A Survey of Synchronous Reluctance Machine used in Electric Vehicle

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Abstract: Due to more environmental problems and more attentions paid on renewable energy, electric vehicle (EV) has been a hot research topic. As a key equipment in EV, various drives have been studied. Synchronous reluctance machine (SynRM) is also studied widely as a drive in EV for its advantages. This paper presents an extensive survey on the application of SynRM in EV and reviews its working principle, various structures and control strategies.

Keywords: Synchronous reluctance machine, Renewable energy, Electric vehicle, Permanent magnet assisted, Sensorless

1. Introduction

Nowadays, environmental problems such as climate change, pollutions and acid rain have been one of the most important issues in the whole world. To change the situation and pursue sustainable and better future, renewable energy (RE) is getting more and more attentions [1]. On the other hand, the emissions of greenhouse gas should be reduced while a main source of air pollution is caused by traffic. To meet the requirements of above two aspects, electric vehicle (EV, hybrid electric vehicle is also included in EV) is the best candidate. The electricity generated by renewable energy can be used by EV [2] while EV has little air pollution.

During EV's development, no matter what specific types of EV are presented, electric drive occupies an important position. The requirements for machines used in EV can be concluded as high efficiency, wide speed range, high torque density and high reliability and accepted cost [3]. From the view of application in EV, SynRM which meets most of the above requirements has been researched and tested widely as drives in EV in recent years [4-12]. [4] shows SynRM drive has almost advantages of IM in terms of cost, weight, cooling and efficiency. [5] designs a SynRM used in electric mine shuttle vehicle and states that SynRM could produce 34% more torque than the IM with 29% more current. It proves that SynRM represents serious future direction in automotive industry [6].

With more and more research attentions paid on SynRM, this paper focuses on the application of SynRM in EV. The principle of SynRM is introduced. Design and optimization of various rotor topologies and control strategies of SynRM used in EV are also reviewed.

2. Principle of SynRM

Unlike IM or DC, SynRM follows the reluctance concept which means the rotor rotates thanks to flux variation in order to fulfill the minimum reluctance path rule. The mathematical model of SynRM has been derived and analyzed by many researchers, therefore the electromagnetic torque is given directly by equation (1), and more details can be found in [6].

$$T_e = \frac{3}{2}\frac{p}{2}\left(L_d - L_q\right)I^2 \sin\left(2\theta\right) \qquad (1)$$

Where p is pole number, L_d and L_q represent inductances of d-axis and q-axis respectively, I is the stator magnetizing current RMS value and θ is current angle.

A conclusion can be made that the torque is dependent on difference of L_d and L_q for certain stator current. So a key parameter, saliency ratio, is defined as L_d/L_q. A number of performances such as power factor, efficiency, torque density and the speed range at constant power are closely related to saliency ratio [8]. To get high performance, L_d should be as large as possible while L_q should be as small as possible. All designs and optimizations of SynRM rotor topology are concerned about how to improve saliency ratio.

3. SynRM used in EV

The revival of SynRM is based on its high performance which is also important for SynRM applied in EV. This part presents researches about rotor topologies, optimization and control strategy.

3.1 Rotor topologies

According to the rotor topology types, SynRM can be classified into three main types: salient pole rotor (SP), axially laminated rotor (ALA) and transversally laminated rotor (TLA). SP rotor is now gained little attention for its structure with small saliency ratio which cannot make the SynRM compare with IM. SynRM with ALA and TLA rotor obtains close or even, in some aspects, better performance than IM. Complex structure and high manufacture cost of ALA limit its acceptability and applications in industry. Compared with ALA, TLA rotor has close performance with simpler structure and lower cost. And commercial SynRMs which apply TLA topology have come out. When it comes to drives used in EV as shown in Fig.2, the main types of SynRM are TLA topology (TLASynRM) [5-7, 10-15] and its redesigned topology namely permanent magnet assisted synchronous reluctance machine (PMaSynRM) [15-20]. TLA structure is manufactured by traditional punch processing method and the layers are connected to each other by ribs. The only difference between TLASynRM and PMaSynRM is that the latter has permanent magnets (PMs) placed in their barriers as shown in Fig.3.

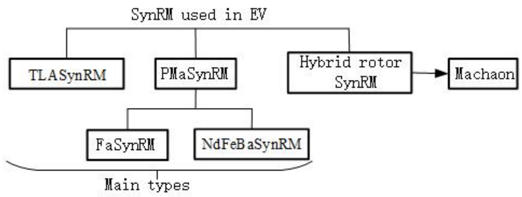

Fig.2 Classifications of SynRM used in EV

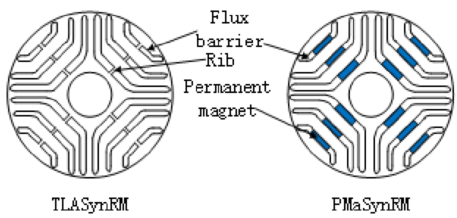

Fig.3 TLASynRM and PMaSynRM

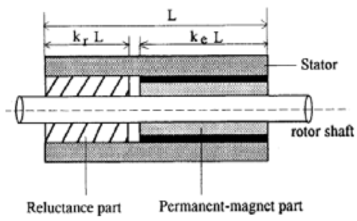

Fig.4 Hybrid motor with two-part rotor [21]

Besides, another special SynRM which has hybrid rotor is put forward for EV in [21]. As shown in Fig.4, its rotor is manufactured combined by two parts which are ALA topology and surface mounted permanent magnet. Compared with interior-permanent magnet machine, it has equivalent performance. A similar rotor structure combined with two different flux barriers parts is also studied in [22] which reduces the torque ripple. The hybrid (with two different rotor structures) type rotor has been developed into another rotor structure, Machaon, which will be presented in next section because the evolution version can be viewed as TLASynRM.

3.2 Design and Optimization of rotor

Different researchers focus on different aspects to design and optimize SynRM. And this section will introduce the design and optimization of TLASynRM rotor, from flux barriers, stator slot and ribs. The design stage is the same for PMaSynRM and TLASynRM. The main difference is that designing and optimizing PMaSynRM has to consider the material of PM and how to place PMs. So the design and optimization process of TLASynRM can be applied to PMaSynRM directly.

Flux barriers can affect the saliency ratio and performance greatly and its number and its shape should be chose carefully. When the number varies from one to three, a rotor with three flux barriers per pole generates lowest torque ripple [7, 11]. Adjusting flux barrier opening widths also succeeds in reducing torque ripple [18]. What's more, a Machaon configuration shown in Fig.5 is presented in [7]. It can be viewed as the evolution of hybrid rotor topology. Its flux barriers of adjacent poles have different shapes and are combined from two different barriers designs, what means that Machaon rotor can obtain advantages of two rotor topologies. Machaon configuration also decreases torque ripple [7]. Similarly, different tip shapes of flux barriers are also designed and studied to maximize average torque and minimize torque ripple. SynRM with full asymmetric flux barrier tips can reduce 50% torque ripples without losing average torque [23].

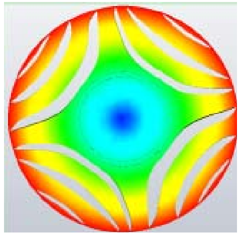

Fig.5 Machaon configuration [7]

Other parameters which also can affect the performance of TLASynRM are analyzed. In the case of stator slot, it can also affect the performance of SynRM. With more stator slot and fixed pole pair, torque ripple can be reduced significantly but when stator slot number is more than 24, the effect will became slight [11]. In the case of rib, [13] studies the performances of SynRM with various ribs dimensions and it presents combination of different rib widths in a rotor which can also improve SynRM's performance. Besides, when stator and rotor are manufactured by various steels, comparisons are implemented and SynRM whose stator and rotor are manufactured by different steels has better performance [13].

3.3 PMaSynRM

To improve performance, another effective way is to add PMs to flux barriers of SynRM. For the application in EV, PMaSynRM can meet the requirements about high performance, space and cost. The torque for a PMaSynRM can be expressed as [20]:

$$T_e = \frac{3}{2}\frac{p}{2}\left\{\left(L_d - L_q\right)I^2 \sin\left(2\theta\right) + \psi_p i_q\right\} \quad (2)$$

Where ψ_p is the flux linkage from PMs and I_q is the current of q axis.

It can be seen that PMaSynRM has two parts of torques: reluctance torque and magnet torque. More PMs can produce larger torque, but from the view of other performances, it may not be good. Effects of PMs placement on performances of PMaSynRM has been analyzed. Compared with concentrated PMs among flux barriers, average torque of distributed PMs is almost the same but torque ripple can be reduced greatly; when distributed PMs are placed along q axis, average torque can be slightly increased than that of distributed PMs along d-axis, while torque ripple will be increased significantly [24]. So distributing PMs in all flux barriers along d-axis can improve performance of PMaSynRM with lowest cost.

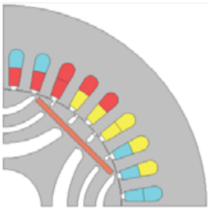

Fig.6 Rotor with PMs outside flux barriers [12]

According to the types of added permanent magnet, there are usually two different PMaSynRM shown in Fig.2: ferrite-assisted SynRM (FaSynRM) and NdFeB-assisted SynRM (NdFeBaSynRM). PMaSynRM have better performance than TLASynRM in terms of average torque, power factor, power density, torque and power changing rate, efficiency and allowable speed range; however, torque ripple is also increased and for FaSynRM, torque ripple is not added obviously [15, 20]. Instead of placing PMs among flux barriers, [12] designs another PMaSynRM topology as shown in Fig.6. The PMs are placed outside the flux barriers. This rotor structure shows good performance with higher power factor and efficiency.

EV can run at different driving cycles. An interesting research is how different driving cycles affect the design and optimization of PMaSynRM. New Europe Driving Cycle (NEDC) which is associated with suburban and highway driving and Artemis Urban which represents driving cycle with more accelerations and stop-and-go motions are considered for the design and optimization of PMaSynRM [29]. For the application in NEDC, reducing the high speed copper and iron loss should be paid more attention which results in lower split, insulation ratios and thicker tooth widths and thinner back iron. However, in the case of Artemis Urban, minimizing the copper and inverter loss at low speed region is more important which means larger split and insulation ratios and higher turn number. According to NEDC, a FaSynRM is designed for EV to maximize efficiency by finite element based tool GOT-It and a representation of energy distribution of NEDC is given for the optimization [17].

3.4 Control strategy

Control strategy is another important research aspect of SynRM. With different control objectives such as maximum torque per ampere (MTPA), maximum efficiency (ME) and maximum power factor, we can apply various control strategies. Actually, MTPA control can achieve the same goal than ME control with the same current angle of $\pi/4$ which also can conclude from expression (1). For SynRM used in EV, MTPA control is usually applied to improve efficiency. For a low power electric propulsion [6], MTPA control is used to simulate and control an analytical model of SynRM. A parameter estimator is proposed for MTPA control by considering high order harmonics equations of back EMF and eventually the controller is robust against load variation and average torque and is not affected by saturation effect [25].

Besides, SynRM is suitable to be controlled with saliency based position sensorless control (PSC) for its good saliency. However, saturation caused by adding loads decreases the inductance difference between d-axis and q-axis which can make PSC malfunction. Besides, mutual inductances between d-axis and q-axis caused by the asymmetrical saturation of rotor result in saliency shift which can make PSC works badly.

Fig.7 Epoxy-filled rotor [14]: (a) design structure (b) rotor manufactured

Saliency shift can be reduced significantly by adding the numbers of flux barriers per pole; but with increased slot opening width, saliency shift can be increased [26]. On the other hand, the author succeeds in compensating saliency shift with alternating high frequency injection PSC and arbitrary injection PSC and an equation is used to predict the saliency ratio accurately. And at near zero current magnitudes, the inductance difference is also too small to make PSC work. To improve the situation, an epoxy-filled rotor without iron ribs which has high saliency at zero reference current, as shown in Fig.7 is introduced in [14]. At zero or very low current, this rotor has large enough inductance difference for PSC and efficiency of SynRM controlled by PSC is almost same to that of SynRM controlled with position sensor. For sensorless control of PMaSynRM used in HEV, when speed is below 50rpm, an observer with fusion strategy applying signal injection is put forward in [16].

4 Conclusion

Comparisons between SynRM and other drives used in EV have proven that SynRM can be a better solution. And to meet the requirements of EV drives, further research can be undertaken from three aspects. One involves the design and optimization of rotor topology and especially optimization of asymmetrical rotor structure which could improve the performance including power converter. Another aspect is to improve PSC performance at small current and under loads. At last, future research on simultaneous designing of SynRM, power converter and innovative control, based on systemic optimization strategy will possibly get better performances of the whole system.

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