CHAPTER I

INTRODUCTION

1.1 Motivations

For high power applications, the three-phase full-bridge switching converters have been broadly used in recent years. However, because of the nonlinear operation characteristics of switching components and the coupling effects between the three phases, the modeling work of a three-phase switching converter is very difficult. In the past studies, most models are expressed in complicated mathematical expression form. Hence, designers have to endure the repeated complex mathematics while finding a trial-and-error solution. In other words, such complicated models that probably has more than six-order dimensions are hard to be applied for controller design. On the other hand, in order to simplify evaluating the performance of the switching converters, many studies proposed some simpler simulation models that can be implemented with computer software. However, most of these simulation models are only suitable for time-domain analysis and lack of a unified form to provide small-signal models. Recently, a simple graphic modeling technique, namely Signal Flow-Graph (SFG) technique, is proposed to model DC-DC converters [32]. These models can be derived easily and be able to provide deep physical intuition about the DC-DC switching converter operations. But the same technique is rather difficult to be applied to three-phase converters because the phase voltages are no longer with unidirectional voltage polarity as in DC converters.

In view of the problems mentioned previously, the author proposes the concept of virtual switch and virtual switching function to overcome the bottleneck of applying the SFG technique for modeling the three-phase switching converters and to reduce the complexity of the modeling work of using equation form model. Moreover, based on the proposed SFG modeling technique, the unified large-signal, steady-state and small-signal model for three-phase switching converters can easily be developed. The proposed SFG models can be implemented straightforward with commercial software for time-domain simulation and also suitable for small-signal analysis. Besides, the graphic representation of the SFG model can reveal the cause-effect relations of the circuit; that is helpful for system analysis and controller design. The proposed SFG model can preserve both advantages of equation-form model and DC-DC SFG model. The proposed SFG modeling technique can provide an easier, more flexible and more practical modeling approach as compared with the existent modeling method.

1.2 Literature Survey

1.2.1 Equation Form Model

Conventionally, a great number of three-phase switching converters' models are represented in equation form [1]-[12]. A great number of the equation-form models are derived based on state-space averaging theory [1] and the dynamic equations of the switching converters can be obtained according to circuit topology. Generally, the dynamic equations are expressed in D-Q coordinate to eliminate the time-varying nature of the switching converters. On the other hand, a few equation-form models are developed by utilizing other concept [7]-[12]. In [10], the switching functions of the active switches are represented in Fourier series, this approach has made possible direct computation of harmonic terms.

These models have complicated mathematical solutions. The main drawback of these models is that large amount of mathematic work is required during the modeling process. The dimensions of the characteristic equations in these models are more than sixth order [2]-[6]. It's very hard to apply such complicated models for controller design. It is also rather difficult to obtain some physical concept of the circuit in a perceivable way from these models.

1.2.2 Non-equation Form Model

A number of the three-phase switching converters are modeled for the purpose of computer simulation. The switching function concept is mainly used to describe the switching operation of the converters [13]-[21]. The concept of switching function is very helpful for understanding the operation of the power converters. The switching converters can be modeled based on the switching functions, rather than the whole circuit configurations. As the switching functions are well defined and when combined into the dynamic equations, the simulation model can easily be implemented. There are many commercial tools available, like MATLAB/SIMULINK, SPICE or PSPICE [22-26], SABER [27], CASPOC [28] and SPECTRE [29] etc. In the case of MATLAB [13]-[20], the switching converters can be modeled by using the functional blocks that contains the state equations of circuit. Nevertheless, when there is any minor modification in the circuit configuration, the state equations should be re-derived. That is a laborious work to find out the new state equations. On the other hand, the PSPICE and Saber are suitable for analysis at circuit level. As simulate with PSPICE [21], there are problems of long simulation run-time and convergence.

The latest version of MATLAB/SIMULINK includes the “Power System Blockset” [30], which allows the simulation of power system and power electronics [31]. There are many well-known topologies created in this toolbox. But in order to generate more complex or novel power topologies, it produces too many algebraic loops. Execute these algebraic loops is rather time-consuming and may resulting in divergence problem [13].

The simulation model is very helpful for evaluating the time-domain performance of the switching converters at system-level. However, the major week point of these models is that they are deficient in supplying a closed-form solution. Most of the simulation models lack of the small-signal model for helping the frequency-domain analysis. Besides, the switching operations in these researches are supposed to be ideal. For example, the ON-resistance and the blanking-time effect of switches are not considered.

Recently, Smedley et. al have developed a general graphical nonlinear modeling tool [32], [33] to reveal both global and local dynamic properties of DC-to-DC switching converters. Basically, this technique can be considered as an extension of the familiar linear circuit flow-graph theory. It is able to provide unified large-signal, steady state, and small-signal models for PWM DC converters. In addition, the switching flow-graph model is very easy to derive, and it provides a visual representation of the converter system [32]-[35]. However, the same technique is rather difficult to apply to three-phase switching converters. Unlike the DC converters, the voltage is no longer with unidirectional polarity. Thus, when applied to a three-phase full bridge converter [36], it is required to divide the whole period of the sinusoidal voltage into six regions such that during each region, the three phase voltages are maintained in their respective polarities. As a result, twenty-four sub-circuits and twelve switching functions are required and let alone to obtain a switching flow-graph. One can see that the SFG model of the APF proposed in [36] is also a simulation model implemented with MATLAB/SIMULINK. Although references [37], [38] propose the concept of effective switching functions to reduce the complexity of applying the SFG technique to model the DC-AC converters, the problem of the different voltage polarities has not been investigated clearly, either.

1.3 Contribution of This Dissertation

Basically, the contribution of this dissertation includes:

1. A graphic modeling tool, namely the switching flow-graph (SFG) modeling technique, for three-phase switching converters is proposed in this dissertation. This technique applies the signal flow-graph theory to model the multi-switch circuits and hence enhances the convenience of analyzing the nonlinear

characteristics of the switching converters.

2. The SFG technique can be applied to model the three-phase/single-phase inverters and rectifiers. The large-signal, steady-state and small-signal models of the switching converters can easily be developed. At the same time, SFG model is able to provide deep physical intuition about the switching converters, which is helpful for the controller design and system analysis.

3. The concept of the virtual switch and virtual switching function are introduced into the modeling work. Major advantages are given as follows:

   (a) By defining the virtual switch and virtual switching function, the difficulties of modeling a AC circuit can be obviated successfully.

   (b) Based on the concept, the effect of ON-resistance and blanking-time of the active switches can easily be taken into account. It is very valuable for actual application.

   (c) As the definitions of a virtual switch and its virtual switching function are completed, the six active switches and six diodes of the three-phase switching converters can easily be integrated and simplified to three virtual switches. According to the equivalent circuit with the virtual switches, the switching flow-graph of each phase is almost decoupled. Therefore, the complexity of modeling work between phase and phase is greatly reduced.

   (d) Only three virtual switches and three virtual switching functions are required during the modeling work. The switching flow-graph for three-phase switching converters can be developed very easily.

   (e) The corresponding large-signal, steady-state and small-signal models can be obtained straightforward from the simple switching flow-graph.

   (f) The virtual switching function can be obtained easily by using the logical operators to combine the switching functions of active switches and the judgment of current directions. Simultaneously, the switching functions of diodes can be found.

(g) Because the switching functions of diodes can also be obtained, the model of the corresponding three-phase diode bridge rectifier can be obtained trivially.

4. The SFG model can be implemented with MATLAB/SIMULINK facilely to carry out the time-domain simulation. It effectively enhances the system-level design and reduces the execution time of simulation.
5. The large-signal SFG model can predict the dynamic performance of switching converters correctly and quickly as comparing its simulation with the results of PSPICE model.
6. The SFG technique can also be applied to various applications like DCM DC-DC converters, soft-switching circuit and parallel VSI, etc.

In this dissertation, the proposed SFG modeling technique is mainly focus on the three-phase full-bridge switching converters with the assumptions:

(a) The three-phase switching converters are operated under low source frequency.

(b) The switching frequency is much larger than the converter operation frequency.

(c) The three-phase switching converters are operated in linear PWM range.

(d) The switching spike and the parasitic effect of the circuit layout are neglected.

1.4 Outline of Contents

Contents of the following chapters are outlined as follows:

First, the signal flow-graph modeling technique for DC-DC converters is reviewed in chapter II. Then the proposed switching flow-graph model for three-phase

PWM inverters is developed in chapter III. In this chapter, the concept of the virtual switch and virtual switching function are explained in detail. The modeling procedure is also described explicitly. One can follow the procedure to obtain the large-signal, steady-state and small-signal models of the three-phase PWM inverters. By following the similar modeling concept introduced in chapter III, the SFG model for three-phase PWM rectifiers can be constructed easily, as elaborated in chapter IV. The corresponding SFG models based on DQ-coordinate are also elucidated. The large-signal SFG model of the three-phase diode bridge rectifier is mentioned by way of parenthesis in this chapter. In chapter V, the applications of the controller design and system simulation with the proposed SFG models are discussed. Several experimental results are also presented in this chapter. Finally, some conclusions are given in the last chapter.