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SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATIONS

A Single Stage Grid-connected PV System

by

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Abstract

The review of current design of single phase grid-connected photovoltaic system, initial model of the system and the concept of hardware-in-the-loop simulation are presented in this paper. A model of the system including solar cell model, MPPT controller, converter controller are developed both in Matlab and RT-LAB. Some initial results demonstrate the overall system performance.

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Abbreviations

BE Bachelor of Engineering

EE&T School of Electrical Engineering and Telecommunications

SSGPVC Single Stage Grid-connected PV Converter

SSGPVS Single Stage Grid-connected PV System

DSP digital signal processor

AC Alternating Current

DC Direct Current

PV Photovoltaic

PVS Photovoltaic System

MPPT maximum power point tracking

HIL hardware-in-the-loop

SIL software-in-the-loop

ADC analog to digital converter

DAC digital to analog converter

SOGI second order generalized integrator

GPIO general purpose input output

CPU central processing unit

FPGA field-programmable gate array

IC incremental conductance

PO perturb and observe

PLL phase-locked loop

PI proportional integral

RT real-time

Contents

Chapter 1

Introduction

Human activities reply on intensive use of energy generated from various source. Primarily, energy can further divided into two groups, renewable and non-renewable. Renewable energy which has drawn more and more attention in recent years, is energy supplied from renewable source. Renewable energy sources including solar, hydro, wind, biomass, tidal wave, ocean thermal and the like. They may be replenished in nature on human timescale, which mean there is little chance that the energy could be depleted. The four major areas which rely on renewable energy are: electricity production, heating/cooling, transportation, and rural energy services.

Solar power as one of the most important renewable energy is generated when energy from the sun (sunlight). Energy gather from sunlight is converted into electricity or used to heat air, water, or other fluids. There are two mainstream technology to harvest solar energy and put it into good use. The first technology is solar thermal which thermal energy is resulted from concentration of solar radiation. Air, water, or other fluid is widely used as carrier to carry harvested thermal energy which usually can be used directly for heating up space or generating electricity by means of steam and turbine. Solar thermal is commonly used in residential area to provide hot water for living. Solar thermal electricity, also known as concentrating solar power, is typically designed for large scale power generation. The Ivanpah Solar Electric Generating System is a good example of concentrated solar thermal plant in the Mojave Desert. Solar Photovoltaic (PV) converts sunlight directly into electricity using photovoltaic cells by means of photovoltaic effect. Photovoltaic System (PVS) can be mounted on rooftops, integrated into building designs and vehicles, or scaled up to multi-gigawatt scale power plants. PVS can also be used together with concentrating mirrors or lenses for large scale centralized power. It is also not rare to combine solar thermal and PV technology into a single system which provide heat as well as electricity at the same time.

With great ambitions to create a green future for human beings and pressure to reduce production of greenhouse gas, many governments of developed and developing countries encourage people to increase the usage of renewable energy. The installation of PV have been increasing within recent decade. It is safe to say, the total number of installation would keep increasing for a long time before human being can find some better solutions to solve the thirst of reliable and clean energy.

Nowadays, majority of household electrical appliances rely on alternating current (AC), however, solar PV is only capable of generating direct current (DC) current or voltage. As a result, in order to make the most the solar power, various types of DC to AC converters are needed to meet different kinds of requirements for different applications. Microinverter, one of the most popular converters which features simplicity and great efficiency for solar applications has become more and more prevalent than ever. Although suffers from slightly higher upfront cost compared with PV strings with centralized inverter solutions. The market calls for cheaper and smaller microinverters in order to help integrate solar panels together with inverter as a single solution which would make building solar PVS more convenient and much easier.

The focus of this project is the development of a single stage grid-connected PV system (SSGPVS) which might be useful in real life. The development may be finished using simulation and no real circuit prototype is required due to limitation on time and budget. However, in order to make the project as close to real life product development as possible, hardware-in-the-loop (HIL) is used which enable the possibility to divide the system into two parts, simulated and actual part. The controller of the system would be implemented using a digital signal controller(DSC) or a microcontroller which is the real hardware in the system and the rest of the systme including PV panels, switching elements and grid are simulated using a Real-Time (RT) simulator. The simulator which is developed by Opal-RT is able to simulate any amount of time and generate the results using the same amount of time in real life while maintains a small enough time resolution. The closing stage of this project, I have managed to make....

Chapter 2 explains the background for this document. Chapter **??** states the style and submission related requirements to theses submitted at the school. Chapter **??** explains content related requirements to theses and how to avoid some commonly seen problems. Chapter 5 evaluates the thesis requirements template. Finally, Chapter 6 draws up conclusions and suggests ways to further improve the thesis requirements template.

Chapter 2

Background

This chapter present more detailed introduction to solar PV and PVS in section 2.1. The following is context of HIL and its applications and advantages in section 2.2.

2.1 General Introduction

PVS is type of power system which convert solar power into electricity by means of photovoltaic effect. PVS have many advantages and become more and more popular nowadays compared with traditional fossil fuel based energy generation method. It has became a vital part of renewable energy or green energy, since it generate zero green house gas during operation. The module or panel price have experienced huge decline since middle of 2008[2], which makes the the whole PV industry prospered. According to the literature, PV cell is able to become an important alternate renewable energy source till 2040[11].

Power electronic is a vital part for solar power generation. Typically, a single stage grid-connected PV converter (SSGPVC) consist of a solar panel which absorb and convert sunlight into electricity and one or more stages of power converters that transform the electricity from DC into AC, as well as other accessories for mounting and connecting different components.

figures/pv.png

Figure 2.1: Typical PV system block diagram

Figure 2.1 on page 9 indicate a general configuration of PVS. Due to the output characteristic of a typical solar cell and the need to inject power into the grid, there are at least two stages in a grid-connected PVS conventionally. The use of optional DC/DC convert(s) is to extract maximum power from upstream solar cells or units, of which is also known as maximum power point tracking (MPPT). Additionally, it is able to provide required voltage for next stage inverter to work with a appropriate duty cycle. The functionality of DC/AC converter is to inject sinusoidal current whose phase may or may not be synchronized with grid voltage(depends on applications) into grid.

Currently, there are various configurations for grid-connected PVS including centralized structure, the string structure, the multi-string structure and ac-module structure.[18]. Especially, multi-string and ac-module structure have been used in a broad range of applications. Although multi-string configuration have many advantages like reducing loss due to solar panel unbalanced and a centralized MPPT over centralized configuration, it also suffers from lacking redundancy and scalability. With optional DC/DC converter, the overall system efficiency is compromised compared with a SSGPVC.

As a result, ac-module configuration which is based on SSGPVC is gaining more and more attention. The ac-module configuration is consist of only one power electronics devices which can integrate MPPT function and convert DC into AC at the same time. Current design of PVS requires for simplicity, modularity and efficiency. Those requirements are exactly the advantages of the single stage system. However, there are some issues related to the grid-connected system. The sinusoid power injected into the grid caused by the fluctuation in the dc link is one of the issue.[6] It can force the MPPT function to be voided so that the system can not operate at the maximum power point. Due to complexity of such converter and power rating limitations, SSGPVC is often used in residential PV system.

Although the SSGPVC has some limitations, it is worth to improve the system performance and make it a better solution. Its 'apply and plug' characteristic can be consider to be a general solution to various grid-connected PV applications.

2.2 Hardware-in-the-loop Simulation

Nowadays, the complexity of various digital algorithms for power electronic applications, circuit topology is rising incredibly, which makes the simulation and development of power electronics related product increasingly time-consuming.[15] In order to fulfill the need for fast prototyping, verified the controller functionalities without implementation of hardware, and avoid hazardous situation while testing the controller on a real hardware, the HIL simulation or more specific PIL simulation is deployed and used intensively for such applications.

High-performance embedded system enabled a power electronic revolution. The increasing demand for digital controlled power electronics system requires the development to verify the controller functionalities before the controllers are tested on a real hardware platform. PIL allow developers test and verify processors' performance on a simulator which host the virtual hardware, so it become a crucial part of developing a digital controlled power electronics system.

Compared with traditional software-in-the-loop (SIL) simulation, HIL and PIL simulation is another level of simulation which runs way faster than the SIL simulation. In conventional SIL simulation for power electronics application, the time it takes to run the simulation is often longer than the simulation time span of interest, which means, for example, people need to speed more than one second in order to generate one second of results. On the contrary, the HIL and PIL simulation run in real-time without sacrificing simulation time step resolution. If one second is spent on the simulation process, results for one second can be generated with corresponding resolution that preserves all the transient state of prototype under simulation.

Comparing HIL simulation with PIL simulation, the PIL simulation offers a more close-to-real results since in many applications the functionalities needed is hard to abstract and model using software. In PIL simulation, the controller functionalities are executed inside by a real controller, so the developers do not need to worry about how to implement a precise controller model inside software environment.

Fig.2.2 illustrate a basic setup for PIL simulation. The power converter operate inside the

figures/pil.png

Figure 2.2: The basic PIL system

RT computer. There are multiple ways that the real controller can communicate with the RT simulator. The simulator is capable of generating necessary voltage or current signal through digital to analog converter (DAC) so that the external controller can sense the signal and generate proper trig signal feeding back to the RT computer. The RT computer also have general purpose input output (GPIO) to read all the controller generated signal and carry them into runtime simulation. Another way mentioned in this papar[15] is to use direct file exchange and there is a solution support this method with any type of controller architecture.

For the sake of running PIL simulation, a power converter testbed needed to be implement inside the software environment. The RT computer has equipped with a powerful central processing unit (CPU) as well as field-programmable gate array (FPGA) acceleration card. For the sake of fully utilize the computation power of the simulator, the model should be construct complying to some rules and regulations. But converting an existing converter model into RT simulation compatible model requires a bit of work and experience which is described in detailed in chapter **??**.

2.3 Previous work

PIL simulation has been used for PV application. In paper,[9] a two stages PVS was implemented using RT-LAB which is a software for controlling the RT simulator. In this paper, the simulation setup compose of a solar panel model, a grid-connected inverter and a DC/DC converter in the software environment. Also, there is a physical controller controlling DC/DC converter so that the author could perform PIL simulation. This paper proves that it is feasible to use PIL for PVS simulation and gave a detailed example of how to implement RT simulation model using the corresponding software. The major improvement to the results of the paper would improving the pulse width modulation (PWM) frequency of the controller since the state-of-art digital controlled converter's PWM can be as high as a few mega hertz while in the paper the PWM frequency is only 10 kHz. Also, making use of the FPGA acceleration card in the RT simulator would be beneficial to provide finer time resolutions and enable higher PWM processing capabilities.

Many researchers have already completed lots of research work regarding SSGPVC as well as PV panels as a whole system. In particular, Paper [11] presents approaches on modeling of single stage PVS for RT simulation. This paper focus on discrete time modeling of the whole system, while at the same time it proposed a new MPPT method which is based on incremental conductance (IC) and had the new algorithm tested using RT simulation. In this paper, the author had the RT simulator investigated and concluded that the RT simulators have sufficient computation power to perform simulation for PV applications.

Chapter 3

A Single Stage PV System

3.1 The System

The system is shown in Figure 3.1 on the next page and can be divided into three major parts, solar panel/cells, H-bridge, controller and LCL filter. The transformer is optional depending on local rules and regulations. In some countries, it is compulsory to add the transformer for the purpose of isolation and protection, while in some countries it is not required. It is allowed to have transformerless system in Australia according to regulations[14]. The whole system design is fairly simple and straightforward. Detailed description on solar cell model can be found in section 3.2.

3.2 Modeling of Solar Cell

There are lots of solar cell models existed so far and the most widely used model is presented here. The equivalent circuit of a single solar cell is shown in Figure 3.2 on page 16. It is composed of a photo-generated current source, a parallel connected diode, a shunt resistor and a series connected resister[17]. In present of parasitic resistors, the solar cell output characteristic can be represent be the following equations[3][16].

$$I = I_L - I_o(e^{\frac{V+IR_2}{(\frac{nkT}{q})}} - 1) - \frac{V + IR_2}{R_1} \tag{3.1}$$

In this equation, I is the output current which flows out of the solar cell for positive value. It is possible produce negative current which is equivalent to current flows into cells, however, this situation should be avoided because . V is the terminal voltage of the cell. I_o is the parallel dido saturation current. I_L is the light generated current. n is the number of cells in series. q is the elementary charge. T is the current ambient temperature of the cell. Equation (3.1) indicates that when the terminal voltage is low, almost all the current can flow out of the cell. When the voltage goes higher, the saturation current of the parallel diode begin to increase, thus reducing the output current. Eventually the output current can go to zero as the increasing of terminal voltage.

Temperature can affect the output characteristic of the solar cell as well, since under different temperature condition, electron have different electron mobility. Generally, the higher the temperature, the higher is saturation current of parallel connected diode, thus leading to the decreasing of total output power. Figure 3.4 on page 17 illustrate a solar panel ouput characteristic with respect to various temperature.

The solar panel on the market usually consist of multiple solar cells connected in series or in parallel to increase the terminal open circuit voltage or maximum short circuit current. A typical output characteristic of a solar panel module is shown in Figure 3.2 on the following page. Due to the output characteristic of solar cell, there exist a maximum power point which have been marked in the figure with a red circle. If we want to extract the most power out of the panel or cells, MPPT algorithm is needed to archive this goal.

figures/system_diagram.png

Figure 3.1: A single stage grid-connected PV system

3.2.1 MPPT

As mentioned before, MPPT is a method for extracting the most power out of solar cell. MPPT have been studied by many researchers many algorithms have been proposed, such as perturb and observe (PO), IC[4][7][10][12][19].

PO also known as ”hill climbing” method, is one of the most classic and simple algorithm and have been widely used in many PVS. The method actively adjust the output voltage of the connected solar panel by a small amount ΔV and sense the ouput current to calculate the resulted change in output power ΔP by substrate current power with previous power. If ΔP is greater than zero, it means that output voltage may be set higher to gain more power. If ΔP is less than zero, it means that MPP has been passed and output voltage needed to be reduce. The power trajectory moves like climbing up a ”mountain” which is the maximum power archivable under current sunlight condition. the whole algorithm can be described in Figure 3.6 on the next page.

The problem with PO method is the adjustment of power output based on perturb. The algorithm tries hard to get close to the maximum power point instead of staying at the maximum power point, of which lead to compromise of system efficiency. The system may operate around MPP depending on the size of perturb. Large perturb may lead to fast response when irradiance is changing dynamically but largely compromised steady state efficiency. Small perturb may result in high steady state efficiency, however, the algorithm may have little transient performance.

figures/cell_equal.png

Figure 3.2: Equivalent circuit of single solar cell

figures/typical_solar.png

Figure 3.3: Output characteristic with different sunlight

figures/typical_solar_temp.png

Figure 3.4: Output characteristic with different temperature

figures/topology.png

Figure 3.5: H-bridge with LCL filter

3.2.2 H-bridge and PWM

There are lots of different types of circuit topologies for inverter applications[1][5], but the simplest one is classical H-bridge configuration. Figure 3.5 shows a simple H-bridge with LCL

figures/pando.png

Figure 3.6: P&O Algorithm

filter configuration which would be used in the later simulation.

H-bridge, in this case, has four switching components which are represent by the symbol of MOSFET. By turning on and off the switching, three different levels of voltage can be sense from output terminals which are $\pm V_{dc}$ and zero. The state of the switches are controlled by desired PWM signals to generate desired voltage levels at between switching intervals.

PWM is particular important for success of converting DC to AC. PWM is a modulation technique to encode signal or signals into a pulse train. There exists two different types of modulation technique for a classic four switches H-bridge, bipolar and unipolar modulation for solar PV applications. The difference between the two is that in bipolar modulation, the output voltage can only be either $\pm V_{dc}$ compared with unipolar modulation. With one additional voltage level, unipolar modulation can produce higher efficiency and lower TOTAL Harmonic Distortion(THD).

One issue related with PVS is common mode voltage which usually cannot be found in other applications of DC to AC inverters. Since usually PV panels are mounted on large plates of mental, voltage potential difference, also known as common mode voltage between panels and ground, can build up due to capacitor effect leading to malfunctioning of circuit breaker at the grid side. One way to get around this issue is to use bipolar PWM if a H-bridge configuration is used. The reason why unipolar may suffer the issue is that when all the switches are turned off, the output terminals are flouting with respect to ground, thus lead to common mode voltage building up at the terminals. When the switches are turn on, closed circuit loop can be create with protection devices on grid side connected to earth ground. Anther way to get around the issue is to use the different inverter topologies to isolate panels and converter. One good example of such configuration proposed by this paper[5].

There is a limitation on the SSGPVC which is the voltage rating. The voltage on the input side need to be higher than the output voltage which means the overall voltage gain of H-bridge is always less than one. Interfacing with high voltage grid would results in large number of PV panels or cells connected in series on the input side to build up the voltage.

3.3 LCL Filter

As shown in Figure 3.5 on page 17, the circuit make use of a filter which is consist of two inductors and one capacitor. High frequency modulation signal requires a proper filter to eliminate figures/SOGI.png

Figure 3.7: Basic structure of SOGI

any undesired high frequency harmonics to fulfill the requirement imposed by THD. The filter is a high orders passive filter which has superior performance compared with traditional single inductor filter in terms of harmonic elimination. However, high order filters are more difficult to control, it's resonance frequency can cause stability issue if not carefully deal with[8].

3.3.1 Grid Synchronization

AC voltage generated by the inverter should have identical phase with the grid voltage so that there is not cancellation of voltage which might cause instability of the grid. In order to archive synchronization with the grid, phase-locked loop (PLL) is used. The PLL served as a servo system controlling the signal phase of its output. The performance of it has a direct impact on control loop of grid-connected power applications. It should be able to reject source of errors including voltage unbalance, line notching, line dip, frequency jump. The most critical thing is to keep maintaining a clean and reliable phase lock to grid voltage. There are lots of PLL structures designed for various applications.

Among those PLL structures, second order generalized integrator (SOGI) have been widely discussed and used in many PVS. It can be selectively tuned to eliminate other frequency components other than grid frequency and its nominal frequency would not be affected by the frequency change[12]. The basic structure of SOGI is shown in Figure 3.7.

3.3.2 Feedback Control

$$T(s) = K_p + \frac{K_i}{s} \tag{3.2}$$

$$T(s) = K_p + \frac{K_i}{s^2 + \omega_1^2} \tag{3.3}$$

$$C(s) = \sum_{n=3,5,7}^{k} \frac{K_n}{s^2 + \omega_n} \tag{3.4}$$

For current control of SSGPVC, proportional integral controller (PIC) and proportional-resonant controller (PRC) are common choices. The transfer function of a typical PIC is illustrated in Equation (3.2). In a negtive feedback system, PIC can be used to eliminate error between target and output value. The proportional term may help reduce the error quickly and the integral term may be used to eliminate steady state error. It features simplicity as well as reliability and has been used widely in many control engineering applications. Since PIC is a first order system, the performance to track a sinusoidal target is actually not very great and the error cannot be eliminated. It also suffers poor high frequency components rejection performance.

Equation (3.3) represents PRC where ω_1 is the fundamental frequency of the grid in radiance. ω_1 is either $50 \times 2\pi = 314.16$ rad/s for 50 Hz system or 377 rad/s for 60 Hz system. Equation (3.4) represents harmonic compensators for output current where ω_n are harmonics. Typically in a PVS, both PRC and compensator are used in conjunction to archive better performance. One good aspect offered by the compensator is that harmonics can be selectively eliminated by varying ω_n where $\omega_n = n \times \omega_1$ and $n = 3, 5, 7 \ldots$. The downside of the compensator is that it may result in high orders system which requires more computation power that some low end microcontrollers may struggle to offer.

3.4 Opal-RT Simulator

Opal-RT is a company based in Canada which provide RT simulators and its software solutions to make RT simulation possible. In this project, their simulator model OP4500 which is shown

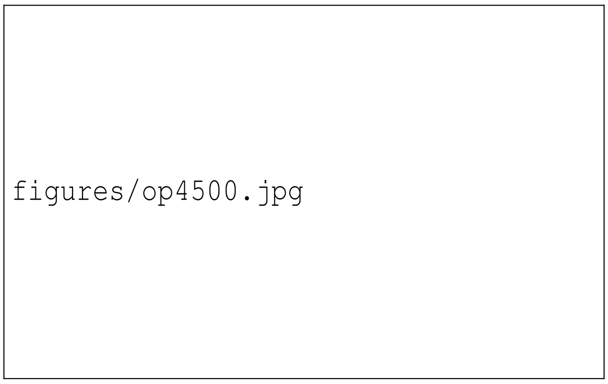

Figure 3.8: OP4500 RT simulator

in Figure 3.8 on page 20 is used. OP4500 combine traditional X86 architecture and latest FPGA simulation technique to accelerate the process. The onboard Intel CPU can archive minimum time step of 7 μs without getting overrun and *eHS* FPGA based simulation solver is able to archive minimum time steps of 250 ns. It also multiple Input and Output(IO) modules including both analog and digital types, for interfacing external hardware to perform HIL simulation. The simulartor can be either a controller to run control algorithm and generate desired signal to control actual hardware or become a simulated plant to develop and verify functionalities of external controller.

RTLAB is the software running inside a host personal computer(PC) in order to be able to use the box for simulations. *RTLAB* currently is fully compatible with *MATLAB* and *SIMULINK* which make it easy to develop models for RT simulation. currently, *RTLAB* only supports up to *MATLAB 2014B* and not all models in *SIMULINK* are supported.

3.5 Controller Development Kit

Implementation of all controller functionalities is an vital part of this project. As stated in previous chapter, cost need to be considered since upfront cost of modular SSGPVS is still a bit higher at the moment. Microcontroller as the most important part of controller system, could be expensive sometimes depending on performance configurations. Obviously, higher the performance, greater the cost on microcontroller. The controller is implemented in using

figures/control_card.png

Figure 3.9: TMS320F28027 Experiment Kit

a Texas Instrument C2000 microcontroller (TMS320F28027). The experiment controller kit is completely off-the-shelf and it is quite inexpensive to obtain. The volume price for this microcontroller is quite competitive considering the performance it can offer. This is a 32-bit fix-point microcontroller with clock frequency up to 60 Mhz and some necessary peripherals, of which is designed for microinverter applications. The microcontroller structure block diagram is shown in Figure 3.10.

figures/tms320.jpg

Figure 3.10: TMS320F28027 structure and on-chip peripherals

Chapter 4

Implementation

4.1 Breaking Down the Problem

Having examined the state of art developments of SSGPVS, what are essentials to successfully make a SSGPVS using RT simulators and microcontroller is pretty clear. Although theory behind SSGPVS has been studied for quite a long time and there has been existing products on the market already, documentations on development process of a RT or HIL simulation are still limited. So far the reviews have shed the light on tasks needed to complete the whole project.

The first task is to develop a SSGPVS in the pure software environment which may pave th way for developing a RT model for the simulator. The process involved is described in detail in Section 4.2. The second issue which is discussed in Section 4.3 on page 25 is to revise the model so that it can be load into RT simulator and runs in RT. The third issue is to implement the controller functionalities using a digital signal processor (DSP). The implementation involves some advanced C language programing which is something I enjoy doing. The details of implementation are presented in Section 4.4 on page 25. The fourth issue which discussed in Section 4.5 on page 25 is to perform PIL simulation. This issue is a little bit complicated since it requires me to be well familiar with the real time simulator. And I have not found much resources on this so far. It is a milestone to this project.

4.2 Building Model in *SIMULINK*

The purpose of a pure software simulation model is to verify the correctness of circuit topology, solar panel model and proper design of LCL filter. Luckily, *SIMULINK* has a build-in SSGPVS model which can be found in *MALTAB 2015B* and later versions[13]. It provide a good starting point of this project. Since the project focus on performing RT simulations, any already known to work model can be used to accelerate the process of building the whole model and save some time avoid doing everything from scratch.

The model was quite well designed and simulation ran with not error. Minor adjustment may be made before turning it into a RT model. The system was design for North America market which result in a 60 Hz operation of grid frequency. Since the grid voltage in Australia is 50 Hz, the grid frequency of original model need to be change to 50 Hz. In order to change the frequency, the minimum time step, PWM frequency of the inverter and controller sampling time need to be changed as well. The reason for changing the minimum time step is that fixed time solver for solving ordinary differential equations(ODE) is used for simulation which means grid frequency, controller sampling time or any other components' sampling time need to be integer multiple of minimum time step. Section 4.2 is a summary of different configurations between models.

Items Changed	Origin Configuration	New Configuration
Minimum time step	$1.323e^{-6}$ s	$6.25e^{-7}$ s
Carrier frequency	3780 Hz	8000 Hz
Controller sampling	$2.6455e^{-5}$ s	$1.25e^{-5}$ s

Noticing that the switching frequency is set to 8 kHz because higher switching frequency may lead to less bulky inductors in real life which is less expensive. Instead of setting switching frequency to nearer 4 kHz, double of the frequency is chosen. In order to ensure the accuracy of simulation and avoid limited resolution on duty cycle, $6.25e^{-7}$ s of minimum time step has been chosen to ensure minimum stepping of duty cycle is 0.5%. The duty cycle resolution could affect SSGPVC creating high output current THD and undesired phase shift since duty cycle can only vary in discrete steps.

Changed made in PWM frequency lead to smaller minimum time step, thus, more time needed to generate one second simulation results. The time it takes to run the simulation depends on configurations of the host PC and it is common to run simulation for around five minutes to generate one second of results.

The controller design in the model is different from what has been mentioned previously. Bearing in mind that the purpose of using this model is to obtain a working plant for performing RT simulation in the next stage, as a result, the design of the controller is not thoroughly studied.

4.3 Convert to Real-time

4.4 Implementation In Microcontroller

4.5 Performing PIL Simulation

Chapter 5

Evaluation

This chapter is mainly provided for the purpose of showing a typical thesis structure. There are no more thesis requirements described.

5.1 Results

The result of this work is the present document, being both a LaTeX template and a thesis requirement specification.

5.2 Discussion

The dual function of this document somewhat de-emphasises the primary purpose of the document, namely the thesis requirements. It would be better, perhaps, if these could be stated on a few concise pages.

Chapter 6

Conclusion

A thesis requirements/template document has been created. This serves the dual purposes of giving students specific requirements to their theses — both style and content related — while providing a typical thesis structure in a LaTeX template.

6.1 Future Work

Extract the requirements from the template in order to have very concise requirements.

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Appendix 1

In the source code for this document, some commonly used LaTeX operations can be found. The typesetting opportunities with LaTeX are vast, and there exist an enormous collection of packages that give added functionality. Modern LaTeX distributions come with many of the most common packages (some used in this document) and many more can be found on the web.