ADAPTIVE ACTIVE DAMPING METHODS FOR DC-AC POWER-ELECTRONIC-BASED SYSTEMS WITH CONSTANT-POWER LOADS

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Abstract

Many electronic loads in fast-developing power systems behave as constant-power loads (CPLs) which are known to exhibit negative incremental impedance and have a destabilizing effect in the system. To improve the stability of modern power systems with CPLs, research efforts have been focused on impedance-based and small-gain stability criterion, the design of advanced controllers, and passive or active damping solutions. Some disadvantages for most of the existing solutions include unnecessary energy losses in their passive elements, requirements of beforehand knowledge of the system characteristics, and inadaptability to the change in system operating conditions.

This thesis presents new methods for stabilizing power systems with CPLs using tunable active damping based on an auxiliary converter circuit. Therein, the load bus voltage is monitored and an active damper is used to stabilize the system once an instability is detected. The methodologies are first developed in DC power systems and later extended for three-phase AC power systems as well. The proposed methodologies are less conservative than traditional methods and its damping characteristics are established “on-the-fly” in real-time to achieve effective stabilization under various CPLs and different operating conditions that may be unknown a priori. The proposed methodologies are verified under three different power systems: a simplified version of an aircraft power system with two sources, a 48/24 VDC telecom system consisting commercially available converters, and a three-phase AC power system. It has been shown that the proposed methodologies can detect instability and damp the unstable oscillations in all three systems when the CPL power level becomes high.
Lay Summary

Modern power systems are facing many challenges due to the trend of using electronically-interfaced devices such as computers, LED lights, etc. From the perspective of the power systems, these devices have floating power demand that depends on required real-time computational resources and can be classified as constant-power loads (CPLs) which can destabilize the system when CPL power consumption becomes high. This thesis presents novel methods to solve the stability problems created by the CPLs, by using a smart auxiliary device that can be connected directly to any existing power system with large number of electronic loads. This smart auxiliary device determines the stability using the information it gathers from the bus to which it is connected to and injects damping current depending on the system operating conditions. The proposed method can be easily integrated into the existing power systems, and it is envisioned to become the stabilizing tool for the next-generation power systems with large number of electronic loads.
Preface

I am the main contributor to the material in this thesis and the associated publications. Some of the contents and results have already been published in conference papers, and some material is being summarized for a future publication. I am responsible for deriving equations, building simulation models, and analyzing results in all manuscripts as well as this thesis. My research supervisor, Dr. Juri Jatskevich, has provided feedback and comments throughout the writing process of this thesis and the corresponding papers. The co-authors of publications coming out from my thesis include Mr. Navid Amiri and Mr. Seyyedmilad Ebrahimi, who also helped in revising the manuscripts. I also received help from our former graduate student Mr. Alex Pizniur in terms of the simulation platform used for verification of some of the proposed stabilization methods.

Chapter 2 and 3 are based on the following conference papers that have been published:


Chapter 4 and 5 are based on the following conference paper that has been submitted for publication:

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<td>Alternating Current</td>
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<td>CPL</td>
<td>Constant-Power Load</td>
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<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
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<td>DPS</td>
<td>Distributed Power Systems</td>
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<td>RMS</td>
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Chapter 1: Introduction

1.1 Motivation

Presently, powers systems are expanding faster than ever due to the penetration of renewable energy sources and the development of power electronic devices. The hybrid AC-DC and pure DC distribution systems can be found in aircraft [1], ships [2], vehicles [3], computers and data centers [4], telecom systems [5], LED lighting [6], etc. The AC-DC and DC distribution systems are receiving wider acceptance and are envisioned to play a major role in the distribution systems of buildings and homes. In such distribution systems, most sources are interfaced through the power electronic converters, and the loads are also predominantly electronic loads that are tightly regulated and behave as constant-power loads (CPLs) [7].

A typical DC distribution system composed of multiple sources and loads is shown in Figure 1.1. The interactions between the loads and sources can make the system vulnerable to instability due to the negative incremental impedance exhibited by the CPLs [8].
To discuss and demonstrate the phenomenon of stability as pertains to the power electronic systems, a recently-developed microgrid as shown in Figure 1.2, is considered here. The microgrid is designed for AC-DC distributed energy resources (DER) system that has been installed by Alpha Technologies Ltd. in the Kaiser building on UBC campus. The system consists of several battery banks with a total capacity of a 1MWh and has the ability to feed the DC loads in research labs, shave the peak power of the building demand, and supply uninterrupted power to several points on the UBC campus. Within the system, many different electronic loads are connected to the 380VDC, 48VDC, and 24VDC buses as shown in Figure 1.2. These DC electronic loads are tightly regulated by power electronic devices and have floating power demand that depends on required real-time resources, in which constant power will be drawn regardless of the change in bus voltages. Thus, these electronic loads behave as
CPLs. As a result, when the bus voltage increases/decreases, the current drawn by each CPL will
decrease/increase, resulting in a negative incremental equivalent impedance.

![Block diagram of the Alpha Technologies Ltd. DC microgrid with multiple CPLs installed in the Kaiser building at UBC.](image)

Figure 1.2 Block diagram of the Alpha Technologies Ltd. DC microgrid with multiple CPLs installed in the Kaiser building at UBC.

At the same time, the three-phase AC systems that are formed by electronically-interfaced
sources (e.g. renewable energy sources and any energy storage that requires DC-AC power conversion) and loaded with tightly regulated electronic loads [9], may exhibit similar stability problems and interactions as the DC systems. For the purpose of discussion in this thesis, a three-phase AC distributed power system (DPS) composed of multiple sources and electronic loads is shown in Figure 1.3. Examples of such electronic loads in three-phase AC systems include energy-efficient appliances, energy storage devices, etc., most of which also behave as CPLs that may lead to instability problems over a wide frequency range [10].
To investigate the dynamic instability caused by the interactions of different components in the power-electronic-based systems, several stability criteria have been recently developed [7], [11] – [15]. According to the impedance-based stability criterion [11], the stability of a DC system can be guaranteed when the system source-to-load impedance ratio $Z_s/Z_l$ (as depicted in Figure 1.1) satisfies the Nyquist stability criterion. If the Nyquist criterion is not met, the system impedances can be shaped using passive [16] or active [17] – [20] elements to stabilize the DC system. Similarly to the DC systems, the stability of three-phase AC systems can be analyzed by extending the impedance-based stability criteria. For example, in three-phase AC systems, small-gain stability criteria [7] can be applied to determine the system stability, and passive [21] or active [22], [23] damping methods can be used to stabilize an unstable AC system.

Figure 1.3 A typical AC distributed power system divided into source and load subsystems at a common bus.
1.2 Existing Solutions for Instability Problems

A common method to stabilize a power-electronic-based system is to use passive damping [16], [21], in which series or parallel configurations of passive elements are used. A major drawback of such a method is that the system parameters must be known beforehand to calculate the damping circuit parameters [16], [21]. Furthermore, excess energy is consumed by the passive damping elements (resistors).

Various active damping methods for stabilizing unstable power-electronic-based systems have been proposed in [17], [18], [20], [22], in which the system is stabilized by modifying the control strategies of the source or load converters. However, changes in control strategies may affect the performance of the original converters, and variations in system conditions could influence the effectiveness of the damping methods themselves [24].

A recently proposed active damping method [19] for stabilizing the DC power-electronic-based systems is able to save the excess energy and pass it over to another stable DC bus in the system while achieving the desired stabilizing effect. However, the system oscillation frequency $\omega_{osc}$ at which instability occurs must be known beforehand to design the damping. Moreover, in modern distribution systems, the CPLs can be plugged/unplugged in different locations, and change the system impedances significantly as a result, which makes it very difficult to design damping circuits with fixed parameters (without making the design too conservative). Therefore, it is more desirable to have a method that is adaptive and able to change damping parameters using online measurement data.
Online impedance measurement methods have been proposed in [25] and [26], in which stability of the system can be predicted in real time by applying the impedance-based stability criterion. However, these methods cannot predict the high-frequency response of the system precisely, and therefore will not work in systems where the unstable frequency is high. An instability detection method based on voltage monitoring has been proposed in [27], in which the system stability is defined using a regulation band that sets the stable range of the load bus voltage. However, such a method does not work in systems with frequently changing input voltage [27] or systems with slow transient response.

An LC-filtered active damper that can be connected in parallel with the loads has been proposed in [23]. However, here the damper only changes its equivalent resistance value using real-time measurement data, while the filter is realized using passive elements with pre-set values that limit the functionality of the active damper. Overall, a more general solution for the stability problems caused by CPLs should be both adaptive and highly flexible, such that instability can be predicted, detected, and damped effectively and efficiently.

1.3 Research Objectives

To propose a working solution, it is important to identify the root cause of stability problems in power-electronic-based systems with CPLs. As different stability criteria have been recently developed for DC systems and AC systems [7], [11] – [15], it is possible to analyze system stability if appropriate models of a given power system can be developed. Therefore, the first step involves modeling of different components in the power-electronic-based systems, including
voltages sources, constant-power loads etc., as well as applying the recently-developed stability criteria to evaluate the system stability.

In this thesis, we propose two novel control methods which use active damping techniques to stabilize DC and AC power-electronic-based systems with constant-power loads. Compared to the existing stabilization methods, the proposed methods overcome the limitations of existing damping and instability detection methods (such as fixed frequency bandwidth, excess energy use, etc.) without the need of prior knowledge of other system parameters. Both proposed methods are based on an add-on auxiliary circuit [19] that injects damping current into the unstable load bus of the system, the voltage of which is monitored online to determine system stability. The methods envision the use of a low power auxiliary circuit that can be connected to any load bus that has a potential problem of going unstable for the purpose of ensuring system stability. Specifically, the following objectives are considered to advance the goal of this research:

**Objective 1 – Propose stabilization methods for DC systems with CPLs**

Objective 1 is to propose stabilization methods based on an auxiliary circuit for DC systems with CPLs. As system voltages/currents will oscillate with increasing magnitude when the system becomes unstable, it is possible to determine system instability by monitoring the load bus voltage. Once the system is determined to be unstable, an auxiliary circuit can be used to inject damping current to the load bus to stabilize the system. As a result, this objective involves determining DC system stability using online measurement data, modifying the system transfer
functions using active damping techniques, and realizing the injection of the damping current to the load bus using an auxiliary circuit.

**Objective 2 – Extend the proposed stabilization method to three-phase AC systems**

Objective 2 is to extend the proposed stabilization method based on an auxiliary circuit for DC systems with CPLs to three-phase AC systems with CPLs. In AC systems, the load bus voltage naturally oscillates at a fundamental frequency, which makes it more difficult to determine system instability directly. However, by applying synchronous reference frame transformation [28], system voltages/currents become constant in the steady state, and the stabilization methods proposed for DC systems can be extended to the three-phase AC systems with some modifications. As a result, this objective involves determining the three-phase AC system instability using the transformed online measurement data; modifying the proposed stabilization methods to fit in the three-phase AC systems by modifying system transfer matrices using active damping techniques; and realizing the injection of the damping currents to all phases using a three-phase auxiliary circuit.
Chapter 2: Stability of DC Systems with Constant-Power Loads

2.1 Impedance-Based Stability Criterion for DC Systems

To investigate the stability and the interactions between various elements at the system level in a DC system, an impedance-based stability criterion has been developed and reviewed in [11]. In the traditional approach, a DC system is divided into a source subsystem and a load subsystem, with each having its own small-signal frequency response and impedance characteristic. Figure 2.1 shows a DC system that is represented using the impedance model, in which the source subsystem is represented as an ideal DC voltage source $v_s(s)$ in series with the source impedance $Z_s(s)$, and the load subsystem is represented as a load with impedance $Z_l(s)$.

![Figure 2.1 A DC system represented using the source and load subsystems for impedance-based analysis.](image)

With the assumed model in Figure 2.1, the source current $i_s(s)$ can be found as

$$i_s(s) = \frac{v_s(s)}{Z_s(s) + Z_l(s)}.$$  \hspace{1cm} (2.1)

Rearrange (2.1) to get
\[ i_s(s) = \frac{v_s(s)}{Z_l(s) \frac{1}{1 + Z_s(s)/Z_l(s)}}. \]  
(2.2)

According to [11], if it is assumed that, the source is stable when unloaded and the load current is stabled when supplied from an ideal source, both \( v_s \) and \( Z_l \) will be stable. If this is the case, the stability of the source current will depend on the transfer function \( H(s) \) as

\[ H(s) = \frac{1}{1 + Z_s(s)/Z_l(s)}. \]  
(2.3)

Because \( H(s) \) has a similar format as a closed-loop transfer function with a unity forward gain and a feedback gain \( Z_s(s)/Z_l(s) \), the transfer function \( H(s) \) is stable if and only if \( Z_s(s)/Z_l(s) \) satisfies the Nyquist criterion [11], i.e. its contour does not encircle negative one. To avoid such an encirclement, the phase shift of \( Z_s(s)/Z_l(s) \) must not equal to \( \pi \) when the magnitude of \( Z_s(s)/Z_l(s) \) is equal or greater than one, expressed as [29]

\[
\phi(Z_s(s)/Z_l(s)) \in [0, 2\pi], \quad |Z_s(s)/Z_l(s)| < 1
\]

\[
\phi(Z_s(s)/Z_l(s)) \neq \pi, \quad |Z_s(s)/Z_l(s)| \geq 1.
\]  
(2.4)

where \( \phi \) is defined as an operator to represent the phase shift of a transfer function, same as the phase shift operator \( \angle \).

### 2.2 Ideal DC Constant-Power Loads

A constant-power load is a load that is regulated by power electronic devices such that it draws constant power regardless of the load bus voltage. Ideally, the relationship between the load current \( i_l \), the load voltage \( v_l \), and the CPL power level \( P_{CPL} \) can be represented using

\[ i_l = \frac{P_{CPL}}{v_l}. \]  
(2.5)
Based on (2.5), if $P_{CPL}$ remains constant, any voltage drop in $v_l$ will cause an increase in $i_l$, resulting in a negative incremental equivalent impedance $Z_{CPL}$ expressed as [30]

$$Z_{CPL} = \frac{\partial v_l}{\partial i_l} = \frac{\partial}{\partial i_l} \left( \frac{P_{CPL}}{i_l} \right) = -\frac{P_{CPL}}{i_l^2} = -\frac{v_l^2}{P_{CPL}}. \quad (2.6)$$

If it is assumed that the CPL is ideal and has an infinite bandwidth, (2.6) can be expressed as a transfer function with a constant magnitude and a constant phase shift as

$$|Z_{CPL}(s)| = \frac{v_l^2}{P_{CPL}}, \quad (2.7)$$

$$\phi(Z_{CPL}(s)) = -\pi, \quad (2.8)$$

In real-world applications, because CPLs have limited control bandwidth, (2.7) and (2.8) only hold for a certain frequency range. In this thesis, it is assumed that instability only happens within the control bandwidth of the CPLs, such that the ideal model of CPLs can be used for system analysis purpose.

In the system of Figure 2.1, the load impedance $Z_l(s)$ includes all loads and CPLs connected at that bus. Moreover, since many of the DC loads are tightly regulated, the CPLs can be dominating the overall load behavior. When the considered CPL is the only load in the system, $Z_{CPL}(s)$ becomes $Z_l(s)$. In this case, (2.4) can be violated as long as $Z_{CPL}(s)$ becomes smaller than $Z_l(s)$ while there is no phase shift in $Z_l(s)$, which often occurs when $P_{CPL}$ becomes large.
2.3 Design of Passive RC Damper Based on Oscillation Frequency

When instability happens at the bus of a DC system, the bus voltage/current will begin oscillating with increasing magnitude, while the oscillation frequency $f_{osc}$ depends on the system transfer function(s). Different methods of stabilizing an unstable DC system using passive damping circuits have been reviewed in [16], among which the parallel $RC$ dampers are most effective because no energy is consumed in the steady state.

A parallel $RC$ damper consists of a damping resistor $R_d$ and a damping capacitor $C_d$, which are connected in series. This series $RC$ damper is then connected in parallel with the CPL as shown in Figure 2.2. According to [29], parallel $RC$ dampers stabilize the DC system with CPLs by shaping the frequency response of its equivalent load impedance. Specifically, parallel $RC$ dampers add a 180-degree phase shift to the CPL after a designed cutoff frequency, such that the frequency response of the combined load subsystem becomes resistive [29] (i.e. without phase shift), satisfying (2.4). The cut-off frequency $\omega_c$ of an $RC$ damper is equal to the inverse of its time constant $\tau_{RC}$, expressed as

$$\omega_c = \frac{1}{\tau_{RC}}, \quad (2.9)$$

$$\tau_{RC} = R_d C_d. \quad (2.10)$$
Figure 2.2 Simplified DC system with added parallel RC damper to shape the load impedance.

To make sure that the phase of the overall load subsystem impedance becomes resistive (i.e. current in phase with the voltage) before the system oscillation frequency \( \omega_{osc} \) as shown in Figure 2.3, the cutoff frequency \( \omega_c \) should be at least \( e^{\pi/2} \) times smaller than the system unstable frequency \( \omega_{osc} \) [29], expressed as

\[
e^{\pi/2} \omega_c \leq \omega_{osc}.
\]  

(2.11)

In this thesis, \( \omega_{osc} \) is set to be equal to \( e^{\pi/2} \omega_c \) to ensure system stability, expressed as

\[
e^{\pi/2} \omega_c = \omega_{osc},
\]  

(2.12)

and \( \tau_{RC} \) can be calculated by rewriting (2.9) and (2.12) as

\[
\tau_{RC} = \frac{1}{\omega_c} = \frac{e^{\pi/2}}{\omega_{osc}} = \frac{e^{\pi/2}}{2\pi f_{osc}} \approx \frac{0.7656}{f_{osc}}.
\]  

(2.13)
At frequencies higher than $\omega_c$, the equivalent load impedance becomes the parallel impedance of $R_d$ and $Z_{\text{CPL}}$, expressed as

$$|Z_i(s)| = \frac{|Z_{\text{CPL}}(s)| R_d}{|Z_{\text{CPL}}(s)| + R_d} \forall \omega > \omega_c.$$ (2.14)

To help design the $RC$ damper circuit based on its high-frequency impedance, the actual damper resistance can be set $u$ times smaller than $Z_{\text{CPL}}$ [29], expressed as

$$R_d = \frac{|Z_{\text{CPL}}(s)|}{u}.$$ (2.15)

where $u$ is some safety factor. Substituting (2.15) into (2.14) we get

$$|Z_i(s)| = \frac{|Z_{\text{CPL}}(s)|}{u + 1} \forall \omega > \omega_c,$$ (2.16)

which suggests that different values of $u$ will affect the equivalent load subsystem impedance for frequencies higher than $\omega_c$, and therefore will also affect the damping current $i_d$. These effects have been studied in [29] and [30]. If the value of $u$ is too small (e.g. close to zero), the resulting impedance at high frequency will be close to an open circuit. If the value of $u$ is too large (e.g.
close to infinity), the resulting impedance at high frequency will be close to a short circuit. Selecting a reasonable value for \( u \) (we set \( u = 2 \), as suggested in [29]) can effectively stabilize the system [29], [30]. Using (2.7), (2.10), (2.13) and (2.15) with \( u = 2 \), it becomes possible to design a parallel \( RC \) damping circuit which will stabilize the DC system for the apriori known values of \( v_l, P_{CPL}, \) and \( f_{osc} \).

### 2.4 Injected Current and Auxiliary Converter Circuit for Emulating RC Damper

A specifically designed parallel \( RC \) damper will only work in a specific system at a specific CPL power level. However, in an unknown system where either one or more of the parameters required during the design stage are not known, it would be impossible to design an effective passive damping circuit without making it too conservative. Instead of using passive dampers, the design of which depends on the knowledge of system parameters beforehand, one can use active damping techniques [29] to emulate the response of passive dampers. The advantage of this approach is that it would be possible to measure the required system parameters on-the-fly and tune the parameters of the active damping circuit accordingly.

An active damper injects the damping current \( i_d \) to the load bus of the system to stabilize it as shown in Figure 2.4. If the active damper is set to emulate the response of a passive damper with impedance \( Z_d \), the damping current can be found using the following relationship:

\[
    i_d(s) = \frac{1}{Z_d(s)} v_l(s). \tag{2.17}
\]
With respect to (2.17), if the parallel $RC$ damper is to be emulated, $Z_d$ becomes the series impedance of the damping resistor and capacitor, expressed as

$$
Z_d(s) = R_d + \frac{1}{sC_d} = \frac{sR_d C_d + 1}{sC_d}.
$$

Figure 2.4 Simplified DC system with added active damper injecting the damping current to shape the load impedance.

Compared to passive dampers, active dampers connected as shown in Figure 2.4 can also shape the system impedance. Moreover, some active dampers are capable of supplying the excess energy back to the system [29], which may be a very important feature for energy efficiency. Most importantly, their damping impedance can be changed online using real-time measurement data, making it possible to use this approach in systems with unknown or changing parameters.

Practically, active dampers can be realized using auxiliary devices such as the one proposed in [29]. The auxiliary circuit is made of a bi-directional buck converter (with parameters summarized in Appendix A.1), as shown in Figure 2.5, with the high-voltage side connected to a stable bus (which can possibly contain energy storage devices such as batteries) and the low-
voltage side connected to an unstable bus, allowing energy to flow in both directions during transients. The two switches of the converter are controlled using hysteresis modulation, where the input is the difference between the commanded current calculated from (2.17) and the actual measurement current, hence ensuring good current tracking in a wide range of frequencies. Compared to the auxiliary device built in [29] where \( Z_d \) is a constant transfer function that is specified during the design stage, here, \( Z_d \) is the transfer function in (2.18), where values of \( R_d \) and \( C_d \) are obtained using (2.7), (2.10), (2.13) and (2.15), as explained in Section 2.3.

Figure 2.5 Simplified diagram of the auxiliary converter circuit with its control used to realize the active damping method.
Chapter 3: Proposed Stabilization Methods for DC Systems

The auxiliary circuit emulating a passive $RC$ damper can be used to stabilize DC systems as long as all of the load bus voltage $v_l$, the CPL power level $P_{CPL}$ and the system oscillation frequency $f_{osc}$ are known. While $v_l$ and $P_{CPL}$ can be measured online directly, measurement of the system oscillation frequency requires special consideration. In this Chapter, a method to stabilize DC systems is presented, which uses the auxiliary circuit to stabilize an unstable system, while different ways of calculating system oscillation frequency and determining system instability are used.

3.1 Instability and Oscillation Frequency Estimation

3.1.1 Steady-State Load-Voltage-Prediction-Based Method

The first method to determine system instability and estimate system oscillations frequency is the steady-state load-voltage-prediction-based method (i.e. the “voltage prediction method”). The voltage prediction method is based on the fact that, even though the system voltage/current will start oscillating with increasing magnitude when the unstable mode of the system is excited, there should be a stable mode in the system if it had more damping. Based on this assumption, for the purpose of this thesis with respect to the system of Figure 2.1, the DC bus voltage $v_l$ can be decomposed into a stable predictable voltage $V_{pre}$ and an unstable oscillating voltage $v_{osc}$, expressed as

$$ v_l = V_{pre} + v_{osc}. \quad (3.1) $$
Therefore, as long as $v_l$ is monitored and $V_{pre}$ is predicted, the system oscillation frequency becomes the frequency of $v_{osc}$ that oscillates around zero, which can be measured by monitoring the zero-crossing events. Moreover, if it is assumed that the system only contains one unstable frequency, the zero-crossing events will naturally split the voltage waveform into evenly-spaced intervals, the maximum/minimum of which becomes the amplitude of the waveform that can be used to determine system instability.

3.1.1.1 Load Voltage Prediction

In a typical DC system where the controller of the source has no information about the actual voltage at the load bus, there will be a difference between the source voltage and the actual load voltage caused by the voltage drop across the equivalent resistance of the line cable, as shown in Figure 3.1. This voltage drop in steady state will be proportional to the load current $i_l$, which can be measured directly. As a result, as long as the source voltage $v_s$ and the line resistance $R_{line}$ are known, $V_{pre}$ can be predicted and calculated as

$$V_{pre} = v_s - R_{line}i_l.$$  \hfill (3.2)

![Figure 3.1 Simplified DC system depicting equivalent cable resistance used for predicting the load voltage.](image)
Once the predicted load bus voltage $V_{pre}$ has been found, the unstable oscillating voltage can be extracted as

$$v_{osc} = v_I - V_{pre}.$$  \hfill (3.3)

### 3.1.1.2 Oscillation Frequency Estimation Based on Trigger Signal Generation

To facilitate the discussion in this section, an example of identified voltage $v_{osc}$ is shown in Figure 3.2. Once $v_{osc}$ has been obtained using (3.3), it is possible to generate a trigger signal $g$ to mark the exact time instance when a zero-crossing event happens. In this way, $v_{osc}$ can be split into many evenly-spaced half-cycles of its own with length $t_{osc}$, as shown in Figure 3.2. The system oscillation frequency $f_{osc}$ can then be found using

$$f_{osc} = \frac{1}{2t_{osc}}.$$  \hfill (3.4)

![Figure 3.2 An example demonstrating the voltage prediction method with (a) the load voltage $v_I$, the predicted voltage $V_{pre}$ and the amplitude of oscillating voltage $v_{amp}$ and (b) the trigger signal $g$ and the time interval $t_{osc}$.](image-url)
3.1.1.3 Instability Determination Based on Amplitude of Oscillating Voltage

When instability occurs in a DC system, the voltage/current of the system at the load bus will start oscillating with increasing magnitude. Therefore, one way of determining system instability is to check if $v_{osc}$ is indeed oscillating with increasing amplitude. As $v_{osc}$ has been split by the zero-crossing events into intervals within which all the data points have the same sign, amplitude of $v_{osc}$ inside each interval becomes the corresponding maximum/minimum. As a result, the amplitude of $v_{osc}$ for the most recent interval will become $v_{amp}[k]$, whereas the amplitude for the previous interval becomes $v_{amp}[k - 1]$, as shown in Figure 3.2. Instability can then be determined by comparing the most recent two amplitudes.

The flowchart for the instability determination method has also been depicted in Figure 3.3. At the beginning, the system is initialized by setting all variables to zero. The system then waits for trigger signal $g$ to proceed. When $g$ becomes one, a half-cycle of $v_{osc}$ has been captured, and the amplitude $v_{amp}[k]$ of $v_{osc}$ in the past half-cycle will be calculated. Thereafter, the ratio $m$ of the two subsequent amplitudes $v_{amp}[k]$ and $v_{amp}[k - 1]$ is calculated as

$$m = \frac{v_{amp}[k]}{v_{amp}[k - 1]}.$$  
(3.5)

If the ratio $m$ is greater than one, the oscillation is growing, and an unstable mode of the system has been excited. To make sure this is not caused by transients or noise presented in the system, a counter $n$ is used to store the number of times the ratio $m$ has been greater than one in the same sequence, and the system will wait for $g$ to become one again to repeat the same process with the next amplitude. If the counter $n$ reaches a pre-defined constant $N$ specified by the user, the
system has been determined as unstable, and appropriate damping should be activated to stabilize the system. If the ratio $m$ is smaller or equal to one, oscillation is not growing, and the counter $n$ will be reset to zero.

![Flowchart](image)

Figure 3.3 Flowchart for determination of instability based on monitoring voltage amplitude of oscillations.
3.1.2 Time-Window-Based Method

While the voltage prediction method can be used to determine system instability effectively, it does require a prior knowledge of the system line resistance. Alternatively, system instability can be determined using the time-window-based method (i.e. the “time window method”), in which there is no need for any information of the system. The time window method keeps track of the load bus voltage \( v_l \) for a certain period of time, within a time window. The size of the time window depends on both the sampling frequency and the expected unstable frequency range. Once a time window has been set up, a local extrema search algorithm may be used to locate all local extrema within the time window. The system oscillation frequency can then be calculated directly from the time difference between the local extrema, and system instability can be determined from the ratio of the absolute voltage difference between the local extrema points.

3.1.2.1 Time Window Setup

For a system with an oscillation frequency of \( f_{osc} \), at least two complete cycles are required to eliminate the effect of noise and transients within the system when determining instability. As a result, if the sampling frequency of the online measurement data is \( f_{sam} \), the minimum number of points \( n_{sam} \) required within the time window to determine system instability will be equal to

\[
n_{sam} = 2 \frac{f_{sam}}{f_{osc}}.
\]  

(3.6)

As the actual system oscillation frequency may vary, the minimum possible oscillation frequency will be used as \( f_{osc} \). The size of the time window \( t_{win} \) then becomes
3.1.2.2 Oscillation Frequency Estimation Based on Local Extrema Points

Once all data points within the time window have been obtained, it is possible to find all local extrema presented within the time window. To eliminate the effect of noise, any local extrema with a prominence of less than a certain voltage tolerance $V_{tol}$ will be ignored, while the rest of the local extrema is labeled as $v_x$, with $v_x[k]$ being the most recent local extreme, as shown in Figure 3.4. Then, (3.4) can be used to find the system oscillation frequency, with $t_{osc}$ being the time difference between any two consecutive $v_x$ points.

Figure 3.4 A sample time window of 10ms demonstrating local extrema points and increasing oscillations with different frequencies: (a) 416.7Hz and (b) 232.6Hz.
3.1.2.3 Instability Determination Based on Local Extrema Points

The flowchart for the instability determination method presented in this subsection is depicted in Figure 3.5. At the beginning, all the local extrema \( v_x \) within the time window are extracted. Once all local extrema have been found, it is possible to use their values for determining the system instability by monitoring the magnitude of oscillations. In particular, it is possible to define the ratio \( m \) of the peak-to-peak magnitudes of \( v_x \), expressed as

\[
m = \frac{v_x[k] - v_x[k - 1]}{v_x[k - 1] - v_x[k - 2]},
\]

(3.8)

where \( v_x[k] \), \( v_x[k - 1] \) and \( v_x[k - 2] \) refer to three most recent local extrema of \( v_t \). To make sure the increase in magnitude is not caused by noise or transients, if \( m \) is greater than one, the same approach of counting the number of consecutive time \( m \) has increase can be used. A counter \( n \) is then used to store the number of times \( m \) is greater than one, and the process monitored until \( n \) reaches a pre-defined constant \( N \) specified by the user. If the process ends by reaching \( N \), the system has been determined as unstable, and appropriate damping should be applied to stabilize the system.
3.2 Calculation of Damping Parameters for DC Systems

Once the system has been determined as unstable, a programmable auxiliary circuit as explained in Section 2.4 may be used to stabilize the system. Given that $f_{osc}$ has been found
using one of the methods presented in Section 3.1, the damping parameters $R_d$ and $C_d$ required for (2.18) can be calculated by re-writing (2.7), (2.10), (2.13) and (2.15), as

$$R_d = \frac{|Z_{CPL}(s)|}{u} = \frac{v^2_i}{2P_{CPL}}, \quad (3.9)$$

$$C_d = \frac{\tau_{RC}}{R_d} = \frac{0.7656}{R_d f_{osc}}. \quad (3.10)$$

3.3 Case Studies

3.3.1 Stabilizing an Aircraft Power System Using the Voltage Prediction Method

The voltage prediction method is verified in this Section using a Thevenin equivalent circuit of a sample aircraft power system with AC and DC subsystems. The considered aircraft power system is shown in Figure 3.6, and it consists of two AC generators $G_1$ and $G_2$, rectifiers, and various service loads. The rectified voltages may be configured through the appropriate switchgear for possible redundancy, and are used to supply the CPLs within the DC subsystem as shown in Figure 3.6. The model of the considered example system has been implemented in PLECS [31] blockset in the MATLAB/Simulink [32], [33] environment, and also verified with the real-time simulator Typhoon HIL [34] using the TMS320F28335 Delfino Microcontroller [35].
3.3.1.1 Modeling of an Aircraft Power System

Figure 3.7 shows the Thevenin equivalent circuit of the system represented in source-load form for the stability analysis. For this purpose, the rectified voltage has been modeled as a constant voltage $V_{th}$ and the line cable has been modeled as an $RL$ branch with resistance $R_{th}$ and inductance $L_{th}$. A DC filter capacitor $C$, as well as the proposed auxiliary circuit, is connected in parallel with the equivalent CPL.

Figure 3.7 Thevenin equivalent model of the aircraft system with an auxiliary circuit and a CPL.
In the first test case where the system is supplied by only $G_1$, the impedance for the source subsystem can be written as

$$Z_s(s) = \frac{sL_{th} + R_{th}}{s^2L_{th}C + sR_{th}C + 1}.$$  \hspace{1cm} (3.11)

It can be observed from (3.11) that the transfer function $Z_s(s)$ has a double pole at the system natural frequency $f_n$ that can be calculated as

$$f_n = \frac{1}{2\pi \sqrt{L_{th}C}}.$$  \hspace{1cm} (3.12)

By using the system parameters given in Appendix A.2, $f_n$ is found to be 145.29Hz, and the source subsystem impedance is found to be $2.692\Omega$ at this frequency. On the other hand, the load subsystem impedance is found using (2.6) to be only $-1.356\Omega$, suggesting a violation of the stability criterion presented in (2.4). This relationship can also be seen from the bode plot of the system impedances depicted in Figure 3.8.
If the proposed auxiliary circuit is used to stabilize the system, the transfer function $Z_s(s)$ will be effectively shaped to (III) as depicted in Figure 3.8, satisfying the stability criterion (2.4) as its magnitude is always smaller than $Z_l(s)$ (IV) at all frequencies. The damping resistance and capacitance are found to be $R_d = 678.1\,\text{m}\Omega$ and $C_d = 7.771\,\text{mF}$ using $f_{osc} = 145.29\,\text{Hz}$ in this case.

In the second test case where both $G_1$ and $G_2$ are used to supply the system, the transfer function $Z_s(s)$ is changed to

$$Z_s(s) = \frac{1}{2} \frac{sL_{th} + R_{th}}{s^2L_{th}C + sR_{th}C + 1},$$

(3.13)
which has the same natural frequency $f_n = 145.29\text{Hz}$. The magnitude of the source system impedance is found to be $1.346\Omega$ at this frequency, very close but smaller than the magnitude of the load system impedance $1.356\Omega$ found earlier. As a result, the ratio of the source system impedance and the load system impedance is very close to one at this frequency, which indicates that the system is still stable but very close to the unstable mode, according to the impedance stability criterion (2.4). The Bode plot of the transfer function $Z_s(s)$ when two generators are connected is also depicted in Figure 3.8, in which at all frequencies the magnitude of $Z_s(II)$ is smaller than the magnitude of $Z_l(IV)$. However, if one of the generators is disconnected while the system is still fully loaded, all power will have to be supplied by the other generator and the system will become unstable, as analyzed in the first test case.

3.3.1.2 Simulation with PLECS in MATLAB/Simulink

The Thevenin equivalent model of the aircraft system has been built with the PLECS [31] block set in the MATLAB/Simulink [32], [33] environment. Both of the two test cases are run to validate the effectiveness of the proposed control strategies. Figure 3.9 shows the results of the first test case in which the system is successfully stabilized in a few cycles. Initially, the system is loaded with $P_{CPL} = 20\text{kW}$ and operates normally. At time $t = 0.01\text{s}$, $P_{CPL}$ starts to increase at a rate of $10\text{MW/s}$ up to $50\text{kW}$. When no damping is applied to the system as shown in Figure 3.9 case (I), the system becomes unstable as the load bus voltage and current oscillate with increasing magnitude. However, when the proposed auxiliary circuit is activated at time $t = 0.026\text{s}$ as shown in Figure 3.9 case (II), the oscillations are damped within four half-cycles (as specified by the user) and the system eventually stabilizes.
Figure 3.9 Transient response of several system variables due to a change in the CPL power level: (a) $P_{CPL}$, (b) $v_l$, and (c) $i_l$. Case (I) is when no damping is applied and case (II) is when the proposed auxiliary circuit is used.

Figure 3.10 shows the results of the second test case in which the system is successfully stabilized in a few cycles. Initially, the system is operating normally when loaded with $P_{CPL} = 50$ kW and supplied by two sources. At time $t = 0.01$s, generator $G_2$ is disconnected and all power is transferred to $G_1$. When no damping is applied to the system as shown in Figure 3.10 case (I), the system becomes unstable as the load bus voltage and current, as well as the generator power, oscillate with increasing magnitude. However, when the proposed auxiliary circuit is activated at time $t = 0.024$s as shown in Figure 3.10 case (II), the oscillations are damped within four half-cycles (as specified by the user) and again the system eventually stabilizes.
Figure 3.10 Transient response of several system variables due to the disconnection of one of the sources: (a) $P_1$ and $P_2$, (b) $v_i$, and (c) $i_l$. Case (I) is when no damping is applied and case (II) is when the proposed auxiliary circuit is used.

### 3.3.1.3 Simulation with Typhoon HIL and DSP

The Thevenin equivalent model of the aircraft system has also been built with the Typhoon HIL [34] using the TMS320F28335 Delfino Microcontroller [35] to verify its applicability and implementation in an actual DSPs. The considered system has been built using the Typhoon HIL schematic editor, while all controls have been coded in the TMS320F28335 Delfino Microcontroller. The first test case that has been done using the PLECS [31] block set in the MATLAB/Simulink [32], [33] environment is rerun here with the results depicted in Figure 3.11
and Figure 3.12. Initially, the system is loaded with $P_{CPL} = 20kW$ and the system operates normally. At time $t = 0.01s$, $P_{CPL}$ starts to increase at a rate of 10MW/s up to 50kW. The results are depicted in Figure 3.11 and Figure 3.12.

When no damping is applied to the system as shown in Figure 3.11, the system becomes unstable as the load bus voltage and current oscillate with increasing magnitude. However, when the proposed auxiliary circuit is activated at time $t = 0.026s$ as shown in Figure 3.12, the oscillations are damped within four half-cycles (as specified by the user) and the system eventually stabilizes. The results obtained from the Typhoon HIL controlled by the TMS320F28335 Delfino Microcontroller show exactly the response as the simulation model built with the PLECS block set in the MATLAB/Simulink environment, proving the accuracy of the simulation model and the effectiveness of the proposed control method.
Figure 3.11 Response of several system variables due to a change in the CPL power level obtained from the Typhoon HIL without damping: (a) CPL power level $P_{CPL}$, (b) load bus voltage $v_l$, and (c) load current $i_l$.

Figure 3.12 Response of several system variables due to a change in the CPL power level obtained from the Typhoon HIL with proposed active damping enabled: (a) CPL power level $P_{CPL}$, (b) load bus voltage $v_l$, and (c) load current $i_l$. 
3.3.2 Stabilizing a DC Microgrid Using the Time Window Method

The DC microgrid mentioned in the Introduction of the thesis is used to verify the effectiveness of the time window method. Within the considered microgrid shown in Figure 3.13, the instability may be observed at the output of the 48/24 DC-DC converter [36], which is caused by the interactions of different components connected to the 24VDC bus as shown in Figure 3.13. The 380VDC and 48VDC busses are stable due to the large battery banks installed at these busses. As the 48/24 DC-DC converter [36] has been well modeled and studied in [37], the model built in PLECS [31] block set in the MATLAB/Simulink [32], [33] has been modified to verify the proposed stabilization method. Specifically, two CPLs with different power level are connected to the same 24VDC bus with cables of different length, and the auxiliary converter circuit is installed between the 48VDC bus and the 24VDC bus, as shown in Figure 3.13. For the considered system, the instability will occur at the 24VDC bus when the power level of these two CPLs becomes high. The purpose of the installed auxiliary circuit is to stabilize the system when needed according to the active damping methodology presented in this thesis.
Figure 3.13 Modified block diagram of the Alpha Technologies DC microgrid with multiple CPLs at the 24VDC bus. An auxiliary circuit is installed between the 48VDC bus and 24VDC bus to stabilize the system.

3.3.2.1 Modeling of a DC Microgrid

As instability can be observed on the 24VDC bus of the DC microgrid shown in Figure 3.13, the high voltage side of the 48/24 DC-DC converter is assumed as an ideal 48VDC source and only the 24VDC side of the converter is modeled for the purpose of this thesis. Figure 3.14 shows the detailed schematic of the considered 48/24 DC-DC converter, which is a six-phase interleaved flyback DC-DC converter that steps down 48VDC to 24VDC.
To analyze the instability within the system, all the loads at the 24VDC bus are assumed to the two designed CPLs. As depicted in Figure 3.15, the CPLs are realized using buck converters which regulate their output voltage to control the power consumption of the resistor $R_{\text{buck}}$ connected at the output terminals. These two CPLs are connected to the 24VDC bus through two different cables; with CPL 1 connected using a short cable with a lower inductance $L_{\text{short}}$, and CPL 2 connected using a long cable with a higher inductance $L_{\text{long}}$. Since these CPLs work independently, and because instability occurs in the system at different power levels, for the purpose of studies in this thesis, only one CPL is activated at a time.
Figure 3.15 Block diagram of the two CPLs realized using buck converters connected to the low voltage side of the 48-24 DC-DC converter through cables with different length.

Figure 3.16 depicts the bode plot for the system impedance ratio $Z_s(s) / Z_l(s)$ for both CPLs, which is obtained using the linearized model of the system at different power levels to examine system stability (with parameters summarized in Appendix A.3). The CPL 1 is assumed to operate at $P_{CPL} = 1.6$ kW and CPL 2 at $P_{CPL} = 0.5$ kW, respectively. As it is seen in Figure 3.16, the magnitude of the ratio exceeds 0 dB at 420 Hz for CPL 1 and 223 Hz for CPL 2, respectively, while the phase of the ratio remains at $\pi$, which violates the stability criterion (2.4). This observation implies that oscillations are very likely to occur around these frequencies when the CPLs reach these power levels.
Figure 3.16 Bode plot of the system impedance ratio $Z_s(s) / Z_l(s)$. Case (I) is when CPL 1 is connected as the only load of the system at 1.6kW, and case (II) is when CPL 2 is connected as the only load of the system at 0.5kW.

3.3.2.2 Simulation with PLECS in MATLAB/Simulink

As the detailed characteristics of the 48/24 DC-DC converter have been well studied in [37], for the studies presented in this thesis, an average model of the converter has been built using PLECS [31] in MATLAB/Simulink [32], [33] to speed up the simulation process. To verify the correctness of the developed average model, an unstable case with CPL 1 has been considered and compared to the experimental results. In this study, the power level of CPL 1 is increased at a rate of 1kW/s until it reaches the 1.6kW. The experimentally measured source voltage, load voltage, and load current have been captured in an oscilloscope and are depicted in Figure 3.17. The same study has been also reproduced using the developed average-value models of the
considered part of the DC microgrid with CPLs, and the corresponding results are presented in Figure 3.18.

As it can be observed in Figures 3.17 and 3.18, the instability occurs when CPL 1 power increases to 1.6kW at a rate of 1kW/s. The oscillations are clearly visible in both load voltage and load current, whereas a very good agreement is also observed between the experimental and simulated results in Figures 3.17 and 3.18. When the CPL power is reduced, the system is able to return to stable operation and the oscillations quickly disappear. This study clearly demonstrates the destabilizing effect of CPLs with high power demand, as well as verifies the models and simulations used for analyzing the considered phenomena.

Figure 3.17 Experimental results demonstrating an unstable system response to CPL 1 increasing power to 1.6kW at the rate of 1kW/s [37].
Figure 3.18 Simulation results for demonstrating unstable system response to CPL 1 increasing power to 1.6kW at the rate of 1kW/s [37].

To investigate the unstable operation further, a magnified view of the simulation results from Figure 3.18 at the instance when the instability occurs has been plotted in Figure 3.19 (a). As can be seen in Figure 3.19 (a), the load bus voltage enters a limit cycle with an oscillation frequency of approximately 416.67Hz, which matches the small-signal predictions observed in Figure 3.16.
Figure 3.19 Simulation results for an unstable system response observed in $v_l$: (a) when CPL 1 power is increased to 1.6kW; (b) when CPL 2 power is increased to 0.5kW.

A similar study is repeated using simulation for CPL 2 as the only load of the system, with its power increasing to 0.5kW at the rate of 1kW/s. As can be seen in Figure 3.19 (b), the instability also occurs with CPL 2. But this time, the oscillations happen at approximately 232.6Hz, which also matches the small-signal results presented in Figure 3.16. The difference between the instability with CPL 1 and CPL 2 is a result of their cables with different lengths that are used to connect the CPLs to the source, i.e. CPL 1 is connected through a short cable of 52μH, while CPL 2 is connected through a long cable of 200μH. This study also demonstrates that the instability and its frequency may vary depending on the type of loads, their power level, and even connections and cable wiring.
Next, the proposed active damping method as described in Section 2.4 is activated to stabilize the system. The previously verified average model of the system is used for the subsequent simulation studies. To eliminate the effect of noise and transient presented in the system, the voltage tolerance $V_{tol}$ is set to 1V while the maximum number subsequent increases in oscillation magnitude $N$ is set to 4. The sampling frequency is set to 20 kHz and a time window of 30ms is assumed, corresponding to a minimum oscillation frequency of 66.7Hz.

In the first study, the CPL 1 with a short cable of 52$\mu$H is considered. As in the previous study, the CPL power is commanded to gradually increase at a rate of 1kW/s while the system load bus voltage is being monitored for stability according to the time window method. The simulation results depicting the CPL power level and the load bus voltage and current are depicted in Figure 3.20. As it is observed in Figure 3.20 [see case (I)], when the proposed stabilization method is not enabled, the system becomes unstable when the $P_{CPL}$ is increased to 1.6kW. The observed instability is consistent with the similar observation presented in Figures 3.17 – 3.19. However, when the proposed stabilization method is applied, the instability is detected at $t = 2.174$s, and the auxiliary circuit is activated to provide the required active damping and stabilize the system, as shown in Figure 3.20 [see case (II)]. Moreover, the stability is maintained even for higher power demand of CPL 1.
To demonstrate that the proposed active damping method is adaptive to the system conditions and can stabilize the system under different destabilizing CPLs and oscillation frequencies, the second study with the CPL 2 connected through a long cable of 200μH is considered. The CPL power is commanded to gradually increase at a rate of 1kW/s while the system load bus voltage is being monitored for stability according to the time window method. The simulation results depicting the CPL power level and the load bus voltage and current are depicted in Figure 3.21. As it is observed in Figure 3.21 [see case (I)], when the proposed stabilization method is not used, the system becomes unstable when the \( P_{CPL} \) is increased to 0.5kW, which is consistent with the similar observation presented in Figure 3.19. However,
when the proposed stabilization method is applied, the instability is detected at $t = 1.148s$, and the auxiliary circuit is activated to provide the required active damping and stabilize the system, as shown in Figure 3.21 [see case (II)]. Moreover, the stability is maintained even for higher power demand of CPL 2.

Figure 3.21 System transient response for CPL 2 increasing power demand: (a) $P_{CPL}$, (b) $v_i$, (c) $i_i$; case (I) is when the proposed stabilization method is not enabled, and case (II) is when the proposed stabilization method is enabled.
Chapter 4: Stability of Three-Phase AC Systems with Constant-Power Loads

In the previous chapters, it has been shown that CPLs can destabilize DC power systems when their power demands become too high. In three-phase AC power-electronic-based systems, the CPLs can greatly affect the system stability in a similar fashion. Figure 4.1 shows a simplified three-phase AC power system that has also been divided into source and load subsystems for the purpose of stability analysis. The source subsystem may be composed of several parallel converters feeding the common AC bus. For the purpose of analysis in this thesis, the AC subsystem is represented by its combined Thevenin equivalent source, line impedance, and a capacitor filter that is commonly used for power quality purposes. When the power level of the three-phase CPL becomes high, instability can also be observed on system load bus in the form of high-frequency components with increasing magnitude. In this chapter, the small-gain stability criterion is reviewed to help determine system stability, and passive and active damping methods are proposed to stabilize the AC system under consideration.

Figure 4.1 A simplified three-phase AC power system with line impedances, output capacitors, and a three-phase CPL. The system is divided into source and load subsystems for stability analysis.
4.1 Small-Gain Stability Criterion for Three-Phase AC Systems

Stability criteria of DC power systems with CPLs have been presented in Chapter 2, wherein stability can be determined using the system impedance ratio $Z_s(s) / Z_l(s)$ as specified in (2.4). Since in three-phase AC power systems both $Z_s(s)$ and $Z_l(s)$ become matrices, the stability criteria derived for DC power systems cannot be applied directly. Instead, the source system impedance matrix $Z_s^e$ and the load system admittance matrix $Y_l^e$ in the synchronous reference frame [28] can be used to determine the system stability according to the small-gain stability criteria [7]. To simplify the analysis, it is assumed that the system is balanced and does not have zero-sequence, so both $Z_s^e$ and $Y_l^e$ can be written as 2x2 matrices [7]. The product matrix $W$ is defined as

$$W = Z_s^e Y_l^e,$$

which is also a 2x2 matrix. The induced 2-norm of $W$ can be expressed as

$$\|W\|_2 = \sigma(W),$$

where $\sigma$ represents the largest singular value of $W$. The matrix $W$ is frequency dependent i.e. $W(j\omega)$. Each singular value $\sigma_i$ of $W$ can be found using the corresponding eigenvalue $\lambda_i$ of $W$ as long as the matrix is normal, i.e.

$$\sigma_i = |\lambda_i|.$$

If the induced 2-norm of $W$ is restricted to less than unity for system stability, the determinant of $W$ will always be less than one, which can be expressed as

$$\det(W) = \prod_i \lambda_i < 1.$$
Condition (4.4) indicates that the characteristic loci will lie within the unit circle and the system will meet the generalized Nyquist stability criterion [38]. As a result, the stability of three-phase AC systems can be guaranteed if the induced 2-norm of $W$ is less than one, or the induced 2-norm of the product of $Z^e_s$ and $Y^e_l$ is less than one, i.e.

$$\|W\|_2 = \|Z^e_s Y^e_l\|_2 < 1.$$  \hfill (4.5)

Moreover, by the Cauchy-Schwarz’s inequality [39],

$$\|Z^e_s Y^e_l\|_2 \leq \|Z^e_s\|_2 \|Y^e_l\|_2 = \sigma(Z^e_s)\sigma(Y^e_l).$$  \hfill (4.6)

Therefore, combining (4.5) and (4.6), it can be concluded that the stability of three-phase AC systems is guaranteed if the product of the largest singular value of $Z^e_s$ and the largest singular value of $Y^e_l$ is less than one, resulting in the following

$$\sigma(Z^e_s)\sigma(Y^e_l) < 1.$$  \hfill (4.7)

Condition (4.7) is the induced 2-norm small-gain stability criterion that has been proposed in [7]. The criterion (4.7) also holds for $W$ that is not normal, as the magnitude of the eigenvalue $\lambda_i$ of $W$ is always less than or equal to the largest singular value of $W$, expressed as

$$|\lambda_i| \leq \sigma(W).$$  \hfill (4.8)

Other small-gain stability criteria, namely the infinity-one norm and the $G$-norm stability criteria, have also been proposed in [7]. However, since these two stability criteria are more conservative [7], only the induced 2-norm small-gain stability criterion will be used in this thesis to determine the stability of three-phase AC systems.
4.2 Ideal Three-Phase AC Constant-Power Loads

Unlike in DC systems where currents/voltages are constant in steady state to produce a constant power demand of CPL, in a three-phase AC system, currents/voltages oscillate with a fundamental frequency, and the instantaneous power $P(t)$ is controlled to produce a constant power. The instantaneous power can be expressed as

$$P(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) = v_{abc}^T i_{abc}.$$  \hbox{(4.9)}

Given that the fundamental frequency of the system voltages is $\omega_e$, a transformation matrix $K^e_s$ defined as

$$K^e_s = \frac{2}{3} \begin{bmatrix} \cos \theta_e & \cos(\theta_e - 2\pi / 3) & \cos(\theta_e + 2\pi / 3) \\ \sin \theta_e & \sin(\theta_e - 2\pi / 3) & \sin(\theta_e + 2\pi / 3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}.$$ \hbox{(4.10)}

The matrix $K^e_s$ is used to transform the voltages and currents of stationary three-phase AC circuits into the synchronous reference frame [28], as

$$v^e_{qd0} = K^e_s v_{abc},$$ \hbox{(4.11)}

$$i^e_{qd0} = K^e_s i_{abc},$$ \hbox{(4.12)}

where the subscripts $qd0$ denotes the $q$-axis, $d$-axis, and 0-sequence components of the synchronous reference frame variables. The transformation angle $\theta_e$ is defined as the reference frame angle and its relationship with the synchronous frequency $\omega_e$ can be expressed as [28]

$$\theta_e = \int \omega_e dt.$$ \hbox{(4.13)}

Applying the transformation (4.11) and (4.12) to (4.9), the instantaneous power $P(t)$ can be written in terms of voltages and currents in synchronous reference frame as
\[ P(t) = \left[ \begin{bmatrix} K_s^e \end{bmatrix}^{-1} v_{qd0}^e \right]^T \left[ \begin{bmatrix} K_s^e \end{bmatrix}^{-1} i_{qd0}^e \right] = \frac{3}{2} v_{qd0}^e \ T \ i_{qd0}^e. \] (4.14)

If it is assumed that the considered ideal three-phase AC constant-power load does not have a neutral point, the zero-sequence terms can be dropped as the sum of the current becomes zero and (4.14) can be re-written as

\[ P(t) = \frac{3}{2} \left( v_{q_d}^e i_{d}^e + v_{d}^e i_{q}^e \right). \] (4.15)

Similarly, the instantaneous reactive power \(Q(t)\) can also be written using voltages and currents in the synchronous reference frame as [7]

\[ Q(t) = \frac{3}{2} (v_{q_d}^e i_{q}^e - v_{d}^e i_{d}^e). \] (4.16)

The relationship between \(P(t)\) and \(Q(t)\) can be expressed as

\[ P^2(t) + Q^2(t) = \frac{9}{4} (v_{q}^2 + v_{d}^2)(i_{q}^2 + i_{d}^2). \] (4.17)

As the transformed voltages and currents in the synchronous reference are constant in steady state, neglecting harmonics, the real and reactive powers \(P(t)\) and \(Q(t)\) also become constant in steady state. As a result, the required \(q\) and \(d\)-axes currents become functions of the \(q\) and \(d\)-axes voltages and can be found using (4.15) and (4.16) as

\[ i_{q}^e = \frac{2}{3} \frac{P v_{q}^e - Q v_{d}^e}{(v_{q}^2 + v_{d}^2)}, \] (4.18)

\[ i_{d}^e = \frac{2}{3} \frac{P v_{d}^e + Q v_{q}^e}{(v_{q}^2 + v_{d}^2)}. \] (4.19)
Finally, the required $q$ and $d$-axes currents can be linearized around a voltage operating point $V_{qd}^{e} = v_{qd}^{e} - v_{qd}^{e}$ using the two-variable Taylor series to the second term, which in vector form can be expressed as

$$\dot{i}_{qd}^{e} = F(V_{qd}^{e} + \dot{v}_{qd}^{e}) \approx F(V_{qd}^{e}) + \nabla F(V_{qd}^{e}) \dot{v}_{qd}^{e} = \dot{I}_{qd}^{e} + Y_{qd}^{e} \dot{v}_{qd}^{e}, \quad (4.20)$$

where $\dot{I}_{qd}^{e} = i_{qd}^{e} - \dot{i}_{qd}^{e}$ is the corresponding current operating point. Based on that, the small-displacement model can then be written as

$$\dot{\ddot{i}}_{qd}^{e} = Y_{qd}^{e} \dot{v}_{qd}^{e}, \quad (4.21)$$

where $Y_{qd}^{e}$ is the admittance of the considered three-phase AC constant-power load given as

$$Y_{qd}^{e} = \frac{2}{3(V_{q}^{e2} + V_{d}^{e2})} \begin{bmatrix} P - 3V_{q}^{e2}I_{q}^{e} & -Q - 3V_{d}^{e2}I_{d}^{e} \\ Q - 3V_{q}^{e2}I_{d}^{e} & P - 3V_{d}^{e2}I_{d}^{e} \end{bmatrix} = \begin{bmatrix} y_{qq} & y_{qd} \\ y_{dq} & y_{dd} \end{bmatrix}. \quad (4.22)$$

Equation (4.22) also defines the admittance matrix for the load subsystem when the considered ideal three-phase CPL is connected as the only load. Since $P$ only appears in the diagonal terms, it can be observed that higher values of $P$ will result in a higher singular value of $Y_{qd}^{e}$, which will make the system more vulnerable to instability. This general observation is consistent with the destabilizing effect of CPLs in DC systems.

### 4.3 Design of Passive $RLC$ Damper Based on Oscillation Frequency

Passive damping techniques that can be used to stabilize an unstable DC system have already been discussed in Chapter 2, where parallel $RC$ dampers have been considered because they do not consume power in the steady state. In AC systems, in parallel $RC$ dampers, the
damping resistor will consume active power even in the steady state, which makes this damping circuit not applicable.

Different passive damping filters for AC systems have been reviewed in [21], where it is suggested to use a resonant tank to block the fundamental frequency of the system from entering the damping resistor, while allowing the high-frequency oscillations to be damped by the same damping resistor. A resonant tank consists of an inductor \( L_r \) and a capacitor \( C_r \) that are connected in parallel. The impedance transfer function of the resonant tank is defined as

\[
Z_r(s) = \frac{sL_r}{s^2 L_r C_r + 1}.
\]  
(4.23)

It can be observed in (4.23) that the transfer function \( Z_r(s) \) has a double pole at the resonant frequency \( f_r \) that can be calculated as

\[
f_r = \frac{1}{2\pi \sqrt{L_r C_r}}.
\]  
(4.24)

Therefore, \( f_r \) is set to the system fundamental frequency \( f_e \). Then a damping resistor connected in series to the resonant tank will consume minimum power at the steady stage. As a result, the parallel \( RC \) damper designed in Chapter 2 can be modified by adding a resonant inductor in parallel with the damping capacitor to form a resonant tank, as shown in Figure 4.2. Such an \( RLC \) damper can be connected in parallel at the considered load bus to stabilize the AC systems. By re-writing (4.24) and using the damping capacitance \( C_d \) as the resonant capacitance \( C_r \), the resonant inductance \( L_r \) can be calculated as

\[
L_r = \frac{1}{4\pi^2 f_e^2 C_d}.
\]  
(4.25)
In Chapter 2, the value of $C_d$ has been calculated based on a time constant $\tau_{RC}$ that depends on the system oscillation frequency $f_{osc}$ and on the damping resistance $R_d$, all of which also depend on the CPL power level $P_{CPL}$ and the load bus voltage $v_l$. While it is still possible to measure these quantities online in three-phase AC systems, $v_l$ is time-variant and (2.7) cannot be applied directly. As a result, the transformation to the synchronous reference frame (4.10) is used to extract the instantaneous magnitude value of the AC voltage at the load bus. For the purpose of analysis in this thesis, the zero-sequence is neglected, and the magnitude of $v_{qd}$ is calculated as

$$v_{mag} = \sqrt{(v_q^e)^2 + (v_d^e)^2}.$$  \hspace{1cm} (4.26)

As a result, (2.7) can be re-written to calculate the magnitude of the equivalent per-phase impedance of the AC CPL as

$$|Z_{CPL}(s)| = \frac{v_{RMS}^2}{P_{CPL} / 3} = \frac{(v_{mag} / \sqrt{2})^2}{P_{CPL} / 3} = \frac{3}{2} \frac{v_q^2 + v_d^2}{P_{CPL}},$$  \hspace{1cm} (4.27)

where $P_{CPL}$ represents the total power consumed by the three-phase CPL.
Using (2.10), (2.13), (2.15) and (4.25) and (4.27) (with \( u = 2 \) as in DC systems [29]), it is possible to design a parallel \( RLC \) damper for AC systems, as long as \( v_{mag}^e \), \( P_{CPL} \), \( f_e \), and \( f_{osc} \) are known beforehand.

### 4.4 Injected Current and Auxiliary Converter Circuit for Emulating \( RLC \) Damper

Similar to the damping techniques presented in Chapter 2 for the DC systems, (2.17) can still be used to calculate the damping current \( i_d \) for AC systems. Since a parallel \( RLC \) damper will be used, the equivalent impedance transfer function now becomes

\[
Z_d(s) = R_d + \left( \frac{1}{sC_d} \right) = \frac{s^2R_dL_dC_d + sL_d + R_d}{s^2L_dC_d + 1} = \frac{s^2R_d + s/C_d + R_d\omega_r^2}{s^2 + \omega_r^2},
\]

(4.28)

where \( \omega_r \) is the damper resonant frequency in rad/s that is set to be equal to the fundamental frequency \( \omega_e \). Substitute (4.28) into (2.17) to get the equation for the injected damping current for each phase as

\[
i_{abcd}(s) = \frac{s^2 + \omega_e^2}{s^2R_d + s/C_d + R_d\omega_e^2} v_{abcl}(s),
\]

(4.29)

where the subscript \( abcl \) denotes the three phases \( al, bl, \) and \( cl \) of the load bus variables, the subscript \( abcd \) denotes the three phases \( ad, bd, \) and \( cd \) of the damping circuit variables, and the values of \( R_d, L_d \) and \( C_d \) are determined using (2.10), (2.13), (2.15), (4.25) and (4.27), as explained in Section 4.3.

Without loss of generality, a simple two-level converter shown in Figure 4.3 is used here as the auxiliary circuit for injecting the needed damping currents into each phase. The converter is
assumed to operate in a current-source mode and is capable of injecting high-frequency components in the range of possible oscillations due to instability. The injected damping currents for each phase are calculated using (4.29). The parameters of the considered three-phase auxiliary converter circuit are summarized in Appendix A.4.

Figure 4.3 Simplified schematic of the three-phase auxiliary converter circuit used to inject damping currents.
Chapter 5: Extension of the Proposed Stabilization Methods to Three-Phase AC Systems

Different methods for stabilizing DC systems have been proposed and verified in Chapter 2 and Chapter 3, where it has been shown that by using the online measurements of the CPL power level $P_{CPL}$, load bus voltage $v_l$, and system oscillation frequency $f_{osc}$, it is possible to determine system instability and use the proposed auxiliary circuit to stabilize the system. In this Chapter, it will be shown that the proposed stabilization methods with some modifications can also be extended to three-phase AC systems.

5.1 Instability and Oscillation Frequency Estimation

As the voltages/currents in three-phase AC systems naturally oscillate at a fundamental frequency, it can be hard to directly estimate high-frequency oscillations. However, it is possible to apply (4.10) to transform the needed voltages into the synchronous reference frame, such that in steady-state their values become constant. If the system becomes unstable, the oscillation with a frequency of $f_{osc}^e$ will also appear in the transformed voltages and currents. Since $f_{osc}^e$ is determined after the transformation to the synchronous reference frame, the actual oscillation frequency $f_{osc}$ becomes the sum of the synchronous frequency $f_e$ and the measured frequency, expressed as

$$f_{osc} = f_{osc}^e + f_e.$$  \hspace{1cm} (5.1)
As a result, \( f_{osc} \) in three-phase AC systems can be estimated if the oscillation frequency estimation methods proposed in Chapter 3 are applied to the transformed voltages magnitude \( v_{mag}^e \) defined in (4.26), which will be monitored to determine system instability.

### 5.1.1 Extending the Voltage Prediction Method to AC Systems

Similar to the DC systems presented in Section 3.1.1, the voltage prediction method can also be applied to three-phase AC systems with some modifications. After \( v_{mag}^e \) has been obtained by applying the transformation (4.10) to the load bus voltages, the predicted magnitude of the voltage \( V_{pre}^e \) can be found by considering the voltage drop on the line cable impedance, expressed as

\[
V_{pre}^e = v_s^e - Z_{line}i_{mag}^e, \tag{5.2}
\]

where \( Z_{line} \) represents the equivalent impedance of the line cable, \( v_s^e \) is the transformed source voltage magnitude, and \( i_{mag}^e \) is the magnitude of the transformed load current defined as

\[
i_{mag}^e = \sqrt{(i_q^e)^2 + (i_d^e)^2}. \tag{5.3}
\]

Thereafter, the oscillating voltage term \( V_{osc}^e \) can be extracted from the transformed voltage similar to (3.3), expressed as

\[
V_{osc}^e = v_{mag}^e - V_{pre}^e. \tag{5.4}
\]
The same technique used to compute the trigger signal \( g \) still applies to \( v_{osc}^e \), except that the time difference between two trigger signals becomes \( t_{osc}^e \), as shown in Figure 5.1. The system oscillation frequency in the reference frame can then be estimated similarly to (3.4) using

\[
f_{osc}^e = \frac{1}{2t_{osc}^e}.
\]  

(5.5)

![Figure 5.1](image.png)

Figure 5.1 An example demonstrating the oscillation frequency using voltage prediction method: (a) the voltages \( v_{mag}^e, V_{pre}^e, \) and \( v_{amp}^e \), and (b) the trigger signal \( g \) obtained from the zero-crossing, and the time interval \( t_{osc}^e \).

Finally, by finding the amplitude of \( v_{osc}^e \) denoted by \( v_{amp}^e \) in each interval separated by the zero-crossing trigger signal \( g \), the ratio \( m \) between the two of the most recent amplitudes \( v_{amp}^e[k] \) and \( v_{amp}^e[k-1] \) is expressed as

\[
m = \frac{v_{amp}^e[k]}{v_{amp}^e[k-1]}.
\]

(5.6)
This ratio can be used to determine system instability as shown in the flowchart in Figure 5.2. If $m$ is greater than one, the counter $n$ will be increased, and the process will be repeated for another trigger signal $g$. If $n$ reaches a pre-defined number $N$, the system will be determined as unstable, and the active damping will be applied to stabilize the system. If $n$ has been smaller than $N$ for a long time and there is no change in the CPL power level $P_{CPL}$, the present $P_{CPL}$ must be a stable power level for the system and it will be marked as the power threshold $P_{th}$. The system must be stable for any $P_{CPL}$ that is lower than $P_{th}$, therefore, if $P_{CPL}$ becomes lower than $P_{th}$, the damping circuit will be deactivated to save energy.
Figure 5.2 Flowchart for determination of instability based on the amplitude of oscillating voltage in AC systems.
5.1.2 Extending the Time Window Method to AC Systems

The time window method proposed in Section 3.1.2 can be applied directly to the transformed voltage magnitude $v^e_{mag}$ to determine system instability, with $t^e_{osc}$ being the time difference between any of the two local extrema of $v^e_{mag}$ that can be used to find $f^e_{osc}$ using (5.1) and (5.5). Figure 5.3 shows a sample time window of 5ms in which $v^e_{mag}$ is monitored. To start, a certain voltage tolerance $V_{tol}$ is set on $v^e_{mag}$ to eliminate the effect of noise depending on the noise level presented in the system. If $v^e_{mag}$ is still within the tolerance and there is no change in the CPL power level $P_{CPL}$, the present $P_{CPL}$ is assumed as a stable power level for the system and it will be marked as the power threshold $P_{th}$. The system must be stable for any $P_{CPL}$ that is lower than $P_{th}$. When $v^e_{mag}$ oscillates and exceeds the voltage threshold, the proposed method depicted in Figure 5.4 is used to determine the system instability. All data points within a certain period are stored in a time window, the size of which is determined by the assumed minimum oscillation frequency. The sample time window depicted in Figure 5.3 is chosen to be 5ms assuming a minimum system oscillation frequency of 400Hz. Within the allocated time window, all local extrema $v_x$ of $v^e_{mag}$ are found, and a ratio $m$ can be defined as

$$m = \frac{v_x^e[k] - v_x^e[k-1]}{v_x^e[k-1] - v_x^e[k-2]}.$$  \hspace{1cm} (5.7)

This ratio is calculated to determine if the voltage is oscillating with increasing magnitude, i.e. with $v_x^e[k]$, $v_x^e[k-1]$ and $v_x^e[k-2]$ referring to three of the most recent local extrema of $v^e_{mag}$. If $m$ is greater than one, the same process will be repeated with $v_x^e[k-1]$, $v_x^e[k-2]$ and $v_x^e[k-3]$. A
counter $n$ is then used to store the number of times $m$ is greater than one, and the process will be repeated until $n$ reaches a pre-defined number $N$ specified by the user. If the process ends by reaching $N$, the system has been determined as unstable, and appropriate active damping will be applied to stabilize the system, while the $P_{CPL}$ will be monitored and compared with $P_{th}$. If $P_{CPL}$ drops below $P_{th}$, the system should be stable without the additional damping, and the active damping circuit will be deactivated to save energy, as shown in the flowchart in Figure 5.4.

![Flowchart](image)

**Figure 5.3** A sample time window of 5ms applied for determining instability of AC voltages: (a) the phase $a$ load bus voltage $v_{al}$, and (b) the instantaneous voltage magnitude $v_{mag}$. 
Figure 5.4 Flowchart for determination of instability based on the difference between local extrema in AC voltage at the load bus.
5.2 Calculation of Damping Parameters for AC Systems

Once the system has been determined unstable, the auxiliary converter circuit described in Section 4.4 is activated to inject the damping currents and stabilize the system. Given \( f_{osc}^e \) has been found using (5.5), (where \( f_{osc}^e \) can be found using either the voltage prediction method or the time window method), the damping parameters \( R_d, C_d \) and \( L_r \) required in (4.28) can be calculated by re-writing (2.10), (2.13), (2.15) and (4.25) and (4.27) as follows:

\[
R_d = \frac{Z_{CPL}(s)}{u} = \frac{3}{4} \frac{(v_d^e)^2 + (v_q^e)^2}{P_{CPL}},
\]

(5.8)

\[
C_d = \frac{\tau_{RC}}{R_d} \approx \frac{0.7656}{R_d(f_{osc}^e + f_e)},
\]

(5.9)

\[
L_r = \frac{1}{4\pi^2 f_e^2 C_d} \approx \frac{0.02533}{f_e^2 C_d}.
\]

(5.10)

5.3 Case Studies

5.3.1 Modeling of a Three-Phase AC Power System

To demonstrate the effectiveness of the proposed stabilization methods for three-phase AC systems, a simplified model of a three-phase AC power system presented in [13] has been considered in this thesis, and is shown in Figure 5.5. The system is supplied by a balanced three-phase voltage source, and an ideal three-phase constant-power load is connected to the source through a line cable that is modeled as an \( RL \) branch, with a capacitor filter bank connected at the
end of the line cable. The auxiliary converter circuit is connected in parallel with the three-phase CPL to inject the damping current when the system becomes unstable.

Figure 5.5 A simplified three-phase AC power system with CPL and the auxiliary circuit to implement the proposed active damping.

To analyze the stability of this AC system, the transformed source subsystem impedance can be found using the inverse of the sum of the capacitor admittance and the admittance of the RL branch [7], expressed as

$$Z_s^e = \left(sC + TC + (R + sL + TL)^{-1}\right)^{-1} = \left[Y_s^e\right]^{-1}, \quad (5.11)$$

where $T$ is a 2x2 matrix that depends on the system synchronous frequency $\omega_e$ as

$$T = \begin{bmatrix} 0 & \omega_e \\ -\omega_e & 0 \end{bmatrix}, \quad (5.12)$$

and $R$, $L$, $C$ are 2x2 diagonal matrices with entries $R_{line}$, $L_{line}$, and $C_{bank}$, respectively [7]. Since (5.11) is in the form of the inverse of admittance $Y_s^e$, it is easier to first compute the singular values of the admittance matrix $Y_s^e$. Then the singular values of the impedance matrix $Z_s^e$ will become the inverse of the singular values, expressed as
\[ \sigma(Z_\mathcal{X}^e) = \sigma^{-1}(Y_\mathcal{X}^e). \] (5.13)

Substituting \( j\omega \) for \( s \) and performing algebraic manipulations, the square of the singular values of the admittance matrix can be expressed as

\[
\sigma^2(Y_\mathcal{X}^e) = \frac{\left(\omega_p^2 - 1\right)^2 + \left(\frac{R_{\text{line}}}{Z_o} \right)^2 \omega_p^2}{Z_o \omega_p^2 + R_{\text{line}}^2}, \]
\[
\left(\omega_m^2 - 1\right)^2 + \left(\frac{R_{\text{line}}}{Z_o} \right)^2 \omega_m^2 \right)
\frac{Z_o \omega_m^2 + R_{\text{line}}^2}{Z_o \omega_m^2 + R_{\text{line}}^2}, \]
where \( \omega_p \) and \( \omega_m \) are the normalized sideband frequencies with respect to the system’s natural frequency \( \omega_o \), defined as

\[ \omega_p = \frac{\omega + \omega_o}{\omega_o}, \] (5.15)

\[ \omega_m = \frac{\omega - \omega_o}{\omega_o}, \] (5.16)

\[ \omega_o = \frac{1}{\sqrt{L_{\text{line}}C_{\text{bank}}}}, \] (5.17)

and where \( Z_o \) is the characteristic impedance defined as

\[ Z_o = \sqrt{\frac{L_{\text{line}}}{C_{\text{bank}}}}. \] (5.18)

Based on (5.13) and (5.14), the singular values of the impedance matrix then become

\[
\sigma(Z_\mathcal{X}^e) = \begin{bmatrix}
\frac{Z_o \omega_p^2 + R_{\text{line}}^2}{\left(\omega_p^2 - 1\right)^2 + \left(\frac{R_{\text{line}}}{Z_o} \right)^2 \omega_p^2}
\frac{Z_o \omega_m^2 + R_{\text{line}}^2}{\left(\omega_m^2 - 1\right)^2 + \left(\frac{R_{\text{line}}}{Z_o} \right)^2 \omega_m^2}
\end{bmatrix}. \] (5.19)
It can be observed in (5.19) that the largest singular value of the impedance matrix occurs when any of the normalized sideband frequencies becomes unity, i.e. when \( \omega_p = 1 \) or \( \omega_m = 1 \). Substitute these two conditions into (5.15) and (5.16) to get two frequencies \( \omega_1 \) and \( \omega_2 \) at which \( \tilde{\sigma}(Z_s^e) \) is at its peak, expressed as

\[
\omega_1 = \omega_o - \omega_e, \quad (5.20)
\]

\[
\omega_2 = \omega_o + \omega_e. \quad (5.21)
\]

Then by substituting (5.20) or (5.21) into (5.19), the peak magnitude of the largest singular value is found to be

\[
\tilde{\sigma}(Z_s^e)_{\text{peak}} = \frac{Z_o^2}{R_{\text{line}}} \sqrt{1 + \left(\frac{R_{\text{line}}}{Z_o}\right)^2}, \quad (5.22)
\]

which does not depend on synchronous frequency. Indeed, \( \tilde{\sigma}(Z_s^e)_{\text{peak}} \) is exactly the same as the peak magnitude \( |Z_s(s)|_{\text{peak}} \) of the single phase equivalent source subsystem impedance transfer function \( Z_s(s) \), expressed as

\[
Z_s(s) = \left( R_{\text{line}} + sL_{\text{line}} \right) / \left( \frac{1}{sC_{\text{bank}}} + \frac{sL_{\text{line}} + R_{\text{line}}}{s^2L_{\text{line}}C_{\text{bank}} + sR_{\text{line}}C_{\text{bank}} + 1} \right) = \frac{sL_{\text{line}} + R_{\text{line}}}{s^2 + sR_{\text{line}}/L_{\text{line}} + \omega_o^2}. \quad (5.23)
\]

The peak magnitude of \( Z_s(s) \) can be found by substituting \( j\omega_o \) for \( s \) as

\[
|Z_s(s)|_{\text{peak}} = \frac{Z_o^2}{R_{\text{line}}} \sqrt{1 + \left(\frac{R_{\text{line}}}{Z_o}\right)^2}. \quad (5.24)
\]

Therefore, based on the fact that the peak magnitude of the largest singular value \( \tilde{\sigma}(Z_s^e)_{\text{peak}} \) equals the peak magnitude of the single phase equivalent source subsystem impedance transfer function \( |Z_s(s)|_{\text{peak}} \), it can be concluded that \( \tilde{\sigma}(Z_s^e)_{\text{peak}} \) can be lowered to meet the small-gain
stability criterion (4.7) by shaping the single-phase equivalent source subsystem impedance transfer function \(Z_s(s)\) and lowering its peak magnitude \(|Z_s(s)|_{\text{peak}}\) using the proposed damping technique on each phase.

Figure 5.6 shows the computed frequency response of the product of the singular values of the source impedance and load admittance for the considered AC system (with parameters summarized in Appendix A.5) when the CPL power level is at 450W. It can be seen in Figure 5.6 [see curve (I)] that the product becomes larger than one (i.e. 0 dB) for some frequencies, violating the 2-norm small-gain stability criterion (4.7). However, in Figure 5.6 [see curve (II)] with the addition of the proposed active damping, the peak is effectively reduced to less than one (i.e. 0 dB), thus satisfying the small-gain stability criterion (4.7).

![Figure 5.6 Computed frequency response of the product of the singular values of the source impedance and load admittance for the considered AC system with CPL. Small-gain stability criterion is violated without additional damping and is obeyed with additional damping.](image-url)
5.3.2 Simulation of an AC System using PLECS in MATLAB/Simulink

A simplified model of the three-phase AC power system presented in [13] and depicted in Figure 5.5 has been built using PLECS [31] toolbox in MATLAB/Simulink [32], [33] environment. Two test cases (without and with the proposed active damping) are considered to validate the effectiveness of the proposed active damping strategies.

To demonstrate the instability in this AC system, Figure 5.7 shows the simulation results of the phase $a$ load bus voltage $v_{al}$, phase $a$ load current $i_{al}$, and the computed instantaneous voltage magnitude $v^e_{mag}$. Initially, the system is loaded with $P_{CPL} = 50W$ and operates normally in a stable mode. At $t = 0.05s$, the CPL power demand $P_{CPL}$ starts to increase at a rate of 40kW/s up to 450W. As it can be seen in Figure 5.7 [see curves (I)], when no additional damping is provided, the load bus voltage and current start to oscillate with increasing magnitude and frequency around 1.45kHz (which is within the region predicted by Figure 5.6), and the system becomes unstable. However, when the proposed active damping is enabled at $t = 0.065s$ through the auxiliary circuit, the oscillations are damped within ten half-cycles (as specified by the user) as shown in Figure 5.7 [see case (II)], and the system stabilizes.

In this simulation study, the time interval $t^e_{osc}$ is determined to be 358.9µs, and the oscillation frequency $f_{osc}$ is calculated using (5.1) and (5.5) to be 1,453Hz. The damping parameters are then found using (11) as following: $R_d = 5.25Ω$, $C_d = 412µF$, and $L_r = 17.1mH$. As it can be seen in Figure 5.7 [see case (II)], the proposed active stabilization method is very
effective here, and the high-frequency unstable oscillation is damped very quickly before it becomes significantly noticeable in the load bus voltage.

Figure 5.7 Transient response of several system variables due to increase in the CPL power level: (a) CPL power level $P_{CPL}$, (b) phase $a$ load bus voltage $v_{al}$, (c) phase $a$ load current $i_{al}$, and (d) instantaneous magnitude $v_{mag}^e$. Case (I) is when no additional damping is provided, and case (II) is when the proposed active damping is activated through the auxiliary circuit.

The next simulation study demonstrates how the proposed active damping is automatically activated and then deactivated when the system CPL power demand is first increased and then
decreased. The predicted responses of the system variables are shown in Figure 5.8. Similar to the first test case, the system is initially loaded with CPL consuming 50W. Since this is a stable operation, at the beginning, the stable power threshold is set as \( P_{th} = 50W \). At \( t = 0.05s \), the CPL power demand \( P_{CPL} \) starts to increase at 40kW/s, but this time it goes only to 200W. As can be seen in Figure 5.8, even though some oscillations appear in the system load bus voltage magnitude \( v_{mag}^e \) right after the increase, the system remains stable as the oscillations disappear within a fraction of the fundamental cycle (which is due to the existing natural damping present in the system). As a result, a new stable power threshold is set as \( P_{th} = 200W \). Next, at \( t = 0.075s \), the CPL power demand \( P_{CPL} \) is increased again from 200W to 450W (which is an unstable level) at the rate of 40kW/s. During this time, the oscillations in \( v_{mag}^e \) become stronger and reach the threshold of \( V_{tol} =1V \). Note that these oscillations are not quite visible in the load bus phase voltage and current due to the scale, but are visible in \( v_{mag}^e \). The proposed active damping is automatically activated at \( t = 0.085s \) to stabilize the system, and the oscillations are quickly damped reaching a new stable steady state operation, as expected. Then, at \( t = 0.1s \), the CPL power demand \( P_{CPL} \) is decreased at the same rate back to 200W, which is seen by the system as a stable power level, and the active damping circuit is automatically deactivated at \( t = 0.106s \). The oscillations again appear in the system for a short time right after the deactivation of the damping circuit, and the system returns to a stable operation at this power level.
Figure 5.8 Transient response of several system variables due changes in the CPL power demand, and the activation and deactivation of the proposed active damping: (a) CPL power demand $P_{CPL}$, (b) phase $a$ load bus voltage $v_{al}$, (c) phase $a$ load current $i_{al}$, and (d) load bus instantaneous voltage magnitude $v_{mag}^e$. 
Chapter 6: Conclusions and Summary

6.1 Summary of Achieved Objectives and Contributions

In this thesis, the impedance-based stability analysis and small-gain stability criterion are investigated and applied to identify the root cause of the stability problems present in DC and AC power-electronic-based systems with CPLs. The system models, as well as the design principles of passive dampers, have been presented. Potential stability issues are then analyzed using these stability criteria based on the developed models. It has been demonstrated that when the power level of CPLs becomes high, both DC and AC systems may become unstable.

Two adaptive active damping control methods have been presented for stabilizing DC and AC power-electronic-based systems with CPLs. The proposed methods are innovative and practical, and can be applied to many existing systems and configurations as an “add-on” solution that requires adding of a small auxiliary converter circuit to implement the active damping and ensure stability of the system. The proposed methodologies do not require modifications of existing sources and/or loads (which may not be possible in many cases due to proprietary nature of such devices and their internal controls), while the tuning of required active damping is adaptive to various possible operating conditions.

In the proposed methods, the load bus voltage is monitored online to determine instability, and the oscillation frequency is determined and used to calculate the damping parameters required to stabilize the system. The proposed methods are based on the impedance-based
stability analysis and the small-gain stability criterion using tunable active damping that can shape the system small-signal impedance. The proposed methodologies are verified through extensive simulations and are shown to be highly effective in stabilizing both DC and AC power-electronic-based systems with various CPLs and/or other components with unknown or variable parameters. The contributions of this thesis can be summarized with respect to each of the objectives as follows:

**Objective 1** has been achieved in Chapter 3, where the instability detection methods based on DC load bus voltage monitoring are proposed. The proposed methods estimate the system oscillation frequency and calculate the damping parameters using online measurements from the unstable DC bus. Tunable active damping is realized using an auxiliary converter circuit that injects the calculated damping current to the load bus to stabilize the system. The presented methodology has been applied to a sample aircraft power system and a sample DC microgrid. The demonstrated results suggest that the proposed methodology can be very effective for stabilizing DC systems with CPLs.

**Objective 2** has been achieved in Chapter 5, where the proposed stabilization methods have been extended to three-phase AC systems with CPLs. Synchronous reference frame transformation has been applied to the online measurements of the AC load bus voltage, after which it became possible to identify system instability based on monitoring the bus voltage magnitude. A three-phase version of the auxiliary converter circuit has been considered to realize the needed active damping and inject the three-phase damping currents to the unstable system. The developed methodologies have been applied to a sample three-phase AC power system with
CPL, and the obtained results demonstrate the effectiveness of the proposed stabilization methods.

### 6.2 Impact and Future Work

This thesis focused on stability analysis and stabilization methods for power-electronic-based systems with constant-power loads using auxiliary devices. This area is increasingly important because modern power systems are becoming greatly impacted by the electronically-interfaced sources (such as renewable energy and storage systems) and most of the new and envisioned loads are also electronic and tightly regulated. Since both AC and DC distribution systems technologies are envisioned to co-exist in the future at small and large scales (e.g. from vehicles, to buildings, to community microgrids, to large DC grids connecting several countries), it is important to address a problem of possible dynamic interaction(s) among the system’s components (i.e. sources and loads) and provide a practical and scalable solution. The adaptive and active stabilization methodologies based on a small auxiliary device as proposed in this thesis may be a practical solution to many existing and/or future systems, where the system integrator may not have access to modification of various existing or future sources and loads due to practical restrictions placed by the equipment vendors.

Future research on this subject may include design and implementation of the proposed auxiliary converter device, its interface to the future and envisioned DC and AC systems with multiple points and “plug-and-play” connections of CPLs, utilization of higher-order damping filters to achieve better performance and further advantages over conventional passive filters, etc.
Another important direction may be a combination of the active damping with the online impedance identification methods. These and other topics are currently under consideration by other students of Electrical Power and Energy research group at UBC, as well as by other researchers from leading groups around the world.
References


Appendices

Appendix A  Parameters of the Systems under Studies

A.1  Parameters of the Designed Auxiliary Converter Circuit

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Buck Converter Inductance, $L_b$</td>
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<tr>
<td>Buck Converter Capacitance, $C_b$</td>
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A.2  Parameters of the Studied Aircraft Power System

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### A.3 Parameters of the Studied DC Microgrid

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### A.4 Parameters of the Designed Three-Phase Auxiliary Converter Circuit

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### A.5 Parameters of the Studied AC Power System

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