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A Review of Strategies for Improving 3-Phase Induction Motor Performance

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Abstract— The 3-phase induction motor is an electric motor with a strong, reliable, and easy-to-operate construction, and it is cheaper compared to other types of electric motors, making it widely used by the public. Although this motor is considered reliable, it still has some drawbacks, such as low performance, including starting torque, power factor, and efficiency compared to other types of electric motors. Therefore, research to improve the performance of this motor is ongoing. This paper aims to outline some methods that have been used by previous researchers to improve the performance of induction motors based on literature studies. Some of the methods discussed in this paper include the use of permanent magnets on the rotor, operating the 3-phase induction motor on a single-phase system, developing ferromagnetic materials for the motor, increasing the number of coil phases, and optimizing coil design in the motor. The advantages and disadvantages of using these methods to improve motor performance are briefly outlined.

Keywords: Induction motor, Improve performance, Permanent magnet, Ferromagnetic materials, Multiphase design.

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1. Introduction

The 3-phase induction motor is an electric motor that is widely used, especially in the industrial world [1]–[6], and represents a significant percentage of all motors currently in use [7]. This type of motor is the most common and frequently found in industries due to its simple design, low cost, sturdy construction, and easy maintenance [1]–[6]. Its simple and sturdy construction makes it suitable for heavy industrial applications, and it continues to be the motor of choice in many industrial facilities [4]. Despite the increasing popularity of other motor technologies, such as permanent magnet synchronous motors, induction motors remain the dominant motor technology in the industry [4], [8].

While 3-phase induction motors have many advantages, they also have drawbacks, such as lower performance compared to other types of electric motors [6], [9]–[21]. Therefore, various efforts to improve the performance of these motors are ongoing, including the use of permanent magnets on the rotor [6], [9]–[21], operating the motor in a single-phase system [22]–[35], developing ferromagnetic materials for the motor [36]–[46], and increasing the number of motor coil phases [47]–[63]. In addition, optimizing the design of the rotor and stator slots [64]–[66], and manufacturing processes will also affect the quality of the ferromagnetic materials in the motor [67], which directly impacts motor performance.

All efforts that have been made in an effort to improve the performance of 3-phase induction motors, as mentioned above, have their respective advantages and disadvantages. The use of permanent magnets on the rotor requires expensive additional costs to purchase permanent magnets [6], [9]–[21], operating a 3-phase induction motor on a 1-phase power system requires additional costs to create a control circuit and capacitor circuit [22]–[35], and developing ferromagnetic motor materials also requires expensive additional costs because increasing the quality of materials is

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proportional to increasing material prices [36]–[46]. Besides that, increasing the number of coil phases also requires additional costs to create a new power source that matches the number of motor coil phases [36]–[46]. Therefore, a smart strategy is needed in choosing a suitable technique to improve motor performance.

This paper aims to provide an overview of various efforts that can be made to improve the performance of 3-phase induction motors, compiled from various cited sources. The material is presented concisely for easy understanding. It is hoped that this paper can provide an overview of several strategies that can be implemented to enhance the performance of 3-phase induction motors, tailored to specific needs.

2. Use of Permanent Magnet on Rotor

There is growing interest in increasing the efficiency of induction motors [68]. Various methods have been developed to increase the efficiency of induction motors, including using more copper and steel in the motor to reduce power losses or replacing the aluminum squirrel cage rotor with a copper one [69]. Reconditioning existing induction motors by replacing the rotor with a permanent magnet synchronous motor (PMSM) has been proven to increase efficiency significantly [14]. Therefore, although induction motors are widely used in industry, there is an increasing focus on increasing their efficiency and exploring alternative types of motors, such as PMSM, by making induction motor rotors such as PMSM [14].

The use of permanent magnets in the rotor is usually used in permanent magnet synchronous motors [6], [9]–[21]. As long as good magnetic material is used, the motor will work with better performance. Several studies have tried to compare the performance of induction motors with permanent magnet synchronous motors [6], [9]–[21]. The results of this research show that induction motors are reliable in starting systems because they do not require a more complex starting system, such as synchronous motors [17]. However, in general, the performance of synchronous motors is much better than that of induction motors [6], [9]–[21] where synchronous motors have the advantage of having a smaller rotor design but have output power, efficiency, and a power factor that is greater than that of induction motors. To improve the performance of this induction motor, development has been carried out to use permanent magnets on the rotor.

Shibata [70] has tried to incorporate permanent magnets into the cage rotor of an induction motor. It turns out that by using this method, there is an increase in the performance of the induction motor, where there is an increase in the power factor, efficiency, and output torque of the motor, thereby reducing the motor input current and thereby reducing motor losses. The shape of Shibata's design [70] is shown in Figure 1.

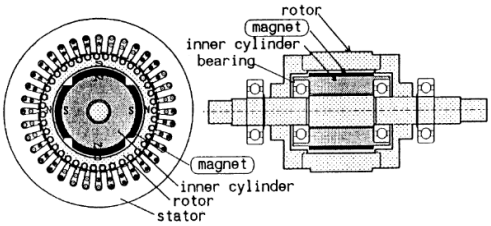
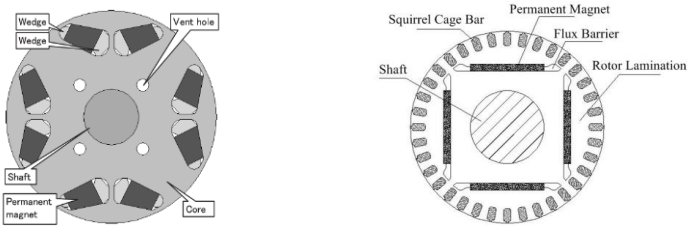


Figure 1. Shibata's induction motor with a magnet in the rotor [70].

Kondo [71] compared the performance of induction motors and synchronous motors and found that synchronous motors have a better power factor, output power, and efficiency. To improve induction motor performance, Kondo [71] added a permanent magnet to the rotor, as shown in Figure 2(a) [71], reducing power losses by up to 50%. Fei [9] also proposed an alternative method using permanent magnets on induction motor rotors, shown in Figure 2(b), resulting in a significant increase in performance, including a decrease in armature coil current of 10–26%, an increase in efficiency of up to 7%, and a power factor increase of up to 19.8%. Lu [69] used a rotor made of aluminum and an NdFeBr permanent magnet placed inside the rotor core, resulting in the motor being able to work at a constant speed for various load conditions, with an increase in motor efficiency of around 3%. Additionally, the thickness of the permanent magnet used in the rotor [5] and the air gap distance

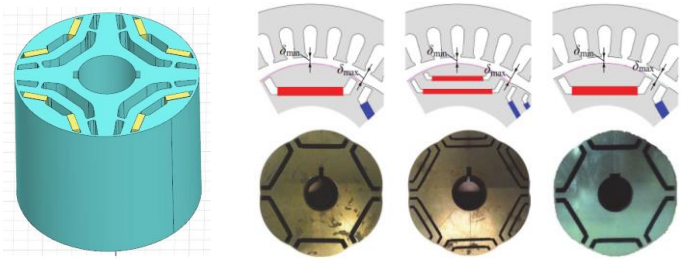
between the stator and the permanent magnet rotor also directly affect the efficiency of the induction motor [18] [72].



(a) Kondo's rotor design (b) Fe's rotor design

Figure 2. Four-pole permanent magnet rotor design in an induction motor

The method of using permanent magnets in induction motors, as demonstrated in the design by Vartanian and Toliyat [14], involves a reluctance rotor design with attached permanent magnets, as shown in Figure 3(a). This rotor is lighter than the commonly used cage or wound rotors, as it does not require copper and end rings. Simulation results indicate that this design can increase the motor's mechanical torque by 25% and efficiency by up to 33%. Ni [6] has also proposed a permanent magnet rotor design to enhance induction motor performance, presenting and analyzing three different designs in Figures 3(b), (c), and (d). Testing these new designs against conventional induction motors revealed that a rotor with a 1-layer permanent magnet design can increase the efficiency of a 2.2 kW induction motor from 77% to 88% and a 22 kW induction motor from 91.4% to 94.4%. This motor achieves its highest efficiency when operating at its standard frequency [6].



(a) (b) (c) (d)

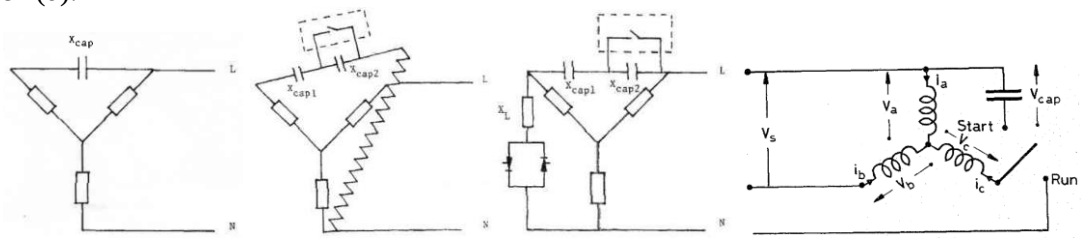
Figure 3. Permanent magnet rotor design provided by: (a) Vartanian and Toliyat; (b) Ni's permanent magnet rotor 1 layer design, with magnets on the 2nd layer; (c) Ni's 2-layer permanent magnet rotor; (d) Ni's permanent magnet rotor 1 layer design, with magnets on the 2nd layer.

All methods of using permanent magnets on the rotor, as described above, can improve the performance of induction motors by increasing efficiency, torque, and motor power factor. However, the use of permanent magnets in the rotor requires quite expensive additional costs to motor production costs because motor production costs increase along with the cost of purchasing permanent magnets of better quality. Therefore, the use of permanent magnets in induction motor rotors is more recommended for induction motors with large power capacities because the increase in motor performance can cover the cost of purchasing expensive permanent magnets.

3. Operation of a 3-Phase Induction Motor on a 1-Phase Power Supply

3-phase induction motors usually have low starting torque, so sometimes these motors are difficult to start under full-load conditions [73]. This problem can be overcome if the induction motor has a winding rotor, because the rotor resistance can be increased by adding external resistance so that it can increase the starting torque on the motor so that the motor can be started properly [74]. However, this problem cannot be solved in the same way as in an induction motor with a cage rotor because the rotor resistance cannot be changed. One thing that can be done to increase the starting torque on a 3-phase cage rotor induction motor is to operate this 3-phase induction motor on a 1-phase electric power system [29], [73]–[75]. Several ways to operate a 3-phase induction motor on a 1-phase electric power system were discovered by Pillay and Brzezinski [29] by adding capacitors, inductors,

and transformers to the motor coils, as shown in Figures 4(a), (b), (c), and Alolah [73], as shown in Figure 4(d).

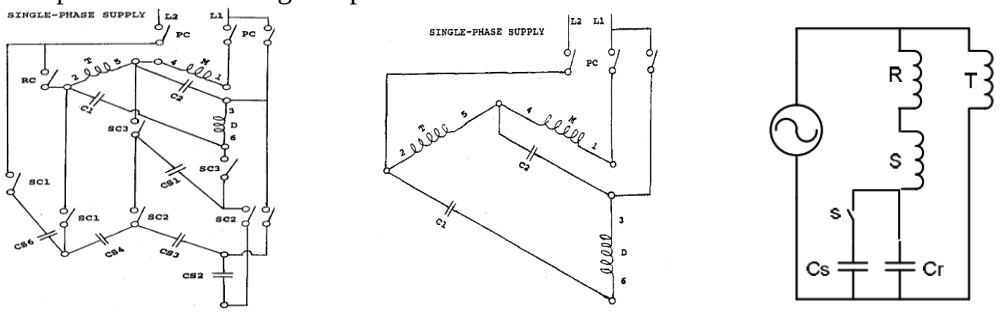


(a) (b) (c) (d)

Figure 4. Several ways to operate a 3-phase induction motor on a 1-phase system: (a) capacitor single-to-three-phase converter; (b) autotranformer-capacitor converter; (c) inductor-capacitor converter; (d) starting capacitor circuit.

Al-Turki and Al-Umari [23] have also studied the use of starting capacitors to initiate 3-phase induction motors in 1-phase electric power systems using a star (Y) or delta (D) connection system. Their research indicates an increase in starting torque, resulting in improved motor performance. Electronic circuits can be employed to control the capacitance value of the start capacitor for more optimal motor performance [22], [28]. The capacitance value of the starting capacitor significantly impacts the optimal starting torque of the motor [76].

Smith [74] and Anthony [24]–[27] have developed a new method for running a 3-phase induction motor on a 1-phase power system, as shown in Figure 5. This method allows the motor to operate with better performance on a single-phase electric power system, with improved starting and running torque and a power factor close to one. The Smith method is more efficient for induction motors with power capacities above 40 HP due to the use of a large number of starting capacitors. On the other hand, Anthony's method uses a lower capacitance of the starting and running capacitors, making it more efficient and cost-effective. Using this method, a 3-phase induction motor can operate with a power factor close to unity at a load condition of 80% to 100%. For optimal conditions, it is recommended to operate the motor at a load condition of 85%, as this achieves the highest efficiency and ensures safe operation with a long lifespan.



(a) Smith's starting circuit (b) Smith's running circuit (c) Anthony's method

Figure 5. The operating circuit for a 3-phase induction motor on a 1-phase power supply.

4. Improve the Quality of Ferromagnetic Materials

One method that can be used to improve the performance of induction motors is to develop and improve the quality of ferromagnetic materials used in motors [36]–[46]. Several methods that have been used to analyze and develop magnetic materials are still being developed to obtain magnetic materials that can improve motor performance [38], [43], [77]–[81]. The stator and rotor cores of electric motors are ferromagnetic materials that are usually made from metal sheets (low-carbon steel sheets) with a thickness of less than 1 mm that are stacked together [45]. Some better-performing electrical machines are made from silicon steel sheets with a silicon content of around 3%. The entire process of making this core basically consists of lamination, stamping, and electrical insulation between adjacent sheets, which are stacked and arranged properly [45].

The stator and rotor cores of electric motors are typically made from metal sheets, such as low-carbon steel or silicon steel with a 3% silicon content, stacked together in a process involving

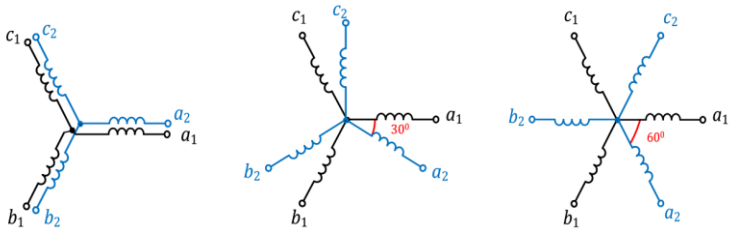
lamination, stamping, and electrical insulation [45]. Additionally, the choice of material, such as amorphous and nanocrystalline materials, can impact performance at higher frequencies due to reduced eddy current losses [67]. The manufacturing process also plays a crucial role, as mechanical cutting can result in increased iron losses and decreased material permeability [36] [67]. Manufacturing methods can have a negative impact on the magnetic properties of the material, where iron losses increase by more than 15% due to the cutting effect, and laser cutting increases iron losses by 30–50% [67]. Thinner laminate thicknesses are known to result in lower material degradation. By considering these factors and using appropriate techniques and materials, the quality of magnetic materials can be improved [67]. The operating temperature of an induction motor also greatly influences the properties of the ferromagnetic material used in the motor, which in turn affects the torque produced by the motor [82].

Soft magnetic composites (SMC) are a type of ferromagnetic material known for their excellent properties, including three-dimensional isotropic ferromagnetic behavior, high permeability, low coercivity, and reduced power losses [83]. Typically, SMC is made up of insulating material and magnetic powder, and its properties are heavily influenced by the insulating material, the size of the magnetic powder, and the proportion of the magnetic powder [84]. The smaller the size of the volume fraction of iron particles, the greater the resistance of the iron core, but the smaller the permeability and flux density [84]. Improving the performance of the magnetic properties of SMC is carried out by selecting appropriate materials and applying appropriate coating methods [84]. SMC material is very suitable for machines that operate at high frequencies with low core losses, but is not suitable for machines that operate at low frequencies [45].

Research has shown that the quality of magnetic materials significantly impacts electric motor performance. Different materials, such as nanocrystalline, amorphous, and crystalline soft magnetic materials, have unique properties that affect their suitability for mid-frequency applications. Material selection depends on factors like operational frequency and desired power density. For example, amorphous and nanocrystalline materials have reduced eddy current losses at higher frequencies, making them more suitable for those applications. Performance factors, including maximum allowable peak flux density and sinusoidal frequency, can be used to evaluate material suitability at a specific frequency. Better materials result in improved motor performance, but they also come with a higher price tag [36].

5. Increase the Number of Motor Winding Phases

Another method that can be used to improve the performance of an induction motor is to increase the number of phases in the induction motor wiinding from 3 phases to 5 phases or more [47]–[63]. This multi-phase induction motor (more than 3) has the advantage of low vibration, increasing flux density, and power [85]. The use of stator windngs in this design is more effective, and the motor can continue to operate even if one of its power sources is removed [85]. Several motors with multiple three-phase windings practically dominate since commercially available three-phase power converters and available control techniques can still be used, whereas standard three-phase motors can be easily used to make 6-phase motors without technical constraints [86]. The form of this 6-phase winding configuration is shown in Figure 6 [86].



(a) Dual 3-phase (b) Asymmetrical 6-phase (c) Symmetrical 6-phase

Figure 6. Six-phase winding design configuration [86].

In Figure 6, it can be seen that the 6-phase design can be made in 3 ways, namely: 1; a dual 3-phase design (D3P) with zero degree coil spacing (Figure 6 (a)); 2; an asymmetrical 6-phase design (A6P) with a distance between adjacent coils of about 30 degrees (Figure 6 (b)); and 3; a symmetrical

6-phase design (S6P), where all coil distances are symmetrical at 60 degrees (Figure 6 (c)). The most widely used design in industrial applications is the non-metric 6-phase design because it can eliminate the fifth and seventh harmonics in the stator, which eliminates the sixth-order torque ripple component. Additionally, the A6P design is the only six-phase winding layout with the capability of increasing torque density using third-order harmonic current injection [86].

Motors with a 6-phase design have the advantages of 3-phase motors with better reliability in the operating system [50], [87], torque [59], [60], and efficiency [88], [89]. To obtain a better and more reliable 6-phase induction motor operating system, the control system and design of the 6-phase inverter used in this motor are still being developed [48], [53], [55], [56], [88], [90]. A reliable safety system also needs to be developed for 6-phase motors so that the motors can work with better performance [48], [53].

Apart from the 6-phase design, the 3-phase induction motor winding design can also be developed into 5-phase or 7-phase [91], 9-phase [57], [92], [93], and 12-phase [52][49]. This motor with a multi-phase design has better performance than a 3-phase induction motor [91]. The 9-phase winding design can reduce the harmonic content in the motor [92] and has a better flux density than a 3-phase induction motor [57]. With a 12-phase design, the motor will operate with better flux density, torque, and efficiency, as well as with lower vibration and noise [49] [52].

6. Optimization of the Induction Motor Winding Design

Using more than three phases can improve motor performance and provide fault tolerance, but it's not the only factor to consider. Studies have shown that unconventional winding configurations in multiphase motors can significantly improve torque quality [60]. Different winding configurations can result in lower losses, better torque ripple, and higher electromagnetic efficiency [94]. Centralized coil designs are more suitable for high-frequency motors, while distributed coil designs are better for low frequencies [95]. Non-overlapping windings and varying coil distribution and turn ratios can reduce torque ripple and increase flux weakening capability. Design modifications such as rotor or stator tilt, taper magnets, and fractional slot motors can also improve motor performance. However, sub-harmonics in the magnetic motive force distribution can cause additional iron losses in high-speed applications, making fractional slot motors less common in high-power applications. Unconventional slot-pole combinations in fractional slot motors can lead to unbalanced and asymmetric winding structures [89].

The performance of a coil design depends on various factors, such as winding type, coil distribution, turn ratio, and slot shape. In terms of reducing torque ripple and increasing flux weakening capability, three- and four-layer windings with varying coil turns have shown good results [94]. Additionally, fractional slot/pole sum designs have been shown to reduce cogging torque and torque ripple while maintaining acceptable torque and electromagnetic loss values [95]. In addition, shaped-profile windings have been introduced to minimize high-frequency AC losses and limit eddy current losses at high frequencies [96]. Overall, the choice of coil design depends on the specific requirements of the application, taking into account factors such as torque ripple, flux attenuation capability, and high-frequency performance.

The winding design that provides better performance is a two-layer stator winding arrangement [94] [96]. This design allows maximum utilization of the available space in the stator, accommodating conductors in all its slots [95]. It offers improved torque performance with lower torque ripple compared to other configurations [96]. Additionally, it exhibits a higher amplitude of the first harmonic component and a reduced harmonic content, resulting in better overall performance [97]. This design also shows the potential for better electromagnetic efficiency and lower losses, especially in healthy conditions [89]. However, rotor losses may be higher under fault conditions, which must be considered in the thermal design. Overall, the two-layer stator winding arrangement proves to be a promising coil design for achieving the desired performance.

The coil design that best improves motor performance is an optimized winding pattern with optimal coil pitch and rotation [8], [95]. This design results in higher torque performance, lower losses, and increased efficiency compared to conventional winding patterns [95]. The optimized winding pattern achieves higher fundamental harmonics of the total winding function, resulting in

increased torque production and a smoother air gap flux density spectrum [97]. It also reduces the negative impact of spatial harmonics of low-level magnetic motive force (MMF), leading to improved motor efficiency, vibration, noise, and torque production [89]. The optimized winding pattern has a higher slot filling factor, lower air-gap MMF total harmonic distortion, and a better power factor compared to conventional windings [98]. Additionally, it exhibits reduced stator leakage inductance and rotor winding Joule losses, resulting in higher overall performance [8].

7. Conclusion

Several methods that can be used to improve the performance of a 3-phase induction motor have been briefly described. There are several methods that can be used to improve motor performance, including using permanent magnets on the rotor, operating a 3-phase induction motor on a 1-phase power system, improving the quality of the ferromagnetic material used in the motor, increasing the number of motor coil phases, and optimizing the coil design. motorcycle. Choosing the right method to improve motor performance needs to be done in order to obtain an increase in motor performance with appropriate goals and costs.

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