Trends and Technical Advancements on High-Efficiency Electric Motors: A Review

Jawad Faiz and Farbod Parvin

Abstract In order to reduce the global energy consumption, the energy efficiency must be improved. Electric motors are the major consumers of electrical energy and their efficiency improvement can have a very large impact on saving electrical energy. This chapter focuses on the latest advancements of various types of electric motors. These advancements spring from the high-end materials, new structures, or improved construction techniques. The chapter classifies electric motors by their types in different sections and the latest trends and advancements of each specified motor are discussed thoroughly. Finally, a brief comparison is conducted using the related literature and future possibilities of different types of motors.

Keywords Efficiency · Induction machines · Losses reduction · Optimal utilization · Electrical motors

1 Introduction

Energy awareness is considered to be one of the most important motives in engineering researches, and electric motors are no exception. In fact, improving electric motors' efficiency is a top priority in this field. Motor-related systems consume over 60% of electricity worldwide and they are the largest consumers of electric power (Lu 2016). Therefore, efficiency improvement of such systems, even below 1%, can make a drastic saving in the electrical energy demand. Because of the multidisciplinary nature of the electric motor field, efficiency improvement can be realized by many ways. Engineering solutions can be electrical, mechanical, material, or even physics based (as in high-temperature superconductor) and all can be applicable here.

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From electrical engineering point of view, efficiency improvement depends on the motor type. This rather diverse category consists of some well-known motors such as induction motor (IM), direct current motor (DCM), permanent magnet synchronous motor (PMSM), and switched reluctance motor (SRM) to more modern and advanced structures such as brushless DC motor (BLDC), synchronous reluctance motor (SynR), segmented SRM (SSRM), and flux switching motor (FSM). Research is still ongoing for nearly all of the abovementioned motors (except DCM) but some of the modern structures are still far from a mature technology.

The aim of this chapter is not only to identify the latest methods of efficiency improvement, but also to classify them and trace them back to their origins. As it will be explained later, different techniques can benefit the machine performance by many ways. Considering copper loss for instance, it can be lowered by using cast-copper rotor in IMs (Lu 2016) or it can be degraded by utilizing fractional-slot concentrated windings in synchronous motor. This review approach has the benefit of identifying all of the latest trends in the field and tracing them back to their origins and see if it is possible to derive another method or technique based on their own origins. A brief summary of reviewed articles has been given in Table 1.

Due to the underlying differences in different kind of motors, various types and advances in each structure have been reported and discussed thoroughly in this chapter.

2 Conventional and Segmented Switched Reluctance Motors

Unlike SynR motors, rotor geometry of conventional SRMs has not been developed significantly over the past 30 years (Mecrow et al. 2002). Nowadays, the SSRM is considered as an improved version of SRM and its advantages over its predecessor will be discussed here. Aside from its manufacturing difficulty (Xu et al. 2016), the SSRM performance in every aspect is superior to the conventional SRM. A tooth-wound SSRM has been proposed by Widmer et al. (2015) as an alternative for traction application and has been optimized as a close competitor of the interior permanent magnet (IPM) motor of the Nissan Leaf car. Since the power-to-volume ratio of the SSRMs is lower than that of the IPM motors, no size constraint has been considered. However, the traction application requires the lowest possible mass. As a result of such requirement, one of the major aspects of this electric motor is its tooth-wound winding, in spite of the other SSRMs. Obviously, another advantage of such winding is lower copper losses and higher efficiency. Strengths and weaknesses of the SSRM have been investigated more thoroughly by Mecrow et al. (2004). Two types of the SSRM with two winding layouts of full pitched and single tooth have been compared with the conventional SRM and a BLCD motor. It has been reported that the whole-coiled motor has a better magnetic utilization; that is, more percentage of the stator core participates in the magnetic circuit of each phase. The other design which has a similar winding with the conventional SRM is lighter since

Table 1 Recent advancements and research trends in various types of motors

SRM		IM	PM motor	
SRM	SSRM		PMSM	FSPM
• Thin ribs for noise reduction	• Displaced segments • Aluminum rotor • Circular slots • Single-tooth winding	• Copper rotor • Low-harmonic windings • Slitted solid rotor • Core lengthening • Rotor replacement • 1-phase utilization of 3-phase motors	• Amorphous alloy core • Phase group concentrated • Sinusoid PM shape • Current harmonic injection • FSCW • Asymmetrical rotor structure	• Flux diverters • Enhanced demagnetization • Hybrid excitation

it has less copper but requires certain design considerations such as stator tooth width.

A novel SSRM (Oyama et al. 2006) has an aluminum rotor, which embodies the segments of the rotor. Such structure can fulfill two requirements. First is the mechanical robustness and ease of manufacturing. Second, which is of more interest here, is the improved torque of the machine, because it has an additional eddy current component. Lower radial force is another advantage of the SSRM, because the air gap flux path is more circumferential rather than radial. A higher number of rotor segments has been suggested in the work of Vandana and Fernandes (2015) for high efficiency and low copper loss, especially in direct-drive applications. However, increasing the number of segments will also increase the core losses of the machine; however, it does not recommend structures with more than 16 segments, because efficiency improvement is insignificant.

One of the intrinsic advantages of the SSRM over the SRM has been introduced by Vattikuti et al. (2008). A better magnetic utilization allows more compact structures. By optimizing this feature in the SSRM, a circular-slot SSRM has been recommended. Such geometry confines the flux to circular paths and removes the need of conventional stator back-iron. The result is a more compact and efficient motor in exchange of higher resistant windings.

Torque ripple can be reduced in a dual-axial SSRM (Madhavan and Fernandes 2014) with displaced rotor segment technique. By increasing the $\frac{dL}{d\theta}$ in the incoming phase, this technique makes the commutation transition more smooth and removes the dips in the torque profile of the motor. In contrast to other SSRMs, a stator-segmented SRM with an outer rotor has been proposed by Mousavi-Aghdam et al. (2017). The geometry of this machine allows the designer to use concentrated winding in the stator and reduce the weight of the active material. Short magnetic path and flux reverse free of its stator segments make an ideal solution for its core loss reduction.

In parallel with the SSRM, development is still ongoing for the conventional SRM structures. A major challenge of SRMs has been addressed by Kiyota et al. (2016). The acoustic noise, windage loss, and vibration associated with the salient structure of the SRM rotor have been significantly reduced by a series of ultrathin ribs connecting the adjacent poles of the rotor. Design considerations of this topology are unaligned inductance and rotor mechanical robustness. Eventually, an estimated efficiency improvement has been reported.

3 Induction Motors

Economically, efficiency improvement of electric motors is the most important factor in the performance evaluation. Reliability is also another important aspect which can be taken into account in the efficient motors. In two motors with the same insulation material class, the one with higher efficiency has lower temperature rise, which means its insulation material aging is slower. Moreover, bearings and lubricants perform better and longer when less heat is generated (de Almeida et al. 2009).

A no tooling cost solution has been introduced by Alberti et al. (2014) for efficiency improvement of IMs. It suggests that simply lengthening the active part of the motor can improve the efficiency of the motors. This argument can be stated reversely; that is, utilizing a larger motor for a lower power means that the magnetic and electric loading of the electric machine is lower than its threshold, and consequently, the machine losses will reduce. Some suggested remanufacturing of industrial IMs (Ni et al. 2016; Li et al. 2017). In the work of Li et al. (2017), synchronous reluctance rotor replacement has been reported. In the work of Ni et al. (2016), rotor of an IM has been replaced with rotor of IPM motor. By utilizing maximum efficiency per ampere control algorithm, the efficiency class has been increased from IE2 to IE4. In the work of Jang (2017), aluminum segments have been placed in the barriers of a SynR motor in order to improve the efficiency. This structure has its own downsides such as starting performance and out-of-step instability.

Most studies on IMs have been concentrated around the cast-copper rotors (Finley and Hodowanec 2001; Goss et al. 2013; Malinowski et al. 2004; Dorrell 2014; Rajkumar et al. 2017; Lin and Hwang 2016). It has been emphasized (Finley and Hodowanec 2001) that simply using a cast-copper rotor may not be satisfactory, because the rotor bar resistance is low causing the low blocked-rotor torque. A copper rotor IM has been designed for traction application (Goss et al. 2013), which is comparable with the Toyota Prius IPM motor. Generally IM has lower efficiency (even with copper-made rotor), a bigger and heavier motor, higher volt-ampere rating of the inverter, and bigger batteries that are inevitable outcomes of such a design. Therefore, such a structure is only recommended for hybrid drivetrains or in the cases where initial cost matters. The cast-copper rotors can improve the overall efficiency of IM up to 1% or 2% (Malinowski et al. 2004). This number may differ depending on the size of the motor (lower for larger motors).

The stray load loss is notably lower in low-slip operation (Dorrell 2014). So, as in Fig. 1, lower rotor resistance is desirable in terms of stray load loss; however, this affects the starting performance of the motor. It has also been reported that removal of the fins at both ends of the rotor drastically reduces the windage loss. A comparative analysis has been conducted by Rajkumar et al. (2017) regarding the material selection of the rotor bars and the end rings. The results suggest that aluminum bars and copper-end rings make the most torque-dense structures. On the other hand, IMs with copper bars (either aluminum or copper rings) have superior efficiency. A more reliable six-phase copper rotor IM has been optimized by Lin and Hwang (2016). A multiphase structure has many benefits such as improved reliability, lower torque ripple, and higher efficiency. Bottleneck of such motors is the manufacturing cost, so a compromised optimization between the mentioned advantages and manufacturing cost can be made.

One of the interesting trends in IM efficiency improvement is single-phase utilization of three-phase motors. By interchanging the winding connections and using capacitors (as phase shifters) between these connections, a three-phase

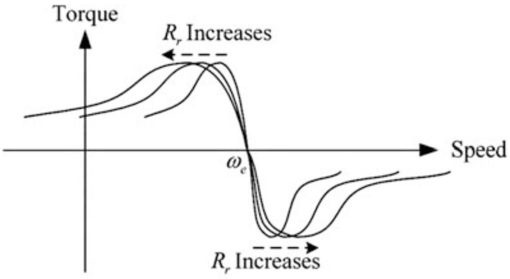


Fig. 1 Impact of increasing rotor resistance on the slip of induction motor

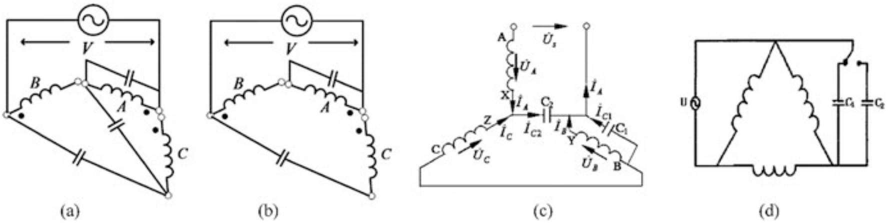


Fig. 2 Single-phase utilization of three-phase IM; (**a**) Smith connection; (**b**) SEMIHEXTH connection; (**c**) connection proposed by Wang et al. (2010); (**d**) connection proposed by Gonzalez et al. (2014)

machine can operate by a single-phase power supply (Gonzalez et al. 2014). Numerous techniques and topologies have been reported so far. Figure 2 presents a number of these configurations. There is another topology that has only two capacitors (Wang et al. 2010). As shown in Fig. 2c, three windings are in series and capacitors are connected in parallel with winding B and windings B and C, respectively. A parallel three-phase winding with two series-connected switchable capacitors can also be recommended (Gonzalez et al. 2014) (Fig. 2d). One pair of capacitors has been considered for the steady-state operation while the other one has been optimized for startup operation.

In addition to the abovementioned research trends, some studies have proposed solutions that are rather unconventional. A megawatt high-speed solid rotor IM has been designed by Zhang et al. (2017). Important feature of a solid rotor is that it enhances thermal conductivity, so the heat can be dissipated more effectively. It uses axially slitted rotor which has some advantages such as ease of penetration of the main component of the flux into the rotor and suppressing the eddy current on the rotor surface. In addition, two copper rings at two ends of the rotor provide high-current conduction paths. An interesting approach has been adopted by Zhang et al. (2014) based on the winding configuration which reduces the stray loss of the machine. Concentric low-harmonic winding and wye-delta mixed connection are the two proposed methods.

4 Permanent Magnet Synchronous Motors

Amorphous alloy (AA) stator core is the main focus in the work of Fan et al. (2014). Laminated steel can be substituted by AA. The AA must be used with care and taking into account its lower saturation level. With a proper optimization, a more compact V-shaped IPM motor has been developed compared to the original steel-laminated motor. Performance of an amorphous made SPM has been investigated by Tong et al. (2016). It has been shown that if the saturation has been taken into consideration, the efficiency can be even higher at high switching frequencies. Two prototypes have been reported by Jang (2017): one is an axial 11 kW motor developed by Hitachi that achieved 96% efficiency and the other one has been manufactured in the University of Adelaide using the water-jetting method.

Because of the intrinsic saliency of IPM motors, torque ripple reduction is a more challenging task. A set of design variables related to magnets and barriers in V-shaped IPM motors have been optimized in the work of Kim et al. (2009). As their objective functions are mostly the torque ripple, these ripples have been significantly reduced. A similar technique has been used for both increasing the torque of ferrite PM motors and reducing their torque ripples (Zhao et al. 2014a, 2015a, b, 2017a, b). Since the ferrite PMs are weak in terms of remnant flux density (B_r), their flux should be focused on air gap. The “concentrated phase-group” winding does so by attracting the flow of flux into one phase group. However, this method causes serious fluctuation in the torque profile. So, in order to minimize this cogging effect, dual-air gap structures have been suggested. Either with two stators or two rotors, they are displaced with respect to each other to alternately fill the void of no-torque areas.

Another technique has been proposed by Zhao et al. (2014b) and Zhao et al. (2015c) for low-ripple applications. In contrast to the common method of skewing, a “sinusoidal PM” shaping method has been suggested (Fig. 3). This method provides a more sinusoidal back EMF and does not have the axial force problem of the common skewing methods. It should be mentioned that since the field distribution is more sinusoidal, core loss will be reduced significantly. The ratio of pole-arc to pole-pitch, duct shape, and saliency are other parameters that have been optimized by Kim et al. (2007) for enhanced torque capability of the IPM motors. Compared to spoke-type IPMs, flared-shape IPMs (Yoon and Kwon 2016) can be a superior solution in terms of torque and demagnetization, but inferior in terms of efficiency. Since the interaction of the non-sinusoidal back EMF and sinusoidal phase current causes the torque ripple, Lee et al. (2008) have suggested that injecting a suitable set of current harmonics can improve the torque performance of the IPM motor. With a similar argument and in a similar motor, some harmonics can be injected into the “shape” of the rotor poles (Wang et al. 2014; Liu et al. 2018). While the former has done this by injecting third cosine harmonic into the rotor pole of an IPM motor, the latter has injected third and fifth harmonics into the shape of the magnets in a surfaced-mounted permanent magnet (SPM0 motor). As expected, both methods have led to a lower torque ripple.

Fractional-slot concentrated winding (FSCW) is defined as follows:

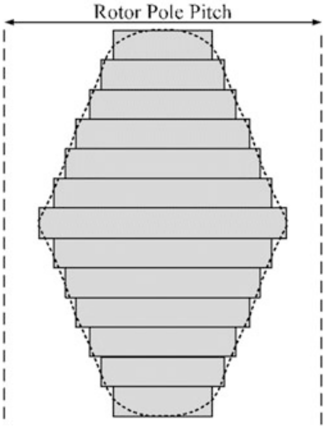


Fig. 3 PM sinusoidal shape and its sine-wave approximation

Table 2 Advantages and disadvantages of FSCW

Advantages	Disadvantages
• High slot fill factor	• High space harmonic
• Increased slot thermal conductivity	• Increased torque ripple
• Short end windings	• Increased iron loss
• Stator segmentation and ease of manufacturing	• Decreased power factor
	• Limitations on slot-pole combinations

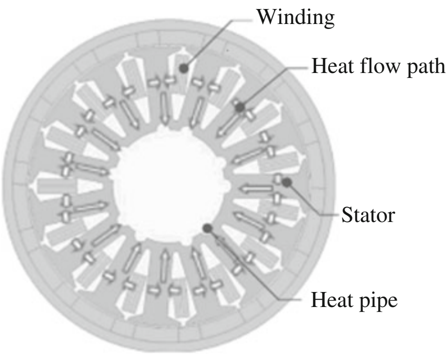
$$q = \frac{Q_s}{6p} = \frac{z}{n} = \begin{cases} \text{Fractional} \leq 1, & \text{FSCW} \\ \text{Fractional} \ > 1, & \text{FSDW} \\ \text{Positive Integer}, & \text{ISDW} \end{cases} \tag{1}$$

A comprehensive review on FSCW in SynR motors can be found in the work of Spargo et al. (2015). For the sake of brevity, positive and negative points of this winding layout have been listed in Table 2. A thorough performance analysis on FSCW motor has been conducted by Min et al. (2018). While the advantages of this winding layout such as low copper loss and improved reliability are well known, many of its performance characteristics should be calculated with FEM. Analytical expressions for the back EMF, inductance, and cogging torque have been given.

One of the most innovative ideas in PM motors has been introduced by Zhao et al. (2014c) and Zhao et al. (2017c). By using special asymmetry in rotor structures, reluctance torque and PM torque components of the proposed IPM motors reach their maximum at the same current phase angle. These topologies can be very attractive in the cases of ferrite PM or SynR motors where torque density is lower.

The aspect ratio and its effect on the efficiency of electric motors have been discussed by Tsunata et al. (2017). In motors with high aspect ratio, i.e., taller ones, conventional radial structures are satisfactory but in low-aspect-ratio structures with flatter shapes, the air gap surface is very low and end winding is a huge fraction

Fig. 4 Utilization of heat pipes according to heat flow path



of the overall length. As a result, torque density is low, and the axial flux motors are preferred. In addition, bonded magnet has been used which has high resistance leading to lower magnet eddy current loss and higher efficiency.

Thermal performance of the PM machines is an important problem (Li et al. 2016). It is clear that high efficiency and high power density are two contradicting demands. High-power motor means that either its voltage or its current should be high. Due to the limitation of bus voltage, often a higher current rating is chosen which imposes limitations on the electric motor efficiency. The heat pipes have been suggested as an efficient heat removal system. The heat exchange path and pipe location have been shown in Fig. 4.

In traction applications, especially electric vehicles (EVs), efficiency has broader meaning. There are certain conditions in this application such as direct-drive power train, operation in a wide range of loads and speeds, and short-duty capability that are not present in other applications. The following are concerned with the efficiency improvement of motors in these conditions.

Since most of the motors operate in speeds higher than their actual need of application, efficiency improvement in direct-drive applications is a challenging topic. The PM Vernier motor may be proposed for such applications (Xu et al. 2015). Comparison of FSCW and integral-slot distributed winding (ISDW) for PMV electric motors suggests that depending on the required application, winding layout varies. In terms of copper loss, fault tolerance, and reliability, FSCW is an absolute choice. On the other hand, ISDW is capable to develop a higher torque.

Electric motors used in EVs must maintain the efficiency in a wide range of speed. Performance of four kinds of SRM, IM, concentrated winding IPM, and distributed winding IPM has been compared by Yang et al. (2015). It has been shown that IM and SRM have high efficiency only when they operate in a narrow-speed region, while the operation regions of two IPM motors are much wider. An optimization scheme for “extended-speed” region has been proposed by Zhang et al. (2016) where the characteristic current (Eqs. 2 and 3) has been increased in the presented IPM motor. A proposed variable leakage flux IPM motor has been considered in the work of Kato et al. (2015). It is noted that the low-load motor needs less flux linkage, so the flux linkage of PMs can be reduced by increasing the leakage flux. This leakage flux, controlled by the stator current, flows in a shorter magnetic path, and thus produces less core losses. This ensures that the high efficiency is maintained even over low-load region:

$$I_{ch} = \frac{\lambda_{pm}}{L_d} \tag{2}$$

$$(i_d + I_{ch})^2 + \left(\frac{L_q}{L_d}\right)^2 {i_q}^2 = \frac{{V_{\max}}^2}{{L_d}^2{}_e^2} \tag{3}$$

The short-duty capability of electric motor as an important aspect of efficiency has been discussed by Deshpande et al. (2015). In some applications such as lightweight urban EVs, this is a prominent matter. The outer rotor SPM motor for in-wheel application has been analyzed and importance of heat exchanging between the copper and the stator core has been notified. The copper bars have been suggested which enhance the heat conduction.

5 Flux Switching Permanent Magnet Motors

For high-speed operation, flux switching permanent magnet (FSPM) motor is a potentially viable solution. There are certain constraints in IPM motors and FSPM motors do not have such constraints. As a general rule, mechanical and magnetic properties of IPM motors are contradicting. The bridges between the PMs should have enough thickness that maintains mechanical robustness and also they must be as thin as possible in order to minimize the leakage flux. Topology of FSPM motor has no such limitations, because both PM and armature winding have been located on the stator.

A flux weakening method can be applied to the FSPM motor (Deodhar et al. 2014). The conventional flux weakening method normally uses d-component of the current to control the flux linkage, which causes excessive copper loss. To overcome this problem a mechanical approach has been proposed by Deodhar et al. (2014). Since the motor has a flux switching structure, all active parts are located on the stator and mechanical methods are much easier to apply. The underlying principle is simple: a set of flux diverting iron segments are embedded on the outer periphery of the stator. These diverters start to get closer to the stator in high speeds and shorten the magnetic circuit.

A torque pulsation optimization can be conducted on a high-efficiency FSPM motor in in-wheel application (Fei et al. 2012). It has been mentioned that cooling procedure of FSPMs is a much simpler task since there are no active parts on the rotor. The IPM and FSPM motors have been compared by McFarland et al. (2015) and it has been shown that the latter is a better choice for low-cost magnets in terms of demagnetization. Usage of similar structures in which wound-field excitation has been adopted instead of PMs has been proposed by Nguyen et al. (2016) and Raminosoa et al. (2015). Although they have lower efficiency, the stator is more robust and flux-weakening process is enhanced. In addition, there are in-between structures (Sulaiman et al. 2011), which is a hybrid structure with both PM and wound-field excitations. These motors have the merits of both FS structures.

6 Comparison and Possible Future Applications

Considering the latest advancements in electric motors, new applications are possible for certain types of motors. There are some applications for new electric motors that were not imaginable before. Utilization of linear FSPM electric motor in transportation is one of these newly realized applications. Prior to the development of the linear FSPM electric motors, the rotating PMS motors were the only option for linear movement. In the linear PMS motor, the moving part can be either primary or secondary, but in railway traction applications none of these two options are cost effective. With the emersion of the FSPM motor, this was no longer an issue. Since both armature and excitation field are placed on the stator (primary), it is highly desirable in traction application. A comparison between the FSPM and PMS motors has been conducted by Tang et al. (2012) for in-wheel application. It has been reported that for an equal volume, the peak torque of the FSPM motor is higher than that of the PMS motor. Flux-weakening capability is also higher in the latter motor.

The structures of rotor of flux switching motor (FSM) and conventional SRM are similar, and they can be compared in terms of acoustic noise (Pollock and Brackley 2001). It has been concluded by Pollock and Brackley (2001) that under the same conditions, the noise level of FSM is about 2 dB lower than that of the SRM. However, it is noted that the SSRM as an alternative version of SRM has less noise than that of the conventional SRM. This means that now they can be used in the lightweight and urban electric vehicles, in addition to their previous applications in heavy machinery such as loaders (Jahns 2017). Another noise-sensitive application has been introduced by Pollock et al. (2003) in which FSM has been compared with an IM for driving fan. It has been observed that FSM structure is a more efficient, but noisier option.

IM is dominant in almost every application, but more efficient designs make them comparable to PM electric motors. The line-start PMSM (LSPMSM) and IM have been compared by Pollock et al. (2003). In the steady-state mode, the LSPMSM is superior in every aspect including efficiency, power factor, and full load current but in startup transients, IM develops larger torque and has a better dynamic behavior and smooth movement.

7 Conclusion

This chapter reviews the latest advancements of a variety of electric motors. Many different techniques and methods were proposed which directly or indirectly affect the efficiency of electric motors. Due to the multidisciplinary nature of the electric motors, a wide variety of fields are involved in the development of these technologies. So, these developments were reported and categorized by their origins. Based on the latest advancements of electric motors, possible future applications of a few types of motors were discussed. Furthermore, different types of motors in different applications were compared and their weaknesses and strengths were mentioned. A more in-depth study of each structure can be presented in the future.

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