

# Parametric Average-Value Converter Modeling for Aerospace Applications

Patrick Norman  
Univ. of Strathclyde

John Timothy Alt  
Rolls-Royce Corporation

Graeme Burt  
Univ. of Strathclyde

## ABSTRACT

Uncontrolled rectifiers are featured heavily in aircraft electrical power systems performing a number of the power conversion and conditioning functions. Detailed modeling and simulation of these and other converters as part of a wider aircraft power system, whilst accurate, can be very computationally intensive, resulting in impractically slow simulation speed. One potential solution to this issue is the use of average-value converter models, which offer a much lower computational requirement and can utilize larger time steps. Of the average-value diode rectifier modeling methods presented in the research literature the parametric method is particularly well suited to system-level simulation because it can be readily derived to represent all modes of rectifier operation. To date however, published results utilizing this methodology have been limited to simpler power system architectures. In order to assess its applicability for more complex networks, such as those found in modern aircraft systems, more extensive study is required. As such, this paper presents a simulation based evaluation of the flexibility and accuracy of the parametric method for operation in aircraft power systems, considering the impact on model accuracy resulting from changing power system network topology, loading, supply frequency and electrical faults. Recommendations are then made for the use of the parametric method in these applications.

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## INTRODUCTION

With the increasing electrification of modern aircraft, designing and optimising electrical power systems which integrate a diverse range of sources and loads, whilst minimising weight and yet adhering to strict safety standards is becoming progressively more challenging [1, 2]. Modelling and simulation underpins component design and is also increasingly employed as a cost effective tool to evaluate system level behaviour. In this manner, risks associated with system-integration and operation can be identified at an early stage in the design process. Key to exploiting the potential value of modelling and simulation for these purposes is the development of methods to enable time efficient completion of potentially computationally intensive studies [3, 4].

However, the simulation of multi-disciplinary aerospace power systems models typically involves wide ranging

system time constants often causing very long simulation times. One method to overcome this problem is to facilitate the use of larger simulation time steps by employing average-value modeling of electrical subsystems and components. Average-value modeling is a process which represents the fast switching operation of power electronic devices over a given period (this is usually a single switching interval) in an approximate time-averaged fashion. This behavior is typically less computationally demanding to solve and facilitates the use of larger simulation time steps. Both aspects can enable significantly quicker completion of simulations without the loss of significant accuracy at frequencies of interest.

The development of average-value models of fully controllable converters, whose outputs are primarily determined by the actions of associated control systems, is

often readily achievable. However, the dependence of a diode rectifier's operating state on its loading conditions and surrounding network topology ensures that the derivation of average-value models for these converter types is far more challenging. Consequently, the state variables of the rectifier must be averaged directly, such that the impact of the network characteristics is effectively included within the rectifier model itself.

Of the diverse range of diode rectifier model averaging methods presented in the literature, the parametric method is particularly appealing due to its versatility and ease of implementation [5, 6, 7, 8, 9]. This method utilizes detailed simulations of the rectifier and surrounding circuit to characterize the relationships between the ac and dc terminals of the rectifier for all conduction modes. In this manner, relatively simple equations of operation can be employed within the resulting average-value model, reducing the development time of models (compared to more conventional mathematical approaches) [5].

As a result of recent research advances [6, 7, 8, 9], developers of the parametric method propose that only a single simulation of the detailed model is required to populate the parametric model and that its implementation can be achieved using relatively simple two-dimensional lookup tables. In this manner a single set of values for the key model parameters is deemed sufficiently accurate for a wide range of circuit states and operating modes. These claims are supported with comprehensive simulation results for the test networks considered. As these networks are typically of simpler configuration than employed in aircraft power distribution systems, the authors in this paper are keen to investigate the robustness of the parametric approach when applied to more complex power networks.

For these reasons, this paper considers the applicability of the parametric method for use in aircraft power systems simulation by assessing the variation in key model parameters for changes in network state which are representative of aircraft power system operation. Following on from the initial work presented in [10], this paper provides a detailed investigation into the impact of additional loading, converters and faults on the ac side of the diode rectifier, and variable frequency supply systems on the parametric average-value model operation and accuracy. Conclusions are then drawn regarding particular parameter sensitivities relating to the application of the parametric method to large signal modeling and simulation of aircraft power systems.

## PARAMETRIC AVERAGE-VALUE METHOD

The parametric method was developed in order to provide an alternative to the more established but complex algebraic methods [11, 12, 13, 14] of modeling diode rectifiers in an average-value fashion. The core principle of this method is to employ detailed simulations of the rectifier and its associated network in order to numerically define the relationships

between the ac terminals and dc link of the rectifier for all conduction modes. In doing so, much simpler equations of operation can be utilized within the average-value model, facilitating quicker model development. Research literature demonstrates this method in use for high synchronous machine-rectifier systems [6, 7, 8], variable frequency systems [9], and more recently for line-commutated converters [15].

Typical equations governing the operation of a three phase average-value parametric diode rectifier model (as provided in [12]) are

$$\bar{v}_{qs}^r = \alpha(\cdot) \bar{v}_{dc} \cos(\delta_r), \quad (1)$$

$$\bar{v}_{ds}^r = \alpha(\cdot) \bar{v}_{dc} \sin(\delta_r), \quad (2)$$

$$\bar{i}_{dc} = \beta(\cdot) \|\bar{i}_{qds}\|, \quad (3)$$

and

$$\delta_r = \arctan\left(\frac{\bar{v}_{ds}^r}{\bar{v}_{qs}^r}\right) = \arctan\left(\frac{\bar{i}_{ds}^r}{\bar{i}_{qs}^r}\right) - \phi(\cdot). \quad (4)$$

The terms  $v_{ds}$ ,  $v_{qs}$ ,  $i_{ds}$ ,  $i_{qs}$  are the ac side voltages and currents of the rectifier defined in the synchronously rotating reference frame (denoted by the superscript  $r$ ),  $v_{dc}$  and  $i_{dc}$  are the dc side voltage and current, and the terms  $\alpha$ ,  $\beta$  and  $\phi$  are the unknown algebraic functions describing the rectifier's switching behavior. Average-value models derived through the parametric approach are readily suitable for large signal dynamic studies and associated small signal models can be easily derived from these for specific stability studies.

The parametric approach inherently incorporates the impact of adjacent machine and network elements into the equations of the rectifier's operation, allowing for a much quicker development for full system models than is typically possible with the more traditional mathematical methods. The main potential drawback associated with the parametric approach is the timely requirement to develop and simulate the detailed network models in order to derive the parameters for the associated average-value model. As such, published research in this field has centered on the proposal of novel methods to mitigate this issue.

Authors in [7] propose using just a single simulation with the detailed model to capture all the data required to populate the average-value rectifier model. In order to achieve this, the authors recommend that the detailed model be used to simulate a transient event whereby the dc side load of the rectifier is varied from a short circuit condition state to a very lightly loaded state (i.e. very high impedance). Following the completion of the detailed simulation, the parameters  $\alpha$ ,  $\beta$  and  $\phi$  can then be defined in terms of the dc side load impedance.

Results given in [7] show that this approach provides accurate model behavior whilst achieving a substantial reduction in the model development overhead (previously, multiple simulations with the detailed model were required to characterize the average-value parameters for various operating points).

The validity of the parametric method for rectifiers within variable frequency power systems is explored in [9]. The authors argue that the governing equations for the average-value model are independent of the supply frequency as long as the parameters derived from the detailed model are evaluated over a single switching interval. In this manner, parameter sets for  $\alpha$ ,  $\beta$  and  $\phi$  can be derived at one particular frequency, but remain valid for a wide range of supply frequencies. Results are presented in [9] to support the claim made by the authors.

The focus of the research on the parametric method to date has largely been on networks which are smaller and less complex than those employed in aircraft power systems. For applications with larger, more varied power system designs, there is a requirement to explore the sensitivity of the key model parameters  $\alpha$ ,  $\beta$  and  $\phi$  to various changes in the surrounding network state. The key research question is whether for average-value models integrated into more complex power systems it remains sufficient to still implement the parameter sets for  $\alpha$ ,  $\beta$  and  $\phi$  as just a function of dc side load impedance only, or whether the dependence of the rectifier's operation on other circuit variables in these instances also needs to be accommodated. If the latter case is found to be true, a greater number of detailed model simulations would be required to populate the parametric average-value model, a more complex implementation of the parametric model may also be necessary.

Given the criticality of these aspects to the successful application of the parametric method, it is important to conduct research into these issues and to propose solutions that, as best possible, preserve the simplicity of the method and its implementation.

## EVALUATION OF PARAMETRIC METHOD FOR AEROSPACE APPLICATIONS

This section presents an investigation into the suitability of the parametric approach for use within aircraft power systems modeling and simulation. More specifically, simulation studies will be conducted to evaluate any variation in magnitude of  $\alpha$ ,  $\beta$  and  $\phi$  when changes in the surrounding network state (representative of an aircraft power system operation) occur. On this basis, the complexity associated with using the parametric approach for aircraft power system modeling and simulation can be assessed.

### Model Overview

Figure 1 illustrates the circuit schematic of the representative aircraft power system model utilized for

simulation based investigation of the parametric method. This model has been developed within Matlab and Simulink [16], using the SimPowerSystems library components.

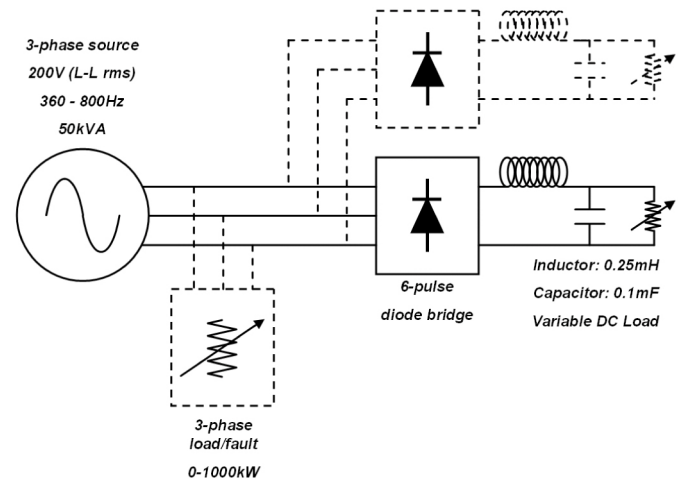


Figure 1. Representative aircraft power system architecture

The representative power system consists of a 50kVA rated, 200V (line-line), 400Hz voltage source, supplying a variable 270Vdc load through a 6-pulse diode rectifier. Necessary measurements are taken from this model in order to derive values for the terms  $\alpha$ ,  $\beta$ , and  $\phi$ , and are based on the expressions given in [7] and earlier in equations (1), (2), (3), (4).

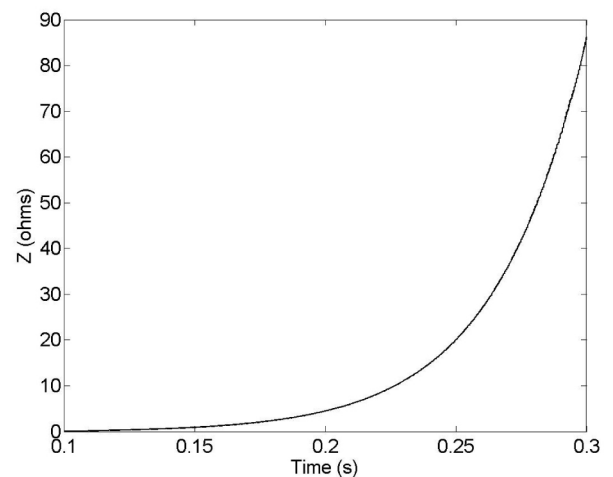


Figure 2. DC load impedance during load sweep

Four separate case studies are presented in the following subsections. In each of these, (and in line accordance to proposed method given in [7]), the dc side load impedance of the rectifier is increased exponentially from a short circuit state to a high impedance value over a period of 0.2 seconds, thereby taking the rectifier through all modes of operation. Figures 2 and 3 illustrate this impedance sweep and the associated dc link voltage. Figure 3 shows the ac side