Design Selection Criteria of Single Phase Induction Machine

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***Abstract*— This paper examines how important design factors, particularly capacitance values and stator and rotor slot dimensions, affect the performance of single-phase induction motors (SPIMs). Results indicate that while increasing stator slot width decreases starting current, it also decreases efficiency and torque Similarly, larger rotor slots increase starting current while reducing starting torque and efficiency. Although it increases capacitor losses, adjusting capacitance improves efficiency, power factor, and starting torque. In order to balance efficiency and performance, ideal ranges for capacitance and slot size are proposed, offering guidance for better SPIM design.**

Keywords—SPIM, Design Criteria, Stator and Rotor Design, Capacitance

1. INTRODUCTION

While three-phase induction motors are widely used in the commercial and industrial sectors, sometimes there are situations where 3-phase power supply is not available. In such cases, single-phase induction motors (SPIMs) come into play. SPIMs are used in a wide range of industrial, agricultural and residential applications, from washing machines to compressors, refrigerators to kitchen appliances, heating pumps to power tools. Demand for SPIMs is growing steadily and millions are produced every year [1][2].

The main characteristic of SPIMs is that they can continue rotating after being initially driven by a rotating magnetic field, despite being supplied with single-phase current. In particular, capacitor-run type SPIMs are supported by a continuously connected capacitor, which increases the starting torque and enhances the motor's stability [3][4]. These machines offer reliability, high and low noise in applications where low power up to 1kW is required. Although the starting and nominal torque seems to be a disadvantage compared to other machines, at the same time the low starting current provides an advantage. [5][6]. The low starting torque makes it possible to easily reverse the direction of motor rotation. It also allows changes to the supply voltage while the motor is running with minimum noise in the on-load.. [7]. In addition, the efficiency is high and the power factor is acceptable [8].

This study focuses on addressing these challenges by exploring the optimal design and operation of SPIMs, with particular attention to capacitor-run configurations. Through a comprehensive analysis of design parameters, this research aims to contribute to the development of more efficient and reliable SPIMs tailored to specific application requirements.

2. FUNDAMENTAL DESIGN STEPS OF SPIM

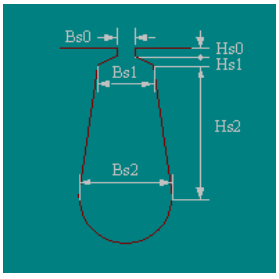
This section will show the basic parameters that need to be determined when starting a SPIM design. In general, critical values such as active length and diameter should be calculated when starting an induction machine design. The technical specifications (Power, Voltage, Current, Efficiency etc.) of the machine that are sufficient for the design should be known. Then, according to these values, general geometrical parameters are determined by analytical calculations. After these parameters are determined in the design process, optimization should be done for the values we want to achieve. In this study, the optimizations will be shown.[9] .

TABLE1. General Data of SPIM

Given Output Power (HP):	3
Rated Voltage (V):	230
Run Capacitance (uF)	35
Number of Poles:	2
Given Speed (rpm):	3500
Frequency (Hz):	50

TABLE2. Main Lenghts of Stator and Rotor

DATA	STATOR	ROTOR
Number of Slots	24	28
Outer Diameter (mm)	165	164
Inner Diameter (mm)	67.31	2
Length of Core (mm)	89	89
Type of Steel:	M19_24G	M19_24G



Stator Slot

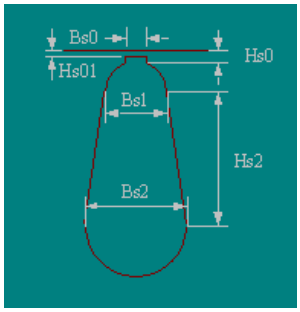
Hs0 (mm):	0.9
Hs1 (mm):	1
Hs2 (mm):	12.3
Bs0 (mm):	2.5
Bs1 (mm):	4.6
Bs2 (mm):	7.8

Fig.1 The Slot Dimensions of the Stator

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Rotor Slot	
Hs0 (mm):	0.25
Hs01 (mm):	0.25
Hs2 (mm):	5.15
Bs0 (mm):	0.1
Bs1 (mm):	3.86
Bs2 (mm):	2.34

Fig.2 The Slot Dimensions of the Rotor

2.1 Formulation of Output Equations

The output equations are an important indicator for calculating the external dimensions of a machine. In induction machines, these equations are used to determine the stator outer and inner diameter and axial length. Once these dimensions are determined, the next stages of the design can proceed. In addition, since we will have data, it is an advantage that the values to be optimized are limited. It is necessary to know the connection between input power (P_{in}) and output power (P_{out}). Here ɲ represents the efficiency. Our phase number(m) is already m=1.

$$P_{out} = ɲP_{in} = ɲmV_{ph}I_{ph}cos\theta = C_oD^2Ln_s \quad (1)$$

where C_o (N/m^2) is the motor's output coefficient. V_{ph} is a given phase voltage(V), $I_{ph.}$ is line current(A). D is inner stator diameter(m), L is active axial core length(m). n_s represents the synchronous speed in revolutions per minute (rpm).

$$C_o = 11B_{av}ack_wɲcos\theta \quad (2)$$

Winding factor (k_w), specific electrical loading (ac) and average air flux density (B_{av}). İncreasing B_{av} leads higher iron losses, though it can reduce both the physical dimensions and the cost of the machine. For motors operating at 50 Hz, typical B_{av}. values range between 0.6 and 0.85 T.

Specific electric loading(ac) enhances power density in electrical machines, enabling greater power output. However, overloaded motors can lead to heat build-up, increasing copper losses and reducing overall efficiency. While higher magnetic field contributes to power and torque, thermal loading can lead to overheating and reduced efficiency if the optimum balance is not maintained. Therefore, selecting an appropriate specific electric loading value is essential to achieving a balanced compromise between power density, efficiency, and thermal performance.

2.2 Design Methodology for SPIM

2.2.1 Sizing Stator Design

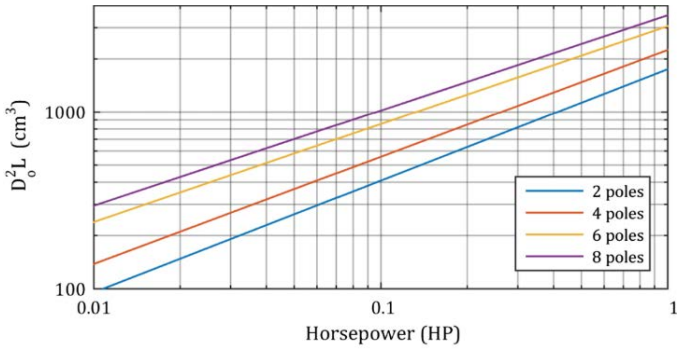


Fig.3 Relationship between D^2L and HP For Various Pole Number [10]

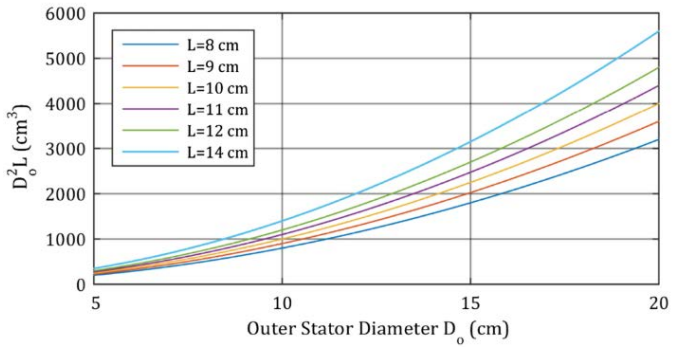


Fig.4 Relationship between D^2L and Outer Stator Diameter D_o For Various Lengths [10]

For 2 to 8-pole designs, as shown in Fig.3, an empirical relationship exists between the inner diameter (D) and the outer diameter (D_o) of the stator. This ratio typically ranges from 0.5 to 0.75 in prior studies, with D/Do≈0.6 as a commonly used value. Additionally, for small induction motors, where the air gap is approximately equal to the inner stator diameter, the ratio of length to diameter can be calculated by the following expression:

$$L/D = \pi\sqrt[3]{p}\,/2p \quad (3)$$

Therefore, to guide the design according to Figure 3 and Figure 4, the following steps are suggested:

- ✓ Select a frame size that corresponds to the power output of the SPIM.
- ✓ Use the frame to set the effective length L, considering the maximum length permitted. This approach is advantageous, as it aligns with the trend toward longer frames with reduced diameters, minimizing rotor tangential stress.
- ✓ Reference Fig.4 to determine Do. To facilitate design, Fig.4 additionally shows the variation of D^2L as a function of the outer stator diameter Do for different lengths.
- ✓ Obtain D using ratio D/Do

It is another important thing to choose proper stator slot number.

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TABLE.3 SPIM Stator Slot Selection Criteria

Criteria	Description
Slot Number (Ss)	The number of stator slots (Ss) is critical in motor design, affecting cost, efficiency, and noise.
Impact of Small Ss	A small Ss reduces manufacturing costs, but requires larger slots, resulting in more copper per slot and higher material costs.
Impact of Large Ss	A large Ss decreases leakage resistance, enhances output power, reduces harmonic problems, and minimizes magnetic noise.
Slot Geometry	A semiclosed trapezoidal slot geometry is preferred, as it limits magnetizing current, reduces vibrations, and leads to quieter operation compared to open slots.

2.2.2 Sizing Rotor Design

a) Air gap length calculation

One important factor for SPIM performance is the airgap (g). In terms of technical feasibility, it should be sufficiently small to reduce the magnetizing current. In general, an airgap of at least 0.2 mm is possible.

The formula can be used to determine the airgap for small induction machines:

.

$$g = 0.007D/\sqrt{2p} \quad (4)$$

b) Number of Rotor Slot

Single-phase induction motors (SPIMs) depend on the rotor slot number chosen to minimize noise, achieve smooth operation, and lessen undesirable effects like crawling and cogging. The main factors to take into account while choosing the ideal rotor slot number are outlined in the following guidelines:

TABLE.4 SPIM Rotor Slot Selection Criteria

Condition	Description
Sr ≠ Ss	The rotor slot number should not equal the stator slot number to avoid cogging torque.
Sr ≠ ±p, ±2p, ±5p	Sr should differ from the pole number and its multiples to prevent magnetic locking and crawling.
Ss - Sr ≠ ±3p, ±4p, ±6p	The difference between Ss and Sr should avoid these values to reduce harmonic effects.
Ss - Sr ≠ ±1, ±2, ±4, (±p ± 1), (±p ± 2), (±2p ± c), where c = 1, 2, 3, 4	These conditions ensure reduced noise and minimal interaction between stator and rotor harmonics.

3. OPTIMIZATION SPIM

The widths and heights of the stator and rotor slots in a single-phase induction motor will be the subject of a thorough examination in this paper. The influence of differences in these slot dimensions on motor performance will be evaluated by analyzing the link between these dimensions and important performance indicators, such as efficiency, starting current, and starting torque. The effects of the run capacitance used to start SPIM motors on the motor performance will be investigated and it will be shown how to choose an optimum value.

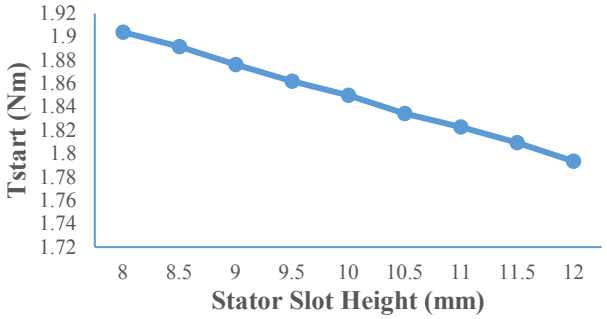
2.3 Stator Slots Review

Stator slot length affects many parameters such as efficiency, starting and thermal performance. Therefore, optimization of stator slot length significantly improves motor performance.

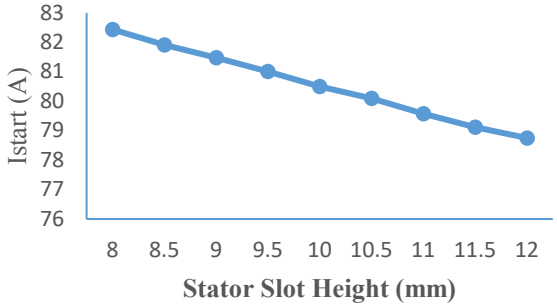
For longer slots, the leakage inductance value will increase, causing energy losses and hence the efficiency of the motor will decrease. However, smaller slots will decrease the leakage inductance value and increase the leakage flux value, so the core may saturate. Smaller slots also increase the starting torque.

When selecting the ideal stator slot width and length, optimum values between starting torque and current, efficiency should be selected. Choose a width that reduces starting current without compromising starting torque too much. When selecting these parameters, an acceptable starting current and torque values can be sacrificed..

When the graphs in Fig.5 are analyzed, it is more appropriate to select the stator slot width between 11-11.5 mm for lower starting current and higher efficiency by sacrificing some starting torque.

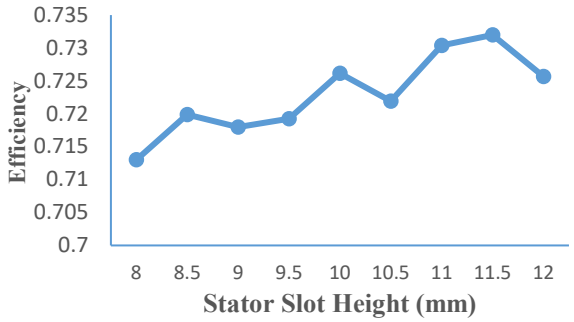


(a)



(b)

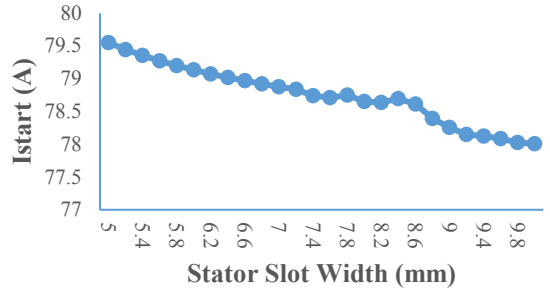
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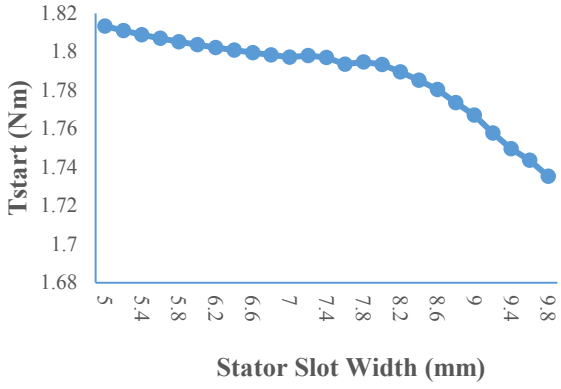
(c)

Fig.5 Stator Slot Height versus (a) Starting Torque (b) Starting Current (c) Efficiency

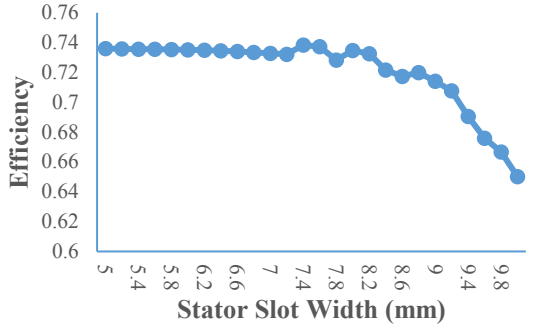
The Fig.6 show that while starting torque and efficiency tend to decline with increasing stator slot width, starting current tends to decrease as well. For optimum value, it can be selected between 6.6 and 7.4 mm. Reasonable levels of inrush current and torque are selected while still keeping the efficiency high.



(a)



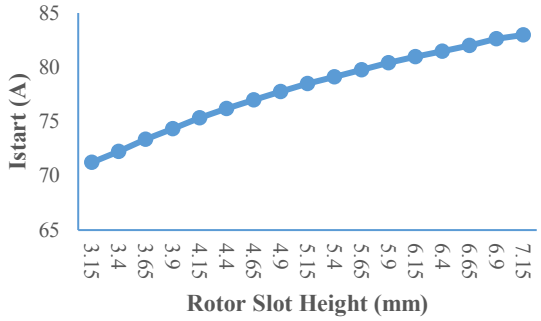
(b)



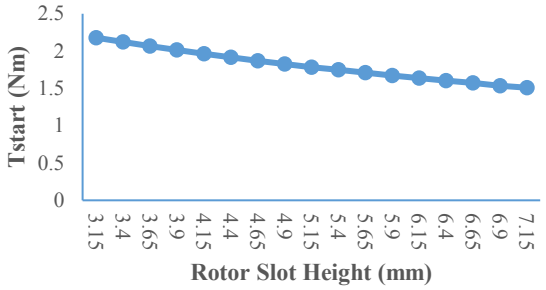
(c)

Fig.6 Stator Slot Width versus (a) Starting Current (b) Starting Torque (c) Efficiency

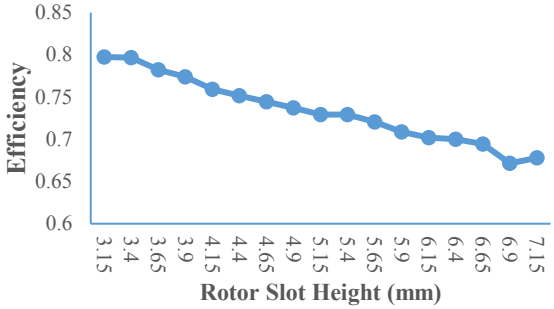
According to Fig.7, an increase in the rotor slot width leads to an increase in the starting current and a decrease in the starting torque. It is also seen that the efficiency decreases. Therefore, it is necessary to keep this height to a minimum considering the winding placement. Therefore, the optimum value would be between 3.4 and 4.4 mm.



(a)



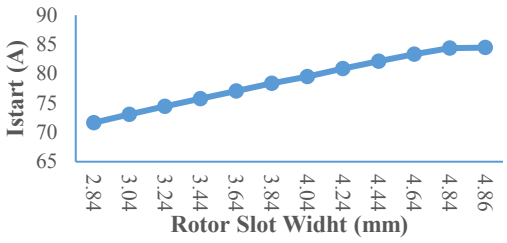
(b)



(c)

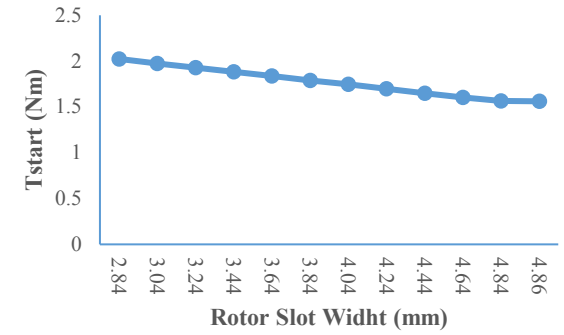
Fig.7 Rotor Slot Height versus (a) Starting Current (b) Starting Torque (c) Efficiency

The evaluations made for rotor slot heights can also be made for rotor slot width. It is seen that the Fig.8 are similar to each other. Therefore, the rotor slot width should be selected between 3 and 3.5 mm.

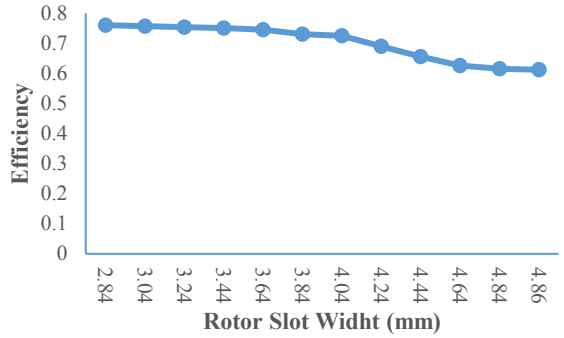


(a)

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(b)

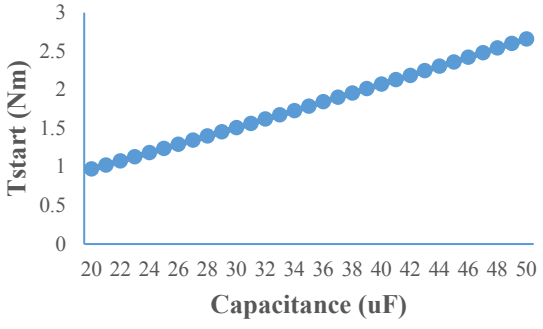


(c)

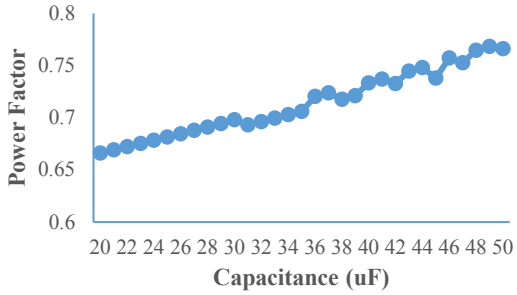
Fig.8 Rotor Slot Widht versus (a) Starting Current (b) Starting Torque (c) Efficiency

2.4 Evaluation of Capacitance

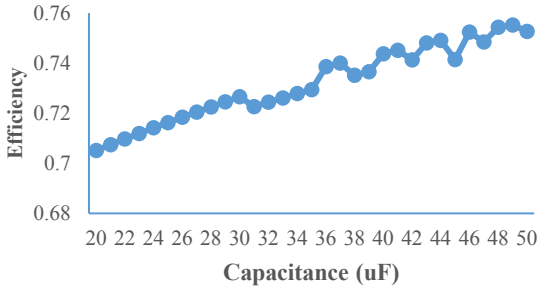
It is seen that as the capacitance value increases, the starting torque, power factor and efficiency increase. However, it is observed that the losses on capacitance increase. Therefore, when choosing a capacitance, it is imperative to make a careful choice, no matter how advantageous it may seem to choose from the upper limits. Considering the capacitance losses and other factors, it should be selected between 46 and 50 uF.



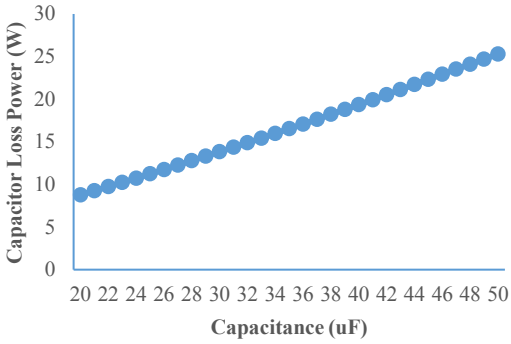
(a)



(b)



(c)



(d)

Fig.9 Capacitance versus (a) Starting Torque (b) Power Factor (c) Efficiency (d) Capacitance Loss Power

4. CONCLUSIONS

This study considers how design optimization is done. The way in which these design values are optimized is presented. In addition, ANSYS software, which uses the finite element method as a design method, is used. Parametric calculations were made through this software. The stator and rotor slot dimensions of a single-phase induction motor were evaluated in terms of starting current, torque, and efficiency. Additionally, the selection of capacitance values was analyzed in relation to power factors and energy loss. During this selection process, compromises may need to be made between starting current and starting torque in certain situations. Furthermore, sacrificing maximum efficiency may also be necessary. Considering all factors, selecting the correct dimensions is a crucial criterion for SPIM design. This study provides guiding information for the optimization of SPIM design.

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