Proportional-resonant controlled NPC converter for more-electric-aircraft starter-generator

Dehghani Tafti, Hossein; Lim, Ziyou; Raj, Pinkymol Harikrishna; Maswood, Ali Iftekhar; Ooi, Gabriel Heo Peng

2015

Dehghani Tafti, H., Maswood, A. I., Lim, Z., Ooi, G. H. P., & Raj, P. H. (2015). Proportional-resonant controlled NPC converter for more-electric-aircraft starter-generator. 2015 IEEE 11th International Conference on Power Electronics and Drive Systems.

<https://hdl.handle.net/10356/98052>

<https://doi.org/10.1109/PEDS.2015.7203443>

© 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: [<http://dx.doi.org/10.1109/PEDS.2015.7203443>].

Downloaded on 26 Apr 2023 22:10:53 SGT

Proportional-Resonant Controlled NPC Converter for More-Electric-Aircraft Starter-Generator

Hossein Dehghani Tafti¹, *Student Member, IEEE*, Ali I. Maswood², *Senior Member, IEEE*, Ziyu Lim³, *Student Member, IEEE*, Gabriel H. P. Ooi⁴, *Member, IEEE* and Pinkymol Harikrishna Raj⁵, *Student Member, IEEE*.

^{1, 2, 4, 5}School 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, ²emaswood@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 ($\alpha\beta$) 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-

Fig. 1: Proposed MEA starter-generator system.

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 (S_{a1} and S_{a2}) including their complementary ($S_{a1'}$ and $S_{a2'}$) and a series connected capacitors C_1 and C_2 in the DC-link.

There are different operation modes (on/off) for the switches FS_{a1} , FS_{a2} and FS_{a3} . During the motoring mode (speed-control and torque-control), FS_{a1} must be closed and FS_{a2} opened so that the DC-source can be connected to the DC-bus to power up the PMSM. Meanwhile during the generation mode, FS_{a1} will be open and FS_{a2} 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 FS_{a3} 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 operating modes given in the following are considered for controlling the MEA gas engine in this study.

$$\text{Op. Mode} = \begin{cases} \text{Speed Cont. (S.C)} & \omega_r < 300 \text{ rad/s} \\ \text{Torque Cont. (T.C)} & 300 \text{ rad/s} \leq \omega_r < 628 \text{ rad/s} \\ \text{DC-bus Voltage Cont. (V.C)} & 628 \text{ rad/s} \leq \omega_r \end{cases} \quad (1)$$

where ω_r 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 ($\omega_r = 300 \text{ rad/s}$), 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 ($\omega_r = 628 \text{ rad/s}$), 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

Fig. 2: Assist/Resist torque of the gas engine.

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 $\omega_r = 300$ 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 $\omega_r = 500$ 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]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega_r L_q \\ \omega_r L_d & R_s + pL_d \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} \quad (2)$$

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
- ϕ_f : Permanent magnet flux linkage (Wb)

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

$$T_e = \frac{3n_p}{2} \left[\phi_f I_q + (L_d - L_q) I_d I_q \right] \quad (3)$$

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.

Fig. 3: DC-bus voltage control strategy.

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

$$T_e = \frac{J}{n_p} p \omega_r + \frac{B}{n_p} \omega_r + T_L \quad (4)$$

where

- J : Moment of inertia (kg.m^2)
- B : Viscosity coefficient (N.s/m^2)
- 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_d^* . With the aid of the inverse Park transformation, the respective reference stationary frame currents (I_α^* and I_β^*) are determined. On the other hand, the instantaneous stationary frame currents (I_α and I_β) 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_α^* and V_β^*) from the instantaneous stationary currents. The PR controller transfer function is expressed as below:

$$G_{PR} = K_p + \frac{K_i}{s^2 + \omega^2} \quad (5)$$

where K_p is the proportional gain term, K_i is the integral gain term and ω is the resonant frequency. The steady-state errors can be minimized here due to the infinite gain in (5) by having

Fig. 4. Space vector representation of the NPC inverter

Fig. 5. Circuit diagram and current path for vectors of one vector pair

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_{α}^* and V_{β}^* 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-

Fig. 6. DC-link capacitor voltage in steady state under the ASVM control.

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
DC-bus Voltage	V_{dc}	270V
Nominal speed during the generation mode	n_r	6000rpm
Stator Resistance	R_s	0.008296Ω
d-axis inductor	L_d	0.17mH
q-axis inductor	L_q	0.17mH
Number of pole pairs	n_p	2
Permanent magnet flux linkage	ϕ_f	0.193Wb
Moment of inertia	J	0.05565 kg.m ²
Viscosity coefficient	B	0.005 N.s/m ²

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.

$$\left. \begin{aligned} V_{c1} &\leq V_{c2} \ \& \ I_a \geq 0 \\ V_{c1} &> V_{c2} \ \& \ I_a < 0 \end{aligned} \right\} \Rightarrow (100) \quad (6)$$

$$\left. \begin{aligned} V_{c1} &\geq V_{c2} \ \& \ I_a \geq 0 \\ V_{c1} &< V_{c2} \ \& \ I_a < 0 \end{aligned} \right\} \Rightarrow (211)$$

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 270V 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 135V (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

Fig. 7: Dynamic performance of the PMSM under proposed control strategy during starting: (a) PMSM speed and (b) PMSM mechanical and electromagnetic torque.

Fig. 8: Dynamic performance of the PMSM under proposed control strategy during generation: (a) DC-bus power, (b) DC-bus voltage and (c) PMSM three phase currents.

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 ω_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 observe 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 $t = 2$ s. 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 $t = 2$ s. 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

Fig. 9: Dynamic performance of the proposed controller under speed step change.

constantly at 4000 rpm speed. The reference speed of the PMSM which is initially at 4000 rpm, has experienced a step change from 4000 rpm to 6000 rpm at $t = 1$ s. Despite of the sudden step change, the speed of the PMSM is tracked quickly to the reference speed and reaches 6000 rpm at $t = 1.008$ s as shown in Fig. 9(a). According to (4), the produced electromagnetic torque of the PMSM should be increased in order to boost the engine speed. On the other hand, according to the 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) as well. 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

V. CONCLUSION

This paper proposed a PR controller together with the ASVM technique to control the PMSM which is applied for the MEA starter-generator. Since the calculated reference voltages obtained from the PR controller can be directly fed into the ASVM, thus it reduces the computational complexity as well as the steady state error. The evaluation results have verified the performance of the DC-link capacitor voltage balancing using ASVM technique. Besides that, the converter switching loss is also greatly decreased due to the reduced switching frequency operation under ASVM. The dynamic performance of the controller under various operation modes (speed-control, torque-control and DC-bus-voltage-control) is evaluated for both the initial starting period and the power generating period. The obtained results have verified the feasibility of the proposed controller. On top of that, the fast dynamic response of the proposed controller is examined under speed step change. The dynamic performance achieved makes the proposed control strategy attractive for the MEA starter-generator system.

VI. REFERENCES

- [1] M. K. Agarwal, "Recent Advances in Aircraft Technology", *InTech*, pp. 289-308, 2012.
- [2] R. T. Naayagi, "A Review of More Electric Aircraft Technology," *Int. Conf. on Energy Efficient Technologies for Sustainability*, pp. 750-753, 2013.
- [3] Cai, W., "Comparison and review of electric machines for integrated starter alternator applications," *Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE*, pp. 386-393, Oct. 2004.
- [4] C. Yuan-Chih, C. Jian-Cheng, C. Jui-Teng, and S. Kun-Han, "Space-vector based current control of permanent-magnet synchronous motor/generator drive applied to flywheel energy storage system," in *Power Electronics and Drive Systems (PEDS), 2013 IEEE 10th International Conference on*, 2013, pp. 726-730.
- [5] A. Griffo, R. Wrobel, P. H. Mellor, and J. M. Yon, "Design and Characterization of a Three-Phase Brushless Exciter for Aircraft Starter/Generator," *Industry Applications, IEEE Transactions on*, vol. 49, pp. 2106-2115, 2013.
- [6] M. Schweizer, T. Friedli, and J. W. Kolar, "Comparative Evaluation of Advanced Three-Phase Three-Level Inverter/Converter Topologies Against Two-Level Systems," *Industrial Electronics, IEEE Transactions on*, vol. 60, pp. 5515-5527, 2013.
- [7] D. Sato and J. Itoh, "Total Loss Comparison of Inverter Circuit Topologies with Interior Permanent Magnet Synchronous Motor Drive System," *IEEE ECCE Asia Downunder (ECCE Asia)*, pp. 537-543, 2013.
- [8] A. I. Maswood, E. Al Ammar, and O. H. P. Gabriel, "Comparative study of multilevel inverters under unbalanced voltage in a single DC link," *IET Power Electronics*, vol. 6, pp. 1530-1543, 2013.
- [9] H. R. Pinkymol, A. I. Maswood, and A. Venkataraman, "Space vector based field oriented control of Permanent Magnet Synchronous Motor with a 3-level inverter scheme," *Transportation Electrification Conference and Expo (ITEC), 2013 IEEE*, 2013, pp. 1-6.
- [10] A. I. Maswood, E. Al-Ammar, and F. Liu, "Average and hysteresis current-controlled three-phase three-level unity power factor rectifier operation and performance," *Power Electronics, IET*, vol. 4, pp. 752-758, 2011.
- [11] B. S. Bhangu and K. Rajashekara, "Control strategy for electric starter generators embedded in gas turbine engine for aerospace applications," in *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE*, 2011, pp. 1461-1467.
- [12] B.S Bhangu and K. Rajashekara, "Electric Starter Generators: Their Integration into Gas Turbine Engines," *Industry Applications Magazine, IEEE*, vol. 20, no. 2, pp. 14-22, 2014.
- [13] M. Kadjudj, M. E. H. Benbouzid, C. Ghennai, and D. Diallo, "A robust hybrid current control for permanent-magnet synchronous motor drive," *Energy Conversion, IEEE Transactions on*, vol. 19, pp. 109-115, 2004.
- [14] R. Teodorescu, F. Blaabjerg, M. Liserre, and P. C. Loh, "Proportional-resonant controllers and filters for grid-connected voltage-source converters," *Electric Power Applications, IEE Proceedings*, vol. 153, pp. 750-762, 2006.
- [15] A. Vidal, F. D. Freijedo, A. G. Yepes, P. Fernandez-Comesana, J. Malvar, O. Lopez, et al., "Assessment and Optimization of the Transient Response of Proportional-Resonant Current Controllers for Distributed Power Generation Systems," *Industrial Electronics, IEEE Transactions on*, vol. 60, pp. 1367-1383, 2013.
- [16] H. Pinkymol, A. Maswood, O. Gabriel, and L. Ziyoun, "Analysis of 3-level inverter scheme with DC-link voltage balancing using LS-PWM and SVM techniques," in *Renewable Energy Research and Applications (ICRERA), 2013 International Conference on*, Oct 2013, pp. 1036-1041.
- [17] N. Celanovic and D. Boroyevich, "A fast space-vector modulation algorithm for multilevel three-phase converters," *Industry Applications, IEEE Transactions on*, vol. 37, pp. 637-641, 2001.