1. INTRODUCTION

1.1 MOTIVATION AND OBJECTIVES

The surge of applications of power electronics in industrial, commercial, military, aerospace, and residential areas has driven many inventions in devices, components, circuits, controls and systems. While the tempo of these inventions will continue to enrich power electronics technology, the demand for compact, low cost, high dynamic performance, highly reliable and efficient power electronics products has increased steadily over the years. A consensus has been reached within the power electronics community that a standardized modular design approach, such as very-large-scale-integration (VLSI) achieved for microelectronics, could lead to significant improvements to not only meet current demand, but also to penetrate into vast new application areas [1], [2].

To reach this goal, a number of issues need to be addressed. Among these issues, parallelability is one of the key components because it is desirable and inevitable to use a parallel architecture with standardized modules. The use of parallel converters provides many advantages, including the following primary considerations.

(1) High reliability. A parallel multi-converter system provides redundancy, thus increases reliability, which is critical in some applications, such as stand-alone distributed power systems on shipboard, aircraft and in aerospace, main-frame computers and servers, etc. System reliability can be drastically improved by using a parallel structure instead of a single-converter solution [3], [4].

(2) High power. Due to the fundamental limitations of semiconductor devices, a single converter always has limited power capability. One way to achieve a high power level is to use parallel operation. Parallel converters have the unique advantage of virtually unlimited output power. Any number of parallel converters can be chosen, according to the specific power requirements encountered.

(3) Distributed power. A parallel architecture has to be used in some distributed power systems due to low-voltage distribution bus and high-current requirement. With the paralleling, the distributed power systems can be easily constructed and expanded.

(4) High performance. Parallel systems significantly reduce harmonics by using interleaving techniques. Therefore, the parallel system has smaller passive components, which leads to a higher dynamic system performance because of higher control bandwidth.

(5) Enabling technology for emerging applications. With increasing concern about environmental issues, interest has grown in environmentally safe power generation systems. One promising candidate is a fuel cell generation system, which features higher electrical efficiency and cleaner exhaust gas. The fuel cell requires high-current (but low-voltage) converters, and is therefore suitable for a parallel arrangement. Superconductor applications also require high current, so it is essentially desirable to use a parallel structure for power conversion.

While paralleling is becoming popular, most parallel applications are still for DC/DC converters only. Until recently, paralleling operation was not a common practice in three-phase power conversion because of interactions that cause additional overhead requirements, such as transformers.

Recently, some active controls have been proposed to minimize the interactions so that the overhead requirements can be reduced. With active controls, parallel operation is becoming a promising solution in three-phase power conversion. However, the existing active controls are too complicated when more converters are in parallel.

In this work, a directly parallel three-phase converter structure is presented. The directly (also called transformerless) parallel connection of three-phase converters presents attractive characteristics, such as simplicity, easy expandability and maintainability. Even with all these advantages, there are potential risks. Couplings and interactions may exist in the parallel system. The objective of this work is to comprehensively address the issues of paralleling three-phase pulse-width modulated (PWM) converters. Four typical three-phase PWM converters, including boost rectifier, voltage source inverter, buck rectifier and current source inverter, are covered in this work.

1.2 LITERATURE OVERVIEW

Because of devices with low frequency and limited power capability, one way to meet application requirements, such as low harmonics and high power, is to parallel devices or converters. It was discussed and concluded that paralleling converters is more desirable than paralleling switching devices [5], [6], [7]. The use of parallel three-phase PWM converters dates back to the late 1980s in motor drives [8] and uninterruptable power supply (UPS) applications [9], [10]. Since the converters are usually designed individually, when they operate in parallel, potential interactions may occur. One distinguishing feature of parallel three-phase converters is a zero-sequence circulating current in the implementations without isolation [8], [9], [11]-[26]. To avoid the zero-sequence circulating current, the following three approaches are commonly used in present technology.

(1) Isolation. Separate AC or DC power supplies [9], [13], [15], [27], [28], or a transformer-isolated AC-side [10], [30]-[33] is configured. With this approach, the overall parallel system is bulky and expensive because of the additional power supplies or the AC line-frequency transformer. Most practical installations use the isolation approach.

(2) High impedance. Inter-phase reactors are often used to provide high zero-sequence impedance [11], [34]-[37]. However, the reactors provide high impedance only at medium and high frequencies. They cannot prevent a low-frequency circulating current. Originally, the inter-phase reactors were for load sharing. The reactors can introduce zero-sequence current if they are not center-tapped. Therefore, with the inter-phase reactors' approach, a zero-sequence current control must be applied to the system.

(3) One-converter approach. If the parallel converters are not isolated, a zero-sequence current control is required. One existing approach is that the parallel converters are basically controlled as one converter [8], [11], [12], [13], [16], [18]-[23], [40]. For

example, two parallel three-phase, three-leg converters are controlled as a three-phase, six-leg converter. The approach has two implementations. One is to use redundant switching vectors [11], [13], [40]. The other is to equalize the current between individual phases of the parallel converters [8], [12], [16], [23], [38]-[39]. With the one-converter approach, the modeling and control design are complicated even for two parallel converters. When more converters are in parallel, this approach becomes extremely complicated and practically unfeasible.

An interleaved discontinuous space-vector modulation (SVM) can cause a beat-frequency zero-sequence current [24]. To avoid the interaction, a modulation scheme without using zero vectors was proposed [24]. The scheme avoided the interaction caused by the particular discontinuous SVM. However, since it was not attempted to reject zero-sequence disturbance, any mismatches between the parallel converters can still cause zero-sequence current even without using zero vectors.

Besides the zero-sequence circulating current, another potential interaction is a reactive power circulation. Normally, if the power factor is not unity, a certain amount of reactive power can circulate between source and load. In a system with parallel three-phase converters, the reactive power could also circulate between the two converters, even if the load power factor is unity. This particular interaction has not been reported before.

Since most existing solutions use the isolation approach, converters can be designed and controlled individually. With the directly parallel structure, the converters are coupled. It can be anticipated that the model developed for an individual converter may not be sufficient to predict the dynamics of the parallel converters. Especially, the control design for the individual converter may not be valid when the converter operates in parallel with others because the open-loop transfer functions may be changed. The existing modeling approach is very complicated because it treats the parallel converters as a single unit [18]-[22]. This approach results in a high-order model, which does not provide much insight into particular parallel interactions, such as zero-sequence current interaction.

Much work has been done in the area of load-sharing control for parallel DC/DC converters [41]-[43]. Most results can be readily applied to the parallel three-phase converters. One difference is that the parallel three-phase converters require both active and reactive load sharing. Therefore, a multiple-loop control design is normally required.

With the advances of fast switching devices, power converters are being built with increasing switching frequency. This leads to more compact size and better dynamic performance for the converters. However, these converters in turn cause high-frequency electromagnetic interference (EMI) noise, for example, differential-mode noise and common-mode noise. The differential-mode noise is usually well taken care of by input and output filters during the power stage design. The common-mode noise, however, is difficult to predict. There is no solid design guideline for most applications. To mitigate the common-mode noise, passive solutions are traditionally used. Active solutions, however, are becoming popular due to the resultant reduced size of the overall system [44]-[51].

1.3 DISSERTATION OUTLINE AND MAJOR RESULTS

Figure 1.1 shows various parallel dynamics at their frequency ranges.

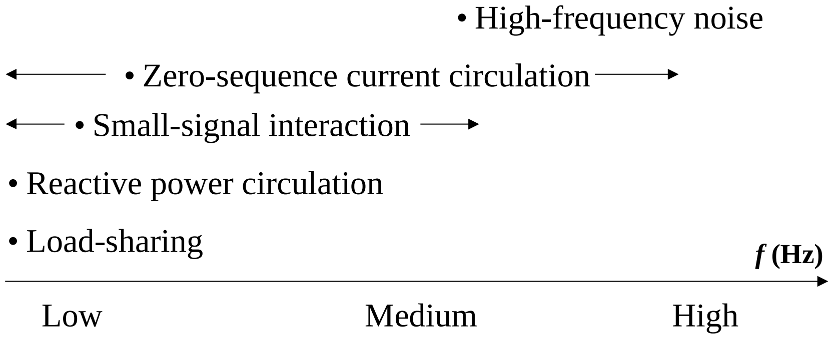

Figure 1.1 Various parallel dynamics at their frequency ranges.

This work comprehensively deals with these dynamics by developing models to predict the dynamics and proposing controls to minimize the interactions. The major results are outlined below.

1.3.1 Modeling of Parallel Three-Phase PWM Converters

Three-phase PWM boost rectifiers and voltage source inverters are classified as current-bidirectional converters because they share the same switching cells that are current bidirectional. Buck rectifiers and current source inverters are classified as current-unidirectional converters because they share the same switching cells that are current unidirectional.

To develop models for the current-bidirectional converters, a generic functional switching unit called a phase leg is identified and averaged. An average model of a converter can be readily obtained by connecting three phase legs. To develop the models for the current-unidirectional converters, a generic functional switching unit called a rail arm is identified and averaged. An average model of a converter can be obtained by connecting two rail arms. Different from the conventional three-phase converter’s modeling that is based on phase-to-phase averaging, the phase-leg and rail-arm averaging can preserve common-mode information, which is critical in the analysis of the parallel converters.

Based on the developed models, parallel interactions, such as small-signal interaction, reactive power and zero-sequence current circulation, can be predicted.

The modeling of the current-bidirectional converters is presented in Chapter 2. The modeling of the current-unidirectional converters is presented in Chapter 3.

1.3.2 Control of Zero-Sequence Current

The control design for a single converter usually does not consider the zero-sequence components because there is physically no zero-sequence current path. This path, however, is formed in the directly parallel converters. This work proposes a new control concept that uses varying zero vectors to suppress the zero-sequence current. The concept is advantageous over others in that it is designed within individual converters and does not need any additional interconnected circuitry. Therefore, it allows modular design so that a parallel system can be easily constructed and expanded.

The control for the parallel current-bidirectional converters is presented in Chapter 4. Simulation and experimental results are provided to validate the developed models and proposed control concept. The modeling and control concept is then generalized to any parallel multi-phase current-bidirectional converters, such as full-bridge rectifiers and inverters, three-phase, three-leg rectifiers and inverters, and three-phase, four-leg rectifiers and inverters.

The control for the parallel current-unidirectional converters is presented in Chapter 5.

1.3.3 A Novel Load-Sharing Control

Proper operation of the parallel converters requires an explicit load-sharing mechanism. In order to facilitate modular design, a droop method is recommended. Traditionally, however, a droop method has to compromise between voltage regulation and load sharing. After parametric analysis, this work proposes a novel droop method using a gain-scheduling technique. The analysis shows that the proposed method can achieve both good voltage regulation and good load sharing. This idea is presented in Chapter 6.

1.3.4 High-Frequency Noise Reduction

Because of its symmetrical structure, the parallel converter system can reduce high-frequency differential-mode noise by using an interleaving technique. With a center-aligned symmetrical PWM scheme, it is found that the parallel system can also reduce high-frequency common-mode dv/dt noise.

Based on the concept that a symmetrical circuit can reduce common-mode dv/dt noise, a conventional three-phase, four-leg inverter is modified so that its fourth leg is symmetrical to the other three legs. The common-mode dv/dt noise can be practically eliminated in the modified inverter with a new three-dimensional SVM strategy. Meanwhile, with a modified control design, the new four-leg inverter still can handle low-frequency common-mode components that occur due to unbalanced and nonlinear load. This subject is covered in Chapter 7.

Chapter 8 presents the conclusions and future work.