Adaptive Stabilization of a Permanent Magnet Synchronous Generator-Based DC Electrical Power System in More Electric Aircraft

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Abstract—Most loads of electrical power systems on a more electric aircraft (MEA) are regulated power converters. These loads behave as constant power loads (CPLs) that can significantly affect system stability. The system will become unstable and will be unable to operate at the rated power. In this article, a novel adaptive stabilization of a permanent magnet synchronous generator-based dc electrical power system in MEA is presented using a nonlinear feedback approach via loop-cancellation technique with a simple equation of feedback gain, which can be calculated from the power level of the CPL. The equation can be derived from a polynomial curve fitting based on the proposed mathematical model derived using the dq method. The adaptive stabilization results are validated by a small-signal stability analysis using the linearization technique, a large-signal stability analysis using the phase plane analysis, an intensive time-domain simulation using MATLAB, and experimentation. The results indicate that the proposed adaptive stabilization technique can provide the considered aircraft power system always stable for all operating conditions within the rated power, and the dc bus voltage can adhere to the MIL-STD-704F standard.

Index Terms—Adaptive stabilization, constant power load (CPL), dq model, large-signal stability analysis, loop-cancellation technique, more electric aircraft (MEA), nonlinear feedback, small-signal stability analysis.

I. INTRODUCTION

The more electric aircraft (MEA) is an essential concept and tendency in modern aerospace engineering that attempts to replace four subsystems, i.e., electrical, pneumatic, hydraulic, and mechanical systems with only an electrical system. The aim of using MEA is to reduce operating costs, fuel consumption, environmental impact, and overall weight. Furthermore, improvement in the efficiency and reliability of overall aircraft systems has been concerned. The ac distribution system is the preferred system for use in MEA, whereas a hybrid distribution system serves as a second option. However, at present (and in the future), a dc distribution system represents a potential architecture for MEA because of the distribution advantages it presents. These include higher system efficiency and reliability, as well as lower overall weight and power losses, due to the absence of reactive power compensation equipment [1]–[6].

The concept and tendency of MEA have resulted in the wide use of power electronic technology because it is easy to control and has high efficiency and low maintenance costs. Hence, the electrical power system loads on MEA typically include regulated power converters, e.g., power converters that are connected to an electric motor to control the current and speed of the motor, as well as ac/dc or dc/dc converters with their output voltage controllers. However, regulated power converters behave as constant power loads (CPLs), which are characterized as having negative impedance to overall systems [6]–[8]. These CPLs can significantly affect system stability. Instability in this regard may affect controller performance or cause system damage [6], [8], [9]. Thus, the stability analysis for an electrical system with CPLs is important and necessary, particularly for the electrical power systems on MEA. System instability on MEA not only affects the controller performance but may also cause damage to the overall system, which, consequently, will impact passenger safety. These are all undesirable circumstances in the context of aviation. From past to present research, stability studies have been proposed to predict unstable points that can be used to avoid unstable operations. However, stability results alone cannot revert an unstable system to a stable system. Therefore, instability mitigation issues have been reviewed to extend system operation.

The basic concept of instability mitigation due to CPL involves the compensation or elimination of the CPL effect by increasing the system damping. These can be categorized into two methods, i.e., passive and active dampings. The passive
and price and system power losses, which results in decreased damping are an increase in the overall system size, weight, practical implementations. However, the drawbacks of such Passive damping involves a simple method for design and system damping, resulting in increased system stability. The main primary disadvantage, however, is a limitation in terms of a usable system. This method can only be applied for the switched converters.

Passive component, e.g., a resistor, a resistor with a capacitor, or a resistor with an inductor to the system to increase system damping, resulting in increased system stability. Passive damping involves a simple method for design and practical implementations. However, the drawbacks of such damping are an increase in the overall system size, weight, and price and system power losses, which results in decreased system performance. Active damping [11]–[26] is an approach based on control structure modifications. A compensation signal, known as a stabilizing signal, is created and introduced to existing control structures. Virtual system damping can also be created to increase system stability in which the active damping approach is not a hardware modification. In this way, the system can achieve higher efficiency and reliability compared with using a passive damping technique. Most of the current research, thus, tends to use the active damping approach for instability mitigation. According to feedback characteristics, active damping can be divided into two methods. The first is the linear feedback method [11]–[12], [14]–[17], [19]–[23], in which the creation of the compensation signal is based on the virtual impedance principle. However, studies [11], [13], [26] reported that the linear feedback compensates only for a limited amount of CPL [11], [13], [18], [26]. The second approach, the nonlinear feedback method, can eliminate a wide range of CPLs. The compensation signal is designed using a nonlinear control technique, e.g., sliding mode control, state space poles placement, a loop-cancellation technique, and neural networks [11], [13], [18], [24]–[26].

The active damping approach can be implemented in three ways, as given in Table I. The first is by implementing modification at the feeder or source side [10]–[17], [22]. The advantage of this approach is that it does not affect the load performance. The main primary disadvantage, however, is a limitation in terms of a usable system. This method can only be used for a feeder system with switched converters. When the feeder system includes nonswitched converters, such as an uncontrolled rectifier, CPL compensation at the feeder side is not possible. In this case, the second approach, i.e., modification at the load or CPL side [11], [18]–[21], [23]–[25], can be used. Modification at the CPL side is a method that can compensate for the CPL effect directly by introducing a compensation signal to the existing control loop. The drawback of this method is that the load performance will be reduced. If the load performance becomes more important than the losses, compensation using an additional auxiliary circuit is a suitable option [11], [26], in which an auxiliary circuit is installed between the feeder and load systems. This will, however, increase the cost and complexity of the overall system, as well as power loss.

On the basis of the advantage of the nonlinear feedback technique, this article presents adaptive stabilization using the loop-cancellation technique. The compensating signal is introduced into the existing control loop at the source side. In addition, the stabilization gain can be adopted based on the system’s operating point to maintain system stability. The simple equation derived from a polynomial curve fitting, alongside the instability line provided by the proposed averaging model, is used to update the stabilization gain. After applying the proposed mitigation technique, the considered MEA system will always be stable within the rated operating point. Furthermore, when stabilization is achieved, the dc bus voltage can adhere to the MIL-STD-704F standard [27].

This article is structured as follows. In Section II, a single-generator-single-bus dc distribution MEA power system with the loop-cancellation technique is introduced. Applying the loop-cancellation technique to the considered MEA and deriving the mathematical model using the dq method are also explained. In Section III, a review of system stability is presented by a small-signal stability analysis using the eigenvalue theorem and large-signal stability analysis using the phase plane analysis. The details of the proposed adaptive stabilization are addressed in Section III. The validation of the theoretical analysis by simulation using MATLAB and the experiment using a test rig built in the laboratory are presented in Section IV. Finally, the advantages and benefits of the proposed adaptive stabilization approach, as well as future research, are concluded and discussed in Section V.

### Table I

| Method                  | Advantages                                        | Limitations                                      |
|-------------------------|---------------------------------------------------|--------------------------------------------------|
| Feeder Side             |                                                   |                                                  |
| Active Damping          | not affect to load performance                    | can only be applied for the switched converters   |
| [10–17 and 22]          |                                                   |                                                  |
| CPL Side                |                                                   |                                                  |
| Active Damping          | can compensate CPL effect directly                | affect the load performance                      |
| [11, 18–21, 23–25]      |                                                   |                                                  |
| Active Damping using Auxiliary Circuits | can be applied for the non-switched converters without the load performance effect | increase cost, power loss, and complexity of the overall system |
| [11 and 26]             |                                                   |                                                  |

ADVANTAGES AND LIMITATIONS OF MITIGATION METHODS

II. CONSIDERED MORE ELECTRIC AIRCRAFT POWER SYSTEM WITH THE LOOP-CANCELLATION TECHNIQUE

Fig. 1 shows the MEA power system considered in this article. It comprises a permanent magnet synchronous generator (PMSG), which is used to generate ac power by converting mechanical power from the aircraft’s engine turbines to electrical power. An active front-end (AFE) rectifier is used to convert the ac power from the PMSG to dc power for all MEA loads, whereas a dc-link capacitor is used to reduce the ripple voltage of the dc bus to obtain a smoother and more constant voltage. Furthermore, the dc transmission line and all MEA loads include the CPL referred to the regulated power converters, resistive load represented to a wing deicing system,
and the capacitor bank. The controllers of the AFE rectifier, indicated by the gray area in Fig. 1, are the vector controllers on the \( dq \)-axis. The current controller on the \( d \)-axis is used to control the PMSG and enable it to function at full-flux operation by setting \( I_d^* \) to 0. The current controller on the \( q \)-axis and the voltage controller are used to regulate the voltage across the dc-link capacitor (\( V_{dc} \)), which, in this instance, equals 250–280 V; this is based on the MIL-STD-704F standard \([27]\), in which the nominal voltage (\( V_o^* \)) is set to 270 V. The droop controller is used to control current or power-sharing from each PMSG for all MEA loads to obtain the desired \( V-I \) droop characteristic. The output of the droop controller is the reference voltage for the \( V_{dc} \) controller (\( V_{dc}^* \)). Furthermore, Fig. 1 indicates nonlinear feedback via the loop-cancellation technique and the adaptive stabilization approach (the green and blue areas, respectively, in Fig. 1). In this section, only the considered MEA with the loop-cancellation technique is studied. The adaptive stabilization approach will be described in Section III.

As shown in Fig. 1, the instability mitigation technique is added to the existing conventional controllers. The application of the loop-cancellation technique for instability mitigation of the considered MEA is explained as follows:

The \( dq \) method is applied for deriving the mathematical model with which to obtain a time-invariant model suitable for a stability study. The assumptions for deriving the model are that the AFE rectifier is operated under the continuous conduction mode (CCM) and an overlap angle (\( \mu \)) below 60\(^\circ\), and all harmonics in the system are ignored.

For model derivation, the considered MEA system can be divided into three parts.

A. Permanent Magnet Synchronous Generator Model

The dynamic equations of the PMSG on \( dq \) frame with a synchronously rotating reference frame \([4]\), \([5]\) are shown as follows:

\[
\begin{align*}
I_d &= -\frac{R_s}{L_d} I_d + \frac{\omega_e L_q}{L_d} I_q - \frac{1}{L_d} V_d \\
I_q &= -\frac{\omega_e L_d}{L_q} I_d - \frac{R_s}{L_q} I_q - \frac{1}{L_q} V_q + \frac{\omega_e \phi_m}{L_q}
\end{align*}
\]  

(1)

where \( R_s \) is the stator resistance, \( L_d \) and \( L_q \) are the induc- tances on the \( dq \)-axis, \( \phi_m \) is the permanent magnet flux linkage, \( \omega_e \) is the electrical rotor angular velocity, \( I_d \) and \( I_q \) are the stator currents on the \( dq \)-axis, and \( V_d \) and \( V_q \) are the stator voltages on the \( dq \)-axis.

B. AFE Rectifier Model

The inner structure of the AFE rectifier includes six switches, herein identified as insulated-gate bipolar transistors (IGBTs). After using the \( dq \) method to eliminate the IGBTs’ switching behaviors, the AFE rectifier can be represented by a transformer on the \( dq \)-axis with the ratios \( M_d \) and \( M_q \) \([4]\)–\([6]\). The time-invariant switching function of the AFE rectifier is shown as follows:

\[
\begin{align*}
M_d &= \frac{m}{2} \cos(\phi - \phi_{con}) \\
M_q &= -\frac{m}{2} \sin(\phi - \phi_{con})
\end{align*}
\]  

(2)

where \( m \) is the modulation index, \( \phi \) is the phase angle of the \( dq \)-axis, and \( \phi_{con} \) is the phase angle of the voltage vector at the converter bus.

First, the open-loop control of the AFE rectifier is considered. According to (1) and (2), as well as setting the \( dq \)-axis rotating at the PMSG rotor angle, the considered MEA without the closed-loop control can be represented by the equivalent circuit on the \( dq \)-axis, as shown in Fig. 2. After analyzing the equivalent circuit in Fig. 2 using Kirchhoff’s voltage law and Kirchhoff’s current law, a mathematical
C. Controller Models

Fig. 3 shows a block diagram of the AFE rectifier controllers without adaptive stabilization. It includes the existing conventional controllers as shown in the gray area. The details for how to design the controllers can be found in [4] and [5]. The green area is the loop-cancellation technique for the considered MEA (see Fig. 1) can be performed by substituting $M_d$ and $M_q$ in (3) with $M_{dq}^*$ from (5) and (6) and by substituting $I_q$ in (3) with $I_{q1}$ in (7). The mathematical model of the considered MEA power system with the loop-cancellation technique in Fig. 1, derived using the dq method, is given in (8). The time-invariant system model in (8) is, thus, a suitable model for studying system stability.

III. Stability Studies and Adaptive Stabilization

In this section, the considered system stability is reviewed using the small-signal stability analysis via the linearization technique and the large-signal stability analysis via the phase
plane analysis for unstable point prediction

\[
\begin{align*}
I_d^\prime &= \left( \frac{K_{pd} - R_d}{L_d} \right) I_d - \frac{K_{id}}{L_d} X_{id} - \frac{K_{pd}}{L_d} I_d^s \\
I_{q1}^\prime &= \left( \frac{K_{pq} - R_q}{L_q} \right) I_{q1} + \frac{K_{pm} K_{pq}}{L_q} V_{dc} + \frac{K_{pD} K_{pD} P_{CPL}}{L_q} V_b \\
&\quad + \frac{K_{pq} K_{D} K_{D} P_{CPL}}{L_q}, \frac{1}{V_b} - \frac{K_{pq} K_{pD} K_{FB}}{L_q} \left( I_{q1}^s - \frac{1}{V_b} \right) \\
V_{dc} &= \frac{3}{2C_{dc}} \\
&\quad - \frac{K_{pd} I_d^2 + K_{id} I_d X_{id} + K_{pq} I_d I_{q1}^s}{V_{dc}} \\
&\quad - \frac{K_{pq} I_{q1}^2 + \omega_c \phi_m I_{q1} - K_{pq} K_{q1} V_{dc}}{V_{dc}} \\
&\quad - \frac{K_{pq} K_{D} I_{q1} V_b + K_{pq} K_{q1} V_{dc} + K_{pq} I_{q1} X_{id} + K_{pq} I_{q1} X_{iq}}{V_{dc}} \\
&\quad + \frac{K_{pq} K_{q1} V_{dc}}{V_{dc}} \\
&\quad - \frac{2K_{pq} K_{pq} K_{FB} I_{q1}}{V_{dc}} \\
&\quad - \frac{K_{pq} K_{pq} K_{FB}}{L_q}, \frac{1}{V_b} + \frac{K_{pq} K_{pq} K_{D} P_{CPL} I_{q1}}{L_q} \\
&\quad + \frac{K_{pq} K_{pq} K_{FB} V_{dc} + K_{pq} K_{pq} K_{FB} P_{CPL} K_{FB}}{L_q} \left( \frac{1}{V_b} \right) \\
&\quad - \frac{K_{pq} K_{pq} K_{FB} X_{id} - K_{pq} K_{pq} K_{FB} X_{iq}}{L_q} \\
&\quad - \frac{K_{pq} K_{pq} K_{FB} X_{id} + \omega_c \phi_m K_{pq} K_{FB}}{L_q} \left( \frac{1}{V_b} \right) \\
&\quad - \frac{2K_{pq} K_{pq} K_{FB}}{L_q}, \frac{1}{V_b} \\
&\quad - \frac{K_{pq} K_{pq} K_{FB}}{L_q}, \frac{1}{V_b} \\
&\quad - \frac{K_{pq} K_{pq} K_{FB}}{L_q}, \frac{1}{V_b} \\
I_c^\prime &= \frac{1}{L_c} V_{dc} - \frac{R_c}{L_c} I_c - \frac{1}{L_c} V_b \\
V_b^\prime &= \frac{1}{C_b} I_c - \frac{1}{C_b} V_b - \frac{P_{CPL}}{C_b} \\
X_{id}^\prime &= -I_d + I_d^s \\
X_{iq}^\prime &= -I_{q1} - K_{pq} V_{dc} \left( K_{pd} + \frac{R_L}{L_q} \right) + K_{pq} K_{D} X_{id} + K_{pq} V_{o} \\
&\quad - \left( K_{pq} K_{D} P_{CPL} + \frac{K_{pq} K_{pq} K_{FB}}{L_q} \right), \frac{1}{V_b} \\
\end{align*}
\]

(8)

In addition, instability mitigation is presented. The details for how to create adaptive stabilization based on the loop-cancellation technique for the considered MEA are also described.

The system model in (8) indicates that \( K_{FB} \) occurred in the equation. If \( K_{FB} \) is equal to 0, it infers that the system is operated without the proposed mitigation technique. After linearizing (8) by the first-order Taylor series, eigenvalues from the linearization of (8) were calculated. The system parameters (as given in the Appendix) represent a scaled version due to laboratory limitations in the experimental setup. Using these parameters, Fig. 4(a) shows the dominant eigenvalue plot of the considered MEA system when \( P_{CPL} \) is varied from 0.8 to 2.2 kW without the mitigation technique \( (K_{FB} = 0) \). It is shown that the real roots of the dominant eigenvalues at \( P_{CPL} = 1.4 \) kW are higher than 0. Therefore, at this operating point, the system is unstable. The system instability occurs before the rated power in this instance reaches \( P_{CPL\text{ (rated)}} = 2.2 \) kW. To return the system to a stable state, instability mitigation via the loop-cancellation technique is applied.

Fig. 4(b)–(e) present the dominant eigenvalue plots of the considered MEA with the proposed mitigation technique when \( K_{FB} \) is equal to 0.25, 0.74, 1.02, and 1.44, respectively. Fig. 4(b) shows that the dominant eigenvalues at \( P_{CPL} = 1.4 \) kW (the unstable point) moved from the right-hand side to the left-hand side of the s plane. This means that the proposed mitigation technique can return the unstable system to a stable state by only increasing \( K_{FB} \) from 0 to 0.25. However, if \( P_{CPL} \) is increased beyond 1.4 kW (here, it is 1.7 kW), while \( K_{FB} \) remains fixed at 0.25, the gain will not be
sufficient for mitigation. Accordingly, the system will become unstable again. To make the system stable at $P_{CPL} = 1.7$ kW, $K_{FB}$ should be increased to 0.74 [see Fig. 4(c)]. For $P_{CPL}$ equal to 1.9 and 2.2 kW (rated power), $K_{FB}$ should be increased to 1.02 and 1.44, respectively. $K_{FB} = 1.44$ can be used to mitigate the system (see Fig. 4), which can make the system stable for all load powers within the rated range. The phase plane analysis is used to investigate the dc bus voltage response ($V_b$) adherence to the MIL-STD-704F standard when the proposed mitigation technique is applied. Using the system model in (8) with the system parameters given in the Appendix, the trajectory of the considered MEA on the $I_c$–$V_b$ plane when $P_{CPL} = 1.4$ kW without the mitigation technique ($K_{FB} = 0$) is determined [see Fig. 5(a)]. The system trajectory motion starts from the initial point and then diverges from the equilibrium point, indicating that the system is unstable at $P_{CPL} = 1.4$ kW, corresponding to the eigenvalue theorem analysis in Fig. 4(a). Fig. 5(b) presents the system trajectory at $P_{CPL} = 1.4$ kW when using $K_{FB} = 1.44$ ($K_{FB} = 1.44$ can stabilize the system for all load powers within the rated range). The analytical result shows that the trajectory can converge to the equilibrium point, indicating that the system is stable at such conditions. However, the transient state $V_b$ oscillates considerably exceeding the range of 200–330 V, as specified by the MIL-STD-704F standard. Moreover, the steady state $V_b$ is also not in the range of 250–280 V, as specified by the denoted standard. Fig. 6(b) shows the simulation results when $P_{CPL}$ is increased from 1.2 to 1.4 kW with $K_{FB} = 1.44$. The results show that the steady-state response of $V_b$ does not adhere to the MIL-STD-704F standard with $K_{FB} = 1.44$ for $P_{CPL} = 1.4$ kW, corresponding to the analysis in Fig. 5(b). Based on the analysis in Fig. 5(c), the system trajectory at $P_{CPL} = 1.4$ kW when $K_{FB} = 0.25$ can converge to the equilibrium point, and the $V_b$ responses in both transient and steady states can adhere to the standard. Fig. 6(a) shows the simulation results, confirming the analytical results.
of Fig. 5(c). Concordantly, $K_{FB} = 0.25$ stabilizes the system for $P_{CPL} = 1.4$ kW, and the $V_b$ responses in both transient and steady states adhere to the MIL-STD-704F standard, while the undesirable $V_b$ response is obtained for $K_{FB} = 1.44$. Hence, a high $K_{FB}$ can cause the nonadherence of the $V_b$ response to the standard. Therefore, the design of a suitable $K_{FB}$ value is required. The phase plane analysis was also performed for other $P_{CPL}$. Fig. 5 shows that $K_{FB} = 0.74$ is suitable for $P_{CPL} = 1.7$ kW [see Fig. 5(d)], while $K_{FB} = 1.02$ and 1.44 are also appropriate for $P_{CPL} = 1.9$ [see Fig. 5(e)] and 2.2 kW [see Fig. 5(f)], respectively. Thus, $K_{FB}$ must be designed sufficiently small to avoid undesirable $V_b$ response. $K_{FB}$ should be adopted based on the $P_{CPL}$ level to ensure that the system remains stable for all operating conditions within the rated power. Hence, adaptive stabilization is proposed to provide the appropriate $K_{FB}$.

The proposed adaptive stabilization is based on a simple equation obtained from polynomial curve fitting (see Fig. 7). The instability line, indicated by the black dashed line in Fig. 7, is first calculated from the stability analysis via the proposed averaging model using the eigenvalue theorem (see Fig. 4). Here, the phase plane analysis is not needed to verify the $V_b$ responses again. The $V_b$ responses adhere to the MIL-STD-704F standard because the sufficiently small $K_{FB}$ was selected on the basis of the above-explained analysis in Fig. 5. The instability line is investigated from the unstable point ($P_{CPL} = 1.4$ kW) to the operating point at the rated power ($P_{CPL(rated)} = 2.2$ kW). Points ①–④ of Fig. 4 for a given $K_{FB}$ are located on the black dashed line of Fig. 7. The red and blue lines are defined via the first- and second-order polynomial fitting functions using function “polyfit” in MATLAB, respectively. The second-order polynomial equation is more accurate than the first-order polynomial equation. The blue line is fitted using (9), where a suitable $K_{FB}$ can be adopted based on the $P_{CPL}$ level

$$K_{FB} = \left(-4.282 \times 10^{-7}\right)P_{CPL}^2 + 0.003P_{CPL} - 3.079 \quad (9)$$

where $P_{CPL} = I_o V_b - (V_b^2/R_L)$.

The blue area in Fig. 1 indicates the proposed adaptive stabilization for the MEA power system using (9). The $P_{CPL}$ value for adapting $K_{FB}$ is calculated from $I_o$ and $V_b$. Both values are measured from the existing current and voltage sensors. In addition, (9) is only added to the code and operated when including the loop-cancellation technique. Consequently, the system is always stable until the rated power can be achieved. $K_{FB}$ varies when $P_{CPL}$ changes.

Fig. 8 shows the analytical results of adaptive stabilization via the dominant eigenvalue plots. It demonstrates that the real roots of the dominant eigenvalues with the adaptable $K_{FB}$ are always on the left-hand side of the $s$ plane. $K_{FB}$ is slightly increased following the proposed adaptive equation in (9) until $K_{FB}$ is equal to 1.449 at the rated power of 2.2 kW.
It can be concluded that, before applying the proposed adaptive stabilization, the system becomes unstable at $P_{\text{CPL}} = 1.4\ kW$ (<rated power). After applying the proposed loop-cancellation technique using a simple equation, the appropriate $K_{\text{FB}}$ is introduced into the system, and consequently, the system can be operated at the rated power.

IV. SIMULATION AND EXPERIMENTAL VALIDATION

In this section, the validation of the theoretical analysis by MATLAB simulation is presented alongside the details of the experiment. A test rig of the considered MEA power system was designed and built in a laboratory (see Fig. 9). In this case, a programmable ac power supply was used rather than a PMSG, and the controlled buck converter was applied to represent the CPL.

Fig. 10 shows the simulation and experimental results for the unstable point prediction and instability mitigation. Both the simulation and experimental results were tested in the same conditions and are summarized as follows.

1) Initially, the system is operated without the proposed mitigation technique. $K_{\text{FB}}$ is designated as 0, and $P_{\text{CPL}}$ is increased by 200-W increments.

2) At $t = 2.5\ s$, $P_{\text{CPL}}$ is increased to 1.4 kW. As predicted by the analysis in Figs. 4(a) and 5(a), the system becomes unstable. Both the simulation results in Fig. 10(a) and the experimental results in Fig. 10(b) demonstrate the huge oscillation of $V_b$, which is no constant within the range of 250–280 V , as specified by the MIL-STD-704F standard. Furthermore, it has a ripple voltage equal to 67.4 V in the simulation and 45 V in the experiment, which does not follow the standard specifying the maximum ripple voltage in the steady state (not exceeding 6 V). This indicates that the analytical, simulation, and experimental results are consistent in their indications that the system is unstable at this operating point.

3) At $t = 3.0\ s$, the proposed mitigation technique is activated. $K_{\text{FB}}$ is designated equal to 0.25. The unstable system at $P_{\text{CPL}} = 1.4\ kW$ returns to a stable state, denoted by the oscillation of $V_b$ decreasing until it is constant within the range of 250–280 V in the steady state, thereby adhering to the standard. This confirms that the proposed mitigation technique can return the unstable system to a stable state.

4) Finally, at $t = 4.0\ s$, $P_{\text{CPL}}$ is again increased to 1.6 kW, while $K_{\text{FB}}$ is fixed at 0.25. The analytical results in Fig. 4(b) show that the dominant eigenvalues at this operating point are on the right-hand side of the $s$ plane. This indicates that the system is yet again unstable due to $K_{\text{FB}}$ being insufficient for mitigation. Both the simulation results in Fig. 10(a) and the experimental results in Fig. 10(b) correspond to the analytical results in which the system is unstable. However, the system instability at this point $V_b$ suddenly decreases without oscillation until the system fails. The system controllers will attempt to stabilize a system with insufficient $K_{\text{FB}}$, resulting in the modulation index reaching the limit specified for avoiding overmodulation. Consequently, the system will fail and will be unable to continue operating, which is an undesirable aviation situation. This confirms the conclusion that if $P_{\text{CPL}}$ is increased, $K_{\text{FB}}$ must be increased to be appropriate for mitigation and to maintain system stability. Therefore, adaptive stabilization based on the $P_{\text{CPL}}$ level is required.

Fig. 11 shows the confirmation results for the adaptive stabilization as expected from the analysis in Fig. 8, and the system with an adaptable $K_{\text{FB}}$ based on the $P_{\text{CPL}}$ level [acquired using the proposed equation in (9)] is always stable.
for all $P_{CPL}$ levels within the rated power. Both the simulation results in Fig. 11(a) and the experimental results in Fig. 11(b) confirm that the system is always stable and can be operated at the rated power, which can be observed as a result of $V_b$ in the steady state being constant within the range of 250–280 V as per the denoted standard. Although $V_b$ in the experiment indicated a degree of ripple voltage, the maximum ripple voltage in the steady state was $< 6$ V and, as such, adheres to the denoted standard. In addition, the transient responses $V_b$ from the simulation and experiment are shown in the zoomed-in area of Fig. 11(a) and (b). The responses have settling time $= 0.02$ s (not exceeding 0.04 s) without the overvoltage and undervoltage more than 330 V and less than 200 V, respectively, of which the results can also follow the standard.

The simulation results using the proposed adaptive stabilization equation when $R_c$ and $R_L$ are changed to $R_c + 10\% = 6.09$ mΩ, $R_c - 10\% = 4.99$ mΩ, $R_L + 10\% = 66$ Ω, and $R_L - 10\% = 54$ Ω are shown in Fig. 12(a)–(d), respectively. Although $R_c$ and $R_L$ change, the system remains stable for all operating conditions within the rated power. Moreover, the transient and steady-state responses $V_b$ adhere to the MIL-STD-704F standard. This means that parameter robustness does not affect the adaptive stabilization results.

Overall, it can be concluded that there is very good agreement between the analytical, simulation, and experimental results. Typically, a system without proposed adaptive stabilization will become unstable at $P_{CPL} = 1.4$ kW (< rated power). After applying the proposed adaptive stabilization approach based on the loop-cancellation technique and including the simple $K_{FB}$ equation, which is defined using the proposed mathematical model including the eigenvalue theorem, system instability due to the CPL effect can be fully eliminated. Accordingly, the system always remains stable for all operating conditions within the rated power, i.e., $P_{CPL(\text{rated})} = 2.2$ kW. As such, it is confirmed that the proposed adaptive stabilization is an effective approach that can be used to guarantee the stable operation of a PMSG-based dc electrical power system in an MEA.

V. Conclusion

This study presented an adaptive stabilization of a PMSG-based dc electrical power system in an MEA. The proposed approach is based on the loop-cancellation technique with a simple equation that can calculate the adaptable gain based on the relevant power level. This simple equation was derived from the polynomial curve fitting based on the proposed mathematical model. The resulting adaptive
stabilization can eliminate system instability due to the CPL effect. Consequently, the considered MEA power system is always stable and can be operated at the rated power. The theoretical analysis results (derived via the linearization technique with the eigenvalue theorem and the phase plane analysis), the simulation, and the experimental results used for results’ validation were consistent. The results confirm that the system is stable for all operating conditions within the rated power using the proposed adaptive stabilization without adding any equipment into the system. Also, the $V_b$ response adheres to the MIL-STD-704F standard, and the parameter robustness within ±10% does not affect the adaptive stabilization results. Consequently, the proposed adaptive stabilization can effectively guarantee a PMSG-based dc electrical power system’s stable operation in an MEA. However, the equation for calculating the proposed approach’s adaptive gain is defined from the polynomial curve fitting based on the eigenvalue plot using the proposed model. If the system parameters are changed, the process of defining the adaptive stabilization equation is repeated following the summarized procedure in Fig. 13. First, a sufficiently small $K_{FB}$ is defined for each $P_{ctrl}$ within the rated power via the stability analysis. Then, the instability line is calculated from the stability analysis results and used for polynomial curve fitting. The polynomial curve fitting is performed until the polynomial equation is equivalent to the instability line. Consequently, the adaptive stabilization equation is defined. Thus, in this context, providing the proposed adaptive stabilization represents a convenient and flexible approach, whereas a general and simple equation of $K_{FB}$ can be developed in future studies. Moreover, adaptive stabilization for a realistic potential architecture of MEA and multigenerator (PMSG) single-bus dc distribution MEA power systems can also be considered.

APPENDIX

The system parameters are given as follows: $V_S = 100$ Vrms/phase, $f_e = 400$ Hz, $R_{ac} = 0.7$ Ω, $L_{ac} = 2$ mH, $C_{dc} = 1.45$ mF, $R_{L} = 5.54$ mΩ, $L_{L} = 16.34$ μH, $C_{b} = 0.99$ mF, $R_L = 60$ Ω, $V_{ds} = 0$ V, $V_{gs} = 270$ V, $I_{g} = 0$ A, $K_D = 0.8$, $K_{pu} = 1.288$, $K_{iq} = 343.462$, $K_{pd} = K_{pq} = 17.069$, $K_{id} = K_{iq} = 78956.835$, $I_{buck} = 5.094$ mH, $C_{buck} = 474.1$ μF, $R_{buck} = 8.1$ Ω, and $P_{CPL(rated)} = 2.2$ kW.

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