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MULTI-DOMAIN, MULTI-OBJECTIVE-OPTIMIZATION-BASED APPROACH TO THE DESIGN OF CONTROLLERS FOR POWER ELECTRONICS

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MULTI-DOMAIN, MULTI-OBJECTIVE-OPTIMIZATION-BASED APPROACH TO THE DESIGN OF CONTROLLERS FOR POWER ELECTRONICS

THESIS

A thesis submitted in partial fulfilment of the requirements
for the degree of Master of Science in Electrical
Engineering in the College of Engineering at the University
of Kentucky

By

Jing Shang

Lexington, Kentucky

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2014

ABSTRACT OF THESIS

MULTI-DOMAIN, MULTI-OBJECTIVE-OPTIMIZATION-BASED APPROACH TO THE DESIGN OF CONTROLLERS FOR POWER ELECTRONICS

Power converter has played a very important role in modern electric power systems. The control of power converters is necessary to achieve high performance. In this study, a dc-dc buck converter is studied. The parameters of a notional proportional-integral controller are to be selected. Genetic algorithms (GAs), which have been widely used to solve multi-objective optimization problems, is used in order to locate appropriate controller design. The control metrics are specified as phase margin in frequency domain and voltage error in time-domain. GAs presented the optimal tradeoffs between these two objectives. Three candidate control designs are studied in simulation and experimentally. There is some agreement between the experimental results and the simulation results, but there are also some discrepancies due to model error. Overall, the use of multi-domain, multi-objective-optimization-based approach has proven feasible.

KEYWORDS: Multi-domain, multi-objective optimization, Genetic Algorithms, power electronics, converters.

Jing Shang

October 1st, 2014

MULTI-DOMAIN, MULTI-OBJECTIVE-OPTIMIZATION-BASED APPROACH TO THE DESIGN OF CONTROLLERS FOR POWER ELECTRONICS

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CHAPTER 1 INTRODUCTION

One of the major reasons why ac electricity was widely accepted in modern electric power systems is the magnetic transformer and its ability to change voltage levels efficiently. Magnetic transformers cannot handle dc. In power electronics, modern semiconductor devices have been used to perform efficient voltage transformations. Power converters are widely applied to provide power for every aspect of life, from high-power transmission and distribution to appliance control, communication, and transportation. In a power converter, control is performed by altering switch action. Goals of control for power converters include stability and high quality output regulation. By stability, it is desirable for the operation of the power converter to recover following small and large disturbances. The power converter is also responsible for maintaining its output voltage in the presence of variations in the load, the input supply, temperature, or other external factors. An example of such a power electronic converter is the buck converter, which is a circuit used to step down the dc voltage. The control of such circuits is necessary to achieve high performance. Thus, this is an important and widely studied area within the study of power electronics.

The simplest way to operate a system is with open-loop control. However, the control inputs are not adjusted, and are independent variables, thus open-loop control methods are not robust when there are unexpected disturbances, parameter variation, or other off-nominal conditions. Closed-loop or feedback control involves the measurement of the output or some other variables in a system. These measurements are compared with the desired action of the system. An error signal is developed and used to modify the control input. Feedback control gives the system more robust performance. Many kinds of feedback control can be implemented in many ways, including analog and digital methods.

In power converter control design, most control design is performed in the Laplace domain. Rules of thumb have been widely used in industrial and academic settings as a way to tune a converter's controller. Such rules of thumb are based on experience and can provide guidance on pole placement, appropriate gain and phase margins, etc. This experience-based method is often used to speed up the process of finding an acceptable controller. However, resulting solutions are not guaranteed to be optimal with respect to the control designer's objectives, may not be appropriate outside of the experience in which the rules of thumb were constructed, and require extensive control designer experience to be successfully applied.

It is proposed herein to use multi-objective optimization methods for power electronic control design. The multiple objectives can be based on many different domains. Control metrics are often specified in different domains. Examples include overshoot and settling time in the time domain and phase and gain margin in frequency domain. Combinations of these metrics can be used as optimization objectives in order to arrive at appropriate controller designs. Genetic algorithms (GAs), which have been widely used to solve multi-objective optimization problems, can be used in order to locate appropriate controller designs.

Herein, a dc-dc buck converter is studied. The parameters of a notional proportional-integral (PI) controller are to be selected. The controller optimization problem is stated as a multi-objective optimization problem with two objectives. The first objective is phase margin, a traditional frequency-domain control metric that gives some indication of the stability of the closed-loop system. The second objective is the rms voltage error following a step change in load, a time-domain performance metric used to indicate the performance of the closed-loop system. These objectives are sometimes contradictory, in which stability must be traded for performance. A GA is used to find the set of optimal tradeoffs between these objectives, and several candidate control designs are studied in simulation and experimentally.

This thesis is organized as follows. Chapter 2 presents background on buck converters, PI control, multi-objective optimization, and GAs and also discusses the present state of research in the area of this work. Chapter 3 discusses the modeling of the converter and controller as well as the optimization objectives. Chapter 4 introduces the optimization technique, optimization results, and simulation results. Chapter 5 presents the experimental results and provides comparisons with the simulation results. Chapter 6 concludes the thesis and lists possible future work.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

In this chapter, background information regarding the research and a review of relevant literature on the research topic are presented.

2.1 Background

In this section, background information of buck converters, multi-objective optimization, and GAs is described.

2.1.1 Buck Converter

A buck converter is depicted in Figure 2.1. A buck converter is a dc-dc converter that is capable of stepping voltage down. The transistor and diode act as a single-pole, double-throw switch and produce a rectangular voltage. The LC output filter attenuates the harmonics resulting in an output voltage that is essentially equal to the dc component. A control system is introduced for regulation of the output voltage. Since the output voltage is a function of the switch duty cycle, a control system is constructed to vary the duty cycle so the output voltage can follow a given reference.

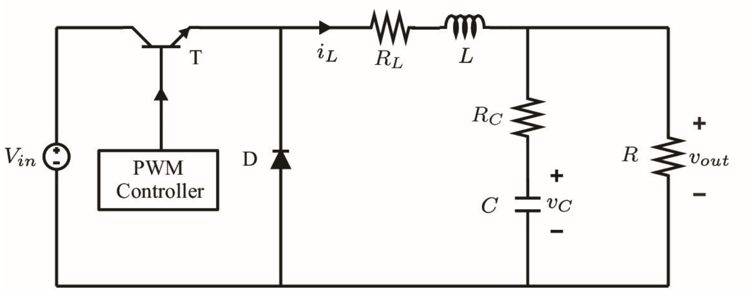

Figure 2.1. Buck converter

Such a circuit has low losses because the switching devices have very low power loss .The reason is that the switches conduct no current when off and exhibit no voltage when on. Voltage and current thus produce zero power loss. As discussed above, the output of a buck converter is determined in part by the switching function. Pulse-width modulation (PWM) is a modulation technique that controls the width of the pulse, based on the modulation signal. PWM techniques are relatively simple to implement and can be used with both analog and digital controllers.

The interceptive method is one of the simplest ways to generate a PWM signal. It produces PWM signal by comparing the modulation signal with a saw tooth carrier waveform. When the saw tooth carrier waveform is less than the modulation signal, the PWM signal is in the high state (1). It is in the low state (0) otherwise.

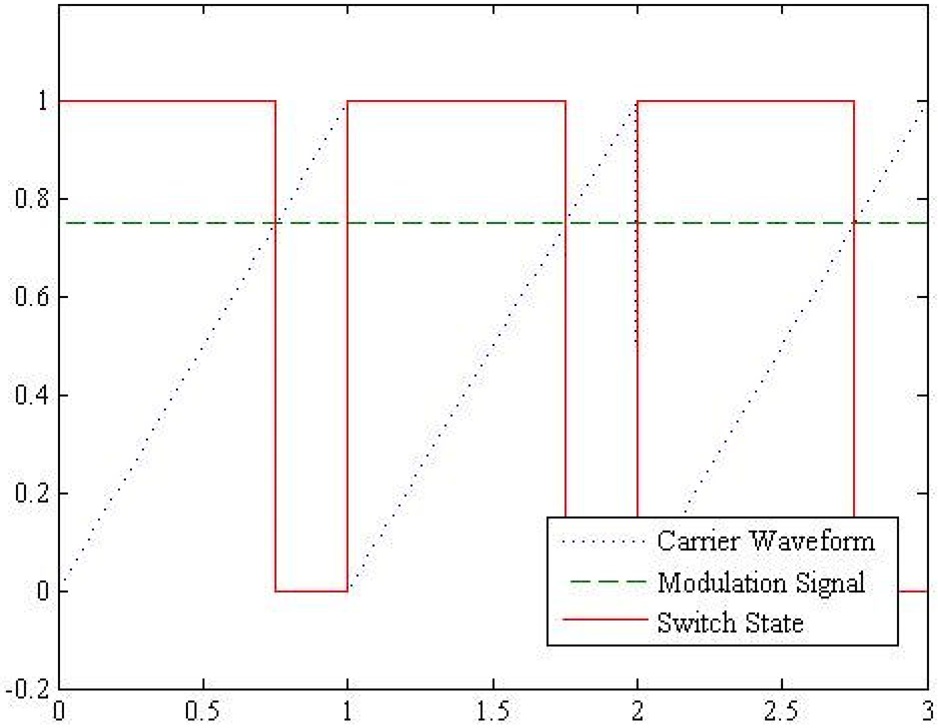

Figure 2.2. PWM

2.1.2 Multi-Objective Optimization

Multi-objective optimization involves the optimization of more than one objective function. Each objective is either to be minimized or maximized. The objectives may be mutually contradictory. For example, minimizing cost and maximizing quality may at some level be conflicting objectives.

While single objective optimization involves locating a single solution that represents the optimum of the single objective function, multi-objective optimization does not generally result in a single solution. Instead, a subset of solutions that describe the best tradeoff between competing objectives is located [1]. The notion of best tradeoff is understood in the sense of nondominance. A solution is said to dominate another solution if the first matches the performance of the second in all objectives and exceeds the performance of the second in at least one objective. The set of feasible solutions for which no other feasible solution dominates one of these solutions is called the Pareto-optimal set. The mapping of these solutions into the objective space is called the Pareto-optimal front, and this is depicted in Figure 2.3. Understanding this front allows the tradeoffs among the objectives to be considered by decision makers. Some decision makers may prefer the minimum cost solution, some may prefer the highest quality solution, and some may prefer a point between these extremes. In no case should a decision maker choose a point outside of this front because an improvement to cost can be made without sacrificing quality, and vice versa.

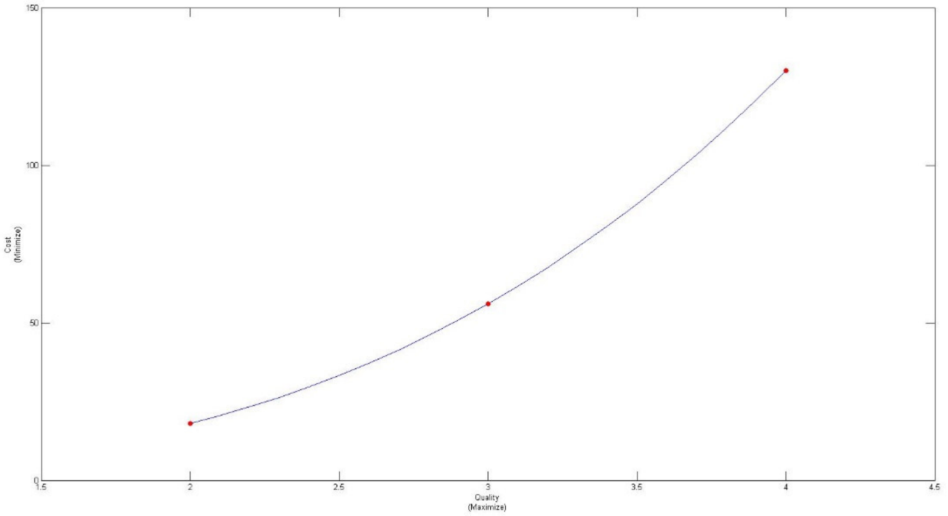

Figure 2.3. Pareto-optimal front

2.1.3 Genetic Algorithms

GAs are methods of producing optimal solutions by mimicking nature's survival-of-the-fittest principle. This is done by taking a population of possible solutions and evolving them according to genetic operators in order to improve the fitness associated with the solutions [2].

In GAs, fitness is defined as a metric that measures how good each candidate solution is as the solution to a given problem. Selection is used to select individuals with high relative fitness. These individuals go through a process called crossover. In crossover, the individuals reproduce in order to form new children candidate solutions that are related to the parent solutions. Next, mutation is applied to the children solutions in order to allow the algorithm to explore the search space. The fitness of the new individuals is evaluated, and the new individuals are inserted back into the population. Elitism can be used to ensure that the best individual in the population is not replaced with an inferior individual. This process repeats through many generations.

GAs have been used in many applications. They are particularly useful if the fitness function is not well understood or is not differentiable. As the desired solution to a multi-objective optimization problem is a set of solutions, the population-based nature of GAs make them well suited to solving such problems [3]. Such multi-objective GAs include the classical nondominated sorting GA (NSGA) [4] and the updated and currently widely used form NSGA-II [5]. This current form alleviates the computational complexity, nonelitist approach, and the need for specifying a sharing parameter [6]. Other approaches include the vector-evaluated GA [7], the strength Pareto evolutionary algorithm, and the Pareto archived evolution strategy.

2.2 Literature Review

Many optimization methods for power electronic control design have been applied, so as to reduce the design effort. Traditional proportiona-integral-derivative (PID) control tuning methods such as the Ziegler-Nichols tuning method [8], linear programming [9], successive quadratic programming [10], and Newton's method [11] have long been successfully applied to power electronic systems. Modified versions of such control methods have also been widely studied to improve system performance [12].

Fuzzy logic is one of the many methods that are used for such optimization. In [13], a fuzzy expert system is built. This is a branch of artificial intelligence that helps designers to design, simulate and optimize power converters. The fuzzy decision maker helps the users to select the converter topology and control parameters.

Particle swarm optimization (PSO) method has proved effective in the optimization field. In [14], a PSO method for determining the PID controller parameters is presented, so as to improve the step response of a third-order system. However, it proved the method's effectiveness simply by comparing the time-domain performance with the results that are produced by using three other classic tuning methods. There is not enough evidence in this paper to say that this method can help the system to achieve its best performance. PSO and Newton's method are combined in [15] to optimize control of a voltage source three-phase three-level ac-dc converter. Multiple optimization goals were reached, including maintaining high power factor, minimizing the total harmonic current distortion, and keeping the dc-link voltage at a reference level.

The application of GAs in control has been widely studied. Determination of control parameters through optimization of time-domain based performance metric has been proven successful in the case of intelligent control. For example, [16] proposed the application of GAs to optimize the parameters of a fuzzy model reference learning controller employed in a speed control loop. In [14], an intelligent automatic landing system using fuzzy neural networks and GAs was developed to improve the performance of conventional automatic landing systems. The application of a GA to the modulators for permanent magnet synchronous machine drives is proposed in [18]. A GA was used for online tuning in [19] and was proven experimentally to optimize the drive's response efficiently.

The same approach has also been applied to the design of traditional linear controllers. For example, [20] considers the application of GAs to a bidirectional inductive power transfer system by tuning a PID controller. GAs are applied to tune a PID controller of a hydraulic turbine regulating system in [22]. An optimal disturbance rejection PID controller was designed using GAs in [23].

Multi-objective GAs has been successfully applied in many areas. The NSGA-II is applied to a thermal model for the converter to minimize the converter volume and the power dissipated in the components in [24].

Determination of control parameters through optimization of frequency-domain and time-domain based performance metric has been proven successful in many cases as well. For example, [25] proposed the application of GAs for solving multi-objective optimization problems in robust control of distillation column. The multi-objective controllers designed are able to synthesize problems with a mixed time and frequency domain specifications. However, it was not able to perform the tradeoff relationship between performance metrics.

CHAPTER 3 MODELING

In this chapter, various models of the buck converter and its controller are set forth. These models are used for optimization and for detailed simulation.

3.1 Buck Converter

The buck converter can be represented in a variety of ways. The most detailed representation is a switching model. The switching behavior can be averaged in order to reach an average model. Finally, a small signal model can be developed and used to extract the transfer function of the converter.

3.1.1 Switching Model

The buck converter depicted in Figure 2.1 can be described by the following equations:

$$L\frac{di_L}{dt} = qV_{in} - R_L i_L - v_{out} \tag{1}$$

$$C\frac{dv_C}{dt} = i_L - \frac{v_{out}}{R} \tag{2}$$

$$v_{out} = \frac{R}{R+R_C}(v_C + R_C i_L), \tag{3}$$

where q is the switching function that takes values of zero and one to represent the transistor state, V_{in} is the input voltage, v_{out} is the output voltage, $i_L$is the inductor current, v_C is the capacitor voltage, R is the load resistance, and $R_C$and R_L are the capacitor and inductor resistances, respectively.

The switching model is the most detailed model of the buck converter, and is used in this study to develop an averaged model which can be further developed into a small signal model. It is also used to simulate the performance of buck converter.

3.1.2 Averaged Model

While the switching model is very detailed, it is also time consuming to perform simulations using this model. The detailed high-frequency behavior of the switching function requires small time steps and increases run time. In many cases, the switching behavior is not of primary importance. In these cases, the details of the switching can be averaged in order to produce a model that can be simulated more quickly.

Switching ripple in the inductor current and capacitor voltage can be removed by averaging over one switching period T_s. Hence, the low-frequency components of the inductor and capacitor waveforms are modeled by equations of the following form:

$$L\frac{d\langle i_L\rangle}{dt} = \langle v_L\rangle \tag{4}$$

$$C\frac{d\langle v_C\rangle}{dt} = \langle i_C\rangle, \tag{5}$$

where

$$\langle x(t)\rangle = \frac{1}{T_s}\int_t^{t+T_s} x(\tau)d\tau. \tag{6}$$

It is straightforward to obtain the averaged model of buck converter from (1)–(3):

$$L\frac{d\langle i_L\rangle}{dt} = \langle q\rangle V_{in} - R_L\langle i_L\rangle - \langle v_{out}\rangle \tag{7}$$

$$C\frac{d\langle v_C\rangle}{dt} = \langle i_L\rangle - \frac{\langle v_{out}\rangle}{R} \tag{8}$$

$$\langle v_{out}\rangle = \frac{R}{R+R_C}(\langle v_C\rangle + R_C\langle i_L\rangle). \tag{9}$$

It should be noted that $d = \langle q(t)\rangle$ is the averaged value of the switching function and corresponds to the duty cycle of this function.

3.1.3 Small-Signal Model and Transfer Function

Small-signal models are used to study the behavior of a system about an equilibrium point. Such models can be used as the basis for linearization of nonlinear systems and to extract the transfer function(s) of systems.

If an equilibrium point is selected such that

$$DV_{in} - R_L I_L - V_{out} = 0 \tag{10}$$

$$I_L - \frac{V_{out}}{R} = 0 \tag{11}$$

$$V_{out} = \frac{R}{R+R_C}(V_C + R_C I_L), \tag{12}$$

then the averaged values can be expressed as a sum of the equilibrium values and a perturbation value:

$$\langle v_C \rangle = V_C + \hat{v}_C \tag{13}$$

$$\langle i_L \rangle = I_L + \hat{\imath}_L \tag{14}$$

$$\langle v_{out} \rangle = V_{out} + \hat{v}_{out} \tag{15}$$

$$d = \langle q \rangle = D + \hat{d}. \tag{16}$$

Substitution of (13)–(16) into (7)–(9) and consideration of (10)–(12) yields the following small-signal model of the buck converter:

$$L\frac{d\hat{\imath}_L}{dt} = \hat{d}V_{in} - R_L\hat{\imath}_L - \hat{v}_{out} \tag{17}$$

$$C\frac{d\hat{v}_C}{dt} = \hat{\imath}_L - \frac{\hat{v}_{out}}{R} \tag{18}$$

$$\hat{v}_{out} = \frac{R}{R+R_C}(\hat{v}_C + R_C\hat{\imath}_L). \tag{19}$$

For this small-signal model, it contains one input $\hat{d}(s)$ and one output $\hat{v}_{out}(s)$. Hence, the small signal voltage variations can be expressed in the Laplace domain as

$$\hat{v}_{out}(s) = H(s)\hat{d}(s). \tag{20}$$

The control-to-output transfer function is defined as

$$H(s) = \frac{\hat{v}_{out}(s)}{\hat{d}(s)}. \tag{21}$$

Transforming – in to the Laplace domain, yields the open-loop transfer function

$$H(s) = \frac{\hat{v}_{out}}{\hat{d}} = \frac{(1+RCs)RV_{in}}{s^2(R+R_C)LC+s(RR_LC+RR_CC+R_CCR_L+L)+R+R_L}. \tag{22}$$

3.2 Controller

A PID controller is a closed loop control system that is used where high accuracy is required. The PID control system achieves this accuracy by utilizing feedback control. This means that the controller is sensing the output of the system and feeding it back so that the controller can adjust the input accordingly.

In a feedback system, there is a reference signal that represents the desired value. This reference signal is compared to the measured output value. The comparison gives the error between the actual output and the desired output. The controller then takes the error and converts it into a command. The goal of the controller is to drive the error to zero as time progresses. The error is zero when the measured output matches the reference signal exactly, making the system meet all of its requirements.

PID controllers are used in many applications because they achieve system requirements with simple yet effective methods. The proportional, integral, and derivative actions of the controller are the three ways the error is processed.

The proportional process takes the error of the output and compensates for that error by adjusting the input proportionally. This is a simple and effective way of controlling simple systems, but can cause problems when the system responds too quickly to large errors. An example of this would be an automobile’s cruise control system. If the desired output of the system is 25 mph and the car starts at less than 5 mph then the automobiles engine will inefficiently approach the desired 25 mph output.

The integral process will examine how the error persists over time, summing it up. The integral process is used to remove steady-state error in the system, as the integrator will not react steady state until the error becomes zero.

The derivative process will adjust the control input based on the rate of change of the error in the output. When the rate of change in error is small the derivative response is small. The faster the error changes, the larger the derivative response becomes. Derivative feedback can be used to improve the transient response of the closed-loop system. However, the use of differentiation can amplify high-frequency noise components. This is particularly true in power electronics system in which high-frequency switching ripple is present. For this reason, derivative feedback is not considered herein.

The controller considered herein is shown in Figure 3.1. It uses feedforward of the output voltage and proportional and integral terms based on the output voltage error. The output voltage is filtered with a first-order low-pass filter to remove the switching ripple present in the voltage. The modulation signal calculated by this controller is used in the PWM modulation described above.

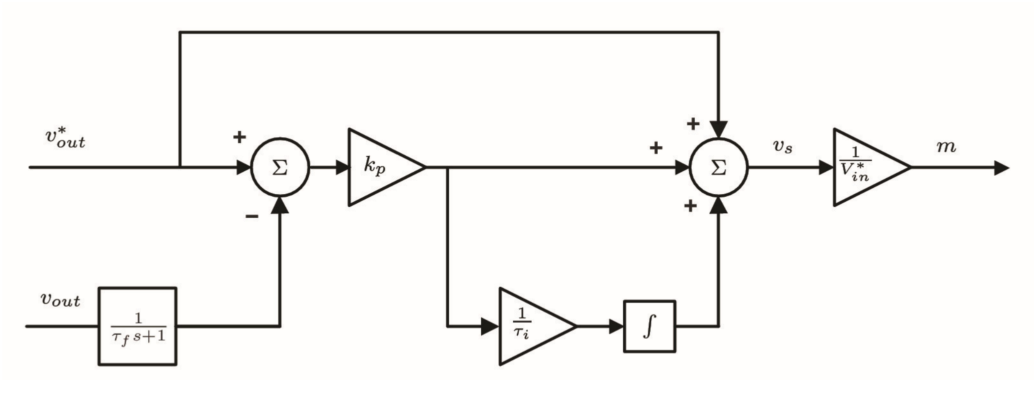

Figure 3.1. Controller

The detailed model of the controller is straightforward:

$$\frac{dv_{outf}}{dt} = \frac{v_{out} - v_{outf}}{\tau_f} \tag{23}$$

$$\frac{de}{dt} = \frac{k_p}{\tau_i}(v_{out}^* - v_{outf}) \tag{24}$$

$$m = \frac{v_{out}^* + k_p(v_{out}^* - v_{outf}) + e}{V_{in}^*}, \tag{25}$$

where v_{out} is the output voltage, v_{out}^* is the output voltage reference, v_{outf} is the filtered output voltage, $k_p$and τ_i are the PI control parameters, V_{in}^* is the nominal value of the input voltage, m is the modulation signal, and τ_f is the filter constant. As shown in Figure 3.1, the modulation signal is compared with a saw tooth carrier signal to determine the switch status q, which is used in the switching model of the converter.

The averaged model of the controller is essentially identical to the detailed model:

$$\frac{d\langle v_{outf}\rangle}{dt} = \frac{\langle v_{out}\rangle - \langle v_{outf}\rangle}{\tau_f} \tag{26}$$

$$\frac{d\langle e\rangle}{dt} = \frac{k_p}{\tau_i}(\langle v_{out}^*\rangle - \langle v_{outf}\rangle) \tag{27}$$

$$\langle m\rangle = d = \langle q\rangle = \frac{\langle v_{out}^*\rangle + k_p(\langle v_{out}^*\rangle - \langle v_{outf}\rangle) + \langle e\rangle}{V_{in}^*}. \tag{28}$$

The averaged modulation signal is taken to be the averaged switch state in the averaged model of the controller.

The small-signal model of the controller is taken based on an equilibrium point with

$$D = \frac{V_{out}^* + E}{V_{in}^*} \tag{29}$$

$$V_{out} = V_{out}^*. \tag{30}$$

Perturbations about the equilibrium point can be expressed as

$$\langle v_{outf}\rangle = V_{out}^* + \hat{v}_{outf} \tag{31}$$

$$\langle v_{out}^{*} \rangle = V_{out}^{*} + \hat{v}_{out}^{*}$$

$$\langle e \rangle = E + \hat{e}. \tag{32}$$

Accordingly, a small-signal model can be constructed as

$$\frac{d\hat{v}_{outf}}{dt} = \frac{\hat{v}_{out} - \hat{v}_{outf}}{\tau_f} \tag{33}$$

$$\frac{d\hat{e}}{dt} = \frac{k_p}{\tau_i}\left(\hat{v}_{out}^{*} - \hat{v}_{outf}\right) \tag{34}$$

$$\hat{d} = \frac{\hat{v}_{out}^{*} + k_p(\hat{v}_{out}^{*} - \hat{v}_{outf}) + \hat{e}}{V_{in}^{*}}. \tag{35}$$

The transfer function of the controller expresses the duty cycle as a function of voltage error and can be expressed as

$$G(s) = \frac{\hat{d}}{\hat{v}_{out}^{*} - \hat{v}_{outf}} = \frac{k_p\left(1 + \frac{1}{\tau_i s}\right)}{V_{in}^{*}(\tau_f s + 1)}. \tag{36}$$

3.3 Optimization Objectives

As discussed above, the performance of a system can be evaluated in many different ways, in both the time and frequency domains. However, various optimization objectives can be competing. For example, increasing stability might result in a corresponding decrease in regulation performance due to a long settling time or a big overshoot. Hence, multi-objective optimization is used to establish tradeoff relationships between competing objectives. The optimization objectives are described below.

3.3.1 Frequency Domain Performance

Frequency domain measures have long been used to assess control system performance. Two important measures are gain and phase margin, which allow stability to be assessed via the loop gain. The system studied herein can be made to have an infinite gain margin for a wide selection of control parameters. Therefore, phase margin is selected as a measure of stability. Good designs should have adequate design margin, and sufficiently large phase margin can result in less overshoot and ringing [26]. Denote the phase margin as φ_m. From the basic definitions of phase margin, the following equations are obtained:

$$\varphi_m = \angle GH(j\omega_c) + \pi$$

where GH is the loop gain of the closed-loop transfer function:

$$\frac{\hat{v}_{out}}{\hat{v}_{out}^*} = \frac{GH}{1+GH}, \tag{37}$$

and the cross-over frequency ω_c is the frequency where the magnitude of the loop gain becomes unity:

$$|GH(j\omega_c)| = 1. \tag{38}$$

An example of phase margin calculation is shown in Figure 3.2.

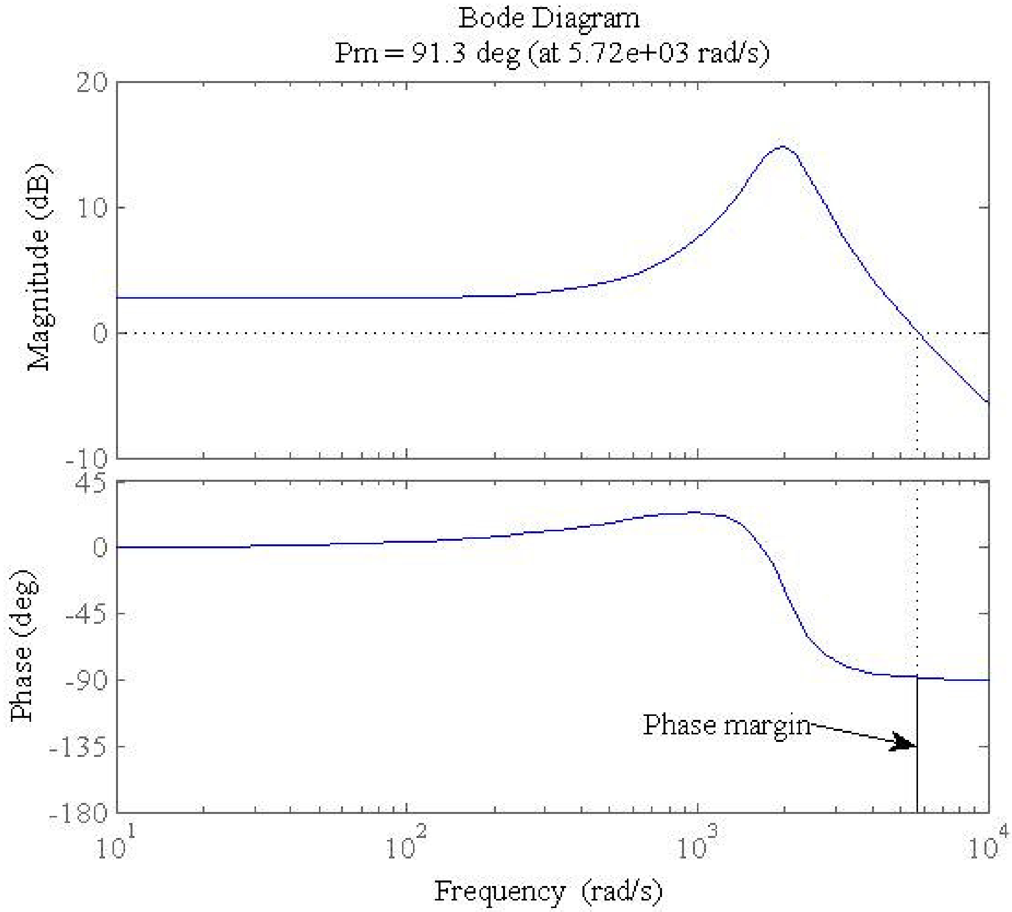

Figure 3.2. Phase Margin

3.3.2 Time Domain Performance

In the time domain, there are various ways to measure the performance of a system in various scenarios. Settling time and overshoot are typical figures of merit for a system's step response.. Overshoot refers to an output exceeding its final, steady-state value. For example, the percentage overshoot for a step input is the maximum value minus the step value divided by the step value. Settling time refers to the amount of time a system uses to reach the final steady-state value. In this study, the converter is intended to produce a constant output voltage. Therefore, a measure of voltage error is considered. In particular, the rms voltage error is considered:

$$v_{err} = \sqrt[2]{\frac{\int_0^T (v_{out}(t) - v_{out}^*)^2 dt}{T}}. \tag{39}$$

This error could be studied for a number of different cases, including changes in input voltage or in load. Herein, step changes in load resistance are considered. One of the optimization objectives is to minimize the voltage error associated with this transient event.

CHAPTER 4 MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization is applied in this chapter to determine the optimal tradeoffs between control performance objectives.

4.1 Optimization Problem

The buck converter and the feedback controller described in Sections 3.1 and 3.2 are studied herein. The parameters are given by Table 4.I. The objective in this work is to find the Pareto-optimal set of k_p and τ_i in the feedback controller with respect to phase margin and voltage error. The voltage error is evaluated based on a step load change from 7.8 Ω to 6.8 Ω.

Table 4.I. Parameters of dc-dc converter

V_{in}	250 V	L	1.52 mH	R	6.8 Ω
V_{in}^*	250 V	C	167 μF	R_L	35 mΩ
v_{out}^*	150 V	f	10 kHz	R_C	50 mΩ
τ_f	0.159 ms				

4.2 Genetic Algorithm

An existing open-source multi-objective GA toolbox named GOSET [27] was used herein to solve the proposed optimization algorithm. It was used with its default parameters, a population size of 200, and 200 generations.

As mentioned above, two objectives are to be optimized. As the GA seeks to maximize its objectives, the negative of the output voltage error is maximized. The values of k_p are varied between 10^{-3} and 10^{1}. The values of τ_i are varied between 10^{-4} and 10^{0} s. In both cases, a logarithmic mapping was used to allow the GA to search efficiently over multiple orders of magnitude. The MATLAB [28] code to call GOSET and the MATLAB code implementing the fitness functions are given in the appendix. The voltage error is evaluated using the averaged model shown in Figure 4.1. The averaged model can be simulated much more rapidly than the switching model. This is important when using a GA because many fitness evaluations are required.

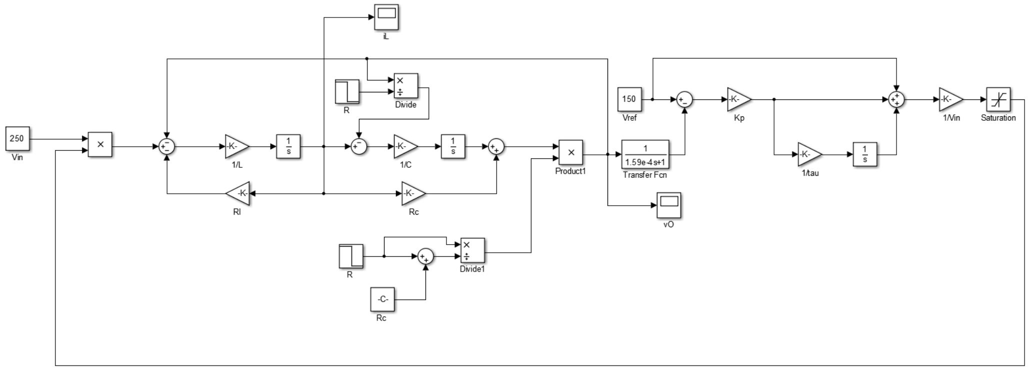

Figure 4.1. Simulink implementation of averaged model of buck converter and controller

The final population of the GA is shown in Figure 4.2. It can be seen that a tradeoff exists between phase margin and voltage error. In order to achieve a higher phase margin, increased voltage error must be tolerated. Three representative control designs are selected from the final population. Design A has the high regulation performance (i.e., low voltage error), but it also has the low phase margin. Design B represents a compromise between voltage error and phase margin. Design C represents high phase margin, but relatively high voltage error. These designs and their performance are shown in Table 4.II and are studied in more detail in the following chapter.

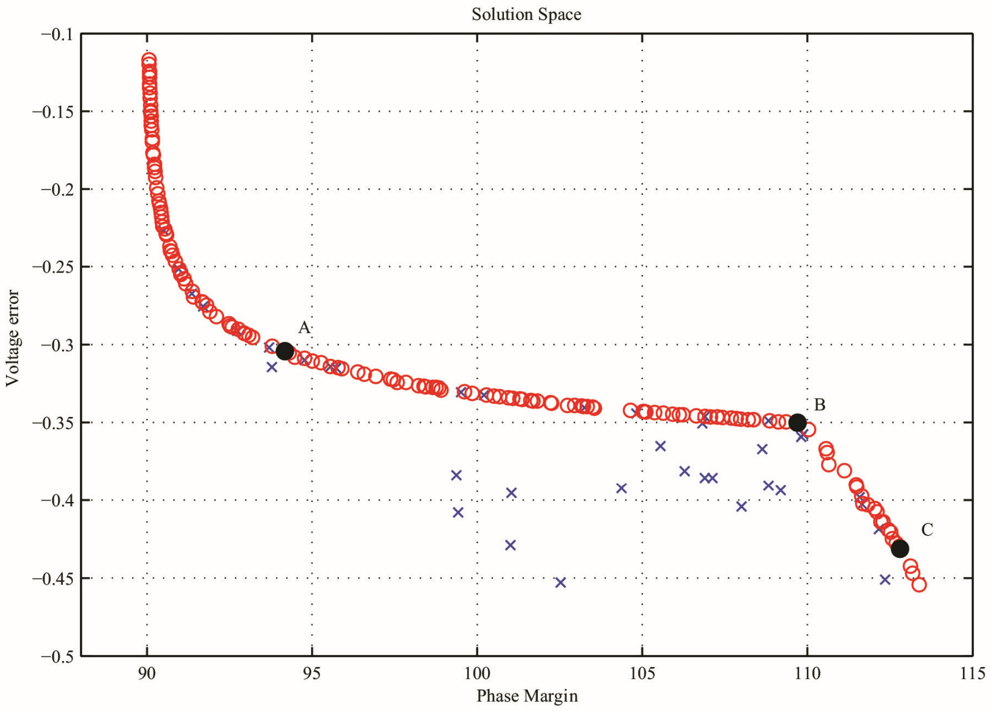

Figure 4.2. Final population located by genetic algorithm

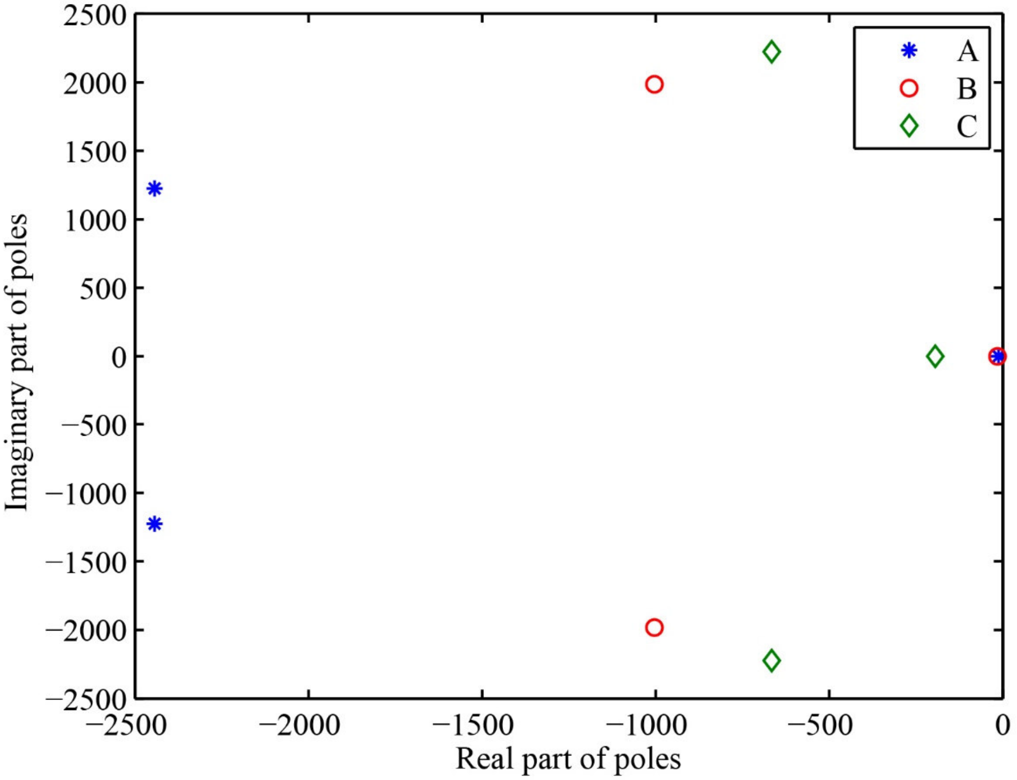

Figure 4.3 Closed-loop poles of each solution

Table 4.II. Performance and control parameters of selected designs

Design	Phase Margin (°)	Voltage Error (V)	k_p	τ_i (s)
A	94.1769	0.3042	0.8936	0.0389
B	109.6988	0.3501	0.2455	0.0130
C	112.8051	0.4312	0.1340	0.0005

CHAPTER 5 HARDWARE EXPERIMENTS

5.1 Experimental Buck Converter

For experimental validation, an existing dc-dc converter is used. This is a bi-directional dc-dc converter, rated for up to 300 V and 15 kW. The parameters of this converter are listed in Table 4.I, and the converter is shown in Figure 5.1. This converter has two IGBTs. The switching signals are used to control the operation of these two IGBTs to achieve voltage regulation. This converter has one capacitor voltage sensor and one inductor current sensor. The sensed data is sampled using the analog-to-digital converter of the Texas Instruments F28335 microcontroller. The microcontroller performs the control calculations using the sensed data and derives the modulation signal. The modulation signal is used by the microprocessors PWM unit to generate the switching signals for the IGBTs. The sampling frequency (100 kHz) is 10 times faster than the switching frequency (10 kHz) such that the discrete PI calculation in the microcontroller is a good approximation of the continuous PI controller shown in Figure 3.1.

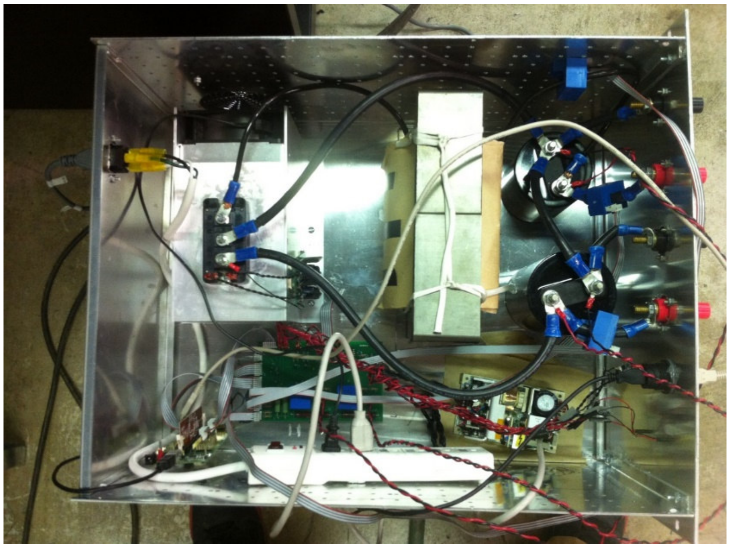

Figure 5.1. Photograph of dc-dc converter

5.2 Simulation and Experimental Results

Each of the representative control designs identified in the previous chapter has been studied using a switching model. These designs have also been implemented in hardware. The simulation and experimental results for each design are discussed below.

5.2.1 Design A: Low Output Voltage Error, Low Phase Margin

The inductor current and output voltage of design A are shown in Figure 5.2 and Figure 5.3, respectively. It can be observed from Figure 5.2 that the hardware experiment result for the inductor current has close agreement with that predicted by the simulation. The hardware result has more oscillation after the initial transient period. However, the hardware result for the capacitor voltage has a small deviation from that predicted by the simulation. The simulation is able to agree with the first and second peak, but it under estimates the peaks afterwards. The oscillations are not dampened as quickly in the experimental result.

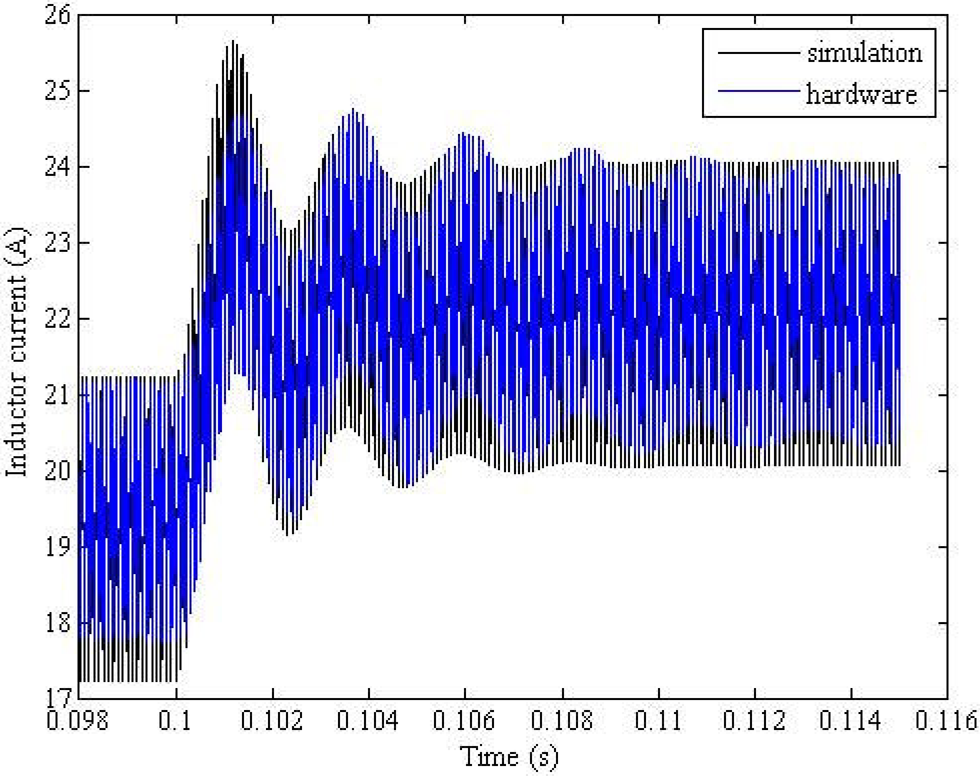

Figure 5.2. Inductor current of design A

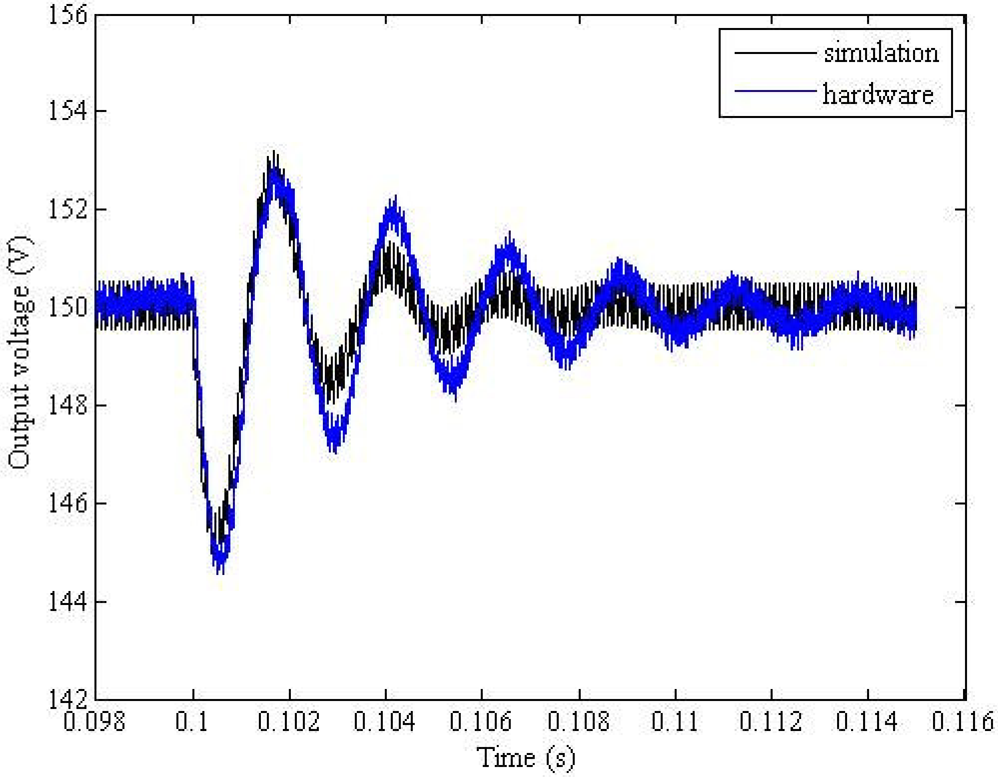

Figure 5.3. Output voltage of design A

5.2.2 Design B: Medium Output Voltage Error, Medium Phase Margin

The inductor current and output voltage of design B are shown in Figure 5.4 and Figure 5.5, respectively. It can be observed that the hardware results for the inductor current and capacitor voltage both have close agreement with those predicted by the simulation.

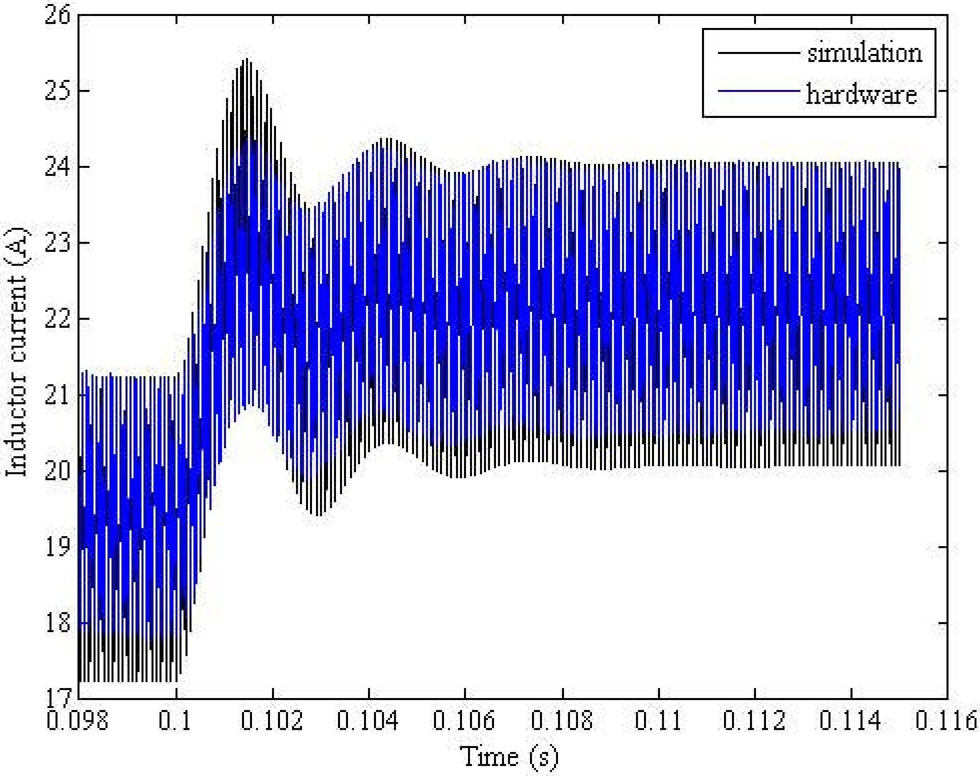

Figure 5.4. Inductor current of design B

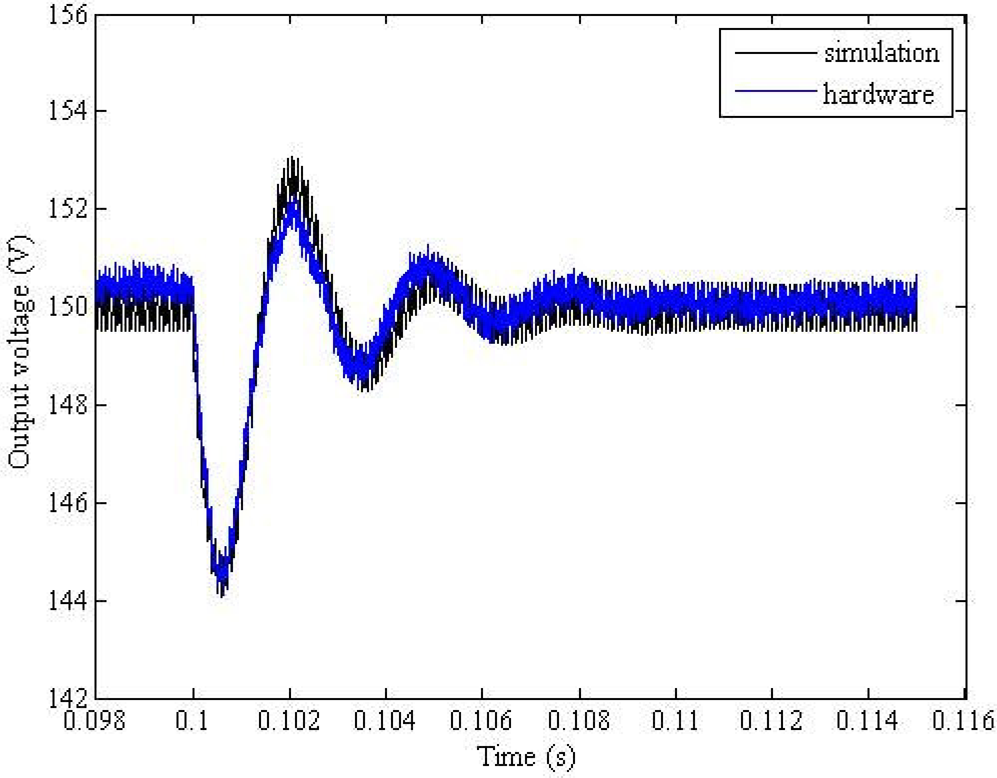

Figure 5.5. Output voltage of design B

5.2.3 Design C: High Output Voltage Error, High Phase Margin

The inductor current and output voltage of design C are shown in Figure 5.6 and Figure 5.7, respectively. It can be observed from Figure 5.6 that the hardware result for the inductor current has close agreement with that predicted by the simulation. However, Figure 5.7 shows that the hardware result for the capacitor voltage has a small deviation from that predicted by the simulation. In particular, the simulation overestimates the second peak. This is due to the differences between the model and the experimental setup. It is noted that the simulation model increasingly underestimates the second peak moving from design A to design C.

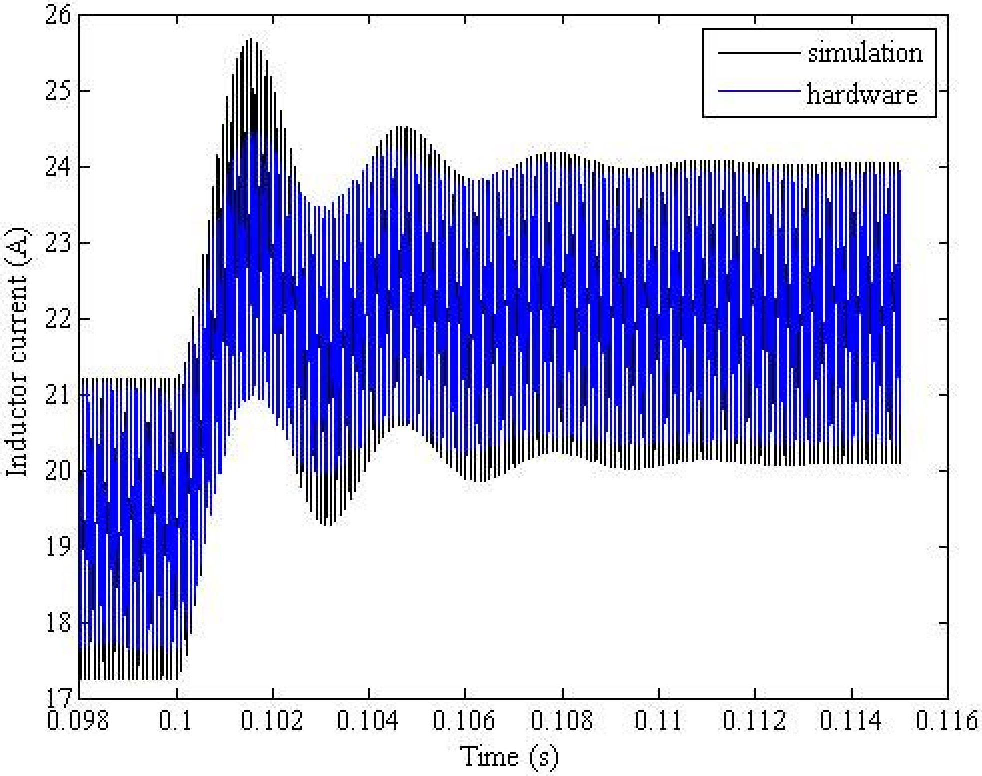

Figure 5.6. Inductor current of design C

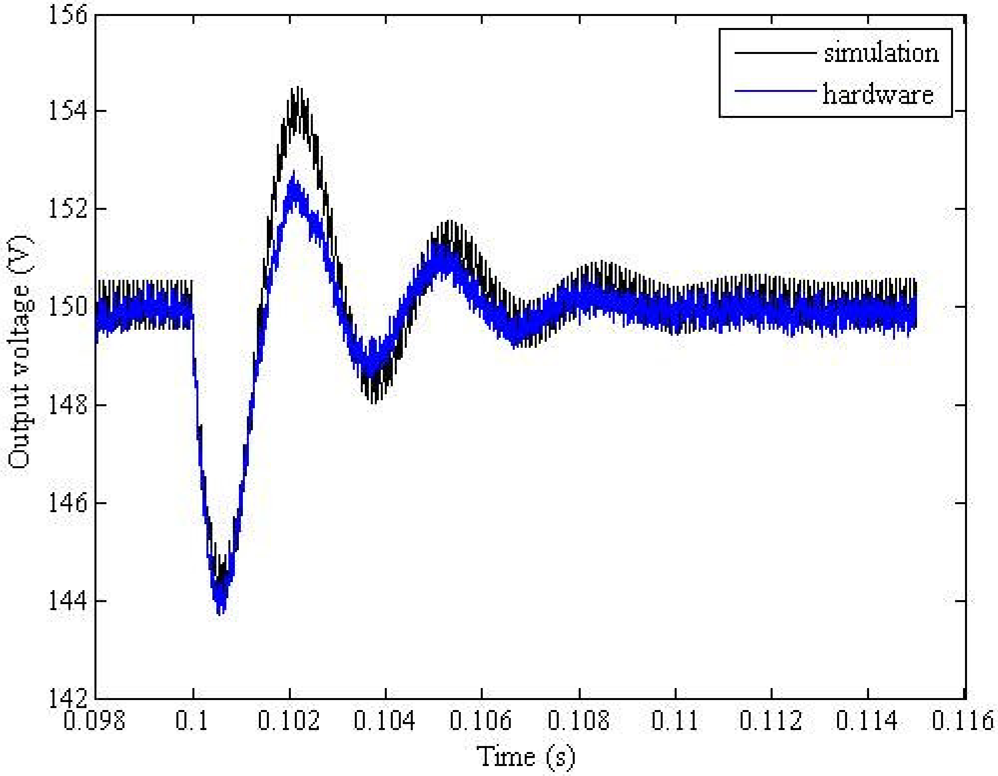

Figure 5.7. Output voltage of design C

5.2.4 Comparison of Simulation and Experimental Performance

The rms output voltage errors for each of the three representative designs can be calculated based on the following equation:

$$v_{err} = \sqrt[2]{\frac{\int_{0.098}^{0.115}(v_{out}(t)-v_{out}^{*})^2 dt}{0.017}}$$

The values for each design are given in Table 5.I. It can be seen that the root-mean-square value of output voltage in the simulation is increasing and agrees to what is calculated in the GAs. However, the value of hardware experiment deviated from the simulation results. This suggests that there is some discrepancy between the model and the experimental setup. Furthermore, it may suggest that design A may be more sensitive to model errors than the other models.

Table 5.I. Output voltage error in simulation and experiment

Design	Simulation	Experiment
A	1.1064	1.3499
B	1.3236	1.2521
C	1.5566	1.3616

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, a multi-domain, multi-objective-optimization-based approach to the design of controllers for power electronics is presented. A buck converter is studied. Several models of the buck converter are described, including the detailed model, the averaged model, and the small signal model. The PI control method is applied. The closed-loop transfer function is obtained and its loop gain is used to obtain phase margin. A multi-objective GA is used to find the set of optimal tradeoffs between two objectives, the phase margin and the rms voltage error. Several candidate control designs are studied in simulation and experimentally. The simulation presented the Pareto optimal front which shows the tradeoffs between the two objectives. There is some agreement between the experimental results and the simulation results, but there are also some discrepancies due to model error. Overall, the use of multi-domain, multi-objective-optimization-based approach has proven feasible.

6.2 Future Work

In the future, this method could be examined for other converter models. The model of other circuits can be built so the transfer function can be obtained and a simulation can be achieved. Such circuits include buck, buck-boost, etc. The methods to measure the performance of systems vary. Voltage error and phase margin are used in this thesis. However, other metrics such as the gain margin can be studied in the future. The tradeoffs between these two objectives are presented in this study so the users are able to choose the control parameters. It is also possible to design the converter (i.e., inductor and capacitor) and the controller simultaneously. Thus the method proposed in this study can also be used to design the overall system. In this case, other metrics such as cost or mass may be important to include in the multi-objective optimization problem. A small-signal model is applied in this research to develop the transfer function and phase margin. Averaged models are used for the simulation. These models may not be sufficiently accurate to predict every relevant detail of the performance. It is possible to apply more advanced modeling methods in the future.

APPENDIX

The following is the MATLAB code used to solve the multi-objective optimization problem.

```
GAP = gapdefault(2,0,200,200);

GAP.gd_min = [1e-3,1e-4];
GAP.gd_max = [10,0.1];
GAP.gd_type = [3,3];
GAP.gd_cid = [1,1];

[fP,GAS,BI4,f] = gaoptimize(@FourObjFunc,GAP);
c4 = GAS.bestfit(end);
```

The following the MATLAB function used to implement the multi-objective fitness function.

```
function [f] = FourObjFunc(x)

    Kp = x(1);
    taui = x(2);

    R = 6.8;
    L = 1.52e-3;
    C = 167e-6;
    Rl = 35e-3;
    Rc = 50e-3;
    Vinref = 250;
    Vin = Vinref;
    tauf = 1.59e-4;

    n_coef = [ C*Kp*R^2*Vin*taui, C*Kp*Vin*R^2 + 
Kp*Vin*taui*R, Kp*R*Vin];

    d_coef = [ Vinref*tauf*taui*(C*L*R + C*L*Rc), 
Vinref*taui*(C*L*R + C*L*Rc) + Vinref*tauf*taui*(L + C*R*Rc 
+ C*R*Rl + C*Rc*Rl), Vinref*taui*(L + C*R*Rc + C*R*Rl + 
C*Rc*Rl) + Vinref*tauf*taui*(R + Rl), Vinref*taui*(R + Rl), 
0];

    hd = tf(n_coef,d_coef);

    [~,pm,~,Wpm] = margin(hd);
```

```
    load_system('DetailedAverage.mdl');

    warning off;

    set_param('DetailedAverage/Kp','Gain',num2str(Kp));


set_param('DetailedAverage/1//tau','Gain',num2str(1/taui));

    t = sim('DetailedAverage');

    index = vO.time >= 0.1;

    vO = vO.signals.values(index);

    t = t(index);

    vOref = 150;

    T = 0.02;

    vtol = sqrt(1/T*trapz(t,(vO-vOref).^2));

    f = [pm;-vtol];

%     figure
%     margin(hd);

end
```

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