An Improved Control Strategy for Switched Reluctance Generator System in More Electric Aircraft

Ganeish Velmurugan, Seang Shen Yeoh, Tao Yang, Serhiy Bozhko
Department of Electrical and Electronic Engineering, University of Nottingham, UK
ganeish.velmurugan@nottingham.ac.uk

***Abstract*—Switched Reluctance Machines (SRM) has emerged as an important possible technology for usage in More Electric Aircraft (MEA) in particular as a starter/generator. As a starter/generator, the SRM operates as a generator as well as a motor (starter). This paper focuses on SRM operation as a generator. The SRM was found to have limitations when handling heavy loads while operating in generation mode. This would not be desirable in aircraft operation where electrical loads are ever increasing. An improved control strategy is proposed in this paper to address the issue of SRM with load handling in generation mode. A custom designed specific 45kW 6/4 SRM was used in this study while designing the controller The performance of the proposed controller in handling heavy load in aircrafts are validated through simulation.**

Keywords—Switched Reluctance Generator, More Electric Aircraft, SRG Control

I. Introduction

The development towards MEA has significantly changed the power system sources in aircraft. Conventional aircraft has seen usages of mainly pneumatic and hydraulic based power systems, followed by electrical and mechanical sources. With the MEA, more aircraft subsystems are being consolidated in being powered through electrical based power systems. This led to the rising demand in electrical power usage for new aircraft, and more studies in efficient and reliable electrical power generation systems on-board aircraft.

A key technology in the development towards MEA is the starter/generator system. The starter/generator technology can be a variable frequency drive system that is essential in providing Main Engine Start (MES) in starter mode, and supplying power to other aircraft electrical loads in generator mode. The starter/generators can be connected directly to the main engine, effectively eliminating the need for constant frequency gearbox and thus increasing the overall aircraft reliability [1]. These requirements therefore provide design challenges for the electrical machine to be able to handle high operating temperatures and wide speed range [2].

Switched Reluctance Machine (SRM) has been considered as a potential starter/generator for the MEA. The idea was first proposed in [3] and followed by further evaluation studies in [4]. Despite being one of the earliest machine topologies, the SRM did not get much attention due to the lack of development in power electronics [5]. It was only in the 20th century, with advent development in power electronic technology which allowed variable speed operation of SRM that the SRM has been getting more research attention for many applications including usage in aircraft as a starter/generator.

One of the inherent advantages of SRM is its very simple structure with windings concentrated only around its salient stator poles, while the rotor structure is a passive salient pole without any permanent magnets or windings. Fig. 1 illustrates a 3-phase 45kW 6/4 SRM used in this paper.

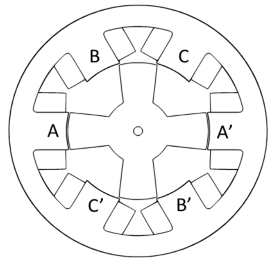

Fig. 1 Geometrical structure of a 3-phase 45kW 6/4 SRM

The SRM is able to operate in harsh environments where machines such as permanent magnet based machines are subjected to de-magnetization and performance degradation especially when operating in high temperature environment [6]. The machine phases of the SRM are magnetically and electrically independent which makes it highly fault tolerant. These properties of the SRM makes it an attractive candidate for potential usage in MEA which requires high reliability operation in harsh conditions [7].

SRM can be operated in motoring (starting) or in generation mode. The operation of the SRM in generation mode, also commonly referred to as Switched Reluctance Generator (SRG), is studied in this paper. Whilst SRGs has not been as widely investigated as much as its usage in motoring mode, a few publications are present. In [8], the power control design for variable-speed wind energy applications has been reported. SRG has also been considered for automotive application other than aircraft applications with potential usages in hybrid electric vehicles. This has been reported in [9, 10]. Studies done on SRG in [3] and [4] has investigated usage of SRG in aircraft and highlighted the need for robust control design especially in dealing with electrical loads.

In this paper, an improved control system with real time switching of firing angles for load handling in aircraft application is proposed. A 3-phase 45 kW 6/4 (6 stator pole, 4 rotor pole) SRG designed to be an aircraft starter/generator by [11] was used as part of the generator system. The paper is organized as follows: Section II lists fundamental information on SRG. In Section III, the SRG generic control system is presented along with discussions on its control limitations. The proposed modification to the control scheme in order to address the problem with the SRG system is then presented in Section IV. Finally, in Section V the simulation results for the proposed control system are presented.

II. Basic SRM Fundamentals

The difference between motoring mode and generation mode can be illustrated via the power flow of the drive system. As seen in Fig. 2, motoring mode electrical power is converted to mechanical power with total power is transferred to from the power converter to drive the machine. While in generation mode, mechanical power is converted to electrical power output with total power being extracted by the power converter from the machine. This is possible with a bi-directional power converter.

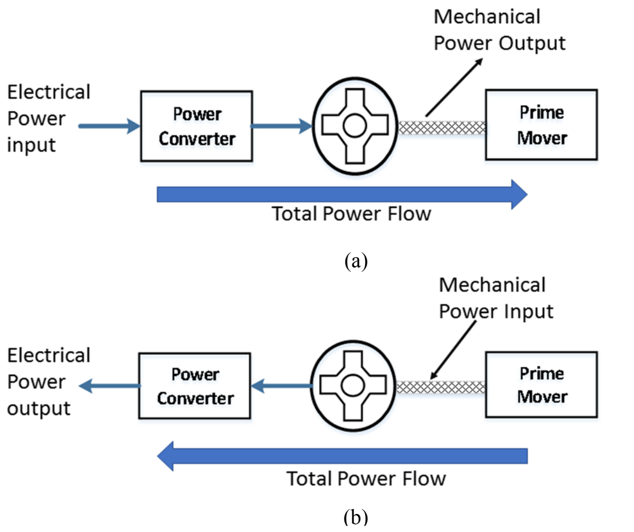

Fig. 2 Power conversion in (a) Motoring mode (b) Generation mode

To understand the torque production in SRG, the electromagnetic behavior must first be understood. The electromagnetic properties of a specific SRG used are obtained through either experimental measurement or through Finite Element Analysis (FEA) tools. Fig. 3 shows the electromagnetic characteristic for the SRM used in this paper.

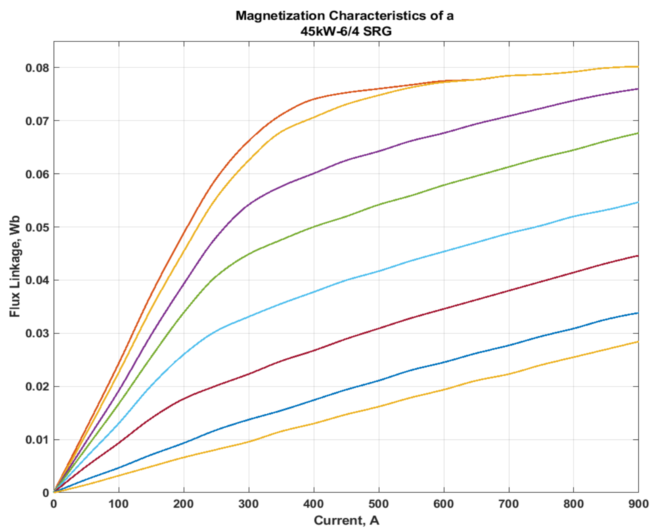

Fig. 3 Magnetization Characteristic of 45kW 6/4 SRG

The magnetization characteristic describes flux linkage behavior to the rotor angle position of machine for different current operating region. Electromagnetic torque produced in SRG is expressed in terms of magnetic co-energy, W_c as:

$$T = \left. \frac{\partial W_C(\theta,i)}{\partial \theta} \right|_{i=cons} \tag{1}$$

The magnetic co-energy, W_c can be found from Fig 3 and is defined as,

$$W_C(\theta,i) = \int_0^i \lambda(\theta,i)\, di \tag{2}$$

Where λ is the flux linkage defined as:

$$\lambda(\theta,i) = L(\theta,i)\, i \tag{3}$$

L is the phase inductance which varies with rotor position and phase current. Replacing Eq (2) and (3) into, (1) the electromagnetic torque, T is then formulated as,

$$T \cong \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \tag{4}$$

According to Eq (4), T produced does not depend on the direction of the current however, the positioning of the phase current with respect to inductance determines the mode of operation of the SRM. In generation mode operation, torque produced are negative which implies the torque is trying to oppose the rotation, hence extracting energy from the machine [12]. The current excitation to the rotor position determines if the machine operates in motoring or generation mode. This control of the current excitation is the fundamental part of the SRM control system.

III. CONTROL SYSTEM

The SRM control system depends on three parameters: reference parameter, turn-on angle, θ_{on} and turn-off angle, θ_{off}. Structure of the general SRM system is illustrated in Fig. 4

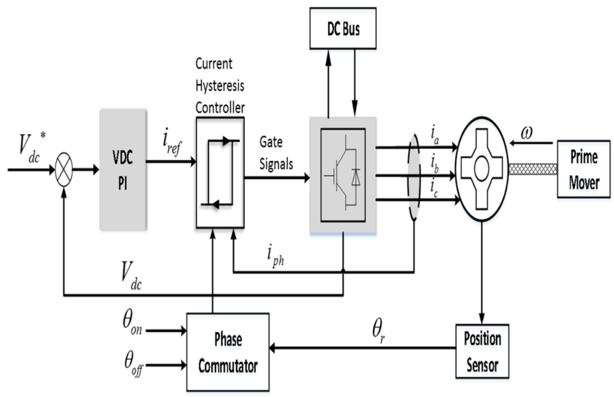

Fig. 4 A generic structure of SRG Drive System for aircraft application

Current hysteresis control are used in SRM drive to limit the torque ripple at lower speed at a pre-determined hysteresis window of, Δi. A PI-based controller is designed to regulate the DC bus voltage, Vdc. For aircraft application, the Vdc reference is maintained at 270 Vdc. The turn-on/off angle selection determines the current excitation based on the position of the rotor which then changes the operation mode of the SRM. Fig. 5 shows current excitation at different rotor position to idealized inductance behavior.

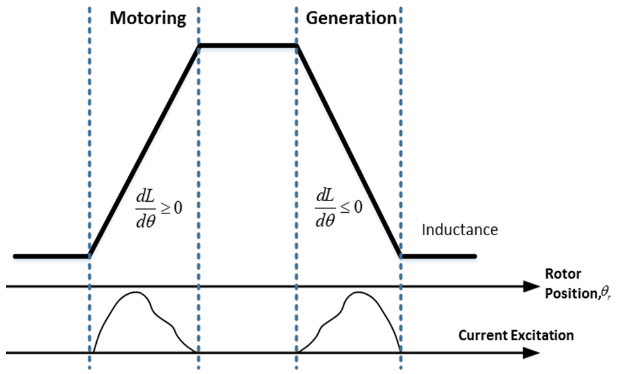

Fig. 5 Current Excitation in reference to idealized inductance behavior

For generation mode operation, the turn-on/off angle is selected at region where, $\partial L/\partial\theta$ has a negative slope. For a specific design of SRM, the torque profile can be calculated using Eq (4) and the magnetic characteristic profile as seen in Fig. 3. Torque profile for the SRM used is shown in Fig. 6. The calculated torque profile has a sinusoidal like behavior. At the range of rotor position where torque profile has negative values, the machine will be able to operate in generation mode. Selecting the appropriate turn-on/off angle at this range in the SRM drive system will then limit the SRM machines operation as a generator. As the power converters used in the SRM drive system are bi-directional, it does not require any reconfiguration for operation in generation or motoring. By merely selecting the appropriate turn-on/off angle, SRM drive can be used in either generation or motoring mode.

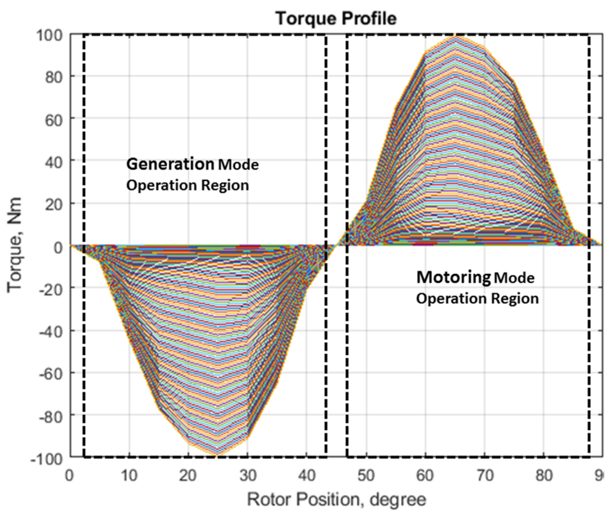

Fig. 6 Torque profile calculated using Eq.(4) and using magnetic properties from Fig. 3

A. Load Handling Limitations

The bus voltage regulation standards for aircraft usages has been established in MIL-STD-704 and DO-160 [13]. The standard requires DC bus voltage is maintained at 270 Vdc for large aircraft when loads are connected or disconnected from the bus voltage. With the MEA, there are significantly larger loads being connected to the aircraft's electric system. As such, power generation in the aircraft requires a stable and robust control system to maintain the power usages in the aircraft.

The generic SRM system shown in Fig. 4 is not able to robustly maintain the DC bus at a steady voltage especially in handling heavy electrical loads that could be used in aircraft. The turn-on/off angle has been chosen for the SRM to operate in the negative torque region so that the machine operates in generation mode. The simulation result in Fig. 7 shows the DC bus voltage behaviour during load impact and dispatch. A 15 kW load was connected at t=0.1s and at this point, the DC bus voltage is still well controlled at 270V. However, when the load is disconnected from the bus at t=0.2s, the DC bus voltage becomes unstable as the SRG controller fails.

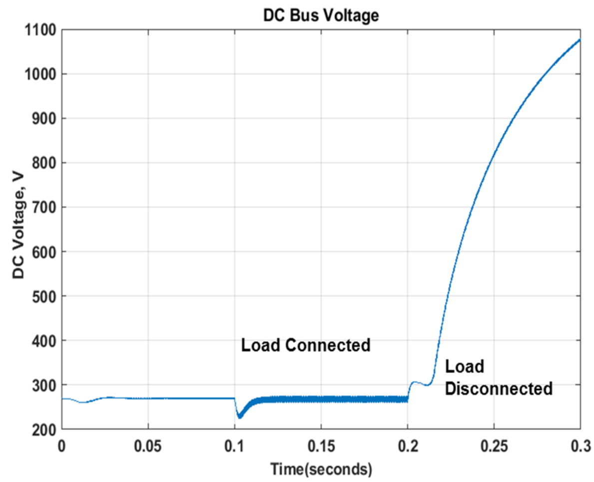

Fig. 7 DC Bus voltage failure when handling load

This can be explained as when the load is connected to the DC bus, more power gets supplied to the now connected load. However when the load is disconnected from the DC bus, the excess power has to be delivered back to the converter to ensure constant DC bus voltage. The SRG system is unable to do so due to the selection of turn-on/off angle being fixed to the operation region where torque is negative as shown in Fig. 6. Such problems would be undesirable for the SRG to be used in aircraft power systems. Hence, an improved control scheme is proposed to handle the problem with load.

IV. Proposed Control System

The proposed controller design is shown in Fig. 8 The proposed control scheme consists addition of PI controller with an angle switching algorithm. The current hysteresis control is similar to the generic control scheme. Additionally, an algorithm is designed to switch the turn-on/off angle when the PI controller detects load being connected or being disconnected from the DC bus. Changing the turn-on/off angle changes the nature of the power flow of the SRG drive system while ensuring a stable DC bus voltage in the event of significant load changes. This is necessary to handle the load handling problem that is highlighted in Fig 7.

A. Angle Switching Algorithm Design

The turn-on/off angle operation region is selected based on the region of torque behavior for motoring and generation as in Fig. 6. The logic behind the switching output of the turn-on/off angle, $SW(\theta)$ can be mathematically expressed as:

$$SW(\theta)=\begin{cases} 0<\theta_r<45, & Y(s)\geq 0 \\ 0<\theta_r<45, & Y(s)=0 \\ 45<\theta_r<90, & Y(s)\leq 0 \end{cases} \tag{5}$$

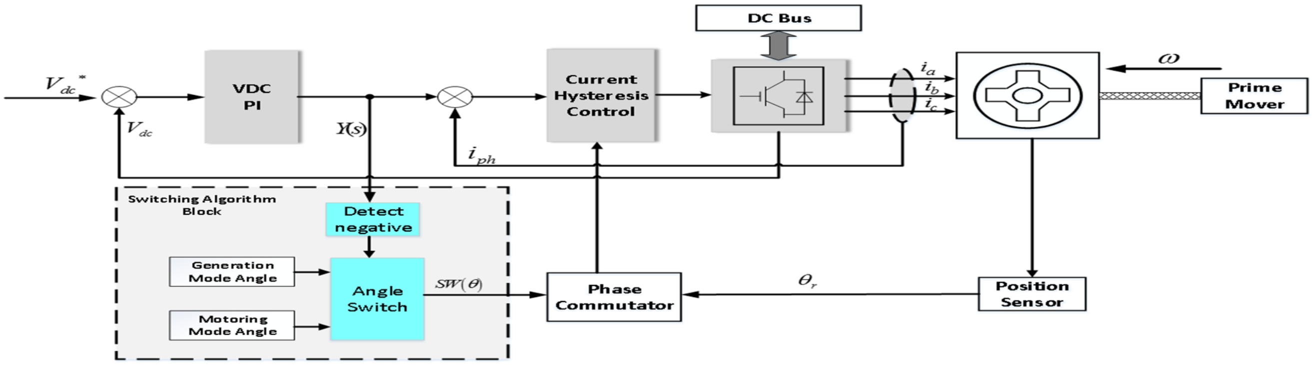

Fig. 8 Proposed improved controlled system solution for SRG load handling

where Y(s) is the output of the PI controller, SW(θ) is the output of the algorithm, and θ_r is the rotor position range to be used with the rest of the control system.

The algorithm used in designing the switching of the turn-on/off angles are illustrated in Fig. 9

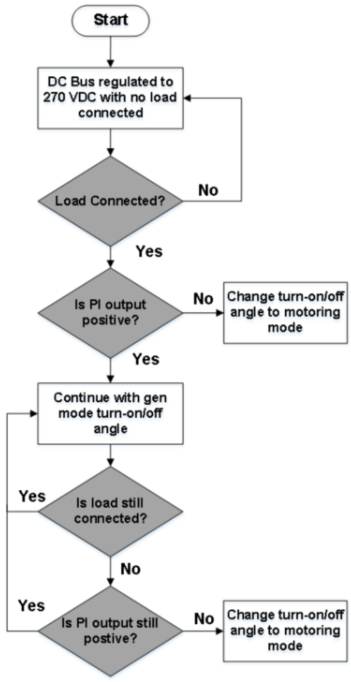

Fig. 9 Angle Switching Algorithm

The angle switching algorithm is designed to detect whether load is connected to the DC bus. Load detection is done by performing a check of the PI output, $Y(s)$. If the output, $Y(s) < 0$ load is detected as being disconnected from the DC bus. At this point, the power needs to be transferred back to the machine where the machine will need to switch operation mode to motoring mode. The algorithm then shifts the turn-on/off angle to operate the machine in motoring mode. Inversely, if PI controller output is $Y(s) \geq 0$ the machine will remain in generation mode operation. This simple algorithm allows the controller to flexibly manipulate the turn-on/off angle of the current excitation to maintain a stable DC bus voltage.

B. PI Controller Design

The PI controller was designed for generation mode operation based on [14]. Using similar PI design principle, the controller values for the plant function, $H(s)$ as defined below was determined

$$H(s) = \frac{1}{Cs} \tag{6}$$

Where C is the capacitance value of the DC bus defined in Appendix. The controller constant values of proportional term, k_p and integral term, k_i were then calculated for a bandwidth of 20 Hz.

V. Simulation Results

The proposed controller was modelled and implemented in Matlab Simulink. Model parameters used are described in the Appendix. The SRG model in this simulation is a specific 3-phase 45kW 6/4 machine as mentioned earlier in this paper. As the model differs from a generic Simulink model, an analytical SRG model was derived using the magnetization characteristic of the machine as depicted in Fig. 3 and using the electromagnetic equation described in Section II.

A. No-Load Simulation

To test the ability of the PI controller to regulate the Vdc bus, simulation was done without any load being applied. Vdc reference was set to 270 Vdc and simulation was done at constant speed operation at 15000 rpm.

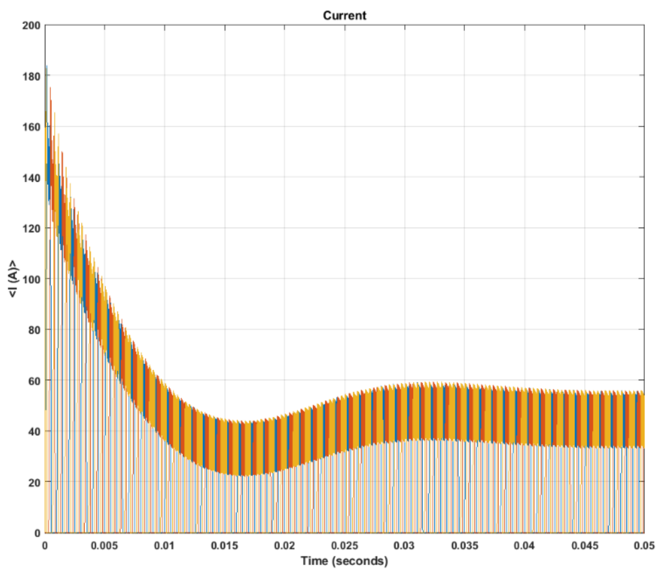

Fig. 10 Current behavior at stator with no load applied

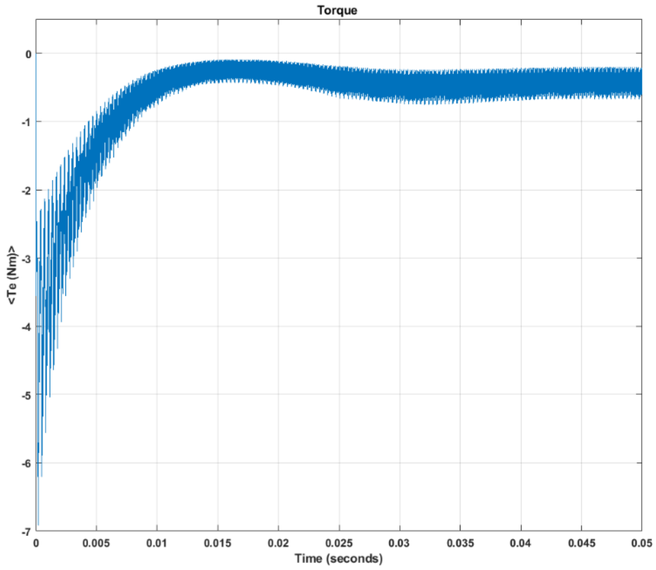

Fig. 11 Torque behavior with no load applied

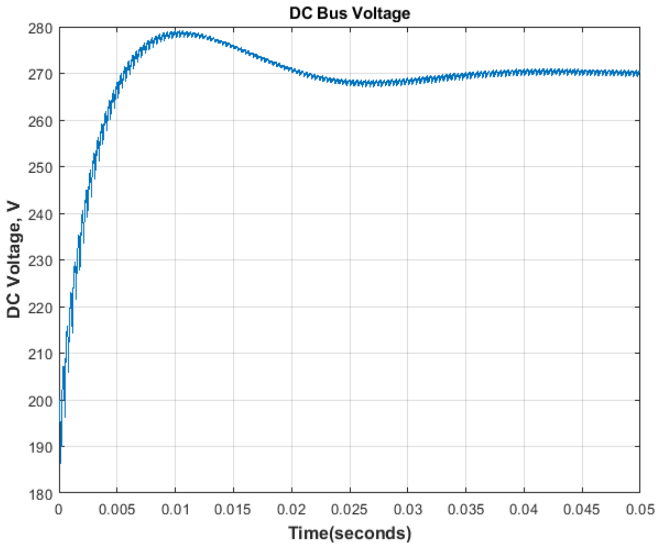

Fig. 12 DC Bus voltage with no load applied

Fig. 10, 11 and 12 shows simulation results of SRG behavior with no load being applied. As observed from the results, PI controller is able to regulate the voltage at DC bus to 270 VDC. The transient time is measured to be about 0.035s with an overshoot of 10V. These are within the operation range specified in MIL-STD-704. Also observed from these results are the torque behavior which are in the negative value range which conforms the SRG drive operating principles in generation mode as explained in Section III. Next, simulation was done to test the robustness of the proposed controller system with load handling.

B. Load Switching Simulation

In this simulation scenario, the proposed controller is tested with load handling. At t=0.1s, load was connected and then disconnected from the DC bus at t=0.2s. A load of 15 kW was applied in the simulation.

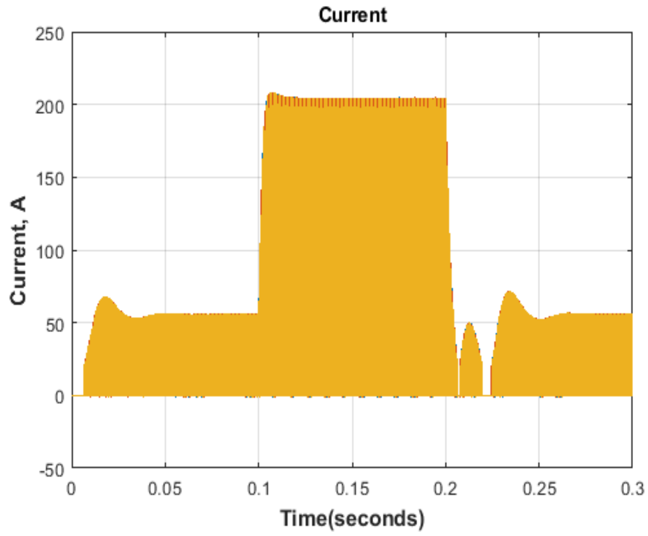

Fig. 13 Current behavior when load is applied (t=0.1s) and disconnected (t=0.2s)

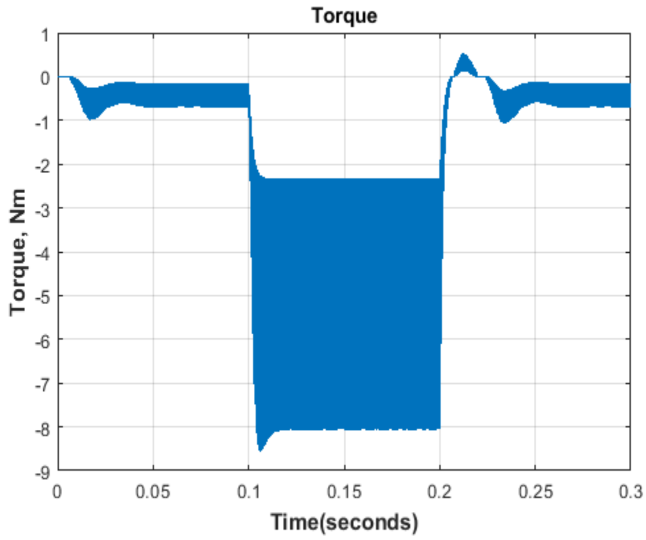

Fig. 14 Torque behavior when load is applied (t=0.1s) and disconnected (t=0.2s)

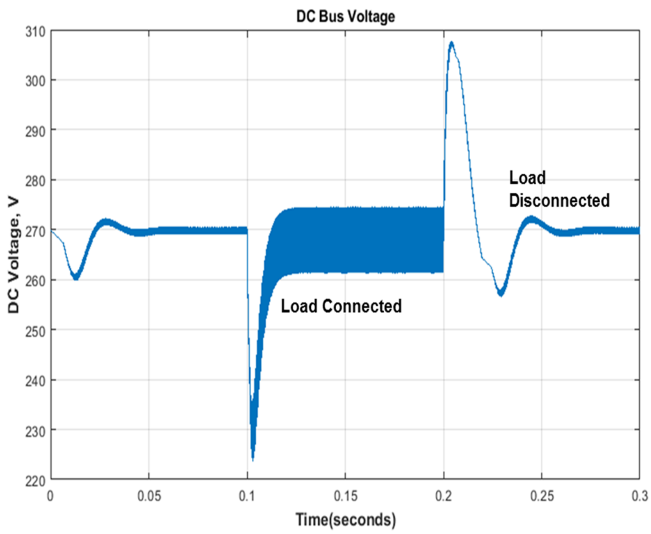

Fig. 15 DC Bus voltage with load applied at t=0.1s and disconnected at t=0.2s.

From simulation results, it can be observed that the proposed controller is able to handle load switching to the DC bus rather smoothly. Fig. 15 shows the DC bus voltage behavior. When load is connected, the current required from the drive system sees a huge increase as seen in Fig. 13. The increase in current is required to provide the necessary power demanded by the connected load. Generated torque at this point also sees a huge increment. Torque behavior is still in the negative region when load is connected indicating generation mode operation.

When the load is disconnected at t=0.2s, the current is seen falling again as the power demand now falls. Unlike the behavior seen in Fig. 7 from Section III, with the proposed controller the DC bus is able to be regulated to a steady 270 Vdc when load switching happens. This proves the angle switching algorithm implemented in the controller works as expected to balance the power transfer SRG when load is disconnected by switching the turn-on/turn-off angle. The switching algorithm can be seen operating at t=0.2s when load is disconnected from Fig. 15. For a short period after load is disconnected, the torque increases to positive torque indicating machine operation being switched to motoring mode to transfer the power back to the machine stabilizing the DC bus when load is disconnected. Torque ripple minimization was not studied as part of this paper, hence high torque ripple is seen especially when load is connected.

VI. Conclusion

In this paper, a new improved control strategy for load handling using SRG machines in MEA is presented. The improved control system consists of a flexible switching algorithm which switches the turn-on/off angle to maintain a stable DC bus during load switching in aircrafts. The proposed controller was proven to be functioning well through simulation. With the proposed controller, it is possible for SRG being a viable solution for on-board aircraft power generation. A major problem with SRG is the undesirable high torque ripple which worsens when load is applied. This is not currently addressed in this paper and will be the focus for subsequent work to be carried out in the near future.

Appendix

Machine Parameters:

Machine Parameter			
Intertia, kgm^2	***Resistance, ohm***	***Viscous Damping, Nm.s***	***Capacitance,F***
0.01532	0.00178	1.8x10-3	1x10-3

Control Parameters:

Control Parameters				
Hysteresis Window	***Turn-On Angle***		***Turn-off Angle***	
	Motoring	***Generation***	***Motoring***	***Generation***
± 10	***45***	***5***	***90***	***45***

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