

Analysis and Control of Energy Storage in Aircraft Power Systems with Pulsed Power Loads

Luis C. Herrera and Bang-Hung Tsao
University of Dayton Research Institute

ABSTRACT

One of the main challenges in the power systems of future aircraft is the capability to support pulsed power loads. The high rise and fall times of these loads along with their high power and negative impedance effects will have an undesirable impact on the stability and dc bus voltage quality of the power system. For this reason, studying ways to mitigate these adverse effects are needed for the possible adoption of these type of loads. One of the technologies which can provide benefits to the stability and bus power quality is Energy Storage (ES). This ES is designed with the capability to supply high power at a fast rate.

In this paper, the management of the ES to mitigate the effects of pulsed power loads in an aircraft power system is presented. First, the detailed nonlinear model of the power network with pulsed power loads is derived. Due to the large size of this model, a model order reduction is performed using a balanced truncation and a second order approximation. The three types of models are then compared in both time and frequency domain. Lastly, a Model Predictive Control (MPC) strategy is designed for the ES. The objective of the MPC is to reduce the dc bus voltage transient during the turn on and turn off of the load while at the same time minimizing the current drawn from the ES. Impact of the response time and saturation levels of the ES will be discussed. In addition, the proposed controller will be helpful to specify requirements for the design of the ES.

CITATION: Herrera, L. and Tsao, B., "Analysis and Control of Energy Storage in Aircraft Power Systems with Pulsed Power Loads," *SAE Int. J. Aerosp.* 9(1):2016, doi:10.4271/2016-01-1981.

I. INTRODUCTION

More electric aircraft power systems are evolving to incorporate loads with more demanding characteristics such as faster rise/fall time and higher power. Pulsed power loads can cause large disturbances in the dc bus voltage and even cause instability due to their Constant Power Load (CPL) behavior [1]. Therefore, it is important to make sure that the negative impact of these loads is analyzed and controlled to ensure compliance with standards [2] and maintain stability in the power system.

The impact of pulsed power loads to the bus voltage transient has been studied for marine applications using reachability analysis [3]. Bounds for the bus voltage during the pulse were computed for a current source load. For nonlinear constant power loads, a region of attraction is commonly used to estimate bounds for system stability [4]. However, it is also important to study ways to mitigate these negative impacts. Energy Storage (ES) is a promising solution to these challenges.

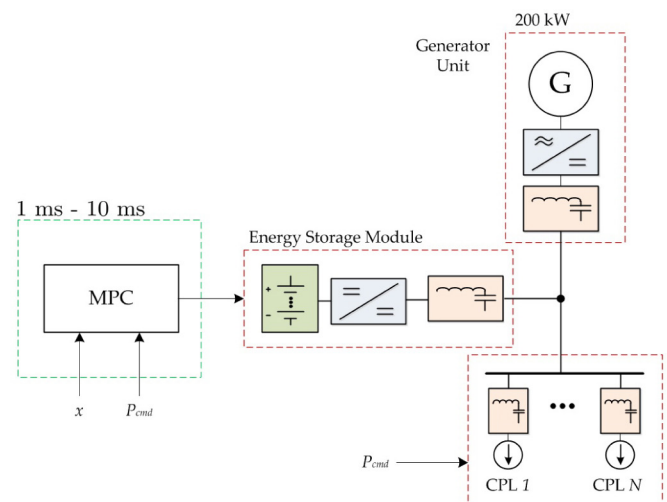


Figure 1. Power network consisting of a generator unit, an energy storage, and pulsed power loads.

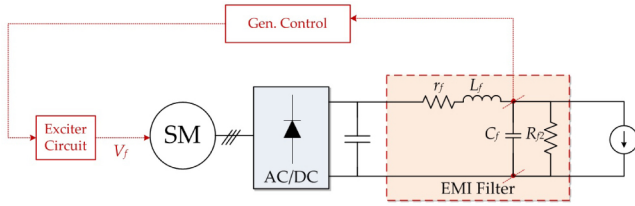


Figure 2. Typical generator configuration including exciter and control unit.

The use of ES for pulsed power loads were studied in [5] for naval applications. In this case, focus was placed on the sizing of the ES to handle large amounts of repeated pulsed loads. Along these same lines, Model Predictive Control (MPC) strategies have been utilized to control the energy flows between generator, load, and a hybrid ES [6].

This paper focuses on the system shown in Fig. 1. In Section II, a detailed description of a generator unit is presented and a reduced order system is computed. This model will be used in the MPC strategy formulated in Section III. The main goal of the MPC is to use the ES to minimize the bus voltage transient while keeping realistic constraints of the ES. In Section IV, a case study is presented with two purposes: first to design/state requirements for the ES which will guarantee a desired transient and primarily to demonstrate the MPC of the ES. Lastly, a conclusion and future work are stated.

II. GENERATOR MODELING

A typical model of a generator unit for aircraft power systems is shown in Fig. 2. The dynamic model of the generator and its control unit are fundamental in the stability study and transient analysis of an aircraft power system. However, as can be seen from this figure, the total nonlinear system can have a large number of states due to the exciter (typically a small synchronous or induction machine), generator model (synchronous machine), and EMI Filter [7]. Furthermore, it is possible to include multiple generators, loads, and energy storage models which will increase the complexity of the overall system. In this section, a simplified model of a closed loop generator unit with a passive rectifier is derived beginning with a nonlinear representation of the diode bridge and followed by a model order reduction and second order approximation.

Nonlinear Model

The synchronous generator model considered is rated 200 kW. The nonlinear model of the generator and rectifier attempts to simplify the switching transitions of the diode bridge by a parametric average value model. The detailed derivation of this model has been presented in [8, 9, 10]. Since the dynamic equations representing a synchronous generator are well known [11], the main challenge lies in the representation of the diode rectifier. Due to its nonlinearities, the input-output relation of the dc side to the ac side (dq frame) are given by:

$$v_{qs} = \alpha(z)v_{dc} \cos(\delta), \quad (1)$$

$$v_{ds} = \alpha(z)v_{dc} \sin(\delta), \quad \text{and} \quad (2)$$

$$i_{dc} = \beta(z) \sqrt{i_{ds}^2 + i_{qs}^2} \quad (3)$$

where v_{qs} , v_{ds} are the inputs to the generator, v_{dc} is the voltage at the dc side, i_{qs} , i_{ds} are the outputs of the generator, and i_{dc} is the input of the dc filter. The parameters $\alpha(z)$ and $\beta(z)$ are the parametric values that describe the rectifier and they are assumed to be a function of the loading factor $z \triangleq v_{dc}^2/P$. Lastly, the angle δ is as follows:

$$\delta \triangleq \tan^{-1} \left(\frac{i_{ds}}{i_{qs}} \right) - \phi(z) \quad (4)$$

where $\phi(z)$ is the power factor. In general, the main values of interests for this model are $\alpha(z)$, $\beta(z)$, and $\phi(z)$ which are obtained from simulations by varying the loading factor z . These are shown in Fig. 3 for the machine parameters considered in this paper.

Note that from Fig. 3, the parameters vary slightly from small power to full power. Hence, in many cases these parameters α , β , and ϕ are chosen as constant in order to simplify the system even further [8]. The nonlinear open loop model of a generator and rectifier can be described as:

$$\dot{x}_{g-fo} = Ax_{g-fo} + Bf(x_{g-fo}) + B_f v_f \quad (5)$$

where x_{g-fo} includes the machine in dq variables and dc side states.

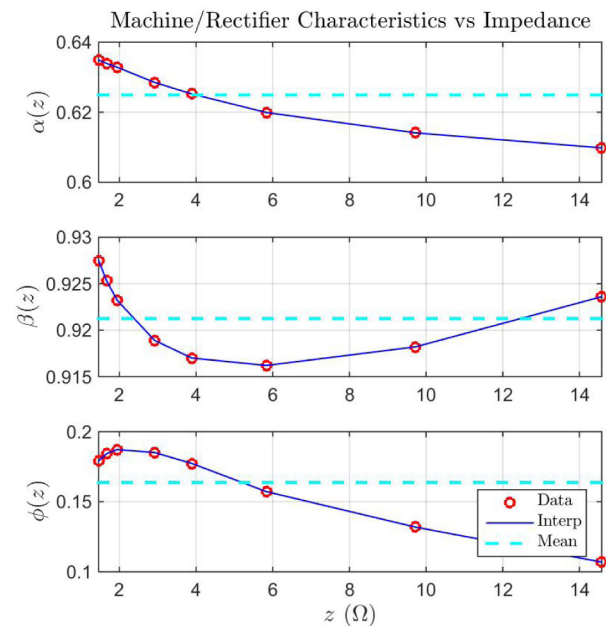


Figure 3. Rectifier values with respect to the loading factor.

One of the advantages of this model is that it is possible to linearize it in order to design the controller to regulate the dc side voltage. A PI controller was implemented to regulate the output voltage to ± 270 V_{dc}. The designed controller has a bandwidth of 395 rad/sec, gain margin of 30 dB, and a phase margin of 64°. The nonlinear model of