ANALYSIS OF SUBSYSTEM INTEGRATION IN AIRCRAFT POWER DISTRIBUTION SYSTEMS

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ABSTRACT

Stability analysis of a baseline power system architecture for modern aircraft is addressed. Power electronic converters are widely used in modern aircraft power distribution systems. Due to their inherent nonlinear characteristics, instabilities may arise while integrating individual subsystems together. Bifurcation analysis is used to identify the type, multiplicity and stability of system trajectories. The complete bifurcation diagram for the baseline power system is drawn. The dependence of the parameter values on the bifurcation behavior of the baseline system is presented.

1. INTRODUCTION

Considerable attention has been paid in recent years to the development of power-by-wire technologies for modern aircraft. As a result, modern aircraft power distribution systems have seen the widespread use of power electronic converters to drive various loads and actuation systems. Power electronic converters are inherently nonlinear systems. The problem of instability that arises due to the integration of these subsystems has been addressed in the past. It is well known that the classical impedance ratio criterion [1] relies on linear analysis techniques in the determination of stability of the interconnected system but it only guarantees local stability in the neighborhood of an equilibrium solution. The application of nonlinear analysis techniques to gain a global understanding of the behavior of the system thus becomes important. However, nonlinear analysis methods do not immediately appeal to the system designer because of their mathematical complexity. In [2] and [3], nonlinear methods were used in the analysis of interaction between an input filter and a regulated power converter modeled as a constant power load. The objective of the paper is to extend this analysis to a baseline power system architecture by studying the bifurcation behavior of the system as a function of a chosen critical parameter. The organization of the paper is as follows: Section 2 introduces the sample power distribution system as a single source-single load system. The source subsystem is a three-phase boost rectifier that feeds the 270V DC bus of the power distribution system. The load subsystem is a regulated DC-DC buck converter with a front-end input filter, which is similar to that studied in [1]. The bifurcation analysis of the input filter-load converter system is presented in Section 3. The bifurcation behavior of the baseline system is then explained in Section 4. Finally, the dependence of the bifurcation behavior of the baseline system on parameter values is presented in Section 5.

2. BASELINE POWER SYSTEM ARCHITECTURE

The sample power system architecture shown in Figure 1 is used as the baseline power system in the analysis of subsystem interaction presented in the paper. The three-phase boost rectifier converts the three-phase sinusoidal voltages from the generator (modeled as an ideal voltage source) to the regulated 270V DC required by the bus. The load subsystem represented by Subsystem 2 in Figure 1 is a regulated DC-DC converter with a front-end input filter. The other loads on the DC bus are modeled by a current source, negative impedance (other regulated power converters) or a simple resistance.

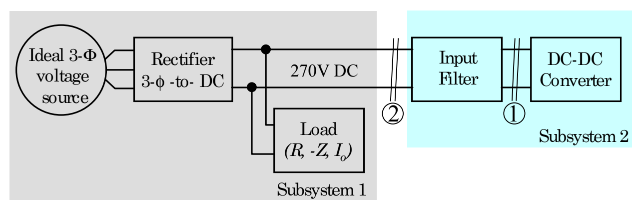

Figure 1. Baseline Power System Architecture

The three-phase boost rectifier is represented by its average model in rotating *dq*-coordinates synchronized with the input line voltages [4]. The load converter is also represented by its corresponding average model. These average models neglect the switching frequency ripple and hence are valid only at frequencies much lower than the switching frequency. The stability analysis of the complete interconnected system starts with identifying the critical subsystem interfaces denoted by (1) and (2) in Figure 1 and analyzing in turn, the stability of each of the interfaces with appropriate terminations.

3. BIFURCATION ANALYSIS

The bifurcation behavior of the input filter-load converter interface (denoted by (2) in Figure 1) in subsystem 2 is studied [7,8]. The circuit schematic of the average model of a closed loop DC-DC buck converter with an input filter is shown in Figure 2. However, the regulated DC-DC converter is represented by the average model in contrast to the constant power model used in [1]. The resistance R_f, of the input filter is chosen as the control parameter. The complete bifurcation diagram is shown in Figure 3.

The normal form equations [5] of the system in the neighborhood of the Hopf bifurcation point are given by Equation 1.

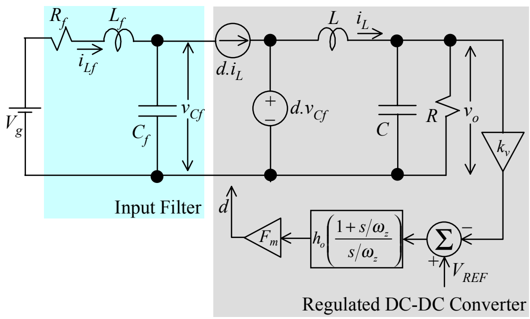

Figure 2. Closed Loop Buck Converter with Input Filter

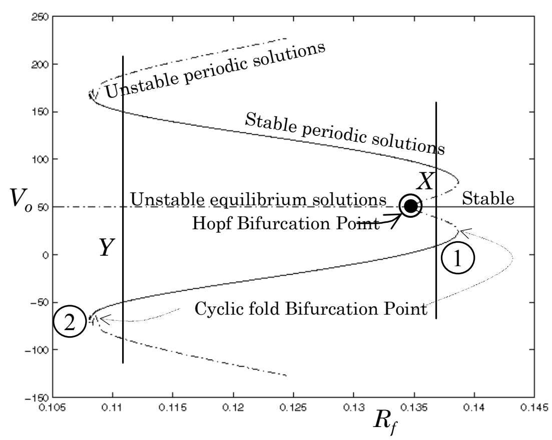

Figure 3. Bifurcation Diagram of Subsystem 2

$$\dot{a} = \Delta R_f \alpha_1 a + \alpha_2 a^3$$
$$\dot{\theta} = \Delta R_f \beta_1 + \beta_2 a^2 \qquad \text{.....} \quad (1)$$

The sign of the constant α_2 determines whether the bifurcating periodic solutions from the Hopf point are stable or unstable (i.e) if the Hopf point is supercritical or subcritical respectively. If $\alpha_2>0$, the bifurcation is subcritical and vice versa. In this case, $\alpha_2=2.93415\text{x}10^{-6}$ and hence the bifurcation is subcritical as expected from the results presented in [1]. The complete bifurcation diagram is constructed using the methods presented in [5, 6]. The bifurcation diagram in Figure 3 thus provides a global picture of the system behavior as a function of the control parameter. For example, a stable equilibrium point (say X in Figure 3) can be disturbed strongly to drive the system to a periodic solution. On the other hand, an unstable equilibrium point (say Y) when perturbed ends up in a stable periodic solution. However, the resulting voltage oscillations may be quite unacceptable for the safe operation of the system. The bifurcation analysis is now extended to the baseline system in the following section.

4. STABILITY ANALYSIS OF THE BASELINE POWER SYSTEM

The circuit schematic of the baseline power system is shown in Figure 4.

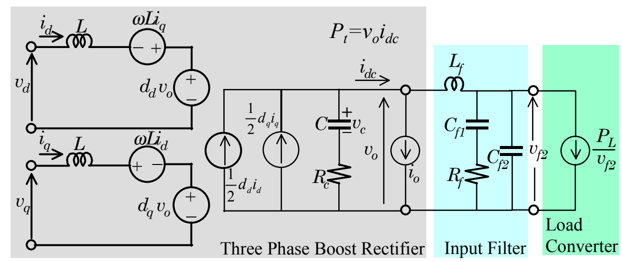

Figure 4. Circuit Schematic of Baseline Power System.

The three phase boost rectifier is represented by its *dq*- average model in rotating coordinates synchronized with the input line voltages [4]. A multi-loop controller for the three phase boost rectifier consists of an outer loop to regulate the output voltage and two inner current loops one each for the *d*- and *q*- axis input currents. The total power supplied by the boost rectifier is given by $P_t=v_o i_{dc}$ (Figure 4). The control block diagram of the three-phase boost rectifier is shown in Figure 5.

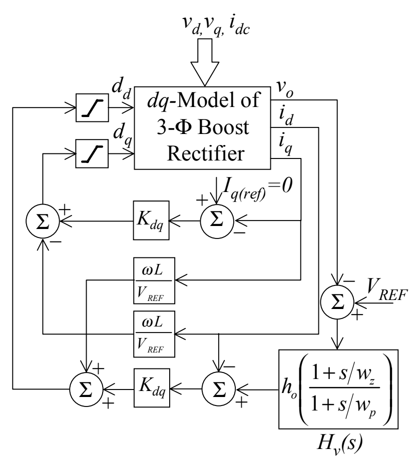

Figure 5. Control Block Diagram of the Three-Phase Boost Rectifier.

The DC-DC converter in subsystem 2 is similar to that presented in the previous section. In order to simplify the analysis, it is represented by a constant power load with the same modifications as in [1]. The input filter, however, is modified to a more practical two-stage configuration with the damping resistance in a shunt path to minimize the power loss.

The first step in the analysis of the baseline system is the determination of the control parameter(s) for the bifurcation analysis. The three phase boost rectifier feeds the DC distribution bus of the baseline power system with a stiff regulated voltage of 270V. One of the critical performance indices of the rectifier is its bandwidth of regulation. This parameter can be related to the transient response and disturbance rejection properties of the rectifier. In addition, the bandwidth is intimately related to the stability of the rectifier and hence of the baseline system. The gain h_o of the voltage controller $H_v(s)$ (Figure 5) is directly related to the bandwidth of the rectifier and hence is chosen as the control parameter for the bifurcation analysis of the baseline system.

The stability analysis proceeds as follows: The stability of the equilibrium solutions of the baseline system is determined as a function of the control parameter, h_o. The total power P_t, supplied by the boost rectifier is divided equally between the constant current load i_o, and the constant power load P_L/v_{f2}. The complete bifurcation diagram for the baseline system for $P_t=8kW$ is shown in Figure 6.

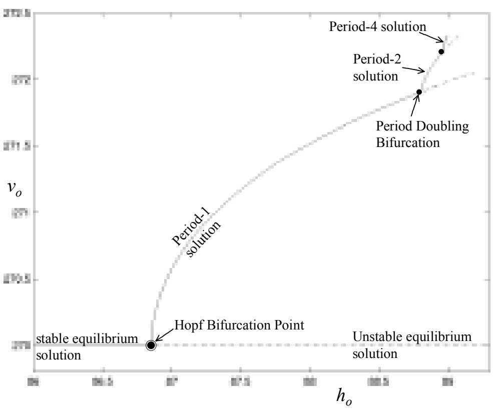

Figure 6. Bifurcation Diagram of Baseline System as a function of h_o for $P_t=8kW$.

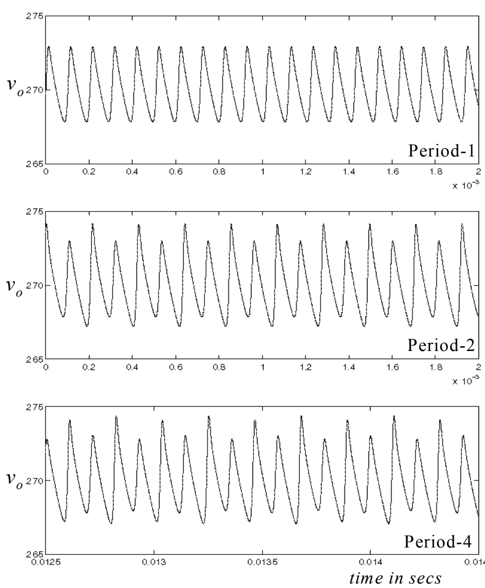

Figure 7. Periodic Solutions of Baseline System

The equilibrium point loses stability through a Hopf bifurcation at $h_o=86.8295$ for $P_t=8kW$. The normal form equations of the system at the Hopf point indicate that the bifurcation is supercritical (i.e) the bifurcating periodic solutions are stable as shown in Figure 6. As the branch of periodic solutions is followed, their stability is also monitored by observing the corresponding Floquet multipliers. A period doubling bifurcation occurs at $h_o=88.7904$ where, one floquet multiplier exits the unit circle through (-1,0). This is followed by another period doubling bifurcation to a period-4 solution. These periodic solutions are shown in Figure 7.

5. DEPENDENCE ON PARAMETER VALUES

The baseline system considered in this paper consists of two interconnected nonlinear subsystems namely, the three phase boost rectifier and the regulated load converter with input filter. The analysis method presented above considers the stability of the baseline system as a whole, regardless of the stability of the individual subsystems. To this end, as the control parameter is varied, the stability of the three phase boost rectifier as a standalone system terminated by the load P_t, is determined, in addition to that of the baseline system. The parameter values that yield the results shown in Figures 6 and 7 are such that, the equilibrium point of the boost rectifier as a standalone system loses its stability before that of the baseline system (i.e) for $h_o<86.8295$. Such a situation is only of academic interest as it defeats the entire purpose of subsystem integration in that, an unstable system (the boost rectifier) is integrated with a stable system (the filter-load converter subsystem) to form the stable baseline system. However, a different set of parameter values can result in an unstable baseline system while preserving the stability of the individual subsystems. It is the parameters of the boost rectifier that determine the manner in which the baseline system loses stability.

Since, the load on the DC bus is not constant at all times, the rectifier should provide "good" regulation of the DC bus voltage at all load levels. Since the baseline system is essentially nonlinear, the bandwidth of the regulator can be expected to change significantly with the load. Hence, it becomes important to study the effect of the regulation bandwidth of the rectifier on the stability of the baseline system for different values of power P_t. The values of h_o for which the baseline system loses stability were determined for different values of power P_t. For each value of P_t, the type of the Hopf bifurcation was determined by obtaining the normal form equations of the baseline system. The values of α_2 in the normal form equations are given in Table 1 for different values of power P_t. In Table 1, case 1 is identified as the situation where the baseline system preserves its stability in spite of the boost rectifier being unstable, and that wherein the baseline system loses its stability with the individual subsystems being stable is identified as case 2.

Table 1. α_2 for Case 1 and Case 2.

P_t	Case 1		Case 2	
(kW)	α_2	$h_{o(hopf)}$	$\alpha_2(10^{-6})$	$h_{o(hopf)}$
8	-0.01213	86.8295	26.9384	19.5325
16	-0.00818	45.8968	12.6145	8.5091
24	-0.00733	31.9366	4.6564	5.4051
32	-0.00854	24.6799	-3.0179	4.0491
40	-0.00773	19.9758	-6.4271	3.3109
48	-0.00214	16.5835	4.6585	2.8485
56	0.005724	14.0965	38.5256	2.5291

It can be seen from Table 1 that, the type of bifurcation for case 2 changes from subcritical to supercritical and back as the power is increased. Further investigation is necessary to identify the reasons for such a behavior. However, the normal form equations provide an idea about the post-bifurcation behavior of the system, which can be used to design fault-clearing systems in the event of an instability. In addition, it can be seen from Table 1, that the values of h_o for which the baseline system loses stability, decrease with increasing power. Hence, with the knowledge of the maximum possible load on the DC bus, h_o can be chosen such that the equilibrium solutions are stable at all load power levels or can be adaptively varied as a function of the load for optimal performance of the converter.

CONCLUSIONS

Stability analysis of a baseline power system was presented. A single source single load system was considered as the baseline system. The bifurcation behavior of the input filter load converter subsystem provided a global picture of possible system trajectories. The analysis was extended to the baseline system with the controller gain h_o as the control parameter. Two distinct cases of loss of stability were identified. The bifurcation behavior of the baseline system was studied for different load power levels.

Acknowledgements

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APPENDIX

Parameter Values:

Three Phase Boost Rectifier		
Variable Name	Case 1	Case 2
ω_z	*2500 rad/s*	*500 rad/s*
ω_p	*25000 rad/s*	*5000 rad/s*
ω	$2\pi 400$ *rad/s*	$2\pi 400$ *rad/s*
L	$18\mu H$	$258\mu H$
C	$350\mu F$	$2400\mu F$
Input Filter		
L_f	$10\mu H$	
C_{f1}	$100\mu F$	
C_{f2}	$10\mu F$	
R_f	0.5Ω	