (T)	0.55	0.567	Accepted
Average flux density in stator teeth (T)	1.281	1.21	Accepted
Average flux density in stator core (T)	1.41	1.004	Accepted
Average flux density in rotor teeth (T)	1.647	1.53	Accepted
Average flux density in rotor core (T)	1.475	1.465	Accepted

It can be seen that the initial design can be considered a good design. In the following, the comparative results of the FEA for initial and optimal design will be carried out.

III. Optimization

Generally, the optimal design of an electrical motor is a multi-purpose optimization problem with several variables and constraints. The optimization problem is defined in three stages. First, the optimization variables including geometric, electrical, and magnetic parameters are determined. Then, the objective function and constraints are written based on optimization purposes. Finally, an optimization approach is used to find the optimal values of the defined variables. The most important step of optimization is the objective function formulation, which is usually a combination of power losses, costs, and volume of consumed materials. The optimization approach can be a non-linear programming approach or a random search based approach, such as Genetic Algorithm (GA) [5].

A. Objective Function

The optimization problem can be solved with the following objective function:

$$Objective\ \ Function\ = cos\ t_1 + 1.5 \times cost_2 \qquad (6)$$

$$cost_1 = \left(\frac{P_{out}}{\eta} \times T_{op} \times P_1\right)\Bigg|_{\substack{T_{op}=10000 \\ P_1=0.1}}$$

$$cost_2 = W_{cu,s} \times P_{cu,s} + W_{Fe} \times P_{Fe} + W_{cu,r} \times P_{cu,r}$$

Where $\cos t_1$ and $\cos t_1$ are the cost functions. The parameters used in (6) are introduced in Table 6.

B. Parameters and Optimization Constraints

In this section, the optimization parameters with their variation range are presented. Design constraints for the desired single-phase induction motor are shown in Table 7.

TABLE 6. THE COST FUNCTIONS PARAMETERS

Parameter	Symbol
Output power	P_{out} (kW)
Efficiency of designed motor	η
Fan operating time	T_{op}
Energy cost	P_1 ($/Kwh)
Copper weight	W_{cu} (kg)
Iron weight	W_{Fe} (kg)
Copper price	P_{cu}
Iron price	P_{Fe}

TABLE 7. DESIGN CONSTRAINTS

Parameter	Unequally Constraint
Length of air-gap (mm)	$0.25 \le g \le 0.35$
Current density (A/mm²)	$1.5 \le J \le 5$
Slot space factor	$0.45 \le Fill_f \le 0.57$
Average flux density in air-gap (T)	$0.4 \le \bar{B} \le 0.65$
Teeth flux density (T)	$1.1 \le \bar{B}_t \le 1.7$
Yoke flux density (T)	$1 \le \bar{B}_c \le 1.6$
Efficiency	$0.63 \le \eta$
Power factor	$0.9 \le P.F$
Starting current to nominal current ratio	$I_{st}/I_n \le 5$
Maximum torque to nominal torque ratio	$1.1 \le T_{max}/T_n$
Starting torque to nominal torque ratio	$1 \le T_{st}/T_n$
Stator winding temperature	$\theta_{TR} \le \theta_{TRB}$
Run capacitor value	$C_{run} \le 6$
Start capacitor value	$C_{st} \le 20$
Stator teeth width (mm)	$3 \le W_{ts}$
Rotor teeth width (mm)	$3 \le W_{tr}$

TABLE 8. OPTIMIZATION RESULTS

Parameter	Optimized Design	Initial Design
g (mm)	0.26	0.3
Z_s	24	24
Z_r	18	18
h_1 (mm)	14.28	13
h_r (mm)	8.54	7.215
W_{ts} (mm)	3.34	3.25
W_{tr} (mm)	3.65	3.5
W_{cs} (mm)	6.90	7.75
W_{cr} (mm)	6.61	5.35
D_{si} (mm)	56	50
L (mm)	59	55
Current density of main winding (A/mm²)	1.7	2.6
Current density of auxiliary winding (A/mm²)	2.1	3.9
Number of turns of the main winding	1344	1320
Number of turns of the auxiliary winding	1560	1728
Stator and rotor copper losses (W)	19.92	40.58
Total loss (W)	30.28	51.43
Efficiency	78.19	67.81
Power factor	0.999	0.999
Output torque (N.m)	0.721	0.719
Output power (W)	108.5	108.4
Objective Function Value ($)	171.55	184.9

The allowable flux densities in different parts of the stator and rotor core are based on saturation curves, as specified in IEC 60404-8. In the optimization process, the fifteen design variables which are the same parameters of Table 8 are considered.

C. *Otimization Algorithm*

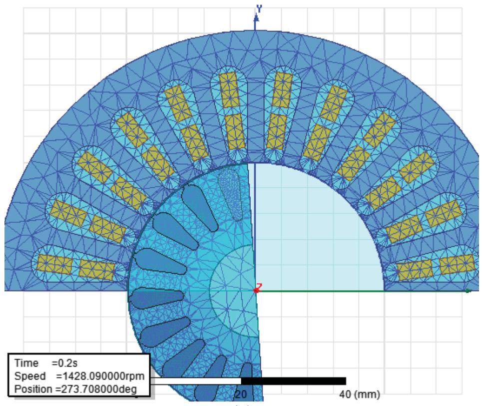
Genetic algorithm is a powerful tool based on random search and derived from evolution theory. The GA for solving the problem does not need complex mathematical calculations and is able to find the global optimum or a point close to it with proper speed. After calculation of the best answers, designing is optimized and GA is converged to an appropriate plan with minimum cost considering all constraints and limitations.

D. *Otimization Results*

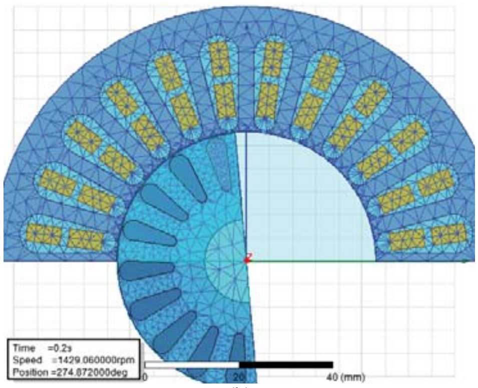
The optimization results and prototype motor specifications are presented in Table 8. It is observed that the objective function value for optimized design has been decreased 7.2% compared to initial design. It should be noted that the initial design is a proper design and if the optimal design is to be compared with a similar motor in the market with efficiency less than 50%, the amount of reduction in the objective function will be much more.

IV. SIMULATION RESULTS

In this section, the validity of the design process and optimization is evaluated by using the finite element method. The motor design has been done by using Ansoft Maxwell v14.0.1 software. In order to prove the design process accuracy, the results of the optimal design are compared with the FEA. This comparison shows the acceptable accuracy of the design model and the optimal design results.

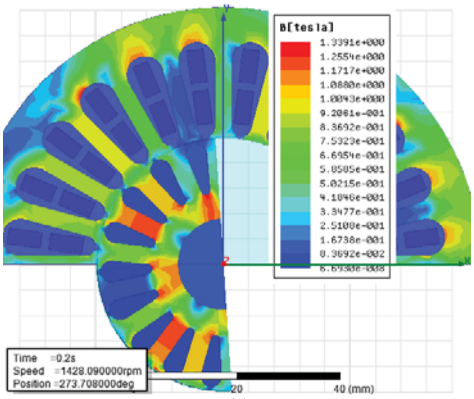


(a)



(b)

Figure 4. Meshing in motor cross-section
(a) Initial design, (b) Optimized design



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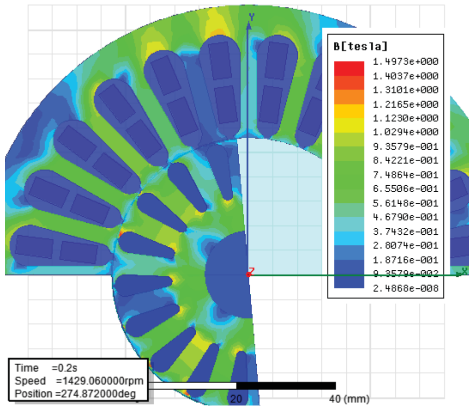
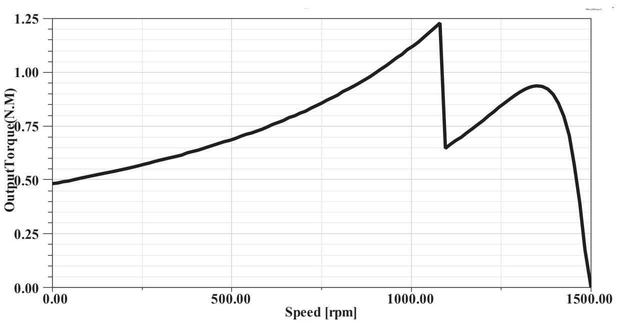


(b)

Figure 5. Two-dimensional distribution of flux density;
(a) Initial design, (b) Optimized design



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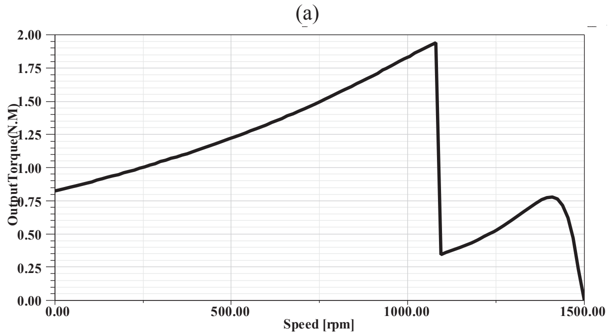
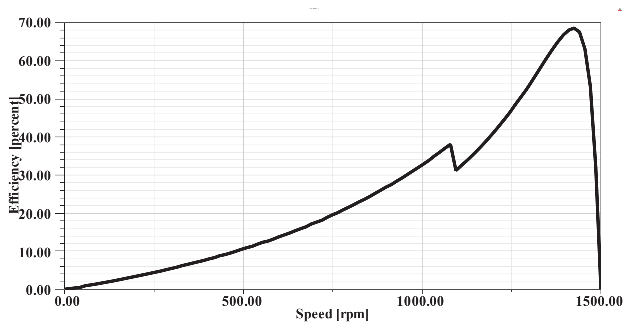


(b)

Figure 6. Torque-speed characteristic;
(a) Initial design, (b) Optimized design



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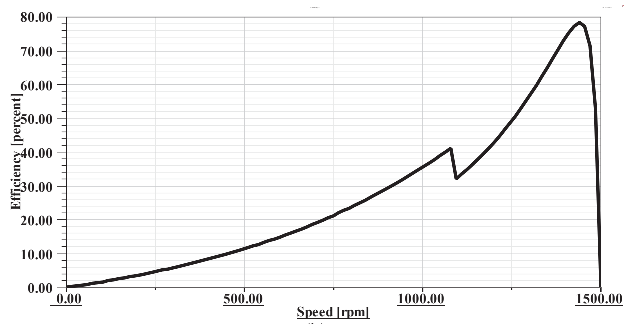
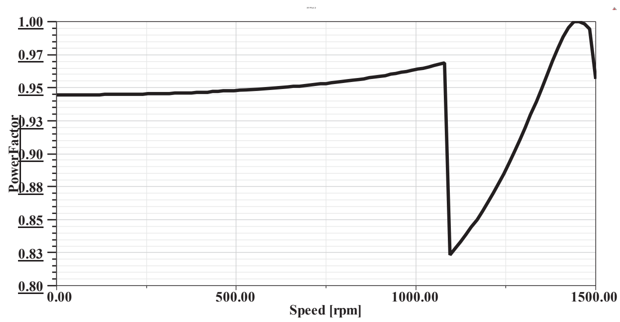


(b)

Figure 7. Efficiency-speed characteristic;
(a) Initial design, (b) Optimized design



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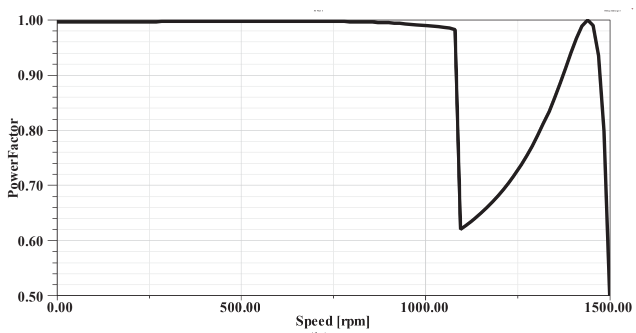

(b)

Figure 8. Power factor-speed characteristic;
(a) Initial design, (b) Optimized design

The simulation results show that the motor's magnetic status is improved in optimal design and the electrical parameters of the motor have better condition. In Table 9, the equivalent circuit parameters of single-phase two-value capacitor motor have been given according to the initial and optimal design.

In the optimal design, by increasing the magnetizing reactance, both no load and nominal currents are decreased. According to the optimization results, although the rotor and stator resistances are increased, but due to decrease the main and auxiliary winding currents, the total copper loss are reduced (Table 10).

TABLE 9. THE EQUIVALENT CIRCUIT PARAMETERS OF SINGLE-PHASE TWO-VALUE CAPACITOR MOTOR

Parameter	**Optimized Design**	**Initial Design**
Main phase resistance (Ω)	40.1	60.03
Auxiliary phase resistance (Ω)	56.4	99.4
Main leakage reactance (Ω)	48.3	38.3
Auxiliary leakage reactance (Ω)	83.9	80.5
Magnetizing reactance (Ω)	876.689	529.88
Turn ratio of Auxiliary to main winding (Ω)	1.16071	1.309
Stator line current (A)	0.604079	0.69509
Main phase current (A)	0.39117	0.41423
Auxiliary phase current (A)	0.393526	0.496511
Capacitor voltage (V)	375.04	421.45

TABLE 10. OPERATIONAL CHARACTERISTICS OF SINGLE-PHASE TWO-VALUE CAPACITOR MOTOR AT RATED CONDITION

Parameter	**Optimized Design**	**Initial Design**
Copper loss of stator winding (W)	14.2	34.72
Copper loss of rotor winding (W)	4.89	5.76
Iron core loss (W)	4.79	4.55
Frictional and windage loss (W)	6.4	6.4
Total loss (W)	30.28	51.43
Input power (W)	138.77	159.8
Output power (W)	108.5	108.4
Mechanical torque (N.m)	0.725	0.724
Efficiency (%)	78.19	67.81
Power factor	0.999	0.999
Rated shaft speed (rpm)	1439	1438

TABLE 11. DETAILED DATA AT RATED OPERATION

Parameter	**Optimized Design**	**Initial Design**
Flux density in stator teeth (T)	1.125	1.21
Flux density in rotor teeth (T)	1.24	1.53
Flux density in stator yoke (T)	1.02	1.004
Flux density in rotor yoke (T)	1.04	1.465
Flux density in air-gap (T)	0.4826	0.567
Main winding current density (A/mm^2)	1.7	2.6
Auxiliary winding current density (A/mm^2)	2.1	3.9
Specific electric loading (A/m)	12955.6	17852.3

As can be seen in Table 10, in the optimized design, the total losses have been decreased. As expected, the stator copper loss which has the biggest portion of total losses, more than other losses has been reduced.

V. CONCLUSION

In this paper, to increase the efficiency of a single-phase two-value capacitor motor, some solutions including the optimal design of both air-gap and core length, the appropriate frame size selection, optimal design of rotor and stator slots and finally, the use of copper bars for rotor cage, were proposed. Comparing the results of the initial and optimized designs, the following points deduce:

1. The total motor losses reduction was 41%.
2. The efficiency was increased by 15.3%.
3. In term of magnetic saturation, motor was in better condition.
4. The stator current harmonics were decreased.
5. The winding currents density were decreased.
6. The value of the objective function in the optimal design was reduced by 7.2% compared to the initial design.
7. Although use of the high efficiency motors have more initial production costs compared to the conventional motors, but during the operating period are more cost effective.

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