# Optimal Control of a High Speed Switched Reluctance Starter/Generator for the More/All Electric Aircraft

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**Abstract** The application background of the switched reluctance starter/generator (SR S/G) system is briefly introduced. The performance requirements of the system are presented, and then the structure and dimensions of an undergoing 30kW switched reluctance machine (SRM) are described. Based on these works, the optimal control strategies of the SRM are studied: on the starting stage of the engine, the switched reluctance machine operates as a motor, the maximization of its average torque is chosen as an optimization objective. Analytic, numerical and floating angle methods of choosing optimal exciting angles are considered respectively and compared with each other in detail. On the generating stage, the switched reluctance machine operates as a generator, the maximization of its efficiency under certain output power rating is chosen as an optimization objective, and the optimal exciting angles to minimize the main losses are obtained.

**Keywords:** More/all electric aircraft (M/A EA), integral starter/generator (IS/G), switched reluctance machine (SRM), optimal excitation, average torque, efficiency maximization.

## 1 Introduction

Many studies have indicated that more/all electric aircraft (M/A EA) technology is the future development trend of the aerospace industry [1], and integral engine starter/generator (IS/G) is a key subsystem of this novel technology [2]. Among kinds of machines that can be used as an IS/G in M/A EA, the switched reluctance starter/generator (SR S/G) is considered as a prime candidate technology to meet the requirements and constraints well. In Refs.[3-4], the design, implementation and test validation of switched reluctance starter/generator system for aircraft engine application are presented.

Because of the special mechanical construction and operating mechanism, control strategies of the switched reluctance machine(SRM) are very complicated and different from the control concepts of the traditional motors. Especially, the characteristics of the motor are sensitive to the firing angles, such as motor efficiency, average torque and torque ripple. How to determine the desired firing angles for optimum operation is a burning problem. In Refs.[5-6], the correct balance between the criteria of high efficiency and low torque ripple is reached based on the optimal control of turn-on and turn-off angles. The problem of choosing the firing angles to maximize the average torque within two control schemes for switched reluctance motor, based on 'current control' and 'voltage control', respectively, is examined in Ref.[7]. A new and machine-independent method to minimize the energy consumption of a speed controlled switched reluctance motor is proposed in Ref.[8]. In Refs.[9-11], the excitation angles are optimized to produce the required electric power with the highest efficiency.

In this paper, when the switched reluctance machine operates as a motor, the maximization of its average torque is chosen as a primary objective to cut down starting duration, when the switched reluctance

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machine operates as a generator, the maximization of its efficiency is chosen as a primary objective to increase its power density and reduce its energy consumption, thereby simplify the structure of its cooling system.

The organization of the paper is as follows: in Section 2, the performance requirements of the undergoing SRS/G system are described. The structure and dimensions of the SRM are described in Section 3. The optimal control strategies on starting and generating stages are presented in Section 4 and 5. Finally, conclusions are drawn in Section 6.

## 2 Performance requirements of the system

The designed SR S/G system is a 270V DC system that performs two primary functions. The first function (0～27 000r/min) is to start a gas turbine engine with at least 15N • m torque using an available source of 270VDC power. The second function (27 000～50 000r/min) is to extract power from the gas turbine engine to generate 30kW 270VDC. Both the starting requirement and generating requirement are summarized by the torque speed curve in Fig.1. It should be noted that the SR S/G is connected to the aircraft engine through a step-down gearbox. The SRM turns at a higher speed than the aircraft engine.

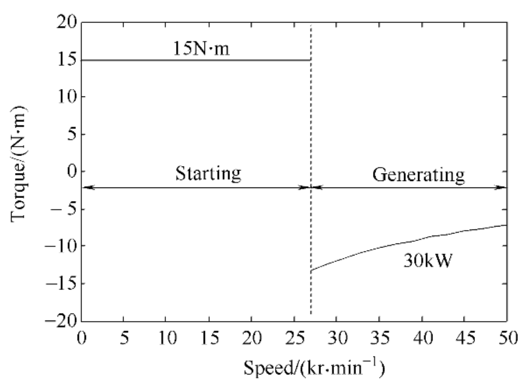


Fig.1　Performance requirements indicated by torque speed curve

The abscissa in Fig.1 represents the shaft speed of the SRM, it is three times as fast as that of the engine. By the way, the SRM speed 27 000r/min and 50 000r/min correspond to the flight idle and maximum speed of the aircraft engine respectively.

## 3 Structure and dimensions of the SRM

Based on the performance requirements above, the SRM can be designed by the method proposed by Miller[12]. In aircrafts, noise of the electrical drives is not a problem due to the noisy turbine. Hence, the three-phase 6/4-pole SRM is adopted to get relatively lower switching frequency, and consequently lower switching power losses. It has six stator poles and four rotor poles. Fig.2 shows the cross-sectional view and dimensions of the machine. All the dimensions are in millimeters. The materials of the laminations and shaft are M270-35A and Mild Steel respectively. This machine is designed to be cooled by water, and the shaded areas in Fig.2 are channels for the water.

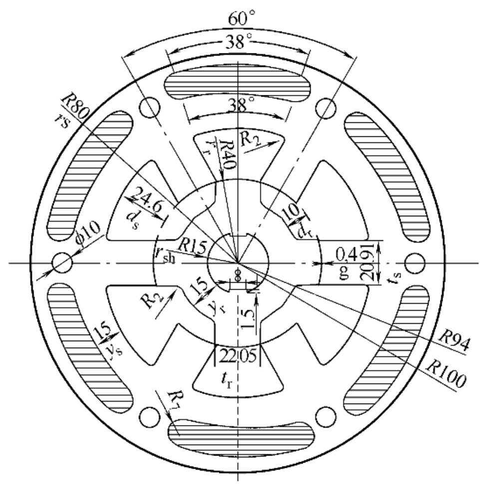


Fig.2　Cross section of machine electromagnetic topology

## 4 Optimal control on starting stage

On starting stage, the maximization of the average torque is chosen as an optimization objective to cut down the starting period. What’s more, a wider torque-speed envelope and faster transient response will be obtained as well.

On starting stage, current chooping control is adopted. The phase current is kept to a reasonable reference value (in this paper, the reference current is 260A), so the turn-on and turn-off angles are controllable parameters to obtain optimal performance. It has long been known that for high performance, the SRM should be operated with variable commutation angles. In this paper, three methods are concerned to maximize the average torque.

The first method is proposed by Gribble in Ref. [7], it's based on the different influences of the turn-on and turn-off angles on the average torque. Simple and explicit equations for calculating the optimal turn-on and turn-off angles can be obtained. In this paper, this method is called analytical optimization method (AOM).

The second method is based on the simulation via PC-SRD[13] and Matlab. The optimal values of turn-on and turn-off angles under each speed can be obtained numerically. During actual operation, these optimal values are stored in a look-up table in EPROM for low cost and quick response. In this paper, this method is called numerical optimization method (NOM).

The third method called floating angle optimization method (FAOM)[8] is based on the results of NOM. Both turn-on and turn-off angles follow a first order function of speed determined by the optimum turn-on and turn-off angles at low and high speed obtained by NOM.

### 4.1 Analytical optimization method (AOM)

The average torque of the SRM is related to its turn-on and turn-off angles. Fig.3 shows the variation of the average torque as a function of turn-on angle with the turn-off angle fixed (on starting stage, the unaligned position is considered as the starting point for counting the angles). It can be seen that the average torque curve is almost flat and the turn-on angle which maximizes the average torque is not well defined. Fig.4 shows the curve of the average torque versus the turn-off angle with the turn-on angle fixed. In contrast to Fig.3, the maximum average torque can be well defined (marked by circle).

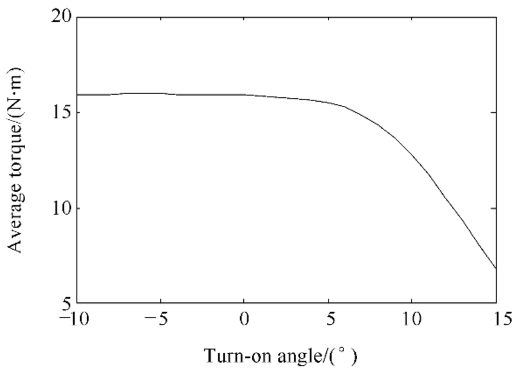


Fig.3 Variation of average torque versus turn-on angle

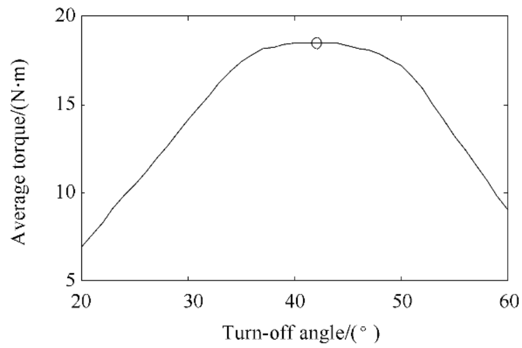


Fig.4 Variation of average torque versus turn-off angle

This property also can be proved by Eq.(1) derived from the quasi-linear model of the SRM.

$$T_{av}=\frac{mN_rU_{dc}^2}{2\pi\omega_r^2}\left[-\frac{1}{2}\frac{(\theta_{off}-\theta_1)^2}{L_{max}-L_{min}}+\frac{(\theta_{off}-\theta_1)(\theta_1-\theta_{on})}{L_{min}}\right] \quad (1)$$

where $T_{av}$——The average torque;

$m$——The number of motor phase;

$N_r$——The number of rotor poles;

$U_{dc}$——The applied source voltage;

$\omega_r$——Angular velocity of the rotor;

$\theta_{on}$——The turn-on angle;

$\theta_{off}$——The turn-off angle;

$\theta_1$——The starting angle of the phase inductance increasing;

$L_{max}$——Aligned position inductance;

$L_{min}$——The unaligned position inductance.

From Eq.(1), it can be seen that if turn-on angle is fixed, average torque follows a quadratic function of turn-off angle, and the coefficient of the quadratic term is negative, so this function has its maximum value. In other words, a turn-off angle can be found to maximize the average torque.

According to the simulations and analysis above, the contributions of the turn-on and turn-off processes to the average torque are independent, and can be optimized separately. In Ref.[7], the turn-off angle is chosen to maximize the average torque, and the turn-on angle is chosen to assure the high efficiency. Eq.(2) and Eq.(3) show the equations for calculating optimal turn-on and turn-off angles respectively. The details of their derivations can be found in Ref.[7].

$$\theta_{on} = \theta_1 - \frac{L_{min} i_{ref} \omega_r}{U_{dc}} \tag{2}$$

$$\theta_{off} = \frac{360}{2N_r} - \frac{\frac{360}{2N_r} - \theta_1}{2}\left(-\frac{R_a}{R_{ua}} + \sqrt{\left(\frac{R_a}{R_{ua}}\right)^2 + 4\left(\frac{i_{ref}\left(\sqrt{2}-1\right)\omega_r}{\sqrt{2} R_{ua} U_{dc}\left(\frac{360}{2N_r} - \theta_1\right)}\right)}\right) \tag{3}$$

where　$i_{ref}$——The reference current.

$R_{ua}$ can be obtained by Eq.(4).

$$R_{ua}=R_u-R_a \tag{4}$$

where　$R_u$, $R_a$ ——Reciprocals of the aligned and unaligned position inductances respectively.

The simulation results show that AOM can enhance the average torque obviously, especially at low and moderate speeds.

### 4.2　Numerical optimization method (NOM)

This method is based on the simulation via PC-SRD and Matlab. Under each operating speed, the average torque of valid combinations of excitation angles are obtained and compared with each other to find the optimal one that generates the biggest average torque.

Fig.5 shows the flow chart of this method. After simulation, the optimal turn-on angle, turn-off angle and the maximum torque will be stored in $\theta_{on}^{opt}$ , $\theta_{off}^{opt}$ and $T^{opt}$ respectively. The function named "Do PC-SRD simulation" in Fig.5 is implemented by PC-SRD, while other works are done by Matlab.

The simulation results indicate that the speed of NOM is very fast. It can enhance the average torque both at low and high speed, a wider torque-speed envelope can be obtained. However, in practical applications, it would require an extensive look up table to store the optimal excitation angles, this will be memory consuming and the programming difficulty will be increased. What's more, due to the differences between the actual system and the motor model and changes in system parameters during the operation, it's very difficult to achieve the desired output under open loop conditions prescribed by a static look up table. To avoid these disadvantages, a method named floating angle optimization method (FAOM) can be adopted.

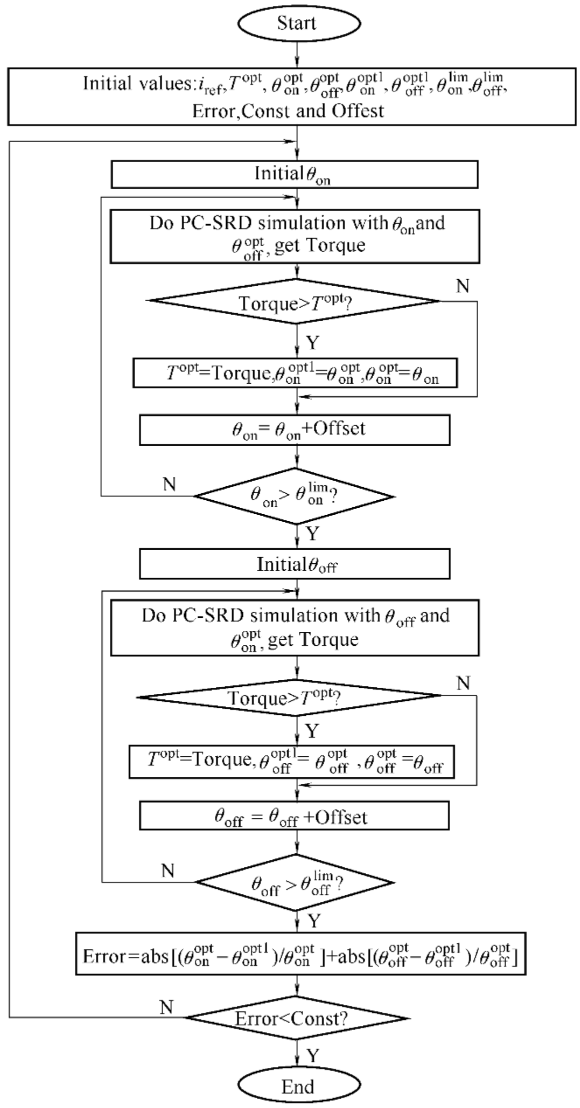


Fig.5　Flow chart of NOM

### 4.3　Floating angle optimization method (FAOM)

Fig.6 shows the optimal commutation angles versus operating speed obtained by NOM above. It can be found that the relationship between the angles and the speed is nearly linear. Hence, in FAOM, the optimum turn-on and turn-off angles are represented as first order functions of speed as follows:

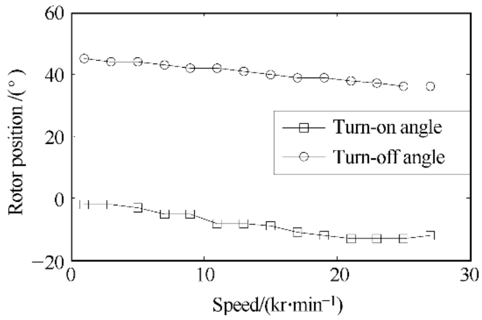


Fig.6 Optimal exciting angles obtained by NOM

$n \leqslant 3000$r/min: $\theta_{on}=-2°$

$n > 3000$r/min: $\theta_{on}=-2°-n\times10°/24\,000$

$n \leqslant 5000$r/min: $\theta_{off}=44°$

$n > 5000$r/min: $\theta_{off}=44°-n\times8°/22\,000$

where $n$ is the rotational speed.

According to Ref.[8], FAOM also can be explained by the fact that a minimum conduction angle is necessary to obtain maximum torque. At low speed, these firing angles are adequate. For speeds exceeding 3000r/min, the affection of back-EMF can't be neglected, so the turn-on angle is adjusted to maintain full torque capability. The turn-off angle is fixed below 5000r/min and adjusted for higher speed to avoid producing negative torque.

The simulation results demonstrate that the performance of FAOM is as good as that of NOM.

### 4.4 Performance comparisions

Fig.7 shows the optimal average torque versus the operating speed obtained by AOM, NOM and FAOM respectively. The average torque before optimization is shown as well, where both the turn-on and turn-off angles are fixed. The comparisons among above three optimal methods are given as follows.

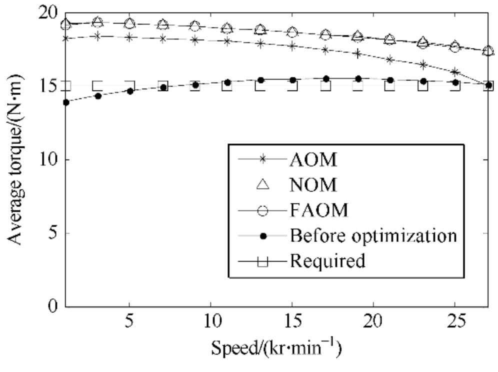


Fig.7 Average torque comparision

The performance of AOM is the worst, especially at higher speed, the reasons are as follows:

(1) Eq.(2) is obtained by assuming that the stator winding resistance is negligible and the phase inductance between $\theta_u$ and $\theta_1$ is constant. However, the inductance between $\theta_u$ and $\theta_1$ varies due to the firing effect of stator and rotor pole corners actually; this will affect the optimal turn-on angles. Therefore, to receive better optimal turn-on angles, firing effect and stator winding resistance should be considered.

(2) In AOM, the optimal turn-off angles are derived on the condition of flat-topped currents, but this condition will be lost at higher speeds. This is why the performance of AOM is much worse at higher speeds.

(3) The turn-off angle obtained by AOM is not the best one to a certain turn-on angle calculated by Eq.(2).

Fig.8 and Fig.9 compare the optimal turn-off angles obtained by AOM and NOM at 1000r/min and 25 000r/min. The turn-on angles are fixed at the optimal values obtained by corresponding optimal method.

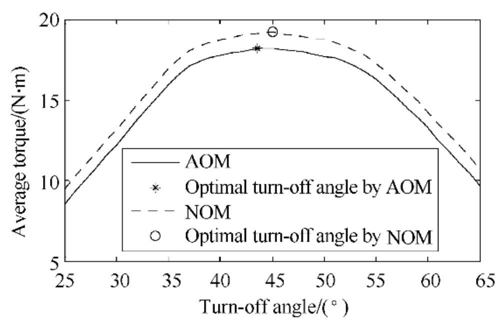


Fig.8 Comparison of optimal turn-off angles at 1000r/min

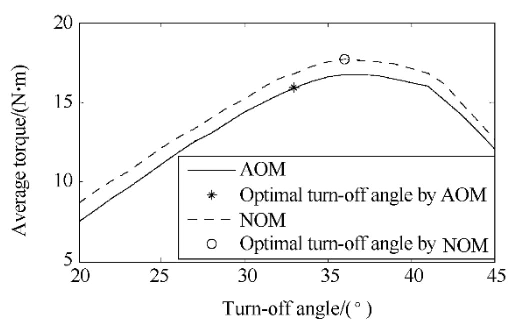


Fig.9 Comparison of optimal turn-off angles at 25 000r/min

It can be seen that the average torque of AOM is smaller than that obtained by NOM because of the firing effect on optimal turn-on angles. The optimal turn-off angles obtained by AOM are not the best one, especially at higher speed.

But AOM also has many advantages. It doesn't need extensive simulations and a large memory. It's easy to program. What's more important, the universality of AOM is high. It can be conveniently used to other situations and motors only by adjusting some of the parameters in the equations, and these parameters are easy to get.

The performance of NOM is the best one. It can find the global optimum turn-off angles. However, it needs extensive simulations and large memory space, the programming is relatively difficult. Furthermore, compared with AOM, the applicability of NOM is worse. If it's used to a new situation, all the exciting angles need to be optimized once again.

The performance of FAOM is almost the same as that of NOM and its programming is very easy. In addition, achieved by experimental observations, the functions in FAOM will only be an initial guess and can easily be machine and load-independent [8].

According to the comparisions above, it can be summarised that AOM can be used to some low speed applications, NOM will be a reasonable choice to some applications that require very high performance and FAOM can be seen as a tradeoff between the performance and the practicability, it can be used in almost all of the applications well.

## 5 Optimal control on generating stage

In this paper, the designed SRM operates as a generator above 27 000r/min. Because the operating speed is very high, the SRG operates in single-pulse control mode. The turn-on and turn-off angles are the only control parameters that can be used to optimize the power conversion.

The SRG performance can be optimized using different criteria that depend on the limitations and the type of applications. In Ref.[14], the optimization is adopted to maximise the output power with constant voltage.

In this paper, the control objective is to produce the required output power with maximum efficiency. Compared with starting stage the optimal control of SRG is more difficult. On starting stage, the optimization is more straightforward because only the turn-on angle dictates the peak phase current, the turn-on and turn-off angles can be optimized separately. For the SRG, both turn-on and turn-off angles contribute to peak phase current, consequently, the output power.

As we know that the main losses of a SRM are copper and iron losses. The copper losses depend on the rms stator phase current.

$$P_{cu} = mI_{rms}^2 R \tag{5}$$

Fig.10 shows the relationship between the rms phase current and the output power, each point corresponds to a valid combination of turn-on and turn-off angles. It's clear that, to a certain output power, there are many angle combinations with different rms phase currents can be selected.

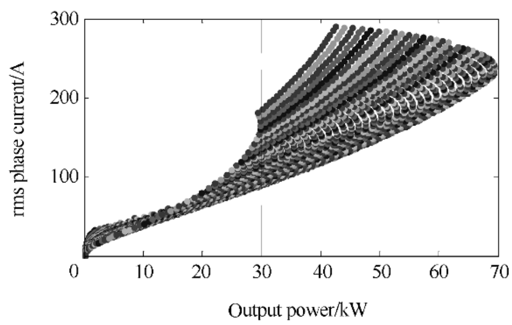


Fig.10　rms phase current versus output power

In some applications, especially at low speed, the copper losses are the major part of the main losses. So the exciting angles with the minimum rms phase currents are chosen among those that produce the same output power to reduce the copper losses and consequently obtain the maximum efficiency.

However, in this paper, the designed SRM operates at very high speed on generating stage. The iron losses become the major part of the main losses because of the high stroke frequency.

Fig.11 shows the copper losses, iron losses, main losses and efficiency versus turn-on angle at 30 000r/min with fixed turn-off angle (on generating stage, the aligned position is considered as the starting point for counting the angles). It can be seen that the iron losses are much bigger than copper losses, the iron losses are reduced and the copper losses are increased along with the increase of turn-on angle. The main losses have a minimum value where the efficiency gets its maximum value. So the optimal exciting angles should be the one with minimum main losses (marked by an arrow) rather than the one with minimum copper losses (rms phase current). This method is called as minimum main losses method (MMLM).

Fig.12～Fig.14 show the optimization results with MMLM, including the optimal turn-on and turn-off angles, the input shaft torque, the efficiency and the output power versus the operating speed. The desired output power is 30kW and the dc-link voltage is fixed at 270V.

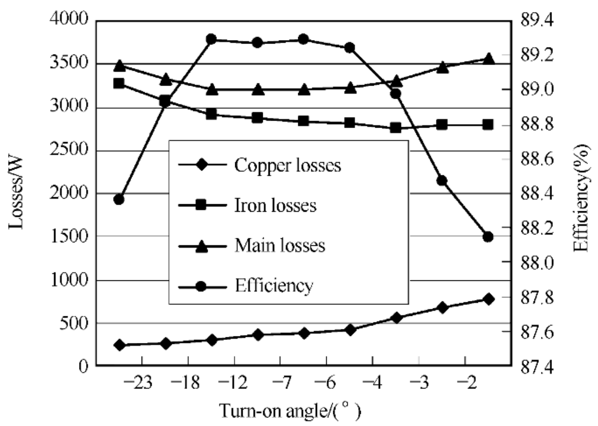


Fig.11 Losses, efficiency versus turn-on angle

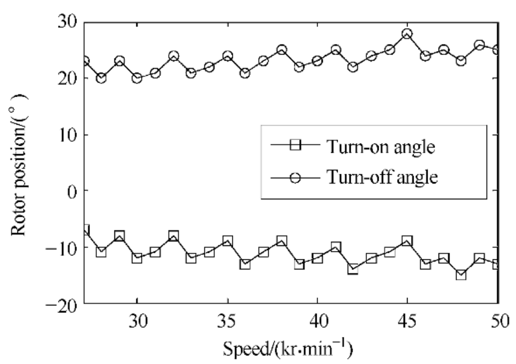


Fig.12 Optimal exciting angles obtained by MMLM

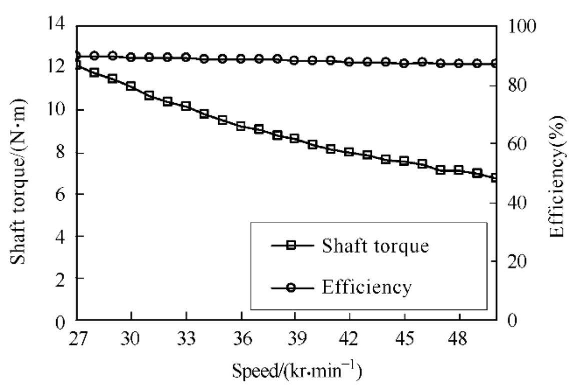


Fig.13 Shaft torque and efficiency versus speed

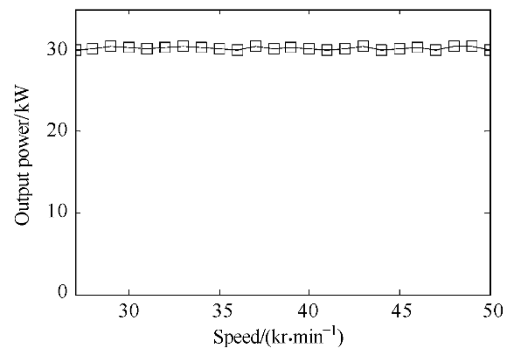


Fig.14 Output power versus speed

The output of the SRG tends to be open-loop unstable. This can be avoided by the application of closed-loop control rather than a look-up table. For instance, it is possible to find a function based on the turn-off angle data in Fig.12 to calculate the turn-off angles online, and the turn-on angle can be obtained by the closed-loop control on output power [9, 10].

According to Ref.[11], the theory of MMLM can be explained in other ways. Fig.15 shows the energy conversion loops of three different cases, and $\theta_{on}$=−11° is the optimal turn-on angle. It can be seen that as the turn-on angle decreases, peak phase flux-linkage and also saturation level increase while peak phase current decreases, high iron loss is attained. On the other hand, when the turn-on angle increases, iron loss is reduced. However, peak phase current is increased and consequently the copper loss is increased. Optimal efficiency operation is obtained at a best balance between iron and copper losses. Furthermore, because the energy conversion area corresponds to the consumed electromagnetic energy and electrical output power is constant, the minimum energy conversion area corresponds to maximum efficiency. By calculation, in Fig.15, the area enclosed by the conversion loop of the optimal turn-on angle is the smallest, so it possesses the maximum efficiency.

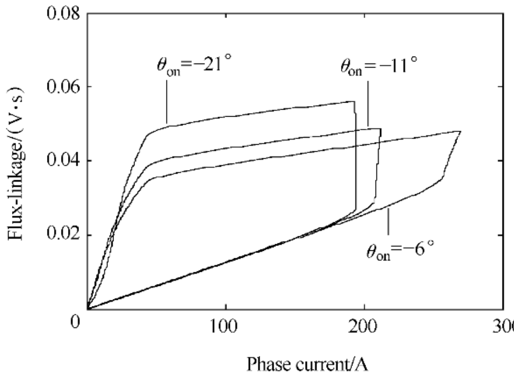


Fig.15　Energy conversion loops of SRG with different turn-on angles

According to the analysis above, the ratio between the average dc-link current $I_{DC}$ and input shaft torque $T_{sh}$ is proportional to efficiency, so it can be used as a guide to optimize the efficiency.

$$R_a = \frac{I_{DC}}{T_{sh}} \quad (6)$$

Fig.16 shows the relationship between $R_a$ and the efficiency.

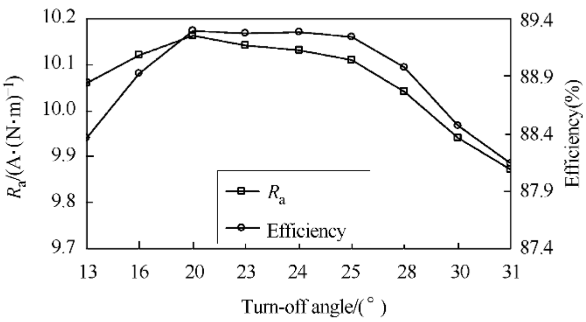


Fig.16　Relationship between $R_a$ and the efficiency

## 6　Conclusion

In this paper, the optimal control of a SRM used in aircraft as a starter/generator is considered. The optimization is researched on starting and generating stages, respectively.

On starting stage, the maximization of the average output torque is chosen as an optimization objective. Three methods are studied respectively and compared with each other. Simulation and analysis results indicate that all these methods can enhance the average output torque significantly, but they have their own advantages and disadvantages and can be used in different situations. AOM can be used to some low speed applications, NOM will be a reasonable choice to some applications that require very high performance and FAOM can be seen as a tradeoff between performance and practicability.

On generating stage, the maximization of the efficiency under certain output power is chosen as an optimization objective. Because the rotational speed of the system is very high, the iron losses become the major part of the main losses. According to this feature, an optimal method named MMLM is presented. The simulation results prove that this method can reduce the main losses significantly, and the efficiency of the system can be kept high.

M/AEA technology is the future development trend of the aerospace industry, and the SR S/G system is a prefered subsystem to implement this novel concept. This paper has certain theoretic value and practical meaning for optimal control of SR S/G system.

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**Brief notes:**Song Shoujun male, born in 1981, PhD student. His currently research interests include switched reluctance machine, starter/generator system used in airplane and car, motor design and optimal control, non-linear modeling and simulation, thermal analysis of the electrical system.Liu Weiguo male, born in 1960, professor PhD supervisor. His research interests include motion control, electrical servo-control, motor control technology research and application.

# 多/全电飞机用高速开关磁阻起动 /发电机优化控制

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**摘要** 介绍了开关磁阻起动/发电（SR S/G）系统的应用背景，对系统的性能要求进行了描述，并给出了一台 30kW 开关磁阻电机（SRM）的定、转子叠片结构及尺寸。基于以上工作，对 SRM 的优化控制方法进行了研究：在起动阶段，SRM 运行在电动状态，以平均转矩最大化作为优化目标，对包括解析、数值及浮角在内的三种优化控制方法进行了深入的研究，并对它们的优化结果进行了详细的比较及分析；在发电阶段，SRM 运行在发电状态，以特定输出功率下的系统效率最大化作为优化目标，得到了使主功率损耗最小的优化励磁角。

**关键词：**多/全电飞机（M/A EA） 集成起动/发电机（IS/G） 开关磁阻电机（SRM） 优化励磁 平均转矩 效率最大化

**中图分类号：** TM352