Chapter 14

CONCLUSIONS

In this book, three-phase rectifiers that provide low harmonic distortions of the input currents applying current injection principle are analyzed. Three types of current injection are analyzed and compared: the third-harmonic sinusoidal current injection, the optimal current injection, and the square-wave current injection. The book focuses on the rectifiers that do not apply high-frequency switching. Instead, the rectifiers that provide current injection applying passive elements are analyzed. Results provided in references [7], [10], [11], and [24]–[40] related to the defined scope of the book are systematized and presented, as well as some new results that have not been published previously.

Chapter 2 presents basic results regarding three-phase diode bridge rectifiers. These results include spectra of the output terminal voltages, spectrum of the output voltage, and definitions of the diode state functions, which are the basic tools for the analyses that follow. Waveforms of the input currents are presented, and their total harmonic distortion (THD) values are computed. Notches in the rectifier input voltages caused by discontinuities in the input currents and parasitic inductances of the supply lines are illustrated for experimental results.

Current injection principles are presented in Chapter 3, where a current injection system consisting of a current injection network and a current injection device is introduced. Basic ideas behind the method are discussed. It is shown that the injected currents should contain spectral components at triples of the line frequency only, in order to provide the same waveforms of the input currents at all three of the phases, with the same amplitude spectra, but mutually shifted in phase for one third of the line period. A common misunderstanding that the third-harmonic current injection is a sort of compensation for the third-harmonic component in the input currents is clarified. It is clearly stated that spectral components at triples of the line frequency did not exist in the input currents before the current injection was applied, nor do they exist after the current injection is applied, since the system considered is a balanced three-wire system. The path where the harmonic currents at odd triples of the line frequency flow is shown, as well as how they affect the input current waveforms.
In Chapter 4, magnetic current injection devices are analyzed in detail, which provides information not available in the references. Volt-ampere rating of a magnetic device is defined, extending the volt-ampere concept of [9]. This quantity is used as a measure to compare various constructions of the current injection devices. Various current injection devices are presented, and their performance compared. According to the results in Chapter 4, it can be concluded that in most applications it would be best to apply a current injection device based on a zigzag autotransformer. In Section 4.6, a novel magnetic device that integrates the current injection device and the inductor of the current injection network is proposed. This result has not been previously published. Application of a three-phase wye-wye connected transformer to adjust the voltage level and to provide current injection, as it is utilized in [13] and [15], is discussed next. Issues regarding the volt-ampere rating are clarified, and it is shown that the transformer can provide the current injection with negligible increase of the volt-ampere rating. Application of a delta-wye connected transformer in the same purpose is discussed in Section 4.8. This transformer arrangement provides a voltage level adjustment, current injection, and negligible inductance of the neutral point, with a minor increase in the device volt-ampere rating.

The third-harmonic current injection is discussed in Chapter 5. Theoretical study of the third-harmonic current injection, in which the amplitude and the phase of the injected current are optimized in order to minimize the input current THD, is presented. It is shown that the input current THD can be improved only at the cost of the power taken by the current injection network. Improvement of the input current THD is related to the power taken by the current injection network, and it is shown that in the case of the optimal third-harmonic current injection the input current THD equals 5.12%, while the power taken by the current injection network equals 8.57% of the input power.

Constructions of the current injection networks are discussed in Chapter 6, where the current injection networks proposed in [12] and [13] are compared. It is shown that these current injection networks behave in the same way at odd triples of the line frequency, while their different overall behavior is caused by their different behavior at even triples of the line frequency. After the harmonics at even triples of the line frequency are identified as the reason that the current injection network proposed in [13] provides lower THD values than the current injection network proposed in [12], a novel current injection network is proposed. The novel current injection network, originally proposed in [30], is analyzed in detail, and it is shown that it provides the lowest THD values of the input currents, with low dependence on the current injection network $Q$-factor. The case when the current injection network $Q$-factor approaches zero is separately analyzed,
showing that the lowest input current THD is obtained here. The last of the current injection networks analyzed in Chapter 6 is utilized in all of subsequently analyzed rectifiers that apply the third-harmonic current injection.

The optimal current injection, the topic of Chapter 7, provides ideal sinusoidal waveforms of the input currents, and it relies on injection of the currents containing spectral components at triples of the line frequency, i.e., the injected current is enriched by higher order harmonics. Basic principles of the optimal current injection are presented in Chapter 7. Waveforms of the diode bridge load currents that provide the optimal current injection are derived, as well as the requirements imposed to the current injection network in order to provide the optimal current injection.

In Chapter 8, current injection networks that provide the optimal current injection are presented. This chapter presents systematized and expanded results of [26] and [35]. Several current injection networks are analyzed, all of them being built applying capacitors, resistors or resistance emulators, and transformers, without any need for inductors. The influence of finite capacitance of the capacitors on the input current THD is analyzed, as well as the influence of the output current ripple.

Chapter 9 is somewhat specific, and it presents the analysis of the discontinuous conduction mode in three-phase diode bridge rectifiers. The problem is mathematically complex, and requires application of numerical methods to be solved. A piecewise linear state-space model of the rectifier is developed, normalization of variables is applied to generalize the results, and special mathematical techniques proposed in [51] are applied to solve the problem numerically. It is shown that the rectifier discontinuous conduction mode might be of practical interest, since it provides acceptable values of the input current THD and high efficiency applying simple and robust circuitry. Dependence of the input current THD, the rectifier efficiency, and the output voltage on various of the rectifier parameters is analyzed.

Application of a current-loaded resistance emulator to recover the power taken by the current injection network is the topic of Chapter 10. The current-loaded passive resistance emulator is described, and it is shown that it provides automatic adjustment of the injected current amplitude to the load current. Choice of the rectifier parameters is discussed. A novel simulation method to analyze dependence of the input current THD on the load current, caused by the higher order harmonics of the injected current, is presented in Section 10.3. This method has not been presented before.

Chapter 11 presents a completely new rectifier that applies voltage-loaded resistance emulator. This rectifier is presented in this book for the first time. The rectifier is simple, requires only one resonant circuit, and a small number of other components that are exposed to relatively low voltage
and current stress. Operation of the rectifier is analyzed in the continuous and the discontinuous conduction modes, and optimization of the rectifier parameters to minimize the input current THD is performed in both of the operating modes. Although adjustment of the injected current amplitude to the load current is not as straightforward as it is in the rectifier presented in Chapter 10, even better results are experimentally obtained.

The switching current injection device is analyzed in Chapter 12. The concepts developed for the rectifiers that apply magnetic current injection devices are adjusted to the switching current injection device. It is shown that application of the switching current injection device provides an attractive opportunity to obtain the same results as obtained applying magnetic current injection devices, but with three times lower amplitude of the injected current and three times lower volt-ampere ratings of the magnetic devices applied in the current injection network. Design of the current injection networks intended for application with the switching current injection device is discussed; one current injection network for the third-harmonic current injection, and two current injection networks for the optimal current injection are proposed. Dependence of the input current THD on various parasitic effects is analyzed. It is shown that operation of the rectifier that applies switching current injection device in the discontinuous conduction mode results in unacceptably high values of the input current THD. This restricted application of the resistance emulators to the current-loaded resistance emulator.

The rectifiers that apply square-wave current injection are analyzed in Chapter 13. In the first part of Chapter 13, the rectifier proposed in [14] is subjected to detailed analysis. It is shown that this rectifier can be treated as a special case of the rectifier analyzed in Chapter 10, which applies the third-harmonic current injection and current-loaded passive resistance emulator. Thus, it was natural to analyze the same special case in the rectifier proposed in Chapter 11, which applies a voltage-loaded resistance emulator. This is the second rectifier analyzed in Chapter 13, and it has not been published before. The rectifier provides the same THD of the input currents as the rectifier proposed in [14], with some differences in regard to realization and sensitivity to losses in the current injection system.