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ACTIVE DAMPING OF DC POWER NETWORKS

by

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Abstract

The research involves devising new control and compensation methods for DC power distribution systems containing power electronics loads with constant power characteristic. A compensation method called an active damping network is examined, which utilises capacitor and inductor energy storage elements and high frequency switching devices. This network is controlled to behave as a small-signal resistor so that any instabilities in the power distribution system due to the interaction between interconnected sub-systems will be damped and eliminated successfully. This method is studied and analysed in detail. The system was designed and simulated, and was verified by experimental results. The results show that stable operation is achieved of a small-scale power distribution system that contains power electronic loads with constant power characteristics such as DC-DC converters and electrical drives.

Dedicated to

My Parents

My wife

Che Ku Noorlaila Che Engku Ismail

and my children

Mohd Asyraf

Nur Amirah

Muhammad Akram

Nurul Afiqah

Muhammad Asmu'i

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AC	Alternating current
CPL	Constant power load
DC	Direct current
DPS	Distributed power supply
HPF	High pass filter
LVR	Line voltage regulator
MEA	More electric aircraft
NSSC	Non-linear system stabilising controller
PWM	Pulse width modulation
SMES	Super conducting magnet energy storage
TRU	Transformer rectifier unit
VSMD	Variable speed motor drive

SYMBOLS

A	Average state matrix
B	Average input matrix
C	Average output matrix
D	Duty ratio
D_L	Load impedance denominator
D_s	Source impedance denominator

f_s	Switching frequency
h_C	Current controller transfer function
h_r	Current reference transfer function
I_c	Capacitor current
I_{in}	Converter inductor input current
I_L	Load current
I_S	Source current
K	Root locus gain
K_v	Voltage controller gain
K_r	Active damping input resistance gain
K_a	Current controller gain
L	Active damping inductor
C	Active damping output capacitor
L_S	Input filter inductor
C_S	Input filter capacitor
N_L	Load impedance numerator
N_s	Source impedance numerator
P_{in}	Converter input power
P_o	Converter output power
Q	Quality factor
R_L	Small-signal input resistance of CPL

R_s	Series input resistor
R_C	CPL line resistance
L_C	CPL line inductance
s	Laplace operator
t	Time
T_m	Small-signal loop gain
U	Input variable
V_c	Filter capacitor voltage
V_{in}	Active damping device input voltage
V_{meas}	DC bus voltage
V_s	DC supply voltage
V_o	Active damping device capacitor (output) voltage
X	State variable
Z_D	Input impedance of active damping device
Z_{in}	Input impedance of LC filter
Z_L	Input impedance of load converter
Z_s	Output impedance of source converter
Z_o	Output impedance of LC filter
Z_T	Total impedance of load and active damping device
δ	Small-signal perturbation
ζ	Damping factor
ω	Angular frequency

ω_{co}	Converter closed-loop controller bandwidth
ω_{vo}	Voltage control loop bandwidth
ω_f	HPF corner frequency
ω_o	Resonant frequency

CHAPTER ONE

1.0 Introduction and Literature Survey

1.0 General Introduction

Over the past few years, there has been extensive research into sub-system interaction and instability phenomena in Distributed Power Systems (DPS). A DPS is a system, usually DC, where the power processing functions are distributed among many power processing units or DC/DC converters at the point of need. The distributed system is increasingly being used in applications such as aircraft, spacecraft, hybrid-electric and electric vehicles, ships, defence electronic power systems, industrial production lines, communication and computer systems and many more. This research is concerned with the generic problem of instability and interaction in DC DPSs and the active damping devices that are required to ensure orderly operation, but is oriented towards aircraft applications.

Integration of small systems to form large and complicated systems is vital for many applications. When two stable sub-systems are combined or integrated together, there is no guarantee that the combined system will be stable, there may be an interaction between the interconnected sub-systems which can result in instability in the system. Even though the sub-systems may be well designed for stand-alone operation, the possible interactions may still occur once the sub-systems are integrated.

Previously, the system oscillation phenomenon was rarely a problem. This is because the individual sub-systems such as a switching regulator, were mainly stand-alone units operating from a low source impedance and driving a passive load. But nowadays since the cost has reduced, switching regulators are more widely used in many applications. Very often with one switching regulator serving as the source for several other converters, for example switching regulators, inverters and motor drives, the potential for load-source interaction is therefore very high.

The interaction arises because each individual converter has internal control functions, such as the regulation of the converter output voltage or motor speed. As a result, the converter tends to draw a constant power and therefore has a negative incremental input resistance within the bandwidth of the converter control loop. When the source voltage falls, then the operation of the internal controller results in the converter drawing more current. This in turn could cause the source voltage to fall even further.

In a stable system, all transient terms die away with time and conversely systems in which a transient term increases indefinitely are unstable. To ensure stable operation, appropriate control techniques need to be investigated. This Chapter gives an introduction and a survey of relevant literature for the area of DC distribution systems in aircraft. It also discusses the issue of modelling, analysis and control/damping methods, the use of software tools as well as the scope of the thesis.

1.1 More Electric Aircraft (MEA) Concept

Traditionally, aircraft have many sub-systems powered by one or more sources of secondary power, namely hydraulic, pneumatic, electrical and mechanical. Secondary power is extracted from the main engines mechanically by a drive shaft and pneumatically by bleeding the compressor. Mechanical power is distributed through gearboxes to drive lubrication pumps, fuel pumps, hydraulic pumps and electrical generators. Pneumatic power drives an air turbine motor for engine start systems and environmental control systems, whereas electrical power is used mainly for lighting, avionics equipment, de-icing equipment and the galleys [1].

In recent years, considerable attention has been paid to the development of fly-by-wire systems for modern aircraft and the replacement of hydraulic actuators with direct electromechanical devices. As a result, the electrical power requirements on aircraft are predicted to rise significantly over the next few years and it is projected that in the future all power except propulsion will be distributed and processed electrically. The emphasis of utilising electrical power as opposed to hydraulic, pneumatic, and mechanical is principally to reduce weight and life-cycle cost and is known as the "More Electric Aircraft (MEA)" ([1]-

[8]). This concept has been promoted across the whole aerospace industry and has been responsible for some of the recent advancements in power electronics, power distribution systems and flight control actuators [9].

MEA approaches result in the widespread use of electrical power and power electronic components and systems to enhance reliability, fault-tolerance, power density and performance of aircraft systems ([10]-[11]). For instance, power density for all power conditioning systems can be increased by using the latest technology in power electronics such as resonant or soft switching techniques which allow higher operating frequencies. Also, the use of new converter topologies with advanced power components as the power switches are predicted to increase system efficiency [12]. For example in [13] new, high power aircraft electric actuation systems with power ratings up to 50kW were proposed. The conventional hydraulic actuators used for flight control surfaces, undercarriage and braking, will be replaced by electro-mechanical and electro-hydraulic actuators and their associated power electronics. Many of the main pumps associated with fuel and lubrication are currently coupled directly to the engine. In the MEA approach, these are likely to be driven by variable speed electrical drives with associated power electronic converters. There is also a growing demand for DC power for passenger in-flight entertainment terminals. Besides, the power distribution system is likely to operate at either DC or with variable frequency AC (400-800Hz) rather than the constant 400Hz AC that is currently used. This allows the variable-ratio gearboxes used in the generators to be eliminated.

Many advantages and benefits are offered by the MEA approach, however, as the electrical systems become more complex with increased numbers of power electronic loads, the possibility of load-source interaction and instability will increase. To reduce and overcome the instability in the system, some methods of compensation or damping need to be devised .

1.2 Distributed Power System (DPS)

In a centralised power distribution system, a single power supply unit provides all the necessary output voltage levels, which are then cabled around the system and used where required. This can result in complex and heavy cabling systems, poor power quality at the point of use, and a system which is difficult to expand.

In the DC DPS or power conditioning system ([13]-[20]), the power is no longer supplied by a single power source but a primary power converter is used to generate a coarsely regulated voltage which is then converted to the required level at the point of use. That is the power processing functions are distributed among many power processing units or smaller power modules at the point of need. Many industries today are considering the use of a DPS since it offers benefits in terms of weight, size, isolation, voltage regulation, flexibility and capability to integrate a large variety of loads and many more. In addition, a DPS also enables one to control more easily the quality of power reaching each separate board [14]. In spite of so many advantages, the DPS has some drawbacks such as interaction between the converters and bus instability, as well as imbalance in power distribution among parallel converters, which leads to an unequal distribution of output current. This problem may create excessive stress on some of the modules and increase their rate of failure [15].

The DC power distribution system may actually be a very large complicated system and it is not easy to model or analyse the whole system. However, in order to understand and investigate the system behaviour more easily, one can consider the problem of a DPS by simplifying it. Figure 1.0 shows a simplified model of a typical two-stage DPS connected in series through an intermediate DC bus.

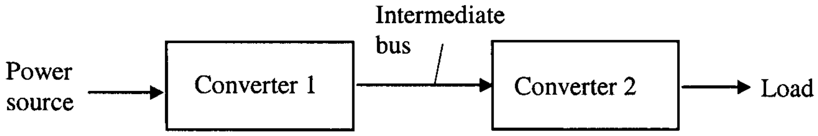

Figure 1.0. Simplified 2-stage DPS system

Converter 1 and converter 2 can be referred to as the source converter and load converter respectively. Both converters could be switching regulators or sometimes the source will be a switching regulator and the load will be a variable speed motor drive (VSMD). The actual load is connected to the output of converter 2. The first converter provides a loosely regulated

DC voltage to an intermediate bus, and the second converter converts the intermediate bus voltage to a regulated voltage for the load. Converter 2 sometimes consists of several converters connected in parallel to drive various loads. For some applications, the first stage may consist of a conventional 6 or 12-pulse transformer rectifier unit (TRU) and output filter or more advanced pwm rectifier with power factor correction capability to provide a regulated voltage required by the intermediate bus. The second converter may consist of an input filter and a DC-DC converter (typically a forward converter) supplying a tightly-regulated low voltage for each load.

Furthermore an input filter is often required between a switching regulator and its DC bus bar in order to prevent the input current waveform of the switching regulator from interfering with the source and to preserve the integrity of the source for other equipment that may be operating from the same input [21]. The source output filter performs similar functions. The cause of sub-system interaction in the intermediate bus is explained in ([22]-[25]) in more detail.

The output filter of converter 1 and input filter and impedance of converter 2 form a complex resonant system with little natural damping. If converter 2 has a constant power characteristic and a negative input resistance, the total system resistance will be affected by this negative resistance, which may tend to destabilise the network. Even though the source converter, converter 1, has a small positive output resistance, the interaction in this complex filter network may cause oscillations which cannot be damped by this resistance [26].

Therefore it is very often necessary to include additional passive damping to prevent instability. The cascading of multiple input supplies and multiple output loads will degrade the stability of the system further. Multiple loads will reduce the total magnitude of the negative input resistance of the load converter, making system instability more likely as explained by the Middlebrook criterion [27].

1.3 Analysis Methods for Load-Source Converter Interaction

The interaction between the source converter and load converter needs to be studied and analysed in detail. A variety of methods has been proposed to examine the instability effects, using either linear or non-linear techniques. These methods are reviewed below starting with the well-known impedance ratio criterion.

1.3.1 Impedance Ratio Criteria

The stability criterion based on the impedance approach for DC power systems was first studied and developed by Middlebrook [27]. His research concerns the system stability due to the interaction between the input filter and the DC power supply for small-signal conditions. The outcome of his research was the establishment of a well known stability criterion based on the ratio of the output impedance of converter 1 and the input impedance of converter 2.

A simple design rule based on this criterion states that the system will be locally stable if the magnitude of the input impedance of the load sub-system is larger than the magnitude of the output impedance of the source sub-system at various system interfaces. In other words, he showed that when the magnitude plots of source and load impedance do not intersect, the system is stable, and if impedance intersection happens, the system may not be stable. Figure 1.1 shows a circuit of a simple two-stage DPS system, where Z_s is the output impedance of the source converter and Z_L is the input impedance of the load converter.

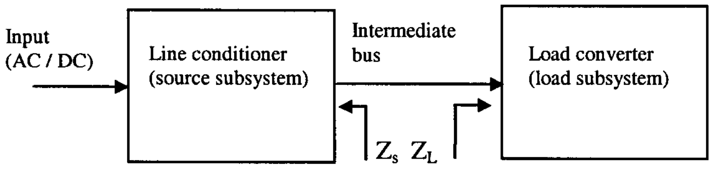

Figure 1.1: Simple 2 -stage DPS system

More precisely, Middlebrook's stability criterion states that if the impedance magnitude intersection occurs, then the system will still be stable providing that the impedance ratio transfer function $\frac{Z_s}{Z_L}$ satisfies the Nyquist stability test. As an example, the plot of the impedance ratio transfer function, $\frac{Z_s}{Z_L}$ in figure 1.2 shows the system is stable since there is no encirclement of point (-1,0) in the complex plane.

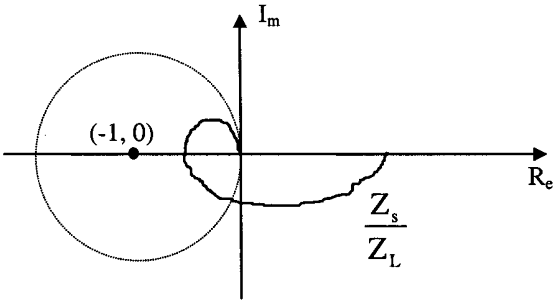

Figure 1.2: Impedance criterion plot

This criterion has been used in [21] where the interaction between the input filters and DC-DC switching-mode regulators was analysed. The analysis of sub-system interaction between an electro-mechanical actuator load and source-rectifier connected via the DC DPS bus has been analysed in detail in ([28]-[30]). The research was done by observing the impedance characteristics of the simplified source and the load sub-system and determining the critical parameters that affect the local stability. In [31], the dynamics of a buck converter connected to a CPL have been examined in detailed. This criterion seems to be very conservative as it requires a total separation between the input and output impedance at the interface, which could be too costly in the implementation [32].

A less stringent criterion based on consideration of the phase of the impedance as well as the magnitude was proposed by Lee. He suggested that both the phase and magnitude can be used to infer the system stability if the magnitude condition is violated. This is similar to the Nyquist test on the impedance ratio transfer function. Lee introduced a method to determine the load impedance specification for a stable DPS system ([33]-[36]). This method shows that a phase specification is necessary for a system to be stable, if the impedance magnitudes overlap at the bus interface. The bus impedance, which determines the quality of the distribution bus is given by the parallel combination of load input impedance, Z_L and source output impedance, Z_S. When impedance overlap occurs, the bus impedance experiences a peaking at the frequency of the overlap. The impedance peaking is a function of the phase margin, where a small phase margin will cause significant peaking and will degrade the quality of the bus.

The impedance ratio criterion has a big advantage over the other stability-analysis tools that have been used for large scale systems in that it analyses the whole system based on the input-output impedance of each sub-system instead of detailed inner properties of sub-systems [40]. This criterion also offers an additional benefit as shown in [27], where the dynamic de-coupling between a switch-mode regulator (load converter) and its input filter is achieved. The full derivation of the impedance criterion is presented in Chapter two.

1.3.2 Other Linear Analysis Techniques

There are many linear system techniques which may be used to analyse the stability of a DC system. Most of the methods are based on linearising the systems about an operating point. Liapunov's theorem of the first approximation states that, if the linearised system is stable then the non-linear system is also stable in a local region about that operating point [37]. Once the linearised system is obtained, the stability of the system can be determined by simply looking at the system eigenvalues. Negative eigenvalues indicate that the system is stable and positive eigenvalues show that the system is unstable.

The root locus technique is a common linear systems technique that has been used to examine the relative stability of a system. This technique enables one to use open-loop system transfer functions so that the closed-loop transfer function eigenvalues can be readily obtained. The relative stability and the transient response performance of a closed-loop control system are directly given by the location of the closed-loop roots of the characteristic equation ([38]-[39]). This technique uses the graphical approach which allows the system gain parameter, K, to be changed on the s-plane. The "gain" K could be any system parameter such as a damping resistor that has been used in a passive damping network. Therefore, by simply varying the resistance over a range, the system eigenvalues can be shown on the s-plane.

In ([22],[33],[40]) an introduction is made to a method called impedance specification and impedance improvement to prevent the load-source impedance, T_m, from circling (-1,0) in the Nyquist plot. Again, the work done by Middlebrook can be considered as the earliest contribution of making an impedance specification. To implement this specification, the concept of a forbidden region for the load-source impedance transfer function was proposed. By keeping the transfer function out of this region, small-signal system stability can be ensured with a gain margin of 6dB and phase margin of 60^o. If the output impedance of the source is known, then the forbidden region can be transformed into a load input impedance specification, Z_L.

In ([41]-[42]), the stability of the Electrical Power System (EPS) of the Space Station Freedom (SSF) is also examined using this method. Since this system consists of multiple sources and loads, few interface points are selected to ease the stability study.

1.3.3 Non-linear Analysis Methods

Small-signal analysis cannot be used to determine the system stability over large disturbances imposed to the system. The principle of superposition cannot be applied, and linear analysis tools such as Laplace transforms, the impedance ratio criterion and transfer functions are no longer valid. Non-linear methods are an alternative to solve these problems and include mixed potential, bifurcation, phase plane and describing function methods.

The mixed potential function is a Liapunov-type function that resembles the Hamiltonian in some of its characteristics [43], where a potential function based on elements and topology of the circuit are searched. In this paper, this technique was used to examine the system stability under large signal disturbances for a circuit consisting of a single source connected to single and multiple filter-load configurations.

The bifurcation methods were used in ([21],[28]-[29],[44]). These techniques can be used to analyse the bifurcation behaviour of the system as a function of critical control parameters. For example in [21], the voltage controller gain of the boost rectifier was chosen as a control parameter since it is directly related to the rectifier bandwidth. This method provides a global picture of the system behaviour such as the possibility of achieving the system trajectory. However, non-linear analysis methods are not preferred because of the complexity and difficulty of their mathematical design.

1.4 Converter Modelling and Analysis Methods

There are many types of converter used in power electronic circuits such as DC-DC converters, AC-DC converters, DC-AC converters and so on. The discussion of modelling methods is oriented towards DC-DC converters since the active damping device examined in the research is essentially a bi-directional DC-DC converter. DC-DC converters are non-linear time-varying devices and a suitable modelling and analysis approach is needed to present the circuits in an appropriate form for design purposes. This is usually a linear model, enabling linear systems analysis to be applied in the design of the converter controller. Various averaging techniques are commonly used to simplify the periodic time-varying nature of power electronic converters and linearisation methods are then used to obtain transfer functions. These techniques are reviewed below.

1.4.1 State-Space Averaging and Linearising Technique

This is a very well known technique which has been widely used to model DC-DC converters ([45]-[47]). This method was initially proposed in [48] to analyse the dynamic properties of power supplies, and has also been used in ([49]-[50]). The simplified converter models using this approach are frequently used in simulation of pulse width modulated (PWM) converters. For a DC-DC converter operating in the continuous conduction mode, the averaging is undertaken by first writing the circuit state space equations for each of the two circuit configurations which occur in a cycle, that is corresponding to the on and off states of the transistor. The number of state-space equations depends on the number of circuit state