

EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON STATOR WINDING TURN INFLUENCE ON SQUIRREL CAGE INDUCTION MOTOR PERFORMANCE: ENERGY EFFICIENCY

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ABSTRACT

In the design steps of the induction machines, reducing the power consumption level of the induction machine is a very important issue. Winding topology is one of the most important design parameters for induction machines. Variation of the number of turns in the slots has a significant effect on the performance of the machine. In this study, unlike the studies in the literature, only the number of turns are changed and analyses are performed. Parameters such as stator outer diameter, inner diameter, package length, number of slots, air gap length, coil section and etc. are kept constant. 6 different induction machines which have 6 different winding topologies are designed. 3 of the machines are designed half-coiled and the other 3 machine are designed whole-coiled. Both winding topologies have different turn numbers for a single slot. The turn numbers are 96, 106 and 116 respectively. No-load, locked rotor, and load tests are conducted on these machines. According to the test results and analytical results, performances of the machines are considered. In this way, increasing the turn number for both winding topologies has a decreasing effect on the iron losses of the motor. Similarly, increasing of the stator and rotor resistances directly affects the copper losses of the machine negatively. When considering the efficiencies of the machines, maximum efficiency is achieved for half-coiled 116 turns numbered topology. Similarly, maximum efficiency is achieved for whole-coiled 106 turns numbered topology.

Keywords: Half-coil winding, Whole-coil winding, Number of winding, Induction motor, Energy efficiency

1. INTRODUCTION

Squirrel cage induction motors are the most widely used motors in electromechanical energy conversion due to being stable to the load and voltage changes, high efficiency [1], easy maintenance, fair self-starting capability, reliability [2], robustness and low price [3], easy operation [4]. Therefore, more than 85% of the motors in use today are actually induction motors. It is possible to reduce the consumption of electric energy by means of better motor design [5]. There are several criteria for the design of induction motors. The first of them is magnetic circuit and the second is the electrical circuit [1]. Three phase alternating current electrical machines windings can coil up different types. These differences lead to major changes in the motor performance. Therefore, selection for winding of electrical machines to be designed is very important [6]. Winding types used in electrical machines can be grouped as follows: armature windings, stator or rotor windings of induction motors, field (magnetizing) windings, damper windings, commutating windings and compensating windings [7]. Coskun and Korkmaz in their work, wound one of the stator winding of 36 slots, four poles, 1.1 kW motors' one layer. The other one is two layers wound. They determined that the efficiency of the half-coiled winding is better than whole-coiled winding but whole-coiled winding's harmonics and power factor performance is better than half-coiled winding [1]. Chandrasekaran and Manigandan proposed a new method in order to increase the motor efficiency. In their method, stator coils are designed to be operated at 415 V, 350 V and 200 V respectively [4]. Kundrotas et al. presented six-phase induction motor winding schemes. They calculated and analyzed magneto motive forces and compared two type motor windings. One of them is concentrated double layer full pitch coil winding, the other one is double layer short pitch coil winding. Their results show that concentrated double layer short pitch coil winding has greater by 22% for the

first harmonic compared with concentrated double layer full pitch coil winding [8]. In their paper, the design of a Dahlander-wound induction machine for operation on mains with variable frequency was presented. The Finite Element Method (FEM) package has been used for simulation procedure and the results have been presented [9]. Hadziselimovic et al. researched the effect of winding type on induction motor's efficiency and performance. They analyzed three different motor winding types. These are concentric single layer winding, concentric double layer winding and fractional concentric winding. From the results, it is shown that the fractional concentric winding type's efficiency value is better than the other winding types [10]. Buksnaitis carried out theoretical and experimental investigations of three phase induction motor containing single layer windings and compared electromagnetic and energy related parameters [11]. Ionescu and friends investigated the motor noise for single layer and double layer winding types. They used the ANSYS program for modelling. They found that the single layer winding type results yields better than double layer winding type [12]. Chen et al. carried out a new slot design to increase the induction motor efficiency. They concluded that efficiency performance of the one layer-short pitched winding is 3% higher than conventional windings [13]. Mohanadasse et al. researched the effect of the windings with coating and without coating on the induction motor performance [14]. Ge et al. proposed a general winding design rule for the pole-phase modulation induction machines. They compared three different structures, such as conventional winding, toroidal winding and dual-rotor toroidal winding. Their results show that the conventional winding has many advantages over the other winding methods [15]. Aguiar and friends proposed the effect of resizing the induction motor stator winding. They stated that change of the number of parallel conductors and the use of chorded coils have shown gains up to efficiency by 2.6% [16]. Tahar's work has been devoted to the calculation of the undulatory parameters and the study of the influence of the number parallel path of a winding on overvoltage compared to the frame and between turns (sections) in a multi turn random winding of an induction motors supplied with PWM-converters [17]. Their paper describes a method to analyze a machine winding through application of Fourier series and Discrete Fourier Transform to determine the efficacy of the winding regarding machine excitation [18]. They expressed reduction of the low-order harmonics to adopt chording of the stator winding. The full pitch motor has more harmonics than the other motors [19]. Their paper presented the design of non-uniform alternative current windings using a new method. Their method is based on the concept of local density of conductors. This type of winding reduces higher harmonic components of magnetic flux density in the air gap which has the fifth and the seventh harmonics. This new method can be used for any three phase windings even for optional irregular windings with different number of conductors in single slot [20]. They investigated how to reduce the losses of the induction motor using different stator winding style, including changing the type and connection [21].

This paper is organized as follows: In Section II, stator winding types of the induction motor is presented and winding design aspects is explained. A detailed explanation of design procedure, stator main dimensions, physical dimensions, slot constructions and winding parameters of the six different motors are given in Section III. Experimental results of the six different motors are presented in Section IV, and conclusions are given in Section V. The focus of the study is the effects of the different winding topologies on induction machine performance. At the same time, the point of the view of the material, all physical characteristics of the materials which are used for building the structure of all machines are the same.

2. TYPES OF THREE PHASE STATOR WINDINGS

Windings are the most important part of the induction machines. In general, windings are prepared half-coiled or whole-coiled in conventional induction machines. These windings are distributed in stator slots with the 120 mechanical degrees for creating the three-phase [1]. In another point of view, these winding topologies have electrical differences. For example, a half-coiled winding topology has lower iron loss but it has a bigger power factor so far as whole-coiled topology. Despite that, coil pitch reduction is limited with only one slot for half-coiled topology but it is not limited to whole-coiled topology [22].

Single layer winding is common in small AC machines of power rating below 15 HP, though this mainly depends on the manufacturer. And such machines have a large number of conductors per slot. Single layer windings have higher efficiency and quieter operations due to the openings of their narrow slots. Single layer windings are highly insulated because of the end connections that are separated by large air spaces which make them suitable for high voltages. The absence of inter-layer separator is due to higher space factor [23]. Single layer windings have a few advantages: higher efficiency, more silent operation because of narrow slot openings, space factor for slots is higher owing to without inter layer separator [24]. Schematic diagram of 36 slots, 4 poles and half-coil winding motors is given in Figure 1 (a).

Double layer winding topology is used for high power induction machines. To decrease the high-level winding harmonics, it should be used coil reduction for wide edges [1]. Double layer windings have many advantages: easier to produce and lower cost of coils, the fractional slot can be used, chorded winding is possible, lower leakage reactance and for this reason the better performance of the motor [8]. The double layer windings are the most widely used types of windings [25]. Schematic diagram of 36 slots, 4 poles and whole-coil winding motors is given in Figure 1 (b).

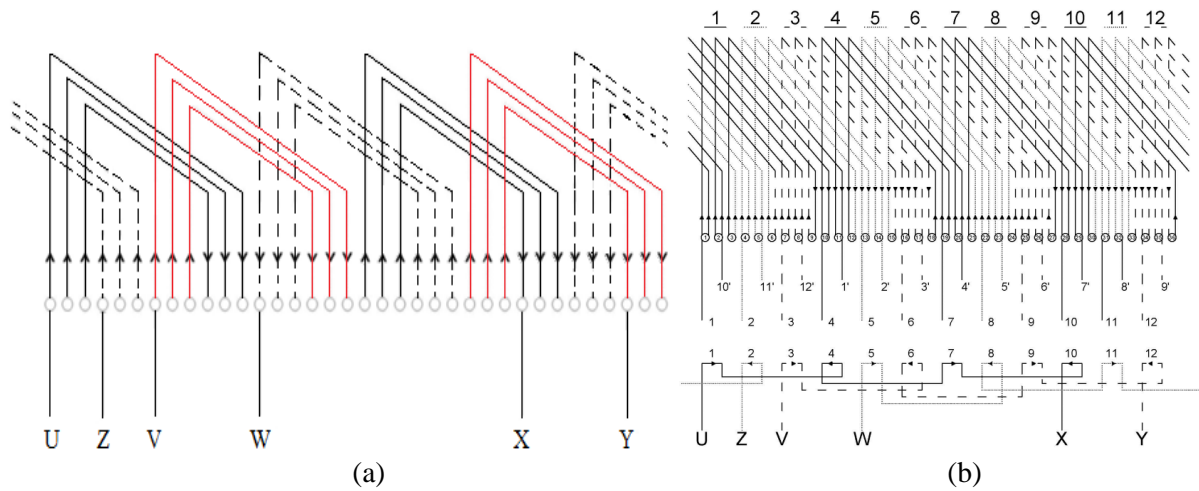


Figure 1. (a) Half-coil winding diagram (b) Whole-coil winding diagram

The electromagnetic design procedure of an induction motor can be described with the following steps:

- Step 1. Determination of the main dimensions
- Step 2. Design of the stator winding
- Step 3. Design of the rotor winding
- Step 4. Design of the magnetic circuit
- Step 5. Verification of the design by means of field calculation

Typically, steps of 1-4 are performed analytically. However, step 5 can either be carried out by analytical computation or by means of numerical simulation, such as the finite element method. Especially, if the application requires high accuracy, numerical techniques are inevitable [9]. Design parameters of an induction motor are formulated in [26].

3. MOTORS AND SPECIFICATIONS

3.1. Physical Parameters of Motors

Three phase squirrel cage induction motors are used in the experiments. Parameters of the stator and rotor slots are given in Table 1 for the six motors which have been used in the experiments. Physical dimensions and nameplate of the six motors are given in Table 2. Winding characteristics of the motors are given as

follows. Three of them have single layer winding (96-106-116 turns/slot), the other three motors have double layer winding (96-106-116 turns/slot).

- Motor 1: Single layer, half-coil winding (HCW), 96 turns/slot
- Motor 2: Single layer, half-coil winding (HCW), 106 turns/slot
- Motor 3: Single layer, half-coil winding (HCW), 116 turns/slot
- Motor 4: Double layer, whole-coil winding (WCW), 96 turns/slot
- Motor 5: Double layer, whole-coil winding (WCW), 106 turns/slot
- Motor 6: Double layer, whole-coil winding (WCW), 116 turns/slot

Table 1. Physical dimensions and nameplate of the six motors

Parameters of motors	Values (Motor 1 to 6)
Stator core inner diameter (mm)	80
Stator core outer diameter (mm)	136
Rotor core inner diameter (mm)	24
Rotor core outer diameter (mm)	79.4
Air gap length (mm)	0.3
Stack length (mm)	96.3
Shaft diameter (mm)	24
Voltage (V) (L-L)	380
Number of poles (2p)	4
Stator winding connection type	Star
Frequency (Hz)	50
Number of phases (m)	3

Table 2. Parameters of stator and rotor slots

Parameters of stator and rotor slots	Values (Motor 1 to 6)
Number of stator slots	36
Stator slot height (mm)	14.8
Stator wedge height (mm)	0.5
Stator back iron height (mm)	12.7
Stator slot upper height (mm)	5.4
Stator slot bottom height (mm)	3.7
Stator tooth width (mm)	3.8
Number of rotor slots	28
Rotor slot height (mm)	14
Rotor wedge height (mm)	0.5
Rotor back iron height (mm)	13.7
Rotor slot upper height (mm)	4.5
Rotor slot bottom height (mm)	2
Rotor tooth width (mm)	4.4

When Table 2 is analyzed, it is seen that the stator and rotor slot construction parameters are the same for the six motors. In Table 1, the nameplate values, stator, and rotor outer-inner diameters values are the same for the six motor types. Parameters of winding which are calculated as the theoretical and are measured as practical are given in Table 3.

Table 3. Parameters of windings for the six motors

Winding Parameters	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5	Motor 6
Winding layers	1	1	1	2	2	2
Types of coil winding	Half	Half	Half	Whole	Whole	Whole
Number of turns / slot	96	106	116	96	106	116
Number of magnetic circuit slots (Z)	3×96	3×106	3×116	3×96	3×106	3×116
Total number of turns	3456	3816	4176	3456	3816	4176
Wire cross-section				0.55		
Winding layout				full-pitch, concentric		
Zone factor (K_{qi})				0.959		
Chording factor (K_{yl})				1		
Stator winding factor (K_{wl})				0.959		
Pole pitch (τ)				9		
Winding span (y)				9		

Electrical degrees (α)	20 degree
Number of phase slots (q)	3
Phase belt	60 degree

When Table 3 is analyzed, it is observed that the other parameters except for a number of turns/slot seem the same. This shows that the obtained results vary depending upon only the number of turns. All the motors winding layouts are full-pitch and concentric winding topology. There is no chording for all motor winding types. Stator and rotor slot geometries are given in Figure 2.

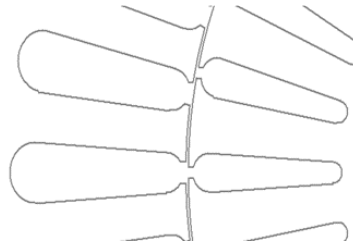


Figure 2. Stator and rotor slot geometries

4. EXPERIMENTAL RESULTS

No-load test, locked rotor test, and load operation test have been carried out for motors with six different winding topologies. General view of the experimental setup is given in Figure 3. Load operation experiments were carried out for nominal values. Fucolt brake has been used for load test. Fluke 43-B power analyzer has been used for measurements of power.

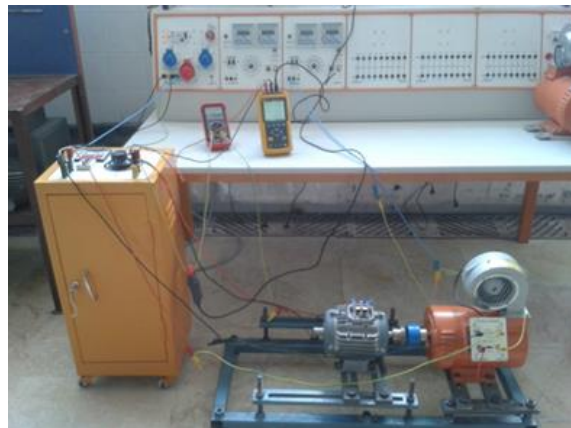


Figure 3. General view of experimental setup

4.1. No-Load Test Results

No-load operation results of the motors are carried out for the six different winding form are given in Table 4 where V_0 is no-load voltage, I_0 is no-load current, P_0 is core loss, $\cos\theta_0$ is no-load power factor and n_0 is no-load speed. Furthermore, the power factor of the whole-coil winding type motor is 50% lower than half-coil winding type motor. Obtained I_0 , I_{fe} (eddy current), and I_m (magnetization current) graphics are given in Figure 4 for the six different winding topologies. Also, the variations of the core loss with the number of the winding are given in Figure 5 for the six different motor types. From the Figure 5, it is clear that when the numbers of winding increases, the core losses are reduced.

Table 4. No-load test results for the six motors

Parameters	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5	Motor 6
V_0 (V)	380	380	380	380	380	380
I_0 (A)	3.525	2.396	1.815	2.64	1.94	1.56

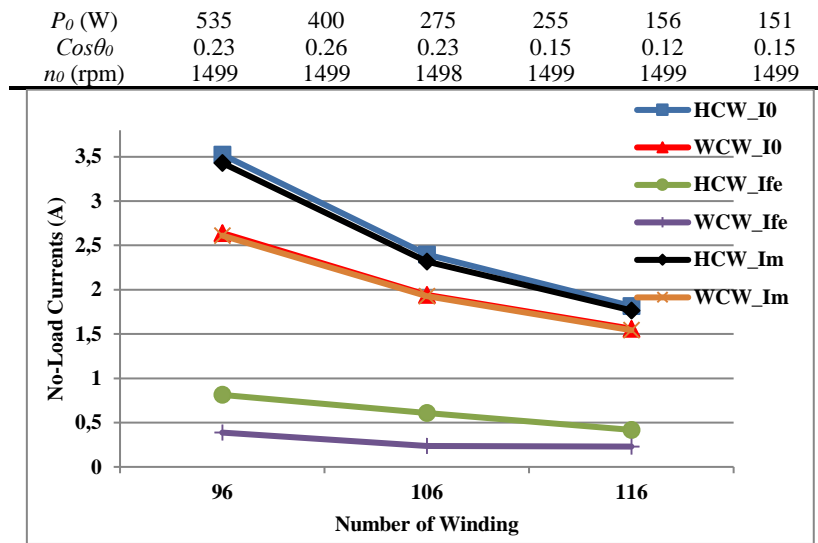


Figure 4. No-load currents vs number of winding graphic

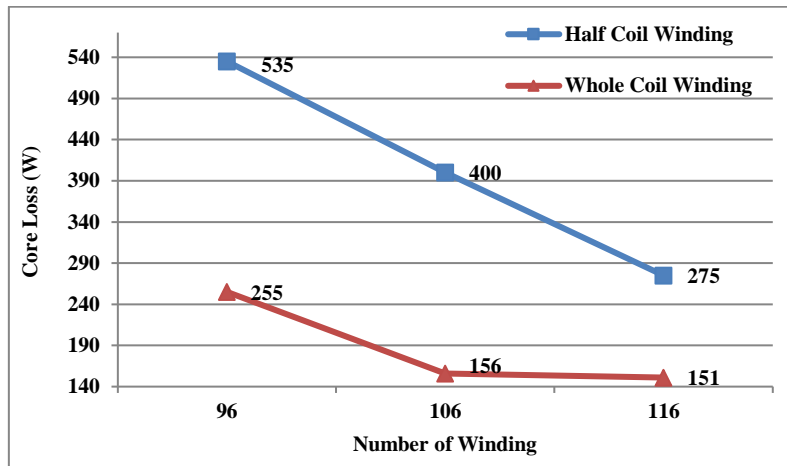


Figure 5. Core loss vs number of winding graphic

The number of winding turns increases for the half-coil and whole-coil windings, no-load currents decreased depending on the increase in the stator and rotor resistance values. The decrease in no-load currents has led to lower core losses for both winding topologies. Core losses of the whole-coil winding type motor are less than half-coiled winding type motor.

4.2. Locked Rotor Test Results

Locked rotor test results of the motors are made up with the six different winding topologies are given in Table 5 where V_k is locked rotor voltage, I_k is locked rotor current, P_k is copper loss and $\cos\theta_k$ is locked rotor power factor. Locked rotor test has been performed by assuming $I_k=I_N$. The variation of the copper loss with the number of the winding are given in Figure 6 for the six different motor types. An increase in the resistance values has resulted in an increase in copper loss. It appears that there is a small decrease in the value of the locked rotor power factor. Locked rotor voltages are increased in a significant manner.

Table 5. Locked rotor test results for the six motors

Parameters	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5	Motor 6
V_k (V)	72	80.1	97.5	87.6	100.8	116.1

I_k (A)	3.7	3.7	3.7	3.7	3.7	3.7
P_k (W)	364	401	485	408	464	513
$Cos\theta_k$	0.8	0.78	0.77	0.73	0.72	0.69

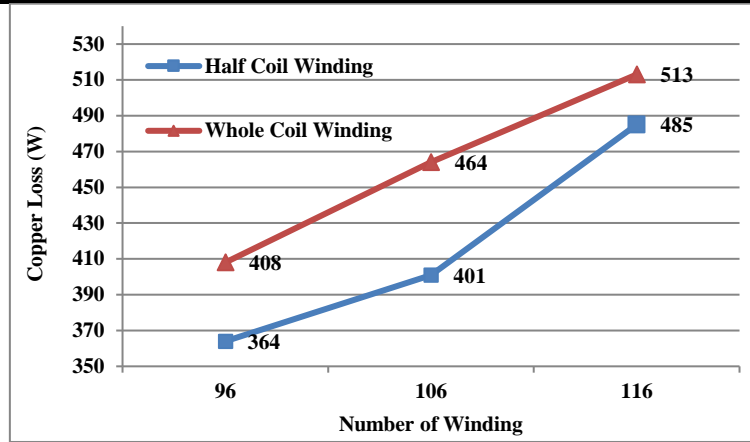


Figure 6. Copper loss vs number of winding graphic.

4.3. Load Operation Test Result

Load operation results of the motors have been carried out for the six different winding topologies are given in Table 6, where, I_N is nominal current, V_N is nominal voltage, P is input power, Q is reactive power, S is apparent power, $Cos\theta$ is power factor and n_r is rotor speed. The changes with obtained powers (P , Q and S) of the number of the winding are given in Figure 7 for the six different motor types.

The load operation tests have been carried out at the nominal voltage and nominal current. It is seen that the input powers is increased and the reactive powers is reduced. It is found that the power factor value is improved. The speed is reduced for both winding topologies when increased the number of winding.

Table 6. Load operation test results for the six motors.

Parameters	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5	Motor 6
V_N (V)	380	380	380	380	380	380
I_N (A)	3.7	3.7	3.7	3.7	3.7	3.7
P (W)	1760	2040	2130	1860	2060	2120
Q (VAr)	1540	1160	1010	1500	1240	1164
S (VA)	2370	2340	2370	2370	2390	2410
$Cos\theta$	0.75	0.87	0.9	0.77	0.86	0.88
n_r (rpm)	1430	1410	1373	1417.3	1378	1352

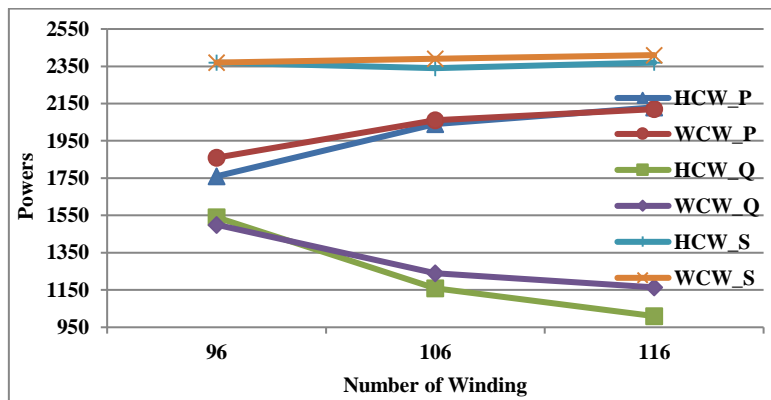


Figure 7. Powers vs number of winding graphic

4.4. Equivalent Circuit Parameters Results

Equivalent circuit parameters of the motors are made up with six different winding topologies are given in Table 7, where, R_1 and R_2 stator and rotor resistances, X_1 and X_2 stator and rotor leakage reactances, X_m magnetization reactance, R_{fe} core resistance, R_k equivalent resistance, X_k equivalent reactance, Z_k equivalent impedance. Stator resistance values are measured over the motor’s terminal box. Results in Table 7 are given in ohms.

Table 7. Equivalent circuit parameter results for the six motors

Parameters	Motor 1	Motor 2	Motor 3	Motor 4	Motor 5	Motor 6
R_1	3.7	4	4.8	4.3	4.8	5.25
R_2	5.163	5.764	7.009	5.634	6.498	7.240
X_1	3.452	3.901	4.796	4.694	5.471	6.560
X_2	3.452	3.901	4.796	4.694	5.471	6.560
R_k	8.863	9.764	11.809	9.934	11.298	12.49
X_k	6.905	7.803	9.592	9.389	10.943	13.12
Z_k	11.235	12.499	15.214	13.669	15.729	18.116
X_m	63.962	94.662	124.21	84.013	113.94	142.18
R_{fe}	269.90	361	525.09	566.27	925.64	956.29

4.5. Torque and Efficiency Results

Nominal torque versus a number of winding graphic which has been obtained by using equivalent circuit parameters is depicted in Figure 8 for both winding topologies. Torque versus speed characteristics of the six motors is given in Figure 9.

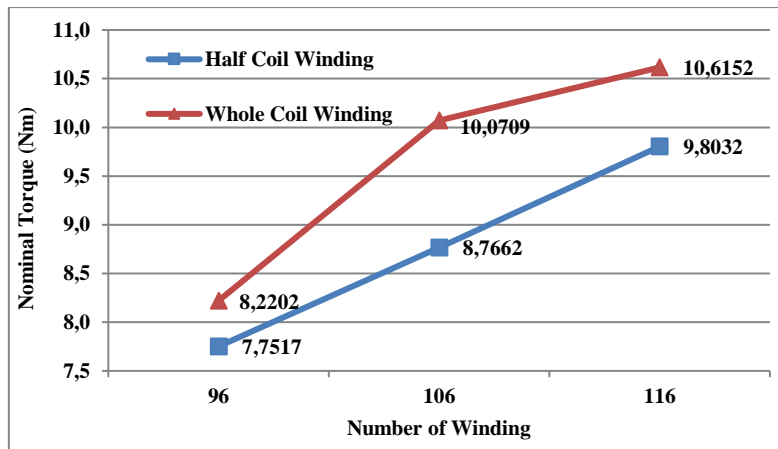


Figure 8. Nominal torque vs number of winding graphic

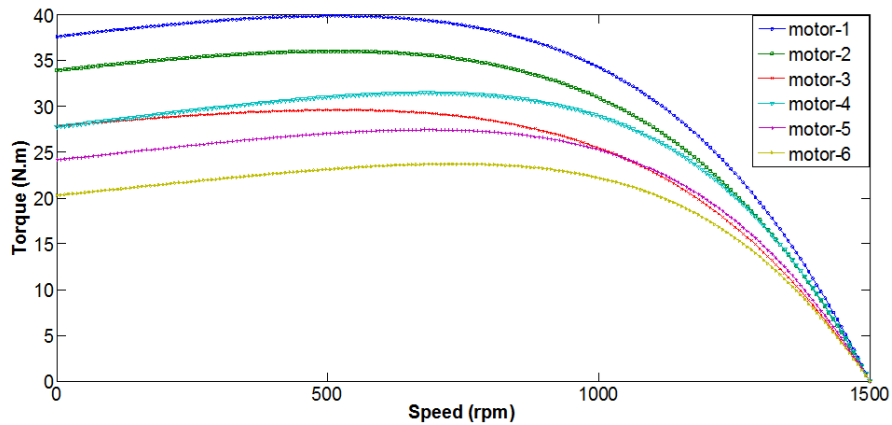


Figure 9. Torque-speed characteristic for the six motors

When the Figures 8 and 9 are examined, increase in the number of windings has led to an increase in the nominal torque values for both winding types. The nominal speed value of the motors, the highest nominal torque value is obtained from the motor 6 which is obtained the whole-coil winding and 116 winding turns. One of the most important effects of the number of winding seems to be on the starting torque. The highest starting torque is obtained from the motor 1. Starting torque of the motor 6 is the smallest value. Efficiency-number of winding graphic for the six motors is given in Figure 10.

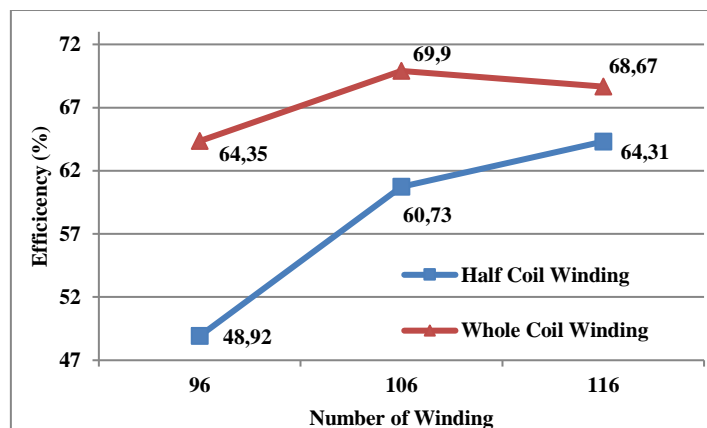


Figure 10. Efficiency vs number of winding graphic

When the efficiency value is examined, it is observed that the number of winding increases, the efficiency values increases. All of the motors with whole-coils winding efficiency values were obtained larger than the motors with the half-coil winding. The highest efficiency value (69.9%) is obtained from the motor 5 which is obtained the whole-coil winding and 106 winding turns. The smallest efficiency value (48.92%) is obtained from the motor 1 which is obtained the half-coil winding and 96 winding turns.

5. CONCLUSION

In this study, unlike the studies in the literature, only the number of turns are changed and analyses are carried out. All the other motor parameters are kept constant. Six different induction machines which have 6 different winding topologies are designed. Three of the machines are designed half-coiled and the others are designed whole-coiled. The efficiency of the motors with the whole-coil was greater. Maximum efficiency has been achieved for 116 turns numbered topology for half-coil winding. Again nominal torque values of whole-coil winding motors gave better results. While the lower core losses have been obtained for the motor with whole-coil winding, the lower copper losses have been obtained

half-coil winding. There has been an increase in the power factor value with the decline in the value of reactive power.

For the future studies, harmonic analysis, transient analysis, and change of current and voltage wave of the six motors will be performed and compared.

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