<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Proportional-resonant controlled NPC converter for more-electric-aircraft starter-generator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Dehghani Tafti, Hossein; Maswood, Ali Iftekhar; Lim, Ziyou; Ooi, Gabriel Heo Peng; Raj, Pinkymol Harikrishna</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2015</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/38524">http://hdl.handle.net/10220/38524</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: [<a href="http://dx.doi.org/10.1109/PEDS.2015.7203443">http://dx.doi.org/10.1109/PEDS.2015.7203443</a>].</td>
</tr>
</tbody>
</table>
Proportional-Resonant Controlled NPC Converter for More-Electric-Aircraft Starter-Generator

Hossein Dehghani Tafti¹, Student Member, IEEE, Ali I. Maswood², Senior Member, IEEE, Ziyou Lim³, Student Member, IEEE, Gabriel H. P. Ooi⁴, Member, IEEE and Pinkymol Harikrishna Raj⁵, Student Member, IEEE.
¹, ², ⁴School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
³Energy Research Institute @ NTU (ERI@N), Interdisciplinary Graduate School, Nanyang Technological University, Singapore
Email: ¹hossein002@e.ntu.edu.sg, ²eamaswood@ntu.edu.sg

Abstract— More electric aircraft (MEA) technology is achieved by exchanging various mechanical and pneumatic elements of a conventional aircraft with their equivalent electrical devices in order to increase the reliability and decrease the maintenance. This paper proposes a proportional resonant (PR) controller together with the adaptive space vector modulation (ASVM) technique for the more electric aircraft (MEA) starter-generator neutral-point clamped (NPC) converter. The proposed controller is implemented in the stationary (αβ) frame where the calculated reference voltages of the PR controller can be directly fed into the ASVM. Hence, the main objectives of the proposed controller are to reduce the computational complexity and the steady state error by decreasing the required number of framework transformations units. On top of that, the ASVM technique provides a proper DC-link capacitor voltage balancing with improved output power quality. The dynamic performance of the proposed controller is evaluated under both initial starting interval and generating mode.

Index Terms— More electric aircraft, starter-generator, NPC converter, proportional resonant control, adaptive space vector modulation.

I. INTRODUCTION

Improving reliability and reducing maintenance costs are the most important trends in the more electric aircraft (MEA). Some mechanical and pneumatic parts in the MEA are now replaced with electrical tools to remarkably decrease the overall weight, the fuel cost as well as the environmental impacts. Many concerns are given to the power generation, transmission, fault diagnosis and reliability of the MEA. Hence, stringent regulations are required for the MEA electric power system. Starter-generator is the key element in the MEA system which is used for starting the main gas engine as well as generating electricity during flight [1], [2].

The permanent magnet synchronous machine (PMSM) has higher efficiency, power density and reliability as compared to both induction and switched reluctance machines, thus PMSM is used in various aerospace applications [3]-[5]. The converter topology connected between the PMSM and the MEA DC-bus must be a bidirectional configuration which can operate as an inverter during the starting mode to power up the PMSM and a rectifier during the generation mode to deliver electricity to the DC-bus. The classical two-level voltage source inverter (2L-VSI) is popularly applied in various aerospace applications due to its low cost and simple design. However, multiple set of 2L-VSC must be parallel-connected in order to transfer large amount of power from the starter-generator. Therefore, it is not a promising solution for the MEA. Multilevel converters in this case can provide higher power and better efficiencies with lower switching frequencies operation. Apart from that, multilevel converters positively influence the entire system such as reducing machine losses, mechanic torque ripples and electromagnetic interference filter volume [6]-[9]. The three-level neutral-point clamped (NPC) converter can perform higher reliability and power density when compared to the three-level flying capacitor converter, thus the 3L-NPC is considered in this paper for the MEA starter-generator system [10].

In the design consideration for the MEA electrical system, the NPC converter must be capable of performing three different operation modes on the PMSM: speed-control, torque-control and DC-bus voltage control. These three different controllers are applied in the outer loop and each time only one output is fed into the inner loop controller depending on that particular operating mode. Since the inner loop current control implemented is same for all operation modes, it should provide a faster dynamic performance [11].

Even though the proportional integral (PI) controller is well-known for its easy implementation, but it has some drawbacks like requiring multiple framework transformation and high computational complexity. Thus, this paper proposes a proportional resonant (PR) controller together with the adaptive space vector modulation (ASVM) technique to control the NPC converter. The main objectives of introducing PR controller for the MEA system are to reduce the computational complexity and steady state error of the control while the ASVM generates the switching signals for the NPC converter to provide a balanced DC-link capacitor voltages. Hence, the MEA system with the proposed control achieves better steady-state operation with the performance evaluated under various MEA starter-
generator operation modes.

The following section provides a comprehensive explanation on the proposed MEA system structure. Section III presents the mechanical behavior of the MEA in different operation modes and electrical model of the PMSM, followed by a detailed explanation of the proposed PR controller in conjunction with the ASVM technique. Both dynamic and steady state evaluation results are given in section IV in order to prove the applicability of the proposed method. Lastly, section V concludes the paper by highlighting the important features of the proposed controlled structure.

II. PROPOSED MEA SYSTEM STRUCTURE

The comprehensive structure of the proposed starter-generator converter is depicted in Fig. 1 which consists of PMSM, gas engine dynamic mechanical model, NPC converter and DC-loads. In this paper, the mechanical dynamic model introduced in [11] is considered to simulate the gas engine mechanical behavior. The NPC converter is constructed with two pairs of IGBT switches (Sa1 and Sa2) including their complementary (Sa3 and Sa4) and a series connected capacitors C1 and C2 in the DC-link.

There are different operation modes (on/off) for the switches FSa1, FSa2 and FSa3. During the motoring mode (speed-control and torque-control), FSa1 must be closed and FSa2 opened so that the DC-source can be connected to the DC-bus to power up the PMSM. Meanwhile during the generation mode, FSa1 will be open and FSa2 closed to allow the NPC converter to deliver power to the DC-load1. In order to investigate the dynamic performance of the proposed controller under DC-load change condition, the FSa1 is used for connecting the additional DC-load2 to the NPC converter.

III. MEA PROPOSED CONTROL STRATEGY

The operation of the gas engine depends on the compressed air produced inside the engine during its rotation, thus the gas engine does not have the self-start capability. Hence, the PMSM is required to start the engine. Consequently there are various operation modes for starting the engine as well as generating the electricity from PMSM which are described with the proposed controller in the following subsections.

A. MEA Operating Modes

Three different operation modes given in the following are considered for controlling the MEA gas engine in this study.

\[
\text{Op. Mode} = \begin{cases} 
\text{Speed Cont. (S.C)} & \omega_e < 300 \text{ rad/s} \\
\text{Torque Cont. (T.C)} & 300 \text{ rad/s} \leq \omega_e < 628 \text{ rad/s} \\
\text{DC-bus Voltage Cont. (V.C)} & 628 \text{ rad/s} \leq \omega_e 
\end{cases}
\]  

(1)

where \(\omega_e\) is the PMSM rotor speed (rad/s).

During the start-up interval, the gas engine is not able to produce the mechanical torque. Thus, it requires the mechanical energy generated from the PMSM to start the engine. During this interval, the NPC inverter is operated using the speed-control (S.C) on the PMSM (S.C = 1).

When the speed reaches the ignition speed (\(\omega_e = 300 \text{ rad/s}\)), the gas engine starts to produce mechanical energy and assists the PMSM to increase the engine speed further more. During the ignition mode, both of the PMSM and gas engine generate mechanical energy together. The gas engine will produce higher mechanical torque values with the increased speed. Therefore, the produced PMSM mechanical torque can be decreased during this moment. In order to control the produced torque from the PMSM, the NPC inverter will be operating using the torque-control (T.C) during this ignition period (T.C = 1).

After a while, when the rotor speed reaches the engine base speed (\(\omega_e = 628 \text{ rad/s}\)), the gas engine can produce the mechanical energy independently and the PMSM can start to generate and supply the electricity to the DC-bus. Subsequently, the control mode is also changed to the DC-bus voltage control (V.C) where the NPC converter operates as a rectifier assuming that the speed of the gas engine is independent of the DC-loads.
and remained equal to the base speed during the generation interval (V.C = 1).

Fig. 2 depicts the assistance and the resistance mechanical torques of the gas engine during the starting transient [12]. As mentioned previously, the PMSM is controlled in S.C. mode to increase the speed of the engine before reaches 300 rad/s. During this period, the engine has resist torque which is linearly increased following the speed. After reaching \( \omega_0 = 300 \) rad/s, the gas engine starts injecting the gas fuel into the compressed air inside the engine. From this speed point onwards, the PMSM is operating at T.C. so that the gas engine cannot produce assist torque until its speed reaches around 400 rad/s. After this moment, it can be seen in the figure that the engine starts producing the assist torque. Thus, the generated mechanical torque of the PMSM can now be reduced. After reaching \( \omega_0 = 500 \) rad/s, the required acceleration torque for increasing the engine speed is now decreased. As a result, both the PMSM and the gas engine produce smaller mechanical torque.

### B. PMSM Model

The voltage equations of the PMSM in the synchronous reference frame can be presented by the following equation [13]:

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} =
\begin{bmatrix}
R_s + pL_d & -\omega L_q \\
\omega L_d & R_s + pL_q
\end{bmatrix}
\begin{bmatrix}
I_d \\
I_q
\end{bmatrix} +
\begin{bmatrix}
0 \\
\omega_0 \phi_f
\end{bmatrix}
\]

where

- \( V_d / V_q \) : d-axis and q-axis voltages (V)
- \( I_d / I_q \) : d-axis and q-axis currents (A)
- \( R_s \) : Stator resistance (Ω)
- \( L_d / L_q \) : Equivalent d-axis and q-axis inductors (H)
- \( p \) : Derivative operator
- \( \phi_f \) : Permanent magnet flux linkage (Wb)

According to the above expression (2), the developed torque can be derived as:

\[
T_c = \frac{3n_p \phi_f}{2} \left[ \tilde{I}_q + (L_d - L_q) \tilde{I}_d \tilde{I}_q \right]
\]

where \( n_p \) is the number of pole pairs. It can be seen that in the round PMSM, the \( L_d \) is equal to \( L_q \). As such, the mechanical torque only depends on the q-axis current of the motor.

Additionally, the mechanical dynamic behavior of the motor is expressed in the following (4).

\[
T_c = \frac{J}{n_p} \omega_0^2 + B \omega_0 + T_L
\]

where

- \( J \) : Moment of inertia (kg.m²)
- \( B \) : Viscosity coefficient (N.s/m²)
- \( T_L \) : Load mechanical torque (Ω)

As mentioned previously the load mechanical torque which relates to the gas engine is modeled based on Fig. 2.

### C. Proposed Proportional-Resonant Controller

There are two control loops (outer loop – operation mode control and inner loop – current control) implemented in the proposed MEA starter-generator system as shown in Fig. 1. According to the operation mode, only one outer loop control is operating at that moment and its calculated reference q-axis current (\( I_{q^*} \)) is fed into the inner current loop control. During the generation mode, the outer loop DC-bus voltage control (V.C) strategy is shown in Fig. 3 where the instantaneous DC-bus voltage is achieved by summing the voltage across C1 (\( V_{c1} \)) and C2 (\( V_{c2} \)). In this case, the \( I_{q^*} \) is calculated by the PI controller based on the difference between the instantaneous and reference voltages. Similarly, both speed and torque controllers calculate the \( I_{q^*} \) accordingly to the operation mode.

The d-axis reference current \( (I_d^*) \) is referred to the d-axis magnetic flux which is usually assumed to be zero. On top of that, the produced mechanical torque of the considered round PMSM in (3) is independent of the \( I_{q^*} \). With the aid of the Park transformation, the respective reference stationary frame currents (\( I_{d^*} \) and \( I_{q^*} \)) are determined. On the other hand, the instantaneous stationary frame currents (\( I_d \) and \( I_q \)) are obtained with the aid of Clarke transformation based on the three-phase current measurements.

This paper proposes using two independent proportional resonant (PR) controllers to determine the reference stationary voltages \( (V_{a^*} \) and \( V_{b^*} \)) from the instantaneous stationary currents. The PR controller transfer function is expressed as below:

\[
G_{PR} = K_p + \frac{K_i}{s^2 + \omega^2}
\]

where \( K_p \) is the proportional gain term, \( K_i \) is the integral gain term and \( \omega \) is the resonant frequency. The steady-state errors can be minimized here due to the infinite gain in (5) by having...
the resonant frequency matching with the PMSM voltage fundamental frequency [14], [15].

It can be clearly observed that the proposed overall control strategy only requires one inverse Park transformation which results in the reduction of computational complexity. On top of that, the calculated $V_a^*$ and $V_b^*$ can be directly fed into the ASVM without the need of inverse Park transformation. Thus, the frame transformation error is also greatly reduced.

D. Adaptive Space Vector Modulation

The output voltage waveforms are synthesized using the adaptive space vector modulation (ASVM) technique as it can provide a better DC-link capacitor voltage balancing. The space vector representation for the NPC inverter is shown in Fig. 4. It can be observed that there are several pairs of vector (e.g. “100” and “211”) in each internal voltage state which generate the same output voltage level. Conventionally, the classical SVM uses the pair of vectors during every switching cycle period. Therefore, an increase in the switching loss is experienced with the classical SVM due to the high switching frequency operation. The overall switching loss is decreased by reducing the switching frequency since one of the vector pair is utilized in each switching cycle. This can be observed from the current flow based on the vector pair “100” and “211” as shown in Fig. 5 [16], [17].

Even though both vectors generate the same output voltage level, but there are different effects on the dc-link capacitor voltages. For instance, when the state vector is “100”, the dc-link capacitors $C_1$ and $C_2$ are in charging and discharging states respectively according to the voltage potentials. Hence, the dc-link capacitor voltage balancing is achieved based on the state vector selection principle as described in (6). The vector selection principle is applicable for other vector pairs as well.

\[
\begin{align*}
V_{cl} &\leq V_{c2} \text{ & } I_x \geq 0 \Rightarrow (100) \\
V_{cl} &> V_{c2} \text{ & } I_x < 0 \\
V_{cl} &\geq V_{c2} \text{ & } I_x \geq 0 \\
V_{cl} &< V_{c2} \text{ & } I_x < 0 \Rightarrow (211)
\end{align*}
\]

IV. EVALUATION RESULTS

The proposed MEA starter-generator in Fig. 1 is modelled and developed using Matlab/Simulink® and PSIM. A two-pole PMSM is considered here to evaluate the dynamic performance of the proposed MEA starter-generator system. The reference DC-bus voltage is set to 270 V and a 5 kW DC-load connected during the generation mode. The detailed setting of the simulated system is presented in Table I.

With the implementation of the ASVM technique together with the PR controllers, it is clearly observed that the DC-link capacitor voltages are balanced around 135 V (half of the total DC-bus voltage) in Fig. 6. Besides that, the obtained result has proven that the DC-bus voltage is well tracked to the desired value during the generation mode.

The dynamic performance of the proposed system during the starting period is shown in Fig. 7 where the gas engine is powering up initially. Hence, the MEA starter-generator will
start operating under the S.C as mentioned previously. Thus, the speed reference in this condition is a step increased from zero to 628 rad/s. When \( \omega_r \) reaches 300 rad/s, the proposed system starts operating under the T.C. A constant reference torque, as shown in Fig. 7(b), is applied to the PMSM during this period. The machine speed is then increased to 628 rad/s within a short period of time due to the total produced mechanical torque from the PMSM and the gas engine. Once the gas engine reaches the base speed, the system is operating under the V.C as shown in Fig. 7(a) which is the generation mode. The injected mechanical torque and the calculated electromagnetic torque of the PMSM are also shown in Fig. 7(b). One can observed that during the starting period, the produced electromagnetic torque is more than the required mechanical torque which will increase the machine speed as a result. On top of that, the produced electromagnetic torque by the PMSM is constantly following its reference torque value during the T.C. In order to achieve the constant PMSM speed during V.C. in the simulation, \( T_e \) is calculated according to (3) based on the PMSM currents which are transformed to dq-axis frame. Subsequently, the required \( T_L \) is computed based on (4) by considering the \( p\omega_r \) to be zero.

The dynamic response of the controller during the generation mode is also evaluated in Fig. 8 by having a sudden DC-load change from the initial 5 kW to 25 kW at \( t = 2s \). In the Fig. 8(b), the tracked DC-bus voltage at 270V before 2s is suddenly decreased which is caused by the DC-load change condition. However, the DC-bus voltage is well-tracked to its desired value rapidly again. The magnitude of three-phase currents of the PMSM in Fig. 8(c) is increased at \( t = 2s \). There is no current spike experienced in the PMSM during this period due to the dynamic response of the proposed PR controller.

In Fig. 9, the performance of the proposed controller is examined under the speed step change. The controller is working under S.C. mode while the PMSM is operating
According to (4), the produced electromagnetic torque of the PMSM is increased in order to boost the engine speed. On the other hand, according to Fig. 2, the resist mechanical torque of the gas engine is increased linearly with its speed during the S.C mode which can be observed in Fig. 9(b). Besides that, the produced electromagnetic torque of the PMSM is increased to assist the PMSM in increasing the speed. After achieving the new reference speed point, the controller decreases the reference q-axis current and subsequently the generated electromagnetic torque is also reduced. The evaluation results have evidently proven that the excellent performance and dynamic response are achieved with the proposed structure and it can be used for the MEA starter-generator.

![Fig. 9: Dynamic performance of the proposed controller under speed step change.](image)

**VI. REFERENCES**