Numerical Optimization for High-frequency Class-E Switching Circuits

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High-frequency power converter circuits are desired because the resonant inductance and electromagnetic interference (EMI) filter become small. However, the switching losses increase proportionally as the switching frequency increases, resulting in power conversion efficiency degradation and the requirement for a large cooling system. Therefore, at megahertz-range operations, it is mandatory to achieve soft switching. For achieving high-frequency power converter, the class-E families, such as class-E, class-DE, class-EF, and class-Phi inverters, are the suitable candidates with only one MOSFET. Additionally, the source terminal of the MOSFET is connected to the ground. Therefore, there is no need for high-side drivers. By applying the ZVS to the class-E2 converter for both turn-on and turn-off switching, the switching loss can be reduced effectively.

Nevertheless, the decision of circuit components of the class-E inverter family is challenging due to the complicated working principle. The circuit component, including the output resonant filter and shunt capacitance, have a complicated effect on the circuit operation. These component values should be found to satisfy the class-E ZVS and ZDS conditions simultaneously. There are two kinds of component-derivation methods in general, including analytical-based derivation procedures and numerical-calculation-based ones. The analysis of class E circuits allows the values of circuit components to be explicitly expressed as functions of circuit parameters. Early papers on the analysis of class E amplifiers are based on some several ideal conditions. Subsequently, the initial assumptions were gradually relaxed. Nevertheless, it requires knowledge and experiment to perform circuit analysis, which is time-consuming.

For the real applications of the power converter, the conditions such as load devices are ever-changing, which may lead to the variation of system output. Therefore, control methods are usually applied to the power converter. For example, regulated output voltage and power factor correction control are usually applied for the AC-DC converter. For that reason, the circuit works in the transient states due to the ac input-line voltage and controlled parameters. To achieve high power-conversion efficiency, it is necessary to ensure the achievement of soft-switching conditions over the entire range of input line-voltage periods. However, there is no numerical design method for the class-E AC-DC converter which can achieve ZVS for the entire line-voltage period.

In this thesis, a numerical design method based on the Newton-Raphson method is presented in this thesis for the designing of novel AC-DC converters based on class-E2 topology at MHz operation. Taking advantage of the class-E switching circuits, a single-switch structure can be achieved. Additionally, a frequency modulation (FM) controller is presented in this section to decrease total harmonic distortion. However, traditional analysis-based design is unpractical because circuit analysis is difficult considering switching frequency variation. For solving this problem, a numerical design procedure is proposed in this section. By visualization of switch voltage patterns, circuit parameters that can achieve ZVS for the entire input line-voltage cycle can be selected. By conducting the circuit experiment, the validity of the design method introduced in this section was proven.

Secondly, the comprehensive numerical design method for the class-E switching circuits is proposed. The proposed design method can be applied to a variety of class-E inverters, including the class-E, class-EF, and class-phi inverters. Unlike the previous equation-solving-based design methods, there is no limitation on the number of design parameters. It is unnecessary to find the initial parameters or partial differential equations. The Particle Swarm Optimization (PSO) algorithm is adopted for optimization. Additionally, only by modifying the PSO algorithm, we also develop the design method, which provides the parameter sets of different operation modes in the identical circuit topology simultaneously, such as the class-E amplifier and the frequency multipliers. Additionally, by evaluating only the system power loss, we can automatically obtain the parameter set for satisfying the class-E ZVS/ZDS conditions.

Thirdly, a numerical design method for achieving load-independent condition for class-E switching circuits are proposed in this thesis. As one of the drawbacks of the traditional class-E switching circuits, the output voltage, current, and ZVS achievement are highly sensitive to load variation. For solving this problem, load-independent technology was proposed.
In this research, evaluation functions for achieving load-independent conditions are proposed. By applying the PSO algorithm, the circuit parameters for achieving the class-E load-independent conditions can be derived.