Emergence of Synchronous Reluctance Motor Drive for an Electric Vehicle

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Abstract: According to recent research, synchronous reluctance motors, or SynRMs, offer innovative and promising technology. Consequently, there has been a growth in research on popular SynRMs drive systems. Recent advances in the design, modeling, and more importantly control of these motors are disseminated in this paper. Prior to moving on to SynRMs, a quick analysis of the leading motor technology is done. In order to help industries and researchers choose the best control method for motor drive systems, the most popular motor control methods are examined and categorized in the second section. In conclusion, the various speed zones of SynRM control techniques are examined, and the changes between trajectories are examined.

Keywords: Synchronous Reluctance Motor, Efficiency Map Analysis, Efficient Motor Technology, Efficient Control Strategy, Direct Torque Control

1. Introduction

Climate change and global warming are significantly impacted by industrial development. There is a great need for efficient systems because of how humans affect the environment in terms of resources. This fact also drives research into alternate advancements in the realm of electrical machinery. The need for energy efficiency has prompted research and development on substitute technologies for the manufacture of electrical motors. Manufacturers now have the chance to reduce energy consumption, use fewer rare earth minerals, and save money on materials and production processes thanks to recent advancements in motor design. A thorough examination of synchronous reluctance motors (SynRM) may be found in Rassõlkin et al.'s life cycle analysis of electrical motor-drive systems. This study demonstrates that SynRMs are efficient during the recycling phase and competitive during the consumption stage, beginning with the acquisition of resources and continuing through manufacture, transportation, and marketing. Because SynRMs, especially the permanent magnet (PM)-assisted ones (PMSynRM), are less expensive, have a comparable constant-power speed range, can produce a maximum torque per ampere, and are efficient, they are a viable option for traction and other electrical aircraft applications. Besides, the need for highly efficient motors in centrifugal machines, conveyor systems, fans and pumps, cranes, compressors, elevators, crushers, and general machine building (winders, extruders, and servo pumps) can be met by SynRM. Although almost a century has passed since the first invention of SynRMs, they have recently gained a lot of attention resulted from the emergence of the power-electronic device. In the last decade, the leading manufacturers such as SIEMENS and ABB have released their newly designed SynRM drive systems. While the line-start capability of SynRMs is provided by new designs, an additional shorted winding in the rotor can decrease the efficiency up to 10% resulting from the damping effect of the shorted rotor winding. On the other hand, variable-speed drives (VSDs) provide highly efficient motor drives, especially for operating at partial-load conditions and high-speed operation. Therefore, SynRMs are mostly applied in the industry with their drive package. From the control point of view, the research into motor control methods has experienced a boom to reach higher performance and efficiency of electric motors. This fact convinced the authors to survey the advancements in the whole SynRM drive system.

2. The Role of SYNRMS

Because of its sturdy mechanical design and low cost and maintenance needs, the mature three-phase induction motor (IM) is acknowledged as a well established and widely available structure. Unfortunately, this motor has a lot of problems because of the placement of the bars on the rotor. Rotor losses, which account for around 20% of all IM losses, can result from the rotor's naturally heated operation caused by the currents in the bars. High significant losses can cause the rotor's temperature to rise, which increases the likelihood of bearing faults which account for the majority of IM defects, per Reference. Additionally, the losses cause the motor's efficiency to decrease. Additionally, the likelihood of mechanical issues in the bars is also high in IM, which reduces this motor's dependability. One potentially troublesome aspect of IMs is their high-frequency slotting harmonics, which are infrequently mitigated through the use of skewing. The most popular structure for small and medium-sized IM motors is an aluminum die-cast rotor cage, which reduces weight and material costs. However, some manufacturers have decided to create a copper cage rotor for specific applications due to the trend toward increasing power density and efficiency. Today, permanent magnet (PM) synchronous motors (PMSMs) are the dominant technologies for many applications, including traction. High efficiency, high torque density, and desirable wide speed range performance of these motors have made the technology popular among manufacturers. PM materials are the most important elements of PMSMs. Two common applicable PM materials for PMSMs are neodymium-iron-boron (Nd-Fe-B) and samarium-cobalt (Sm-Co), both of which contain the rare-earth elements. The dramatic rise and fall of the price of the rare-earth magnets, especially Nd-Fe-B magnets, have directed the research towards rare-earth-free machines to replace high-performance PMSMs. The reliability issues in PMSM due to possible faults of the magnets are also disputable. The rotor design of SynRM distinguishes it from its IM and PMSM counterparts. In comparison with those conventional motors, SynRM attains higher reliability and easier maintenance (due to the very low winding and bearing temperature, and they also lack cage or PMs in rotor structure), lower cost (due to the lack of PMs in comparison with PMSM), faster dynamic response (due to smaller size in the same power range and lower moment of inertia), higher speed range (due to the wide constant-power operation in comparison with IM) and higher efficiency in the same power range with the same frame size (due to the cold rotor operation in comparison with IM), and higher power density and higher torque per ampere (in comparison with IM). In this sense, SynRM offers the high performance of PMSM, while it can be as cheap, simple, and service-friendly as IM. Therefore, the attention paid for these motors in high-speed applications has experienced continuous growth in the literature, which has convinced the electric vehicles (EVs) and hybrid electric vehicles (HEVs) manufacturers to apply SynRMs as an alternative for PMSM. Having said this, the possibility of the drive with the same VSDs for IM and PMSM in various recently designed VSDs has provided a viable development base for SynRM. All in all, the high efficiency of SynRMs against IM has attracted attention for applications such as pumps and fans. Also, the high performance and especially wide speed operation capability with the consideration of lack of rare-earth PMs compared to the PMSM has attracted the researchers to study these motors for traction application.

3. Characteristics of SYNRM Models

Modeling is an essential component of many studies in motor drive fields for a variety of reasons, including design, control, fault diagnosis, heat analysis, loss determination, motor parameter computation, stability analysis, and efficiency gains. When modeling SynRM, it has been important to take into account aspects such as the linearity and nonlinearity of the model, the estimation precision of the parameters, the computation time of the parameter determination, and certain factors for distinct motor operation areas. The parameter identification of SynRM is the most important subject in various modeling techniques of SynRM for various objectives. It is crucial to identify the inductances and stator resistance throughout the self-commissioning process, particularly for more precise SynRM control. The rotor's cross saturation and parameter fluctuation under various heat conditions are the main causes of this. To be more precise, these parameters are functions of currents in various axes, whereas inductances are fixed values. The parameter identification was divided into the following three groups:

1. SynRM's numerical and analytical models
2. Finding offline parameters

3. Using an inverter to identify parameters online

The finite element analysis (FEA)-based motor model is a precise and limited numerical technique. To confirm their findings, new modeling techniques are frequently compared to FEA. Regrettably, the substantial computational load imposed by FEA results in a laborious and time-consuming procedure, thus restricting the applications for online uses, including control applications. Because of this feature, the FEA is more useful for designing and optimizing various electrical machinery, including transformers. Nonetheless, the parameter values could be acquired by FEA and used as a lookup table for simulation needs, as shown in Reference. In accordance with this, the authors think that the FEA-obtained parameters might be used as a lookup table at various operation points in the control loop. References have determined a FEA-based model of SynRMs. A new rotor structure for PMSynRM is suggested in Reference using two-dimensional (2D) FEA analysis. This arrangement suggests reducing torque ripple and irreversible PM demagnetization by adding bypass ribs to the flux barriers. Based on FEA, the placement and size of the bypass ribs are examined and enhanced. The rotor configuration and field distribution of the suggested approach are depicted in Figure 1. Figure 1 shows that the bypass ribs have a very low flux density and only a small amount of the flux flows through them at the rated operation point. In summary, the bypass ribs can shield the PMs and allow some demagnetization flux to flow through.

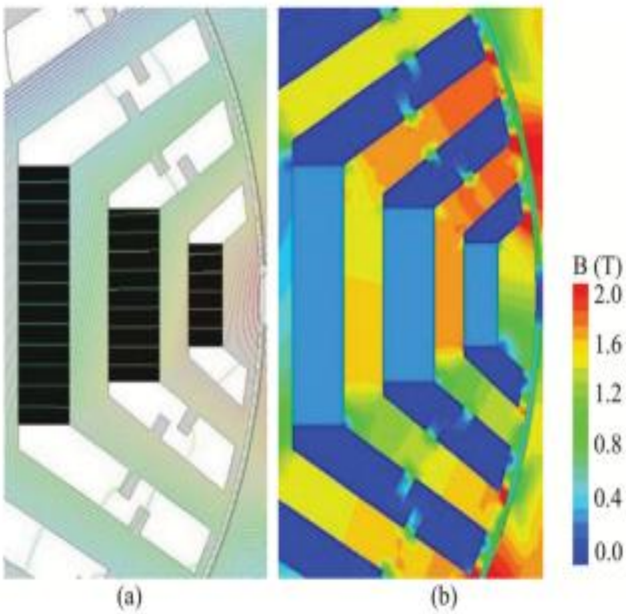

Fig 1: (a) the novel rotor structure and (b) field distribution at rated operation point

4. Current Advancements In SYNRM Control Approaches

In today's world, VSDs are used in numerous industries to precisely, robustly, and efficiently regulate electrical motors. While the expense of adopting VSDs increases, any motor technology that aims to achieve great efficiency must eventually achieve both fixed-speed and variable-speed operation. Furthermore, a reduction in energy costs can offset price variations across drive systems with identical rated powers. The possibility of further broad growth of motor drive systems in the industry in the future is supported by recent research, innovations, and the demand for increased efficiency and improved performance. These parameters need further research in several fields that fall into the following categories:

(i) Maximal motor design
(ii) maximum converter design, and
(iii) Maximum controller design.

The electric drive system's control unit is essential to the operation of the system. A high-performing control system guarantees a dependable and effective energy conversion. Typically, a control unit has the following components:

The behavior of the electric drive systems is characterized by the control algorithms. Therefore, in order to give motors a high-performance drive system, a suitable control strategy needs to be developed first. Utilizing frequency converters that are managed by microprocessors offers researchers a great deal of flexibility in terms of utilizing techniques to improve performance. Conversely, VSDs introduce a small amount of high-frequency currents into the system. As a result, some unanticipated losses happen, necessitating the need for a more exact control method on the drive side. The researchers are persuaded to conduct further research in this area because frequency converters are the primary source of power for SynRMs in industry. Researchers working on SynRM drive systems are primarily focused on improving the performance of the speed and position estimation, modifying the dynamic torque response with smooth transitions between different speed regions, and increasing robustness, suppressing torque and current ripples, decreasing losses, and improving efficiency. Even with current attempts, it is still difficult to look into better control tactics for SynRMs. Scalar and vector control methods are the categories into which control strategies for motors are typically divided. V/f control methods are the most common name for scalar control methods. These are the most widely used and straightforward control strategies for industrial VSDs.

5. The Classification Of Motor Control Methods

The classification of motor control techniques is shown in Figure 2. All of the techniques, which are more especially suited to motor control systems, are shown in this diagram as circular shapes. Below the motor control techniques are square-shaped demonstrations of the general control theories. Lastly, many aspects of the control technique are depicted in rectangular forms of varying colors at the bottom of the diagram. Each hue denotes a distinct characteristic that illustrates, in various words, the potency of each technique. Each control method's salient characteristics are shown by colored bubbles. The method's feature's significance is shown by the size of each bubble.

The approach has a more significant feature in that area the larger the bubble of each hue. The concept in this graphic can also be used to interpret the approaches' shortcomings. For example, minimal torque ripples in the motor shaft and low phase current harmonics are two of FOC's most important benefits. The FOC block displays these two benefits of the FOC approach as bubbles. Furthermore, FOC has a consistent switching frequency, as indicated in its block. However, one drawback of FOC is that, in comparison to other control strategies, it places a significant computational load on the microprocessor. For simplicity, there isn't a bubble that is the same color as the block. The text contains the abbreviations. The features of the block diagram will be covered in more detail later on. The first characteristic of control methods is their simplicity, which indicates that they place less of a computational strain on the microprocessor. Complicated mathematical computations, including proportional-integral (PI) rules, typically need a long execution time. As a result, the microprocessor becomes more expensive, which may reduce the appeal of the control method. For example, because the control loop's calculation is straightforward, scalar control is regarded as a basic control algorithm.

For this reason, scalar control may be a preferable option when searching for a straightforward control technique. The second point to talk about is low current harmonics, which is seen as a benefit of a control strategy. Harmonic currents in the motor-drive systems are derived from a variety of sources, such as the control algorithm, drive systems, and motors. Numerous studies are conducted to reduce harmonic currents, according to the literature. Some control techniques have variable switching frequencies, which raise safety problems in various applications, including electric vehicles. These systems' variable switching frequency makes switching frequency monitoring challenging for fault diagnosis.

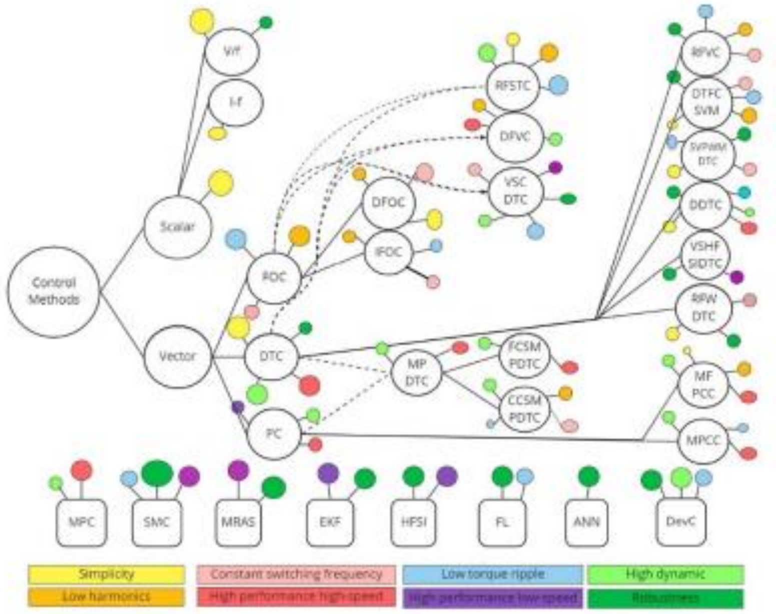

Fig 2: Motor control methods classification

(i) FOC of SynRM- The overall trend toward other approaches has not yet taken hold because of FOC's excellent steady-state performance. Researchers are still interested in FOC because of its accurate control mechanism, minimal torque ripples, and consistent switching frequency. In industries like mining and steel where improved steady-state reaction and efficiency are more important than transient response, FOC is more common. In order to establish a convenient control, this method models the motor as a DC motor and operates it in the d, q reference frame. The two major methods used to control the decoupling currents in the synchronous reference frame are direct field-oriented control (DFOC) and indirect field-oriented control (IFOC).

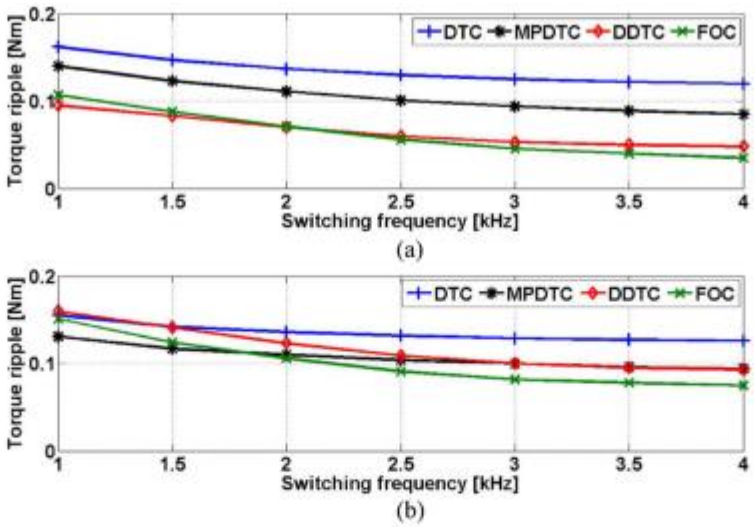

Fig 3: A comparison of torque ripples of different control methods in different switching frequencies under zero load and (a) 500 r/min, (b) 1000 r/min

(ii) DTC of SynRM- Boldea et al. conducted the first attempt to implement DTC on SynRM in 1991, and DTC of SynRM-drives is currently generating attention in the market. The literature attributes this to the intrinsic traits in the following ways:

1. Simplicity brought about by the absence of a current regulation and PWM signal generation module.
2. Quick reaction time and great dynamic brought about by direct torque control.
3. Sturdy control since motor parameter dependence is minimal.

The DTC method avoids coordinate transformation and directly controls the motor's immediate torque as well as the stator flux linkage. The switching table is a lookup table that selects a predetermined set of switching sequences based on the inputs. The stator flux, torque error indicators, and stator flux sector are the inputs used by the switching table. In DTC, stator flux and torque estimators are needed to get these inputs. In a similar manner, the stator flux position sector is computed in relation to SynRM phase.

6. Conclusion

There is no denying the necessity of motor-drive systems for both industrial and residential applications. This article demonstrated that the latest SynRMs drive package, which has the potential to be less expensive and has higher efficiency than the IM drive package, has been released to the market. Furthermore, compared to PMSM drive packages, SynRMs' drive package offers equivalent performance at a lesser cost and with a simpler, greener construction. This study looked at the potential for better modeling and design in SynRM in brief. Our analysis focused on the structures that were identified and suggested ways to improve performance, such as reducing torque ripples, increasing torque and power density, and improving the power factor of SynRM. The study demonstrates a notable improvement in motor function as well as an upward trend in research endeavors with maybe superior overall package performance. According to the literature assessment, SynRM drive systems have made significant progress toward high efficiency, low cost, and environmental considerations. The SynRM drive provides a sustainable mechanism in this regard. The analysis demonstrates an increasing tendency in the investigation of these systems' evolution. The industry is using the most recent SynRM drive packages, and these systems are expected to have much greater potential.

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