POWER IMPROVEMENT OF SOLAR PHOTOVOLTAIC (PV) BASED ON MAXIMUM POWER POINT TRACKING (MPPT) CONTROLLER

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ABSTRACT

This thesis describe the analysis of a DC-DC boost converter for control photovoltaic power by using maximum power point tracking (MPPT) to maximize the photovoltaic array output power. The MPPT system is responsible for extracting the maximum photovoltaic power and transmitted to the load using boost converter which able to step up the voltage to required magnitude. This MPPT using perturb and observe algorithm, the algorithm are general algorithm and use as a code. The analysis using Matlab® and Simulink® simulation software. The methodology of this project to develop Photovoltaic model, maximum power point tracking (MPPT) and modern controller boost dc-dc converter application is performed in the system for analyse the state-space model. Modern controller was simulated in closed-loop condition which employs four types of controller such as state feedback, optimal, state feedback with feed forward and integral. The results from controller simulation are used to analyse transient response and overshoot percentage of output voltage from boost converter. The observer system when the output system is observable, a full state observer able to apply. Based on the findings, comparison has been made to summarize a controller with minimum error and better stability.

ABSTRAK

Tesis ini menerangkan analisis penukar rangsangan DC-DC untuk mengawal kuasa *photovoltaic* menggunakan pengesanan titik kuasa maksimum (MPPT) untuk memaksimumkan keluaran kuasa *photovoltaic.* MPPT bertanggungjawab untuk mengeluarkan kuasa photovoltaic maksimum dan dihantar ke beban menggunakan pengubah *boost* yang dapat meningkatkan voltan ke magnitud yang diperlukan. MPPT ini menggunakan algoritma *perturb* dan pemerhatian, algoritma adalah algoritma umum dan digunakan sebagai kod. Analisis ini menggunakan perisian simulasi Matlab® dan Simulink®. Kajian ini dibuat untuk membina model *photovoltaic*, pengesanan titik kuasa maksimum (MPPT) dan kawalan moden pada sistem DC-DC pengubah *boost* dilaksanakan pada sistem dengan mengunakan analisis model ruang-keadaan. Pengawal moden disimulasikan dalam gelung tertutup terdiri daripada empat pengawal iaitu suapbalik keadaan-penuh, optimum, suapbalik keadaan-penuh dan suap kehadapan dan pengamiran. Keputusan kawalan moden ini disimulasikan untuk menganalisis tindak balas sementara dan peratusan lonjakan bagi voltan keluaran pengubah *boost*. Apabila keluaran sistem boleh dipantau, maka pemantau keadaan-penuh boleh dibangunkan. Semua keputusan keluaran kawalan moden dibanding bagi menentukan kawalan yang terbaik yang mampu memberikan ralat keadaan mantap yang minimum dan stabil.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligent
FLC	-	Fuzzy Logic Controller
FS-MPC	-	Finite Set Model Predictive Control
FNN	-	Fuzzy Neutral Network
IMPP	-	Current Maximum Power Point
MPPT	-	Maximum Power Point Tracking
MIMO	-	Multiple Input Multiple Output
NNs	-	Neutral Network
NREL	-	National Renewable Energy Laboratory
PV	-	Photovoltaic Solar
P&O	-	Perturb And Observation
PID	-	Proportional Integral Derivation
PI	-	Proportional Integral
PMPP	-	Power Maximum Power Point
THD	-	Total Harmonic Distortion
VMPP	-	Voltage Maximum Power Point
VSC	-	Voltage Source Converter

LIST OF NOMENCLATURES

A	:	System state matrix
B	:	Input state matrix
C	:	Output state matrix
$C1$	:	Capacitor
Ci	:	Internal capacitance
D	:	Steady-state duty cycle
$D1$	:	Diode
d	:	Duty cycle
E	:	Feed forward state matrix
EG	:	Bang-gap energy of semiconductor used the PV cell
e	:	Error
f	:	Switching frequency, Hz
i_{C1}	:	Capacitor current
i_{L1}	:	Inductor current
i_{max}	:	Maximum current
i_{min}	:	Minimum current
i_o	:	Current output
i_{RL}	:	Load current
i_{SC}	:	Short circuit current
i_{RS}	:	Cell saturation current
i_{se}	:	Series current
i_R	:	Current reference
K	:	Controller gain
Ki	:	Short circuit current at temperature coefficient
Kb	:	Boltzman constant
L	:	Observer gain
$L1$	:	Inductor
M_c	:	Controllability matrix
M_o	:	Observability matrix
N	:	Feed forward
P	:	Positive definite matrix
P	:	Pole
Q	:	State weight matrix
q	:	Electron change
R	:	Input weighting matrix
RL	:	Load
R_{se}	:	Series resistance
Ri	:	Internal resistance

R_{sh}	:	Shunt resistance
t_{on}	:	Time when ON
t_{off}	:	Tim when OFF
$Tref$	:	Reference temperature
TC	:	Cell working temperature
T_s	:	Settling time
u	:	Input
V_{C1}	:	Capacitor voltage
Vi	:	Input voltage
Vr	:	Voltage reference
V_{L1}	:	Inductor voltage
V_o	:	Output voltage
V_{sw}	:	Pulse voltage
ύ	:	Integral input
$\hat{x}$	:	Estimated state variable
$\dot{x}$	:	State variable
x	:	Steady-state variable
y	:	Output
$\hat{y}$	:	Estimated output
αi	:	Solar irradiation
α	:	Short circuit Current temperature coefficient
β	:	Open circuit voltage temperature coefficient

LIST OF APPENDICES

CHAPTER 1
INTRODUCTION

This chapter provides overview of this research project. It is divided into sub-sections of introduction, problem statement, objective, scope, motivation and project organization.

1.1 Introduction

Solar power is one of the alternative clean energy source, fast to growth and one of the most important renewable energy, this technology hugely increases in global energy consumption rate around the world. Instead of using wind turbine, photovoltaic (PV) is the most efficiency method for producing energy. The energy that generated by photovoltaic cells depend on environmental condition such as irradiation, cell temperature and load condition. The maximum operating point rarely at the maximum power point when the output of PV module directly connected to the load, this is because the PV array is under an unregulated dc power source. The DC-DC converter act like interface by inserted between PV module and the load in order to control output power at PV solar. Almost all the PV system employ maximum power point tracking (MPPT) for extracting the maximum power from the PV solar module and transferring that power to the load. The MPPT algorithm technique using the perturbing and observing (P&O) method, this MPPT module use to determine the maximum power point also give a signal to the Boost converter whereby it can help to sustain the system operating voltage at maximum point. In hardware form MPPT is not mechanical tracking system but it is fully electronic system that varies the electrical operating point of the module so that the module able to deliver maximum power (Sholapur, Mohan, & Narsimhegowda, 2014). The MPPT technique is automatically able to find the voltage VMPP and current IMPP at PV array which should operate to obtain power maximum output PMPP by using constant irradiation and temperature. To develop the MPPT system many method can be used such as perturb and observation (P&O), fuzzy logic and incremental conduction. This project used P&O method which by using algorithm to design MPPT modeling.(Sholapur et al., 2014).

The MPPT algorithm provide generated pulse to boost converter for obtain voltage output (Rohit Kumar1, Anurag Choudhary2, Govind Koundal3, Amritpreet Singh4, & Yadav5., 2017). DC-DC boost converter was used to amplify the input voltage. However the output voltage is tune able with respect to the duty cycle. The converter operation mode depends the ON and OFF state of the power switch. Converter using state-space averaging method such as PID or PI sliding mode controller and neutral network are several common controller used in previous studies. This research involved of vector matrix differential equation which represent the system. Calculations were necessary for controller modeling and controller are created to regulate the power and voltage output preferred without having steady-state oscillation.

This study focusing on design and analysis modern controller in boost converter system. Besides that, this project has employed full state observer to forecast unknown variable at boost converter. Via Matlab® Simulink® software, results are collected and assessed accordingly to conclude the research finding for converter and observer.

1.2 Problem Statement

Solar module is economical and easy to use. If compare to various renewable energy, solar energy is abundant, pollution free and noise free. MPPT is connected between PV system and DC-DC converter, it is used due to the non-linear current-voltage characteristics of the PV systems. Maximum power point keep changing accordingly depending on solar irradiation levels and cell temperature. Other than that the impedance mismatch between solar panel and the load may cause output power decrease. In order to solve this problem DC-DC converter is used between solar panel and load. A maximum power point tracking is used to solve impedance mismatch issue. MPPT technique is required to obtain the maximum power point for voltage and current from PV solar. Boost converter is used to regulate DC power supplies depending on the application which it is usually use in household and industrial instruments. The output value is distorted due to oscillation, poor settling time and high steady-state error, it will causes a negative impact on the transient response and reduce the overall output voltage performance. In order to overcome the issue controller need to be developed. A modern controller consists of state feedback controller with optimal and pole placement technique, state feedback with feed forward controller and integral controller, all these controller proposed to achieve fastest transient response with no overshoot occur.

Otherwise, if the system are fully observable, it can be used to provide estimated state values to use in modern feedback controller.

1.3 Project objective

The objectives of this project are as listed below:

- To design the boost converter and solar photovoltaic model in Simulink which interfacing with the maximum power point tracking (MPPT) algorithm model to extracting maximum power point from PV solar.
- To simulate a modern controller and full state observer model using Matlab® and Simulink® software.
- To perform correlation between settling time, overshoot percentage and steady state error of voltage output from modern controller, also compare observer result with original boost converter system.

1.4 Scope of project

- This research project has been divided into a few parts such as literature review on solar photovoltaic theory, maximum power point tracking (MPPT) and boost converter also its operation for better understanding on the system. After the understanding of the theory, an experiment will be conducted by using Simulink software to analyse the result.
- The focus of this research project to monitor the voltage output of boost converter model. The MPPT technique is required to obtain the maximum power point for voltage PV solar.
- The analysis for modern and observer controller are applied in this research project based on Matlab® and Simulink® approached. This project analysis used to find the best modern controller that able to provide fastest settling time, minimum percentage of overshoot and steady-state error less than 1.

1.5 Motivation

Renewable energy not just an option nowadays but it plays important role in our live. Photovoltaic solar system provide fluctuation power output with various maximum power point to the dc-dc converter before distribute to the load, in order to overcome this problem the maximum power point tracking have been developed. The conventional controller normally used in others research such as PI or PID, fuzzy and neutral network is applied to regulate desired value output of voltage and current to boost converter. However there is some limitation whereby this conventional method result in complex mathematical form. In order to simplify the design complexity of conventional, the alternative method can be used by using modern controller. All the modern controller based on time-domain based, with fast transient response the desired value will achieve. The full state observer be applied so that all initials state able to determine.

1.6 Project organization

This project as in general, mainly consist of five main chapter. It is organized as follows:

Chapter 1: Introduction

In this chapter gives overview crucial aspect of the research such as project background, problem statement, objectives, scope, motivation and project organization.

Chapter 2: Literature Review

This chapter include all the research work and related research about introduction of boost converter, theory of modern controller and observer are explained in details. This literature also review all the important studies which have been done by other researches on similar subject are discussed to provide information on current state of the technology.

Chapter 3: Methodology

This chapter explain on derivation of state space averaging technique, boost converter state-space derivation and modelling are given also involved the parameter on the PV connected system. Furthermore, the description on controllable and observable, analysis of poles location, gain controller and analysis on modern controller using Matlab® & Simulink®.

Chapter 4: Result and Discussion

This chapter discusses on simulation result that have been gain from the analysis. The result analyse in term of controller steady-state, settling time, overshoot percentage and steady-state error.

Chapter 5: Conclusion

This final chapter, conclude the overall research project and provide recommendation of modern controller technique for future work.

CHAPTER 2
LITERATURE REVIEW

This chapter discuss details about photovoltaic (PV) solar model, maximum power point tracking (MPPT) model and boost converter system which based on modern controller and modern observer. This chapter also discuss about previous research work have been done which similar with this project are also explained. The modern controllers consists of state feedback, optimal, integral and state feedback with feed forward including the observer in full state.

2.1 Introduction

A PV model is form by connecting series and parallel with many solar cells, whereby the model of PV system can be done by connecting a current source in parallel and inverted diode is connected with series and parallel resistance. The dc-dc converter at PV array which unregulated dc power output whereby the MPPT will extracting the maximum power and transferring to the load accordingly. The dc-dc converter with an ideal converter convert output dc voltage to different level and deliver as regulated output, the output voltage must be adjustable depending to the application requirement. Unfortunately, the open loop system unable to ensure that output voltage always at desired level. The converter system will step up the input voltage by using switching method. There are two switching technique available for selection which is switch close mode *ON* or switch open mode *OFF*. Value of output voltage depend of steady-state duty cycle (D) of switching frequency. Additionally, automatic error able to rectify at output voltage when applying feedback controller in boost controller to ensure the output voltage always at desired level. The development of modern controller can be achieve with these combination component. However, the modern observer also include in this implementation since there are unknown parameter in the system.

2.2 Previous researches

Referring to paper (Ali & Hasan, 2018) presented the optimization of PV model using fuzzy-neutral network for dc-dc converter systems. To maximize the power point tracking (MPPT) is an important things to improve the solar system power. Additionally, this paper also presented about application of Fuzzy Neutral Network (FNN) in photovoltaic model. The system designed using Matlab® & Simulink® software and connected to boost converter, a maximum power point tracking controller, a one-phase voltage source converter (VSC) and three level bridge. The function of MPPT controller is to support the need for advance controller which can detect the maximum power point in solar cell system that provide unstable current, voltage and remain the power resultant per cost low. The MPPT methods classified into three common control variable like current, voltage and duty control. Instead of using Perturb and observation (P&O) algorithm method for MPPT, this project prefer to use Artificial Intelligence (AI) method like Fuzzy Logic Controller (FLC) and Neutral Network (NNs) to harvest the desired maximum power point from PV panel. DC-DC boost converter convert input voltage to different larger voltage output. The dc-dc using feed forward system because it able to controlling signal from the input to the output without any react response from the output. The design of this PV system able to solve problem of unstable output power from traditional output of PV system that resulted from unstable sun radiances.

(Vivek, Ayshwarya, Amali, & Sree, 2016) approach on MPPT algorithm for solar photovoltaic panel using buck boost converter in the system. A solar module unable to transfer maximum power to the load because of impedance mismatch in the system. The output of the converter have been controlled using microcontroller, additionally two sensor which is voltage and current sensing are used to measured photovoltaic (PV) module output power and send to microcontroller. To track the maximum power point the present output power is compared with the previous output power module and duty cycle of the converter is adjusted continuously. This process repeated until output power is reach near with desired maximum point. The tracking system is implemented using buck-boost converter, whereby the MPPT using perturb and observation algorithm method to transfer maximum power from PV panel. This control method allowing steady-state analysis of the dc-dc converter. The buck-boost converter have been choose due to able to track the maximum power point in various ranging from zero until infinity.

The enhancement for maximum power point tracking (MPPT) technique to achieve high gain dc-dc converter for photovoltaic (PV) applications from (Jothi & Geetha, 2016). This paper presented about MPPT improvement for PV system using switched coupled inductor step up dc-dc converter. For boosting the output voltage, PV array will feed the power to the load through the dc converter. Solar energy have stochastic behavior, the MPPT control technique is used for PV array to operate at maximum power point whereby the MPPT using enhancement of perturb and observation (P&O) and fuzzy controller method for varying solar radiation. The characteristic performance of both methods is compared for output power, output voltage and efficiency. Additionally, the comparison of gain value for step up conventional boost converter and positive output superlift Luo converter also have been done in this project. This paper also presented the advantage of high voltage gain of switched couple inductor converter been integrated with the search of MPP. The P&O with fuzzy controller tracking results is obtained in high efficiency 95.45%. However, PI controller has been used for tune the better regulation and improve time domain in the systems.

Another group of researchers (Mars N, Grouz F, Essounbouli N, & Sbita L, 2017) applied PV panel, dc-dc boost converter, synergic MPPT controller and an output load. This research proposed non-linear power point tracking method of photovoltaic (PV) solar system based on synergic control strategy. For the effectiveness of the MPPT, this research use PV cell with 1000W/m^2 irradiance and temperature is 25^{o}C. Technique used for this research a synergic control strategy to achieve maximum output power point without chattering phenomena. The implementation of synergic control using controllable dynamics toward the origin point and provide maximum power operation under environmental changes like solar radiation and PV cell temperature. By using mathematical modelling approach for develop the model and simulated using Matlab® Simulink® software for analysis under different atmospheric condition. The boost converter allowed adaptation between PV model and load which the power flow through converter controlled by adjusting the *ON* and *OFF* of the switching. From the research shown whole system of PV with optimal control strategy and effectiveness of MPPT are proven in simulation result with significant higher efficiency.

The performance comparison between two step-up topologies, the boost and multilevel boost (MLB) converter for PV system connection using finite set model predictive control has been done by (Remache & Barra, 2018). Finite Set Model Predictive Control, FS-MPC strategies is presented in this research to control the cascade chopper-inverter as a matrix converter. The maximum power point tracking (MPPT) algorithm is directly connected with proposed predictive control in order to achieve global control system significant reduced. MPPT required to trigger controllable switch of dc-dc converter to allow PV panel transferring maximum power under different environment such as irradiation and temperature. This research proposed the method control for two cascaded converter in matrix converter at the same time instead of control each converter separately. A comparative study for boost and multilevel converter are completed under FS-MPC control with different system or called as stand-alone system and grid connected system. From the simulation result can conclude that performance of PV system based on boost converter are better compared with those obtained with multilevel boost converter in efficiency, low grid current Total Harmonic Distortion (THD), dynamic and low ripples.

(L. Guo, J. Y. Hung, & R. M. Nelms, 2009) evaluated a comparison between buck and boost dc-dc converter application connected with digital PID-type and fuzzy-type controllers.

Comparison between both controllers are made in term of design methodology, experimental measured performance and implementation issue. The design of fuzzy logic controller based on heuristic knowledge of converter behavior and tuning requires some expertise to minimize unproductive trial and error. The PID control design is based on frequency response of dc-dc converter. The implementation of linear controllers for digital signal processor is direct, whereby fuzzy logic implementation increases computational burden and memory of processor. Meanwhile, performance of fuzzy controller surpasses performance of PID controller. From the fuzzy controller result achieved faster transient response in most test, able to provide more steady-state response and much more robust when under same operation condition.

2.3 Research Theories

This section explain in particular about theory of Photovoltaic (PV) modelling, maximum power point tracking (MPPT) modelling and dc-dc boost converter which consists of state-space representation of modern controller and full state observer. Additionally about mathematical theory of each controller are also discussed in details.

2.3.1 Basic block diagram

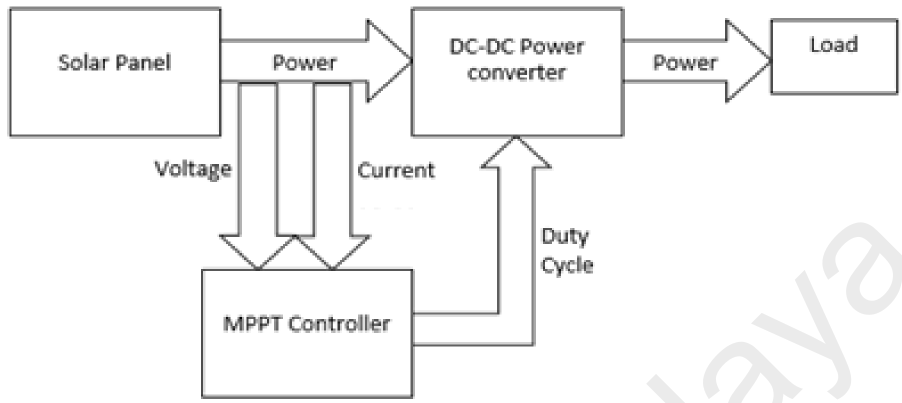


Figure 2.1: Basic block diagram

Block diagram above consists with solar panel, DC-DC power converter, MPPT controller and load. First, the voltage and current are provided from solar panel, whereby voltage and current flow into MPPT controller. These voltage and current value can be proceed according to the MPPT algorithm to track maximum power point of the solar panel. The output of MPPT in duty cycle or voltage parameter transferred to dc-dc converter, it help to maintain the voltage operation at maximum point by varying the duty cycle of converter. In this project used boost converter to step up the voltage at maximum power point. Boost converter is connected between solar panel and load. The MPPT algorithms can helps to find the maximum power point which boost converter able to maintain the operating voltage at maximum point irrespective of solar irradiance and temperature (Sholapur et al., 2014).

2.3.2 Introduction to Photovoltaic (PV) Modelling

An array of photovoltaic (PV) modules implement from PV array block. A sun energy from Photovoltaic cell directly converted to electrical power. The panel in PV modelling work for photoelectric effect whereby the system modeling of photovoltaic system is done by connecting a current source in parallel and diode will be inverted connection with series and parallel resistance. The PV array block consists with parameter model such as a current source *Iph*, diode for reverse saturation current I_s, series resistance *Rse* and shunt resistance *Rsh* to represent the temperature and irradiance depend on IV characteristic of the modules. The power voltage characteristic from Figure 2.3 of PV system are created by the multiplication voltage and current, meanwhile the maximum power point (MPP) can be achieved depend on the amplitude of voltage and current the point denoted as Pm in Figure 2.3 (Rohit Kumar1 et al., 2017). Referring to National Renewable Energy laboratory (NREL) system advisory model database of PV module the manufacturing database under standard test (STC) with irradiance = 1000W/m^2 and temperature = 25^{o}C (P.Gilman, 2015).

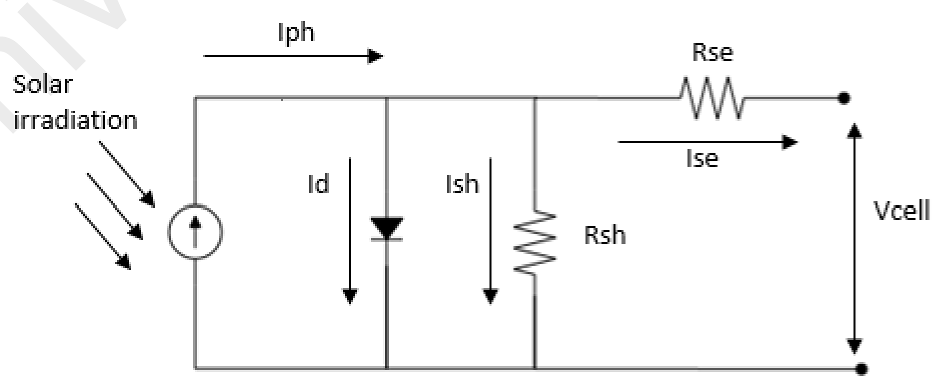


Figure 2.2: Equivalent circuit of photovoltaic cell

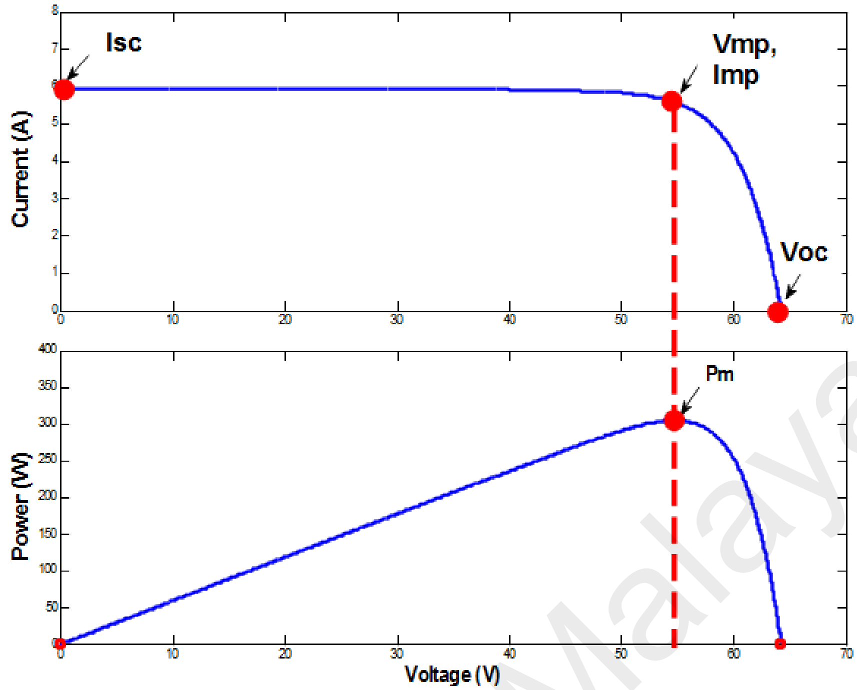


Figure 2.3: I-V and P-V characteristic of photovoltaic model

The P-V and I-V curve of solar cell dependent on solar irradiance values. The solar irradiance not in constant value and always keep in fluctuating depending upon environment condition, however control mechanism are available to track all the changes and able to alter the working of solar cell to achieved load demand. The higher solar irradiance, solar input will be higher, hence power magnitude also increase same with voltage value.

Referring to PV research (Sholapur et al., 2014), the photocurrent or light generated current *Iph* equation generally depend on solar insulation and cell working temperature, which describe as:

$$\mathrm{Iph} = \mathrm{Isc} + \mathrm{Ki}\ (\mathrm{TC} - \mathrm{Tref})\alpha\mathrm{i} \tag{2.1}$$

Other than that, the cell reverse saturation current, *Is* varies with the cell temperature, which describe as:

$$\mathrm{Is} = \mathrm{Irs}\ \left(\frac{\mathrm{TC}}{\mathrm{Tref}}\right)^3 \exp\left[\frac{\mathrm{qEG}}{\mathrm{KbA}}\left(\frac{1}{\mathrm{Tref}} - \frac{1}{\mathrm{TC}}\right)\right] \qquad (2.2)$$

Finally the current and voltage, IV characteristic equation of solar cell given as:

$$\mathrm{I} = \mathrm{Iph} - \mathrm{Is}\exp\left[\mathrm{q}\left(\frac{\mathrm{V+Ise\ x\ Rse}}{\mathrm{KbTCA}}\right) - 1\right] - \left(\frac{\mathrm{V+Ise\ x\ Rse}}{\mathrm{Rsh}}\right) \qquad (2.3)$$

Where:

Isc = Short circuit current at 25°C and 1kW/m^2

Ki = Short circuit current at temperature coefficient

Tref = Reference temperature at 25°C

αi = Solar irradiation in kW/m^2

TC = Cell working temperature

Irs = cell saturation current at Tref

q = Electron change 1.6 x 10^{-19} C

Kb = Boltzman constant 1.38 x 10^{-23} J/K

EG = Bang-gap energy of semiconductor used the PV cell

A = Ideality factor

Ise = Series current

Rse = Series resistance

Rsh = Shunt resistance

2.3.3 Maximum Power Point Tracking (MPPT) Modelling

There are many method available to obtain maximum power point (MPP) from photovoltaic system. In this research by using perturb and observe method, the algorithms develop depending on observation of the array output power and on the perturbation for increment or decrement of the power based on increments of the array voltage and current. This algorithms implemented using Matlab® Simulink®. Based on Figure 2.4, perturbation can cause the power of solar change. If the power increase because of perturbation, it will continued at the same direction until reached at maximum power point or peak power and the power rapidly decrease. After that the perturbation reverses. In order to keep the small power variation, the perturbation must kept in very small size (Sholapur et al., 2014).

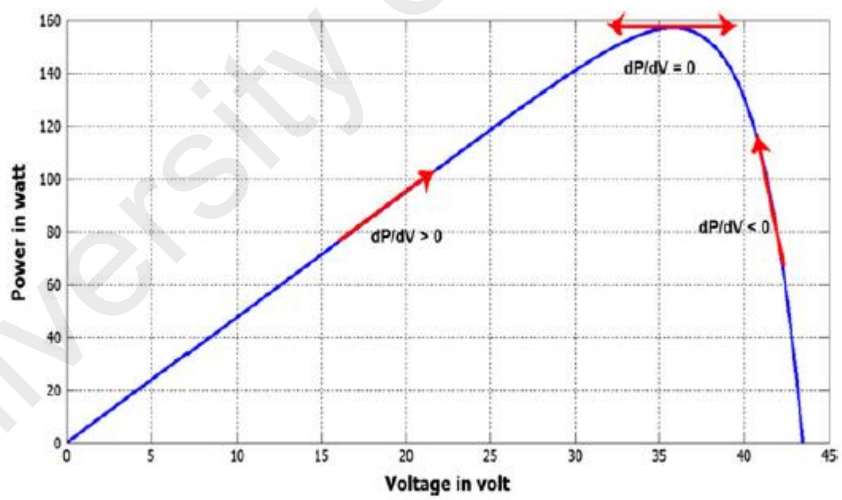


Figure 2.4: PV characteristic of perturbation and observation algorithm.

2.3.4 DC-DC Boost Converter

Boost converter also known as step up converter placed to obtain maximum output and always greater than input. It able to step up the voltage without a transformer. Figure 2.5 shows the schematic diagram of boost converter.

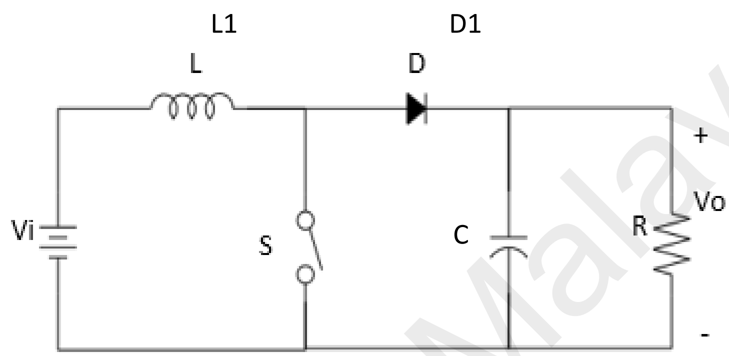


Figure 2.5: Boost converter schematic diagram

Boost converter operation, switch can be open or close rely open the output requirement. The output voltage must always be greater than input voltage for the load and resistor. Boost converter gave high effectiveness because of a solitary switch in the circuit. The output voltage very sensitive with changes of duty cycle D in equation (Sholapur et al., 2014).

$$\frac{\mathrm{Vo}}{\mathrm{Vi}} = \frac{1}{1 - \mathrm{D}} \tag{2.4}$$

From the modern controller methods are used to analyse the performance of boost converter modern controllers by using state feedback, optimal, integral controller, state feedback with feed forward and full state feedback observer.

2.4 Mathematical Theory

This section explain more details in particularly about mathematical theory of state-space representation, state feedback controller, state feedback with feed forward, integral controller, optimal controller and full state feedback observer.

2.4.1 Introduction to state-space representation

Modern control theory, also referred as state-space analysis is a method for modelling, analyzing and designing in wide range of systems. These system typically can be describe using differential equations. Advantage of state-space analysis, it is applicable on non-linear system same with MIMO systems. The state-space easy to computed using advanced digital computer program such as Matlab® Simulink® software. However before proceed to develop model and perform simulation of dc-dc converter, it is important to obtain the suitable state space equation first (Mohammed, Zhou, & Jones, 1990).

2.4.2 Introduction to state-space averaging technique

In general method for describe a circuit that changes over a switch period is called state-space averaging. A state-variable system description can be presented by following equations (Ogata, 2010):

$$\dot{x} = Ax + Bu \tag{2.5}$$

$$y = V_0 = Cx + Eu \tag{2.6}$$

From 2.5 and 2.6 equation, where A is called the state matrix, B the input matrix, C the output matrix, E the direct transmission matrix, u is input and y is the output. This block diagram represented the equation shown in Figure 2.6 (Ogata, 2010).

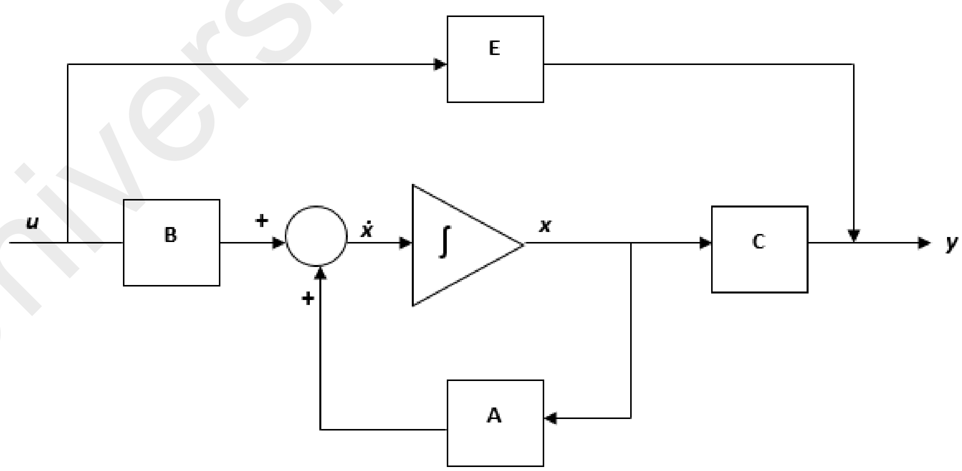


Figure 2.6: State-space representation

When E = [0] and thus will be ignored for mathematical analysis. However in Matlab m-file analysis, D is represented as E because the capital D not used in Matlab commands. In case when switch closed-model, the below equation are implemented:

$$\dot{x} = A_1 x + B_1 u \tag{2.7}$$

$$V_O = C_1^T x \tag{2.8}$$

Meanwhile, when it is in open-model, below equation are implemented:

$$\dot{x} = A_2 x + B_2 u \tag{2.9}$$

$$V_O = C_2^T x \tag{2.10}$$

Time *dT* represented switch closed while *(1-d)T* represents switch open and a weight average equation as per below:

$$\dot{x} = [A_1 d + A_2(1-d)\ ]x + [B_1 d + B_2(1-d)]u \tag{2.11}$$

$$V_O = [C_1^T d + \ C_2^T(1-d)\ ]x \tag{2.12}$$

In general forms to define an average state-variable of the system equation is given below:

$$A = A_1 d + A_2(1-d) \tag{2.13}$$

$$B = B_1 d + B_2(1-d) \tag{2.14}$$

$$C = \ C_1^T d + \ C_2^T(1-d) \tag{2.15}$$

2.5 Controllability

Controller is made to permit the system for accomplish consistent output. However, as main as a feature of fundamental component of controllers, converter must be controllable because to execute the state-space system. The controllability matrix *Mc*, is created from matrix *A* and *B* is shown in below equation (2.16) (Ogata, 2010).

$$Mc = [B \quad AB \ldots A^{n-1}B] \tag{2.16}$$

From above equation shown *n* is the order of the system. The system under controllable if *Mc* is a full rank matrix, whereby the determinate of *Mc* is not allowed to become zero. Else the system is no longer controllable.

2.6 State feedback controller

Designing a state variable require the assumption which all state are variable for feedback and able to access complete state *x(t)*. Input system *u(t)*, refer below for equation:

$$u = -Kx \tag{2.17}$$

From 2.17 equation determining the gain matrix *K* is objective if state feedback design process. Figure 2.7 show block diagram for state feedback controller and K as a feedback gain (Ogata, 2010).

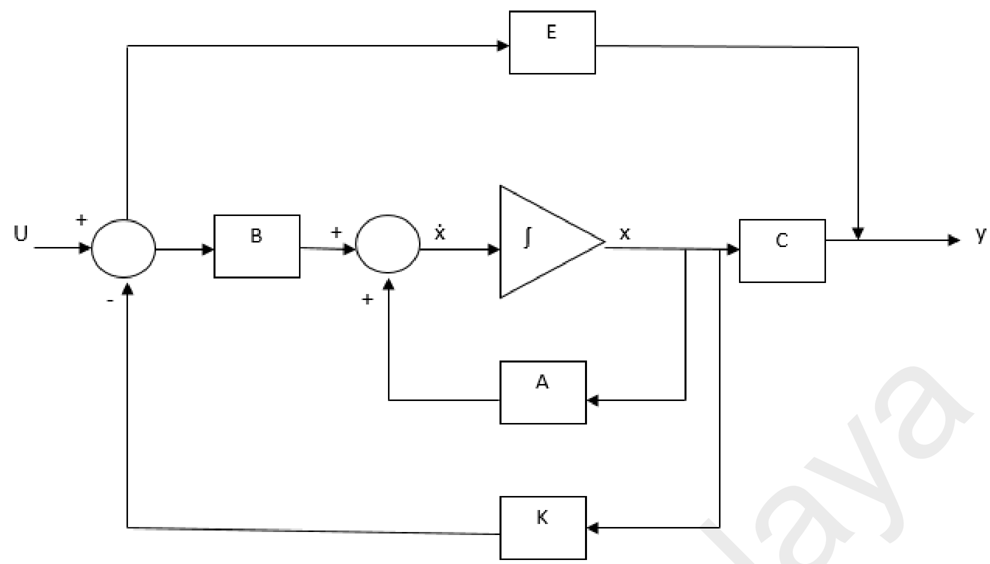


Figure 2.7: State feedback controller

The derivation from the circuit model, closed- loop system equation are:

$$\dot{x} = (A - BK)x \tag{2.18}$$

$$y = (C - EK)x \tag{2.19}$$

2.7 Pole placement technique

All state variable feeding concept which back to the input of the system using suitable feedback matrix in the control approaches defined as the full-state variable feedback control technique. This method to the specified of targeted location of close-loop eigenvalue (poles) in the system. The aim of this system designed for feedback controller that able to move in minority or majority open-loop poles of the measure system to demonstrated closed-loop pole location. It is known as pole-placement design and this system utilized in controller to provide stability, disturbance rejection and set point tracking. State feedback system is closed-loop controller state which be determined in below equation (Ogata, 2010):

$$|\lambda I - (A - BK)| = 0 \tag{2.20}$$

To govern *K* gain matrix, the favored poles should be placed. The values of favored poles relies upon on the system arrange or order. Whereby the poles consists a *n-order*, the poles is *n* and the characteristic equation as shown below (Ogata, 2010):

$$(s - p_1)(s - p_2) \dots \dots (s - p_n) = 0 \tag{2.21}$$

Matrix *K* can be decided by looking at coefficients signature between equation (2.20) and (2.21) and the value used in Figure 2.6. Other than that matrix *K* can be decide by utilized matrix *A* in Matlab simulation software, refer to below equation (Ogata, 2010):

$$eig(A) \tag{2.22}$$

2.8 Optimal control technique

Optimal one of the imperative controller to control system. The development is used to comprehend the system with practical segment that convey wanted operating system later on. System are acclimated to give minimum index performance called as optimal control system. It may be accomplished by modifying the system parameter where the index able to reach an outrageous incentive value in minimum value. This system comprises with feedback gain matrix that minimizes *J*, it is resolved in order to reach system stability. The equation as given below (Ogata, 2010):

$$J = \int_0^{\infty} (X^T Q_X + u^T Ru)dt \quad (2.21)$$

From equation 2.21, matrix *Q* able to derive as below:

$$Q = C^T C \quad (2.22)$$

The *Q* and *R* value which definite positive, in order to overcome the optimization problem over a finite time interval, Ricartti equation is the most popular method have been used (Ogata, 2010).

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (2.23)$$

$$K = R^{-1}B^T P \quad (2.24)$$

Referring to (2.23) and (2.24) equation, *P* is symmetric positive definite matrix and *K* known as optimal gain that used in state feedback controller design. The *K* value can be determined via (2.24) equation and the value will be added in Figure 2.7 state feedback controller block diagram.

2.9 State feedback with feed forward controller

The structure of controller state feedback with feed forward can be enhance state feedback output result, at whatever point there are disturbance happened that can be estimated before it will influence the output process. In fact, it can entirely remove the effect from measured disturbance on the output process. Refer to subchapter 2.7 for calculation of state feedback controller gain *K*. the feed forward gain *N* is calculate using below equation. The matrix value of the system is substitute in below equation, where *I* know as identity matrix (Ogata, 2010).

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} A & B \\ C & E \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{2.25}$$

The result are separated into two values, one for scalar *Nu* and another one for *Nx* in matrix form. Equation (2.26) used to calculate N value, where *K* value as calculated in state feedback controller system.

$$N = N_U + KN_X \tag{2.26}$$

Figure 2.8 show the block diagram of state feedback with feed forward controller (Ogata, 2010).

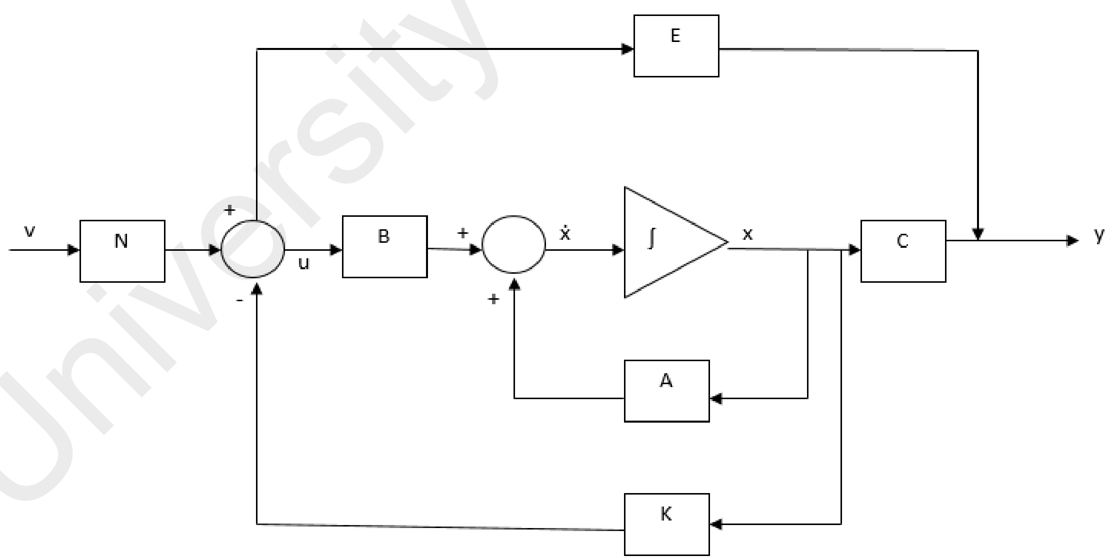


Figure 2.8: State feedback with feed forward controller

2.10 Integral controller

The design for state feedback controller have the major disadvantage large offset occurred when using pole placement. However, an integral controller added in to eliminate the large offset in the step response and also added value to robustness the system. The gain value *K* comes from outside the feedback loop. This system quite sensitive with outside element such as noise and disturbance. Therefore, combination between integral control and state feedback with feed forward controller function to achieve robustness from these external disturbance. The block diagram for integral controller as given below (Ogata, 2010):

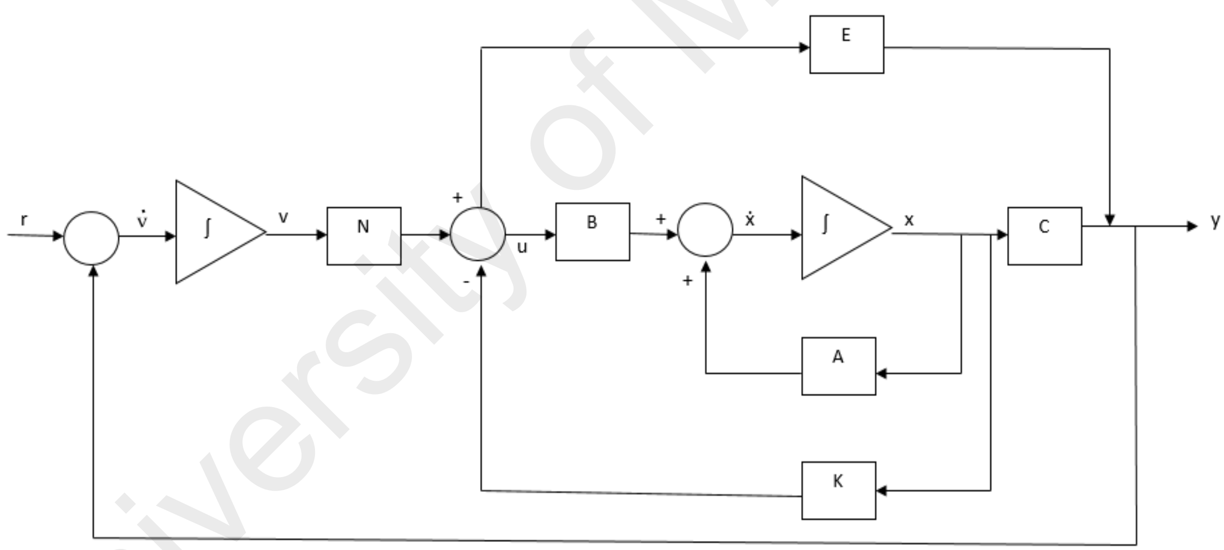


Figure 2.9: Integral controller

The controller mathematical model for state-space controller as given below (Ogata, 2010):

$$\dot{x} = Ax + Bu \tag{2.27}$$

$$\dot{v} = -Cx - Eu + r \tag{2.28}$$

$$u = -[K - N]\begin{bmatrix} x \\ v \end{bmatrix} \quad (2.29)$$

$$y = Cx + Eu \quad (2.30)$$

Where:

ẋ = State variable

ύ = Integral input

u = State feedback with feed forward controller

y = Output

A new gain *N* and matrix *K* are calculated by substitute in matrix *A*, *B*, *C* and *E*, refer below equation:

$$\begin{bmatrix} \dot{x} \\ \acute{\upsilon} \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}\begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} B \\ -E \end{bmatrix} u + \begin{bmatrix} 0 \\ I \end{bmatrix} r \quad (2.31)$$

Result from equation (2.31) will produce a new matrix *A* and *B*. The value for *K* is drive using following equation:

$$K = [K_1 \quad K_2 \quad -K_3] \quad (2.32)$$

The substituted polynomial characteristic is compared with desired eigenvalue by using equation (2.20) and (2.21) and *K* value is determined. The value of $-K_3$ know as forward gain and value of K_1 and K_2 as feedback gain. The equation as given below:

$$N = -K_2 \quad (2.33)$$

$$K = [K_1 \quad K_2] \quad (2.34)$$

When implemented in controller, the compensated system become below equation:

$$\begin{bmatrix} \dot{x} \\ \acute{\upsilon} \end{bmatrix} = \begin{bmatrix} A - BK & BN \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} x \\ v \end{bmatrix} u + \begin{bmatrix} 0 \\ I \end{bmatrix} r \tag{2.35}$$

2.11 Observability

Observer is dynamic system, it used to estimate the state of another dynamic system and given knowledge of input system also measurement of the output system. In order to see the condition inside the system under observation, the system must under observable from the beginning. The system will completely observable with existence a finite time *T* which the initial state *x(0)* can be determine from observation history *y(t)* given from the control *u(t),* $0 \leq t \leq T$. If this is true regardless the initial time and initial state, the system is completely observable. The observable matrix *Mo,* is created from matrix *A* and *C* refer (2.36) for matrix form (Ogata, 2010).

$$Mo = \begin{bmatrix} C \\ CA \\ \vdots \\ \vdots \\ CA^{n-1} \end{bmatrix} \tag{2.36}$$

Where *n* known as the order of the system, the system under fully observable if *Mo* is full rank or the system is observable when the determinant of observability matrix *Mo* is nonzero condition. The system also detectable when the system completely observable.

2.12 Full state observer

The design of observer system used to estimate state of the system. The same pole placement technique can be used for this design. The poles of the observer were change purposely to test the performance of the observer. In Figure 2.10 the design of observer at how the observer estimate the state of the systems. Whereby the $\dot{\hat{x}}$, $\hat{x}$ and $\hat{y}$, this is represent the estimate value (Ogata, 2010). The $\hat{y}$ is compared to the output of the system. If there is any differences found on the comparison can be multiple with an observer matrix L and the feedback to the estimator dynamic.

The calculation of full state observer as given below:

$$\dot{x} - \hat{x} = (A - LC)(x - \hat{x}) \tag{2.36}$$

The characteristic of full state observer can be derive from below equation:

$$|sI - (A - LC)| = 0 \tag{2.37}$$

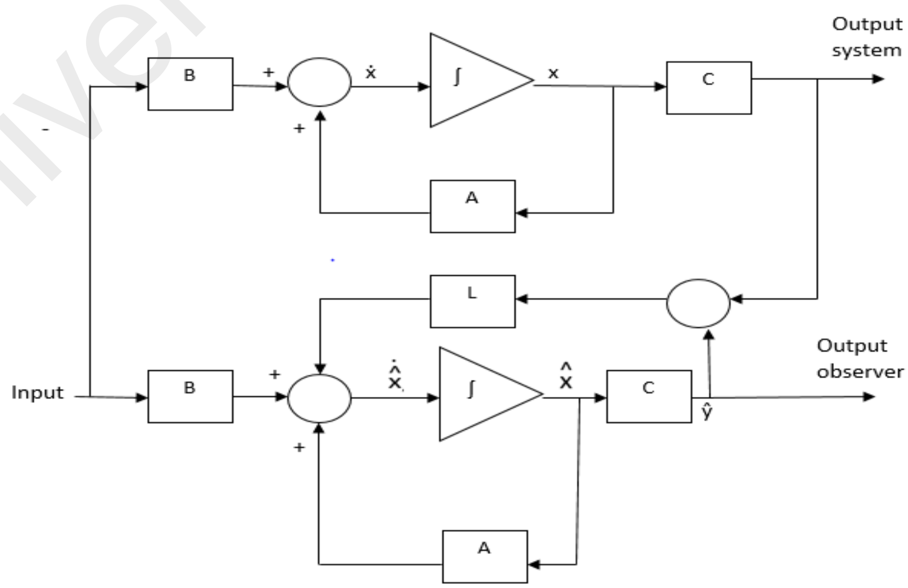


Figure 2.10: Full state observer

2.13 Summary

The purpose for this research to increase the power output and efficiency of the PV system also to perform analysis on boost converter using modern controller method. This system also need the constant voltage to supply to the irrespective load of the variation in solar temperature and irradiance. To increase the system efficiency and at the same time to track the maximum power point (MPP) of PV array. By using MPPT technique will automatically find the maximum point of voltage and current which PV array can obtain the maximum power output under temperature and irradiance effect. The performance of boost converter can be obtain by analysis modern controller method using state feedback, optimal, state feedback with feed forward, integral and observer in full state feedback. This research very popular among researchers and this chapter about previous work have been done by researchers around the world. The theories is very important in order to develop the system from the beginning of the design for photovoltaic modelling, MPPT modelling and boost converter modelling. Additionally the state-space averaging technique is required to design the boost converter system. The controller and observer are tested using simulation software to fulfill the requirement. Thus, this chapter elaborate more details about controllability and observability. Meanwhile the modern controller required gain, where pole placement technique is used to find gain controller of state feedback with feed forward and integral, however pole placement and optimal are used to achieve gain at state feedback condition. While gain for full state observer can be determined using pole placement technique.

CHAPTER 3

METHODOLOGY

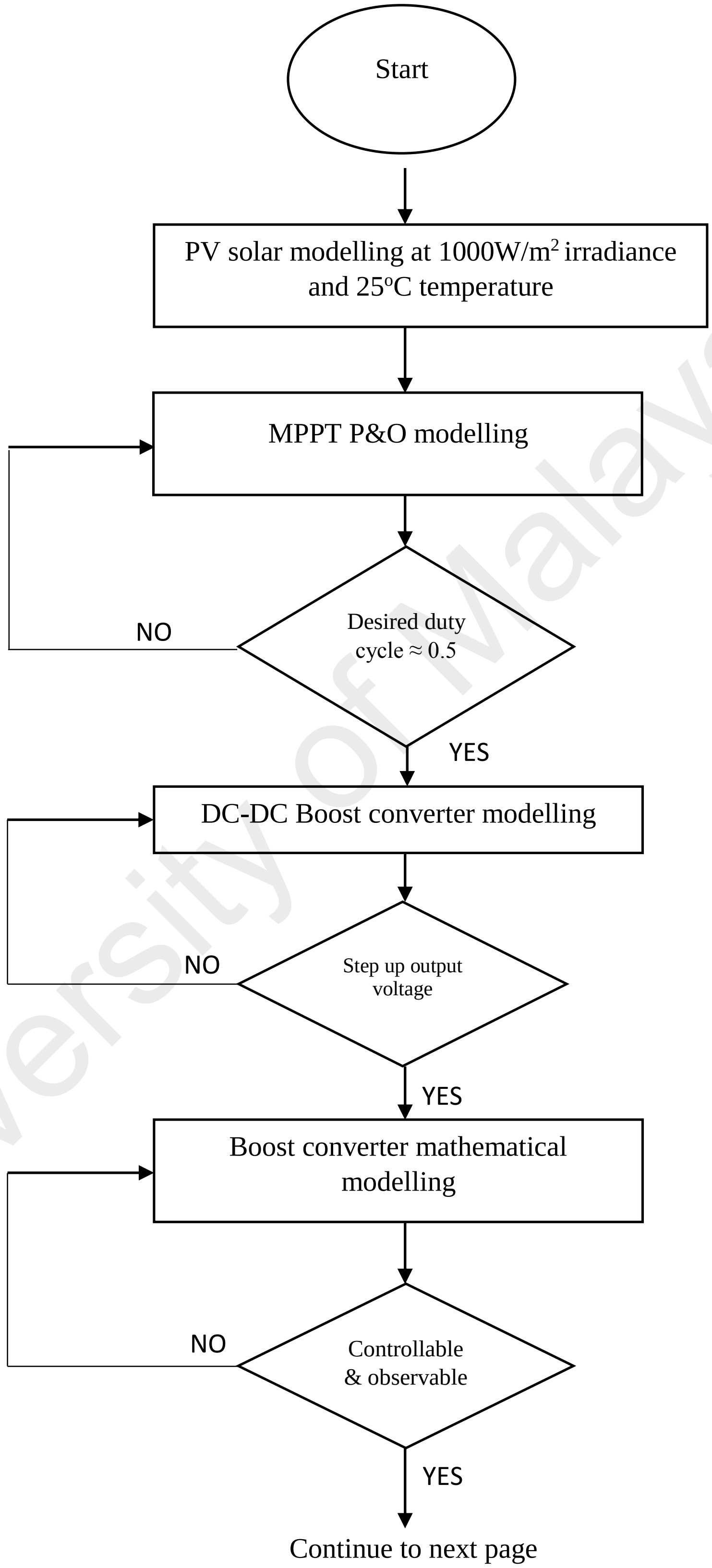
In this chapter shown the photovoltaic modelling, maximum power point (MPPT) modelling with perturb & observation algorithm and boost converter with state-space modelling and parameter values required for boost converter design are calculated. Controllability and observability of the system are verified and gain values for controller and observer will be determined. All methods deployed are based on the theories from previous chapter 2. The simulation process execute by using Matlab® & Simulink® software.

3.1 Introduction

In order to increase the efficiency of solar cell by using MPPT method, this technique can obtain the desired maximum power from varying source. From Figure 2.2 photovoltaic system the I-V curve is non-linear, where it is difficult to use to provide power at a certain load. This problem can be solve by utilizing boost converter which duty cycle is varied by using MPPT algorithm (Vangari, Haribabu, & Sakamuri, 2015). Based on overview of boost converter controller from chapter 2, almost all the research using state-space approach is found applied on PID, PI and fuzzy controller. This project focusing on boost converter by using modern controllers approach.

3.2 Flow of the project

This project start with photovoltaic (PV) modelling followed to MPPT modelling and finally to boost converter modelling. The PV modeling developed using behavioral model based on electrical circuit model and power limited electrical driver model, MPPT modelling designed using perturb and observation algorithm. However this project focusing more details on boost converter, there are five different phases implemented for this project. From the methodology project flow chart in Figure 3.1, it stated with PV solar module under given temperature and irradiance to obtain voltage and current which transferred to MPPT controller to obtain maximum point of power. DC-DC boost converter connected to PV module for the voltage input and MPPT for voltage parameter or duty cycle. The boost converter have been analyse using modern controller and stated with mathematical modelling, then continue with observability and controllability check, next to determine poles location before proceed to simulation and analysis process for the result. The state-space of boost converter are derive and define in mathematical modelling phase. Next, the state-space equation are used to check the controllability and observability of the boost converter. The poles determined after system is found under controllable and observable. These poles location are used to discover gain in modern controllers and observer, the gain value are inserted into respective Simulink controller model. At phase of validation and verification result from open and close loop are analysed. Finally the overall result are compared, discussed and the best controller that deliver the best result is finalized.


Start
PV solar modelling at 1000W/m2 irradiance and 25ºC temperature
MPPT P&O modelling
Desired duty cycle ≈ 0.5
NO
YES
DC-DC Boost converter modelling
Step up output voltage
NO
YES
Boost converter mathematical modelling
Controllable & observable
NO
YES
Continue to next page

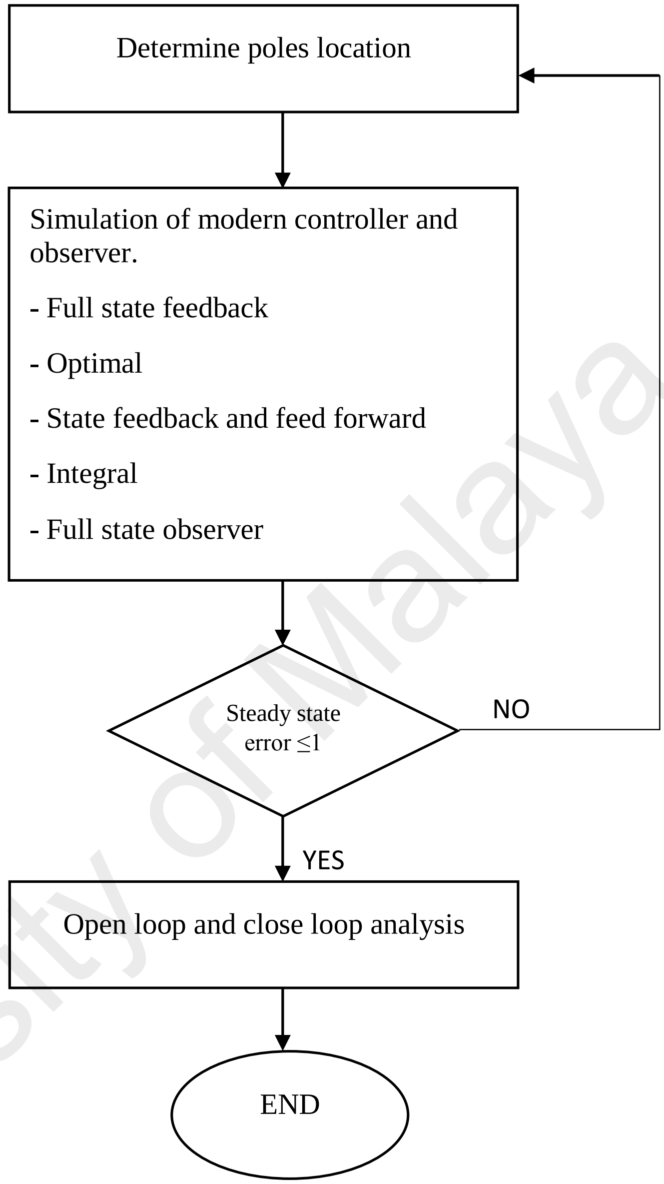


Figure 3.1: Flow chart of project methodology

3.3 Photovoltaic module

Photovoltaic (PV) cell modelling divided into two type using behavioral PV modelling and power limited electrical driver. This project using behavioral PV modelling which is based on equivalent electrical model. Behavioral model consists with current source *Iph*, the current produced by the photons or light generated current. It is constant at fixed value of radiation and temperature. This research used PV cell with 1000W/m^2 irradiance and temperature is 25^{o}C. Figure 3.2 shown behavioral PV modelling (Sholapur et al., 2014).

Parameter setting used in the PV module simulation are presented in Table 3.1.

Table 3.1: PV module simulation parameter (Sholapur et al., 2014).

Module parameter	**Values**
Voltage reference (Vr)	21.1 V
Current reference (Ir)	3.5A
Short circuit Current temperature coefficient (α)	3 x 10^{-3}mA/^{o}C
Open circuit voltage temperature coefficient (β)	-73 x 10^{-3}mW/^{o}C
Short circuit current	3.8 A
Series resistance	0.47Ω
Internal capacitance (Ci)	100µF
Internal resistance (Ri)	10Ω

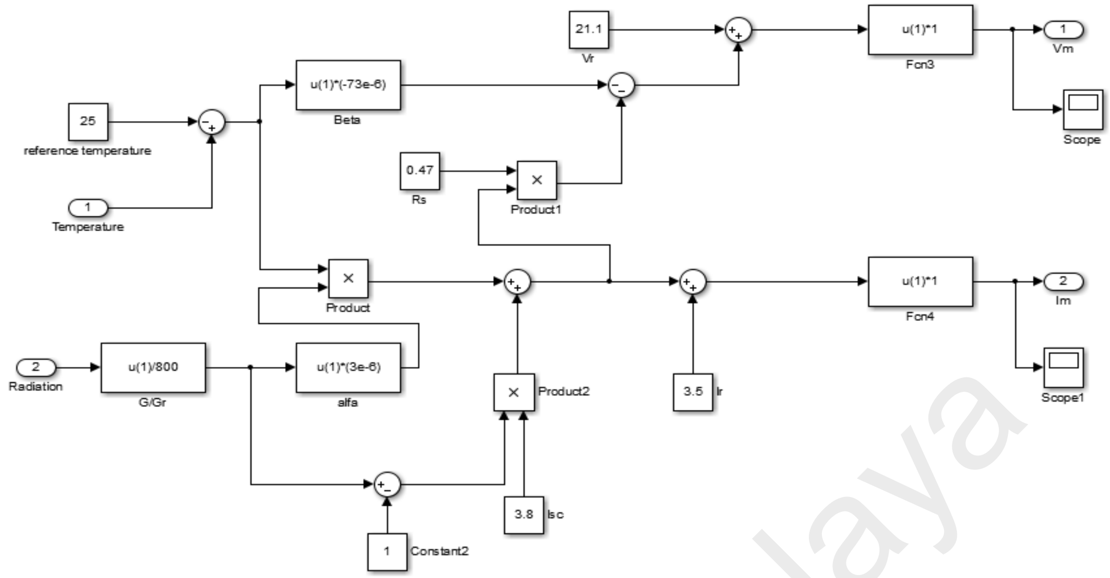


Figure 3.2: Behavioral PV Simulink modelling

Behavioral model in the power system calculated the current and voltage values. In order to develop PV panel power limits, these values need for an electrical driver component that exhibit an I-V PV characteristic complying with the response of PV panels, Figure 3.3 shown power limited electrical driver modelling (Sholapur et al., 2014)

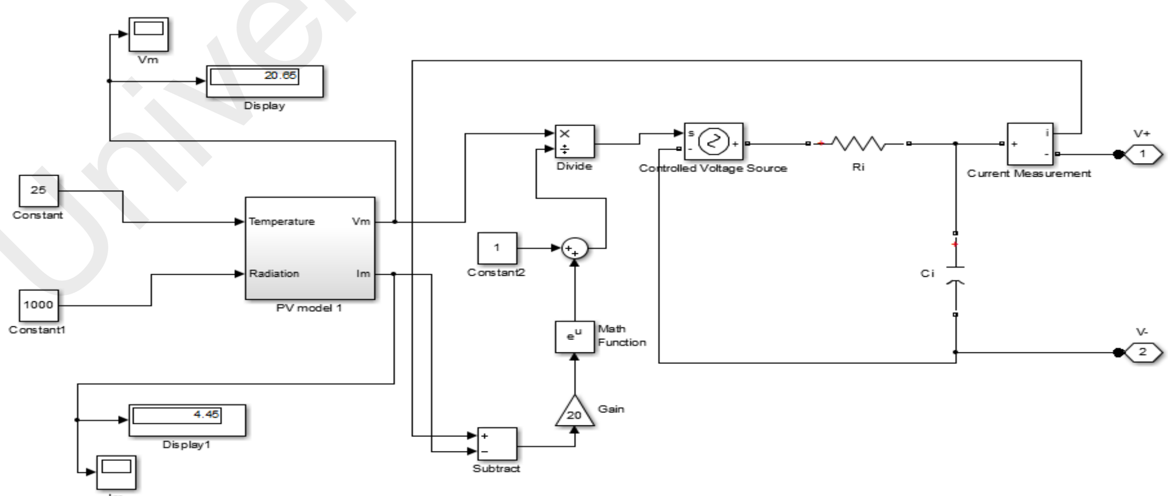


Figure 3.3: Power limited electrical driver Simulink modelling

3.4 Maximum Power Point Tracking (MPPT) modelling

The MPPT modelling developed using perturb and observation algorithm. The logic of perturb and observation algorithm are explained in flowchart Figure 3.4. From the flowchart the operating voltage for PV system is perturbed by small increment *dV*, hence this result change in *dP*. However, for *dP* under positive condition the perturbation of operating voltage need at the same direction with increment. Meanwhile, for *dP* under negative condition the obtain system operating point move away from the MPPT and operating voltage move in the opposite direction of the increment (Sholapur et al., 2014).

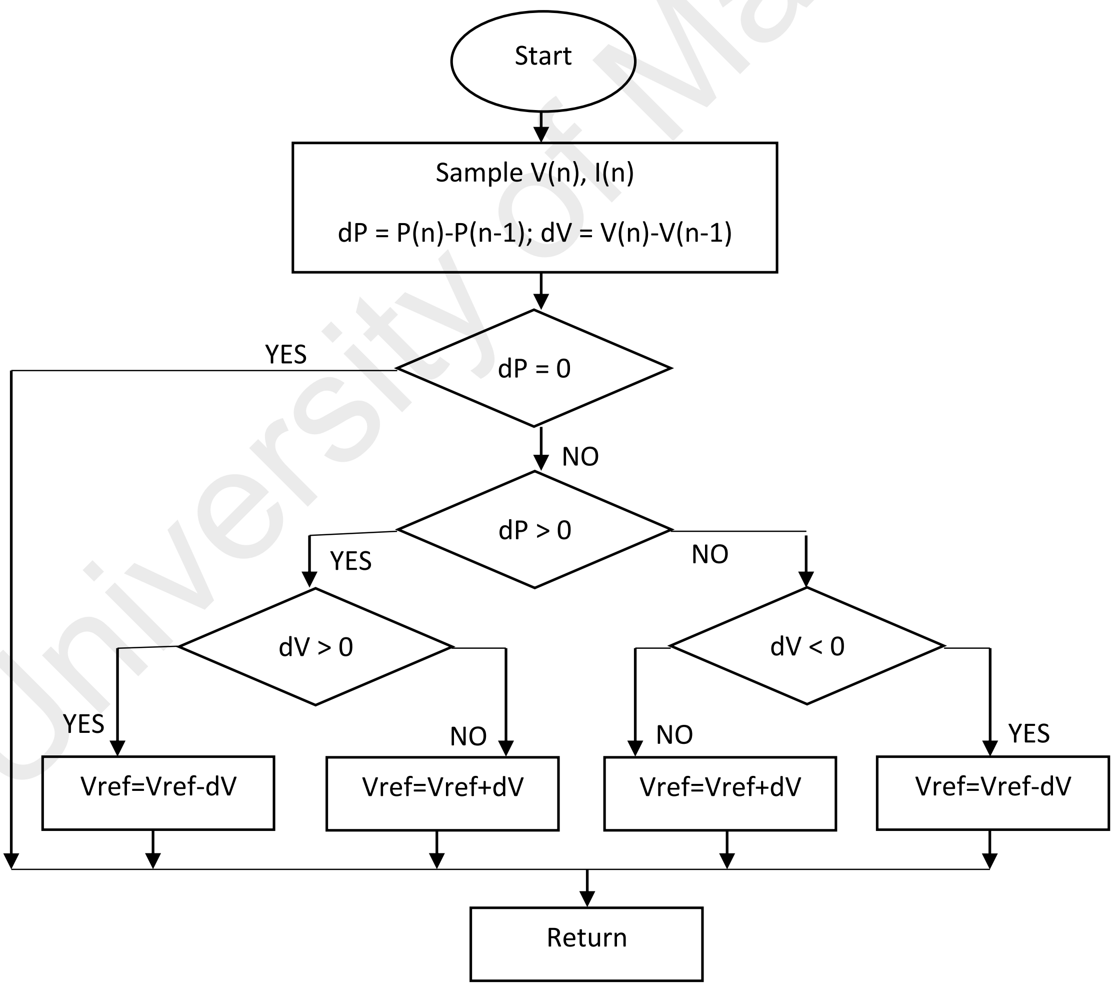


Figure 3.4: Flowchart of perturb and observation algorithm (Sholapur et al., 2014)

From the flowchart of perturb and algorithm, maximum power tracking algorithm is created using Simulink software, shown in Figure 3.5 (Sholapur et al., 2014).

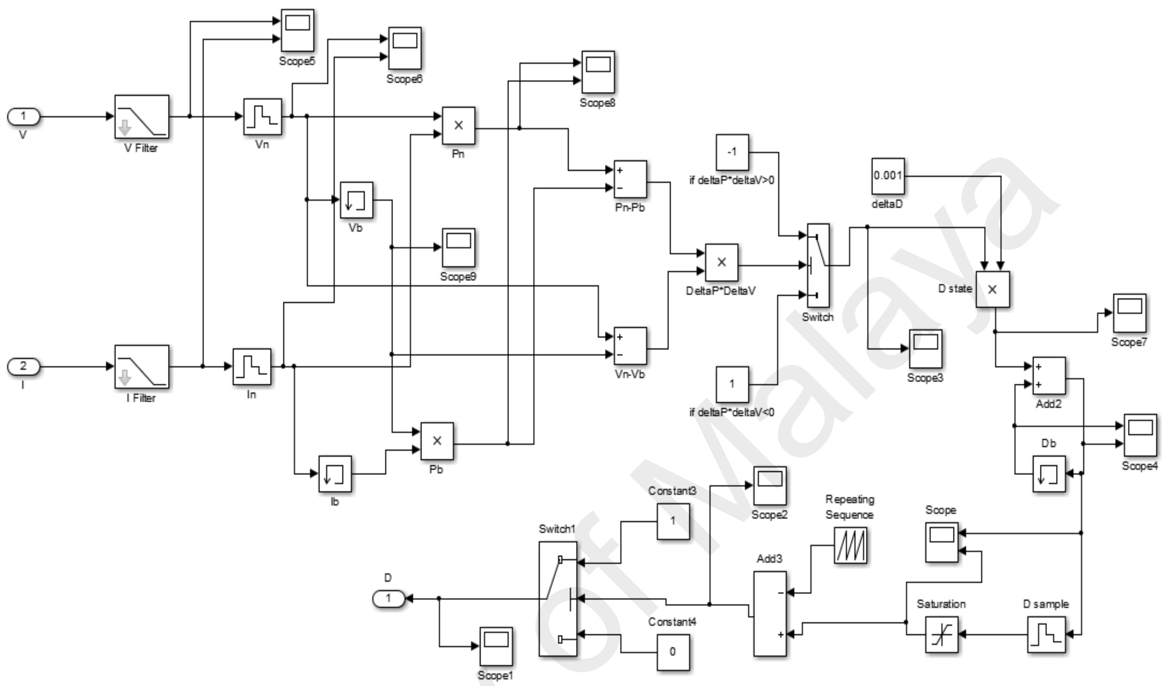


Figure 3.5: Perturb and observation MPPT algorithm Simulink modelling

3.5 DC-DC Boost converter modelling

Boost converter also known as step up converter and always greater than input. The MPPT algorithm connected to boost converter to provide pulse or duty cycle for obtaining output voltage (Rohit Kumar1 et al., 2017). Figure 3.6 shown modelling for boost converter.

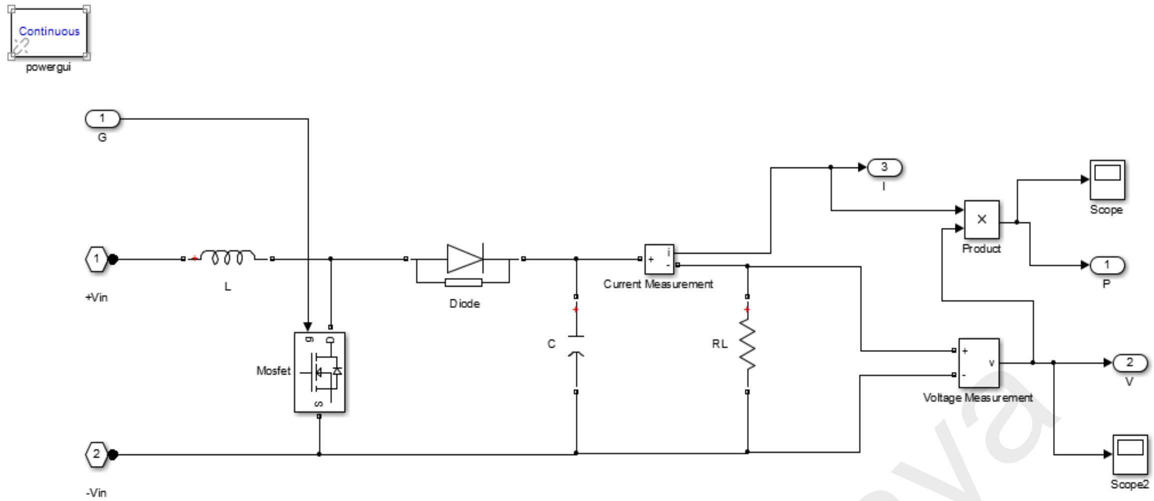


Figure 3.6: DC-DC Boost converter Simulink modelling

From the simulation results, the input voltage provided from PV module is 14.55V and the output voltage obtained from boost converter step up to 29.85V. The parameters used in boost converter system are presented in Table 3.2 (Escobar, Ortega, Sira-Ramirez, Vilain, & Zein, 1999).

Table 3.2: Boost converter circuit parameters

Parameters	**Values**
Vi	14.55V
Vo	29.85V
L1	100mH
C1	1000µF
RL	100Ω

3.6 Complete Simulink model for the project

The Simulink model proposed for this project as shown in Figure 3.7, which consists with solar panel module, MPPT model and finally boost converter. MPPT is important part in this system which help to determine the maximum operating point and the signal transfer to boost converter in order to maintain the operating voltage at maximum point (Sholapur et al., 2014).

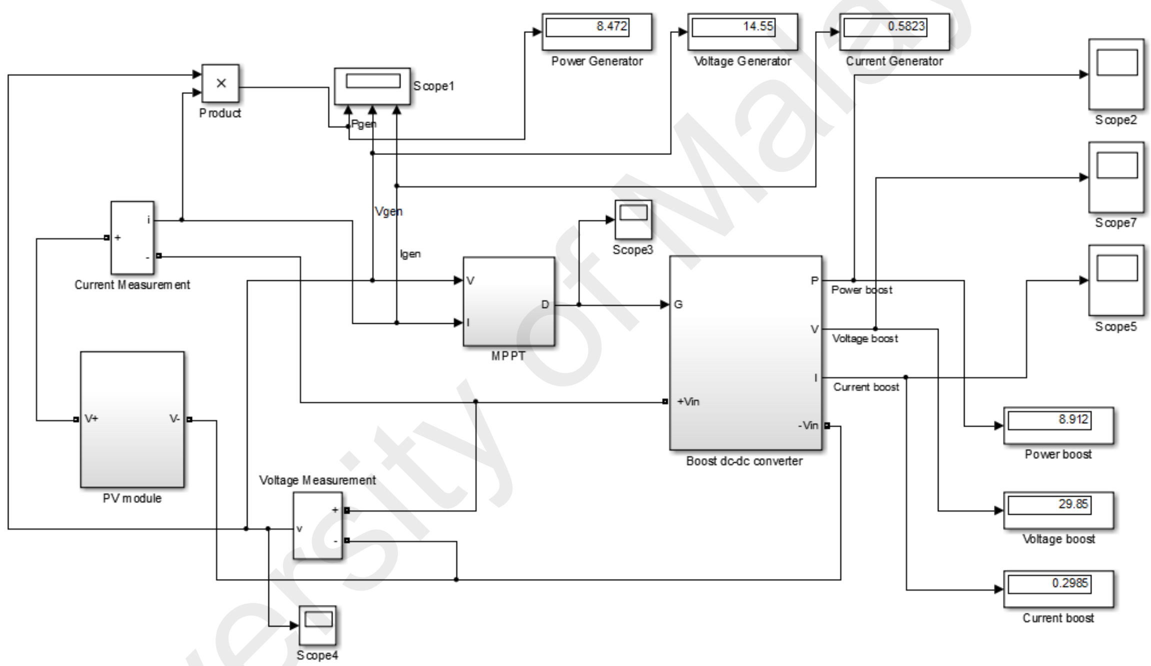


Figure 3.7: Complete project Simulink modelling

In the next section, the analysis in mathematical simulation modelling for performance of boost converter controller by using state feedback, state feedback with feed forward, integral, optimal and full state feedback observer.

3.7 State-space equation derivation

State-space technique useful for creating transfer function for switch circuits like dc-dc converter. This section explained the steps of derivation state-space equation boost converter, Figure 3.8 shows model of boost converter circuit. Additionally, Figure 3.9 shows boost converter operation when the switch is close and Figure 3.10 shows boost converter operation when the switch is open (W.Hart, 2011).

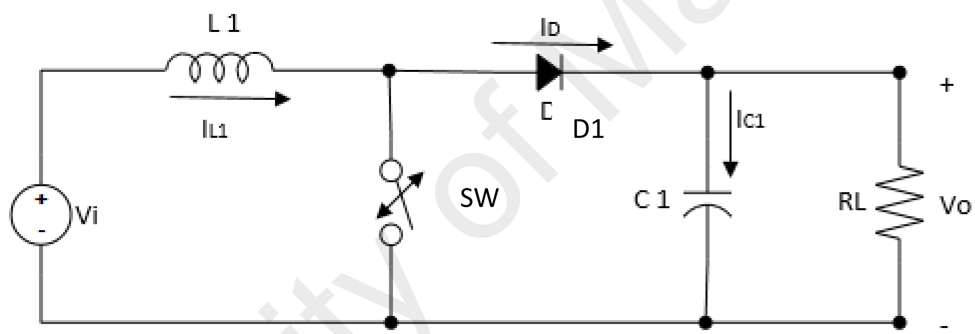


Figure 3.8: Boost converter circuit

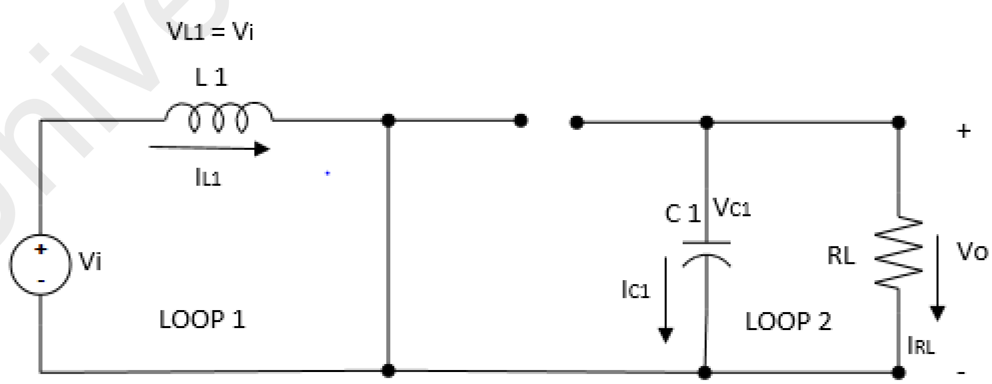


Figure 3.9: Boost converter when close switch

From Figure 3.9, Kirchoff's voltage law equation loops are used for derivation as given below (W.Hart, 2011):

$$V_{L1} = Vi \tag{3.1}$$

$$L1\frac{di_{L1}}{dt} = Vi \tag{3.2}$$

$$\frac{di_{L1}}{dt} = \frac{Vi}{L1} \tag{3.3}$$

While Kirchoff's current low equation as given below (W.Hart, 2011):

$$i_{C1} = -i_{RL} \tag{3.4}$$

$$i_{C1} = -\frac{Vo}{L1} \tag{3.5}$$

$$C1\frac{dV_{C1}}{dt} = -\frac{V_{C1}}{RL} \tag{3.6}$$

$$\frac{dV_{C1}}{dt} = -\frac{V_{C1}}{RL * C1} \tag{3.7}$$

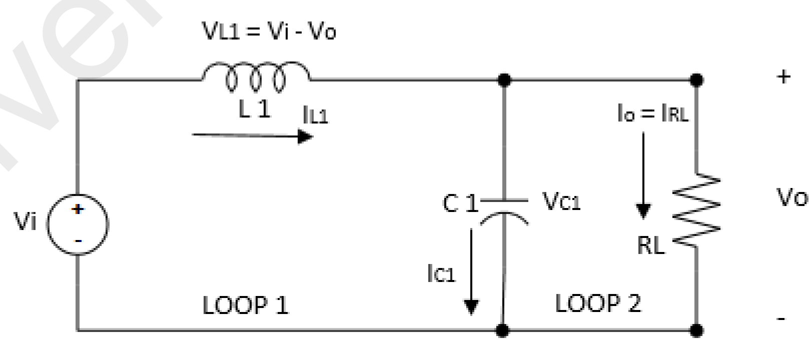


Figure 3.10: Boost converter when open switch

From Figure 3.10, Kirchoff's voltage law equation loops are used for derivation as given below (W.Hart, 2011):

$$V_{L1} = Vi - Vo \tag{3.8}$$

$$V_{L1} = Vi - V_{C1} \tag{3.9}$$

$$L1\frac{di_{L1}}{dt} = Vi - V_{C1} \tag{3.10}$$

$$\frac{di_{L1}}{dt} = \frac{Vi - V_{C1}}{L1} \tag{3.11}$$

While Kirchoff's current low equation as given below (W.Hart, 2011):

$$i_{L1} = i_{C1} + i_o \tag{3.12}$$

$$i_{C1} = i_{L1} - i_o \tag{3.13}$$

$$i_{C1} = i_{L1} - \frac{V_O}{RL} \tag{3.14}$$

$$C1\frac{dV_{C1}}{dt} = i_{L1} - \frac{V_{C1}}{RL} \tag{3.15}$$

$$\frac{dV_{C1}}{dt} = \frac{i_{L1}}{C1} - \frac{V_{C1}}{RL * C1} \tag{3.16}$$

Hence, from equation (3.8) until (3.11) and (3.12) until (3.16), the steady-state of boost converter can be derive as below (W.Hart, 2011):

$$\frac{di_{L1}}{dt} = \frac{Vi}{L1}(d) + \left[\frac{Vi - V_{C1}}{L1}\right](1-d) = \frac{Vi}{L1} - \frac{V_{C1}}{L1}(1-d) \tag{3.17}$$

$$\frac{dV_{C1}}{dt} = -\frac{V_{C1}}{RL * C1}(d) - \left[\frac{i_{L1}}{C1} - \frac{V_{C1}}{RL * C1}\right](1-d) = \frac{i_{L1}}{C1}(1-d) - \frac{V_{C1}}{RL * C1} \tag{3.18}$$

Otherwise, the above equation can be transformed into matrix as given below when assume (1-d) = D, (W.Hart, 2011).

$$\dot{x} = \begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{dV_{C1}}{dt} \end{bmatrix} \tag{3.19}$$

$$A = \begin{bmatrix} 0 & -\frac{D}{L1} \\ \frac{D}{C1} & -\frac{1}{RL * C1} \end{bmatrix} \tag{3.20}$$

$$x = \begin{bmatrix} i_{L1} \\ V_{C1} \end{bmatrix} \tag{3.21}$$

$$B = \begin{bmatrix} \frac{Vi}{L1} \\ 0 \end{bmatrix} \tag{3.22}$$

Steady-state operation, the change value in inductor current must be zero. Below equation shows the relationship between output voltages (Vo), input voltage (Vi) and duty cycle (D) (W.Hart, 2011).

$$\frac{Vo}{Vi} = \frac{1}{1 - D} \tag{3.23}$$

The current average in inductor is determined by (W.Hart, 2011):

$$i_{L1} = \frac{Vi}{(1 - D)^2 RL} \tag{3.24}$$

The output voltage Vo determined from below equation (W.Hart, 2011):

$$Vo = V_{C1} \tag{3.25}$$

Equation (3.26) can be used at both switch position, the resulting in $C_1^T = C_2^T = C$.

$$C = [0 \quad 1] \tag{3.26}$$

And

$$x = \begin{bmatrix} i_{L1} \\ V_{C1} \end{bmatrix} \tag{3.27}$$

3.8 State-space modelling analysis

State-space modelling analysis developed by using parameter of boost converter as shown in Table 3.2. Duty cycle (D) can be calculate based on equation (3.23) by inserting all related parameter required refer below:

$$\frac{Vo}{Vi} = \frac{1}{1 - D}$$

$$D = 0.5$$

All boost converter parameter assigned to find state-space matrices by using equation (3.20), (3.22) and (3.26) as depicted below:

$$A = \begin{bmatrix} 0 & -\frac{D}{L1} \\ \frac{D}{C1} & -\frac{1}{RL * C1} \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{Vi}{L1} \\ 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 145.5 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

The state-space duty cycle value, *D* is 0.5. Equation (3.24) is used to calculate the average current in the inductor, refer below:

$$i_{L1} = \frac{Vi}{(1-D)^2 RL}$$

$$i_{L1} = 0.582A$$

After complete discovered for all matrices needed in boost converter modelling, where for the next stage all the information used for verification of controllable and observable as well as to determine poles location.

3.9 Controllability analysis

A boost converter considered completely controllable if it's Rank [Mc] = 2 or Determinant [Mc] ≠ 0. Thus, for calculation used equation (2.16) to check controllability of the boost converter

$$Mc = [B \quad AB]$$

$$AB = \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix} \begin{bmatrix} 145.5 \\ 0 \end{bmatrix}$$

$$AB = \begin{bmatrix} 0 \\ 72.75 \times 10^3 \end{bmatrix}$$

$$Mc = \begin{bmatrix} 145.5 & 0 \\ 0 & 72.75 \times 10^3 \end{bmatrix}$$

$$|Mc| = 1.059 \times 10^7$$

From the result shows Rank [Mc] = 2 and $|Mc| = 1.059 \times 10^7 \neq 0$. These results can be conclude that the boost converter system is fully controllable.

3.10 Observability analysis

A boost converter considered completely observable if it's Rank [Mo] = 2 or Determinant [Mo] ≠ 0. Thus, for calculation used equation (2.36) to check observability of the boost converter

$$Mo = \begin{bmatrix} C \\ CA \end{bmatrix}$$

$$CA = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix}$$

$$CA = \begin{bmatrix} 500 & -10 \end{bmatrix}$$

$$Mo = \begin{bmatrix} 0 & 1 \\ 500 & -10 \end{bmatrix}$$

$$|Mo| = -500$$

From the result shows Rank [Mo] = 2 and $|Mo| = -500 \neq 0$. These results can be concluded that the boost converter system is completely observable. Apart from above methods, boost converter controllability and observability also can be determine using Matlab Simulink software tool.

When both controllable and observable of boost converter have been proved, both methods are ready to be implement on the boost converter system. The next steps was the analysis to obtain poles location.

3.11 Poles location analysis

Below equation is defined to find poles location and eigenvalues of boost converter:

$$|sI - A| = 0$$

$$\left|\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix}\right| = 0$$

$$s^2 + 10s + 2500 = 0$$

The poles values also can be determined using Matlab software tool. Based on result generated using software, poles of boost converter are placed at below point.

$$P_{1,2} = -5 \pm 4.9749i$$

3.12 State feedback controller gain calculation

Optimal control and poles placement technique are presented in this project to obtain gain value, *K* of state feedback controller.

3.13 Poles placement technique

In the previous steps has been calculated the poles location of boost converter. Hence, in the s-plane poles location point located at -5 ± 4.9749i. Table 3.3 shows three groups of poles placement and would be design to compare the effect of poles placement to the left in s-plane. The poles consists with *Poles 150x*, *Poles 250x* and *Poles 350x*.

Table 3.3: Pole placement group

Poles group	Pole placement	
	P1	P2
Poles 150x	-750	-750
Poles 250x	-1250	-1250
Poles 350x	-1750	-1750

The closed-loop characteristic is revised and equation (2.20) is used to find the *K* gain matrix value from feedback controller.

Where K = [K_1 K_2];

$$|\lambda I - (A - BK)| = 0$$

$$\left| \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix} + \begin{bmatrix} 145.5 \\ 0 \end{bmatrix} [K_1 \quad K_2] \right| = 0$$

$$s^2 + (10 + 145.5K_1)s + 1455K_1 + 2500 + 72750K_2 = 0 \tag{3.28}$$

In order to find gain matrix K_1 and K_2, characteristics equation of a new poles placement is developed by using equation (2.21). The poles at Poles *150x* equation generated as follows:

$$(s + 750)(s + 750) = 0$$

$$s^2 + 1500s + (562.5 \times 10^3) = 0 \tag{3.29}$$

Referring in equation (3.28) and (3.29) are compared to find gain values of K_1 and K_2

$$10 + 145.4K_1 = 1500$$

$$K_1 = 10.24$$

Next steps, substituted $K_1 = 10.24$ to find value of K_2:

$$1455K_1 + 2500 + 72750K_2 = 562.5 \times 10^3$$

$$1455(10.24) + 2500 + 72750K_2 = 562.5 \times 10^3$$

$$K_2 = 7.5$$

From the gain values K_1 and K_2 for poles *150x* can be described as below:

$$K = [K_1 \quad K_2]$$

$$K = [10.24 \quad 7.5]$$

The similar approach can been done for another poles group 250x and 350x by repeated the same steps to determine the feedback gains. From Table 3.4, the K1, K2 and K3 are presented for *Poles 150x*, *Poles 250x* and *Poles 350x.* Feedback gain from each group recoded in table below.

Table 3.4: Designated pole placement from State feedback controller gain

Poles group	Gain, *K* state feedback controller	
	K1	K2
Poles 150x (K1)	10.24	7.53
Poles 250x (K2)	17.11	21.14
Poles 350x (K3)	23.99	41.62

Finally all gains state feedback controller depended on poles placement methods are calculated and recorded on table. The best compensated output voltage is accomplished from the best pole placement group. This project using Matlab Simulation software to analyse the output voltage provided from boost converter. For the next section presented the calculation of state feedback controller gain based on optimal controller.

3.14 Optimal control technique

Linear quadratic cost function:

$$J = \int_0^\infty (x^T Q_x + u^T Ru)dt$$

Matrix Q can be derived from:

$$Q = C^T C \tag{3.30}$$

Substituted matric C to determine matrix Q as below equation,

$$Q = [0 \quad 1]^T [0 \quad 1]$$

$$Q = \begin{bmatrix} 0 \\ 1 \end{bmatrix} [0 \quad 1]$$

$$Q = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

Minimized cost function by manipulating state and leaving input as default R = [1]. On next equation (2.23) is revisited. Calculate matrix P using Ricatti equation and substituted all related matrices.

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$

$$\begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix}^T \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix} - \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} 145.5 \\ 0 \end{bmatrix} [1]^{-1} \begin{bmatrix} 145.5 \\ 0 \end{bmatrix}^T \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} = 0$$

Matrix P can be solved by using LQR function refer below equation:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$$

$$P = \begin{bmatrix} 17.25 \times 10^{-3} & 6.30 \times 10^{-3} \\ 6.30 \times 10^{-3} & 4.90 \times 10^{-3} \end{bmatrix}$$

Next, by using equation (2.24) to calculate state feedback controller gain based on optimal control methods. All parameter must be substituted as shown below:

$$K = R^{-1}B^T P$$

$$K = [1]^{-1} \begin{bmatrix} 145.5 \\ 0 \end{bmatrix}^T \begin{bmatrix} 17.25 \times 10^{-3} & 6.30 \times 10^{-3} \\ 6.30 \times 10^{-3} & 4.90 \times 10^{-3} \end{bmatrix}$$

$$K = [2.5091 \quad 0.9160]$$

K values can be determined by using Matlab m-file. These values will be used in Matlab simulation software for analysis the output voltage.

3.15 Gain calculation for feed forward controller

Poles placement technique for gain *K* still be used in this state feedback. Hence, K3 = [23.99 41.62] has been choose in this controller as feedback gain. By using equation (2.25) to find values of *Nx* and *Nu*.

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} A & B \\ C & E \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ I \end{bmatrix}$$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} 0 & -5 & 145.5 \\ 500 & -10 & 0 \\ 0 & 1 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} 0.02 \\ 1 \\ 0.03 \end{bmatrix}$$

$$Nx = \begin{bmatrix} 0.02 \\ 1 \end{bmatrix}$$

$$Nu = [0.03]$$

Finally, *N* values can be obtain using equation (2.26)

$$N = N_U + KN_X$$

$$N = 0.03 + [23.99 \quad 41.62] \begin{bmatrix} 0.02 \\ 1 \end{bmatrix}$$

$$N = 0.03 + 42.1 = 42.13$$

N values can be determined by using Matlab m-file. These values will be used in Matlab simulation software for analysis the output voltage.

3.16 Gain calculation for integral controller

The implemented of integral controller to eliminate external element with tracking the whole system feedback. Hence, a new value of gain *K* and *N* need to be obtained. Referring to the equation (2.29) and (2.31) to find a new matrices of *A* and *B* before new gain can be determined. By using equation (2.31), new matrix *A* and *B* are obtained in form:

$$\dot{x} = Ax + Bu$$

$$A = \begin{bmatrix} 0 & -5 & 0 \\ 500 & -10 & 0 \\ 0 & -1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 145.5 \\ 0 \\ 0 \end{bmatrix}$$

New *K* can be described as below:

$$K = [k_1 \quad k_2 \quad -k_3]$$

$$K = [0.034 \quad -5.086 \times 10^{-7} \quad -0.17]$$

As per explained in subchapter 2.10 integral controller, *K* and *N* values are written as follows:

$$K = [0.034 \quad -5.086 \times 10^{-7}]$$

$$N = -0.17$$

3.17 Gain calculation for full state observer

To find observer gain L, referring to equation (2.37) to determined characteristic equation of full state observer.

$$sI - (A - LC) = 0$$

$$\left| \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & -5 \\ 500 & -10 \end{bmatrix} + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \begin{bmatrix} 0 & 1 \end{bmatrix} \right| = 0$$

$$s^2 + (10 + l_2)s + 2500 + 500l_1 = 0$$

The characteristic equation for *poles 150x* as below:

$$(s + 750)(s + 750) = 0$$

$$s^2 + 1500s + 562500 = 0$$

The characteristic *poles 150x* equation are compared to find l_1 and l_2:

$$2500 + 500l_1 = 562500$$

$$l_1 = 1120$$

$$10 + l_2 = 1500$$

$$l_2 = 1490$$

The observer gain L for *poles 150x*:

$$L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} = \begin{bmatrix} 1120 \\ 1490 \end{bmatrix}$$

To determine observer gain matrix, *L* values also can be computed using Matlab® & Simulink® Software.

The similar method are used to determine the gains observer for *poles 250x* and *poles 350x*. The observer gain value for each group are recorded in Table 3.5

Table 3.5: Designated pole placement of full state observer

Full state observer gain, L	Poles placement		
	Poles 150x (L1)	*Poles 250x (L2)*	*Poles 350x (L3)*
l_1	1120	3125	6125
l_2	1490	2490	3490

The observer and controller of output voltage boost converter can be analyse using Matlab® & Simulink® Software. However for this research only poles 250x (L2) is selected for further analysis and investigation as observer output result. After all information successfully collected, the next step is run simulation of controller and observer design.

3.18 Simulation block diagram

When all components for the design has been determined. Design of controllers and observer are tested using simulation Matlab Simulink application. This project tested using closed-loop system activation. Result obtained are analysed to find the best characteristics.

3.18.1 State feedback controller

The closed-loop system consists with additional function block of feedback gain, *K*. The gain K can be determined from pole placement and optimal control technique. Feedback gain also able to enable duty cycles controlling to compensate output system to desired output voltage. Below figure shows the State feedback with pole placement controller with *poles 150x*, *poles 250x* and *poles 350x* and State feedback with optimal controller.

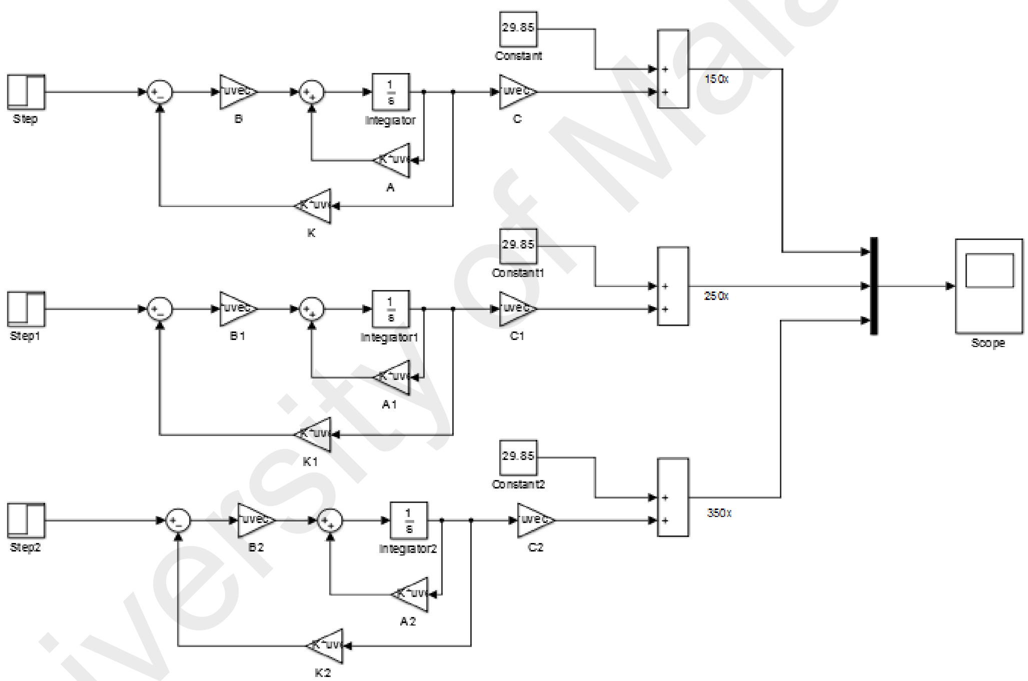


Figure 3.11: State feedback with pole placement controller

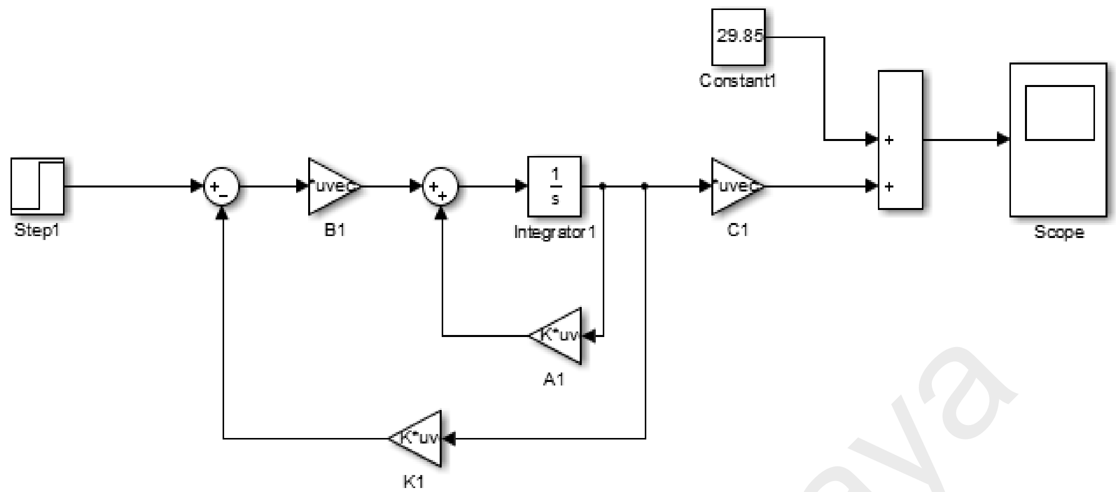


Figure 3.12: State feedback with optimal controller

3.18.2 State feedback with feed forward controller

State feedback and feed forward controller shown in Figure 3.13 consist with feed forward gain, *N*. The gain *K* is taken from pole placement. For simulation analysed this controller by using *poles 350x.*

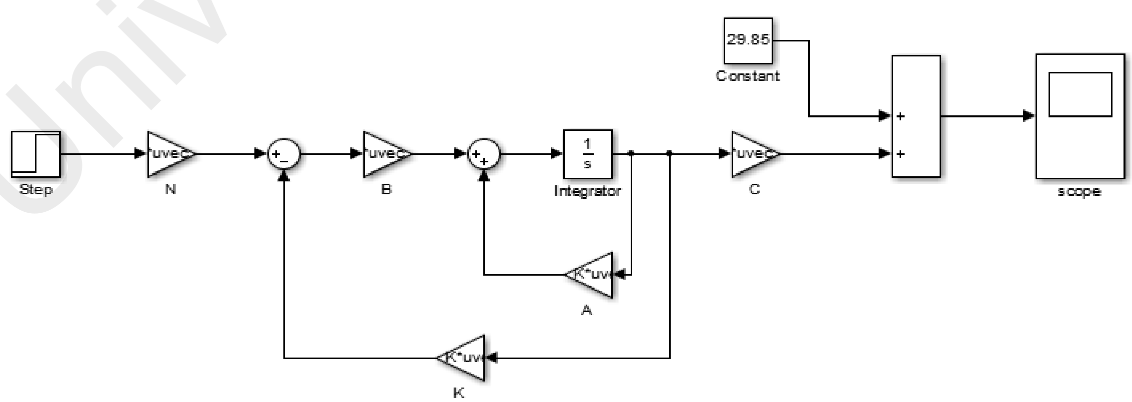


Figure 3.13: State feedback with feed forward controller

3.18.3 Integral

The integral controller have additional integrator in front of state feedback with feed forward of the system. From figure below the feedback from output system is placed before the integrator with summation point. This configuration used to monitor the whole system and to ensure the output still same as input.

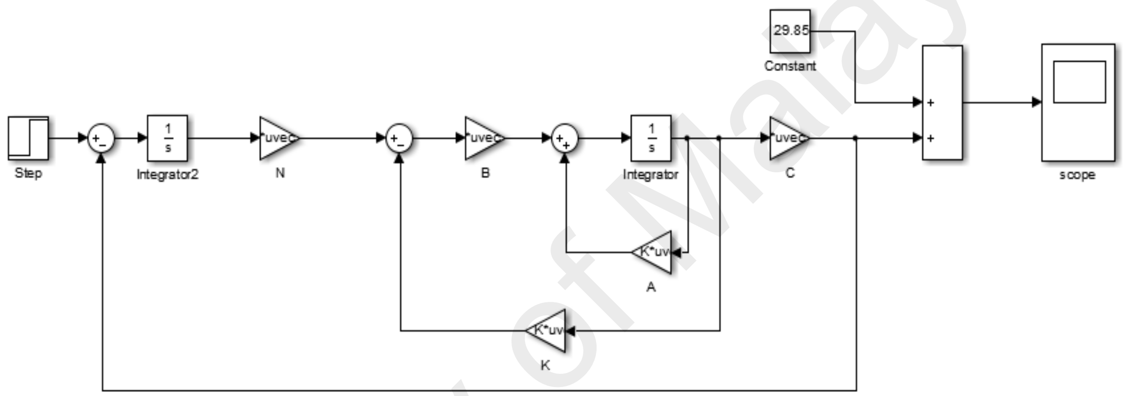


Figure 3.14: Integral Controller

3.18.4 Comparison of modern controller

For the comparison of modern controllers, there are full state feedback controller, optimal controller, state feedback with feed forward controller and integral controller. The modern controllers perform the analysis by combined in one single Simulink block diagram for better comparison and the signal for each controller are display at the same scope. The configuration of Simulink block diagram shown in Figure 3.15.

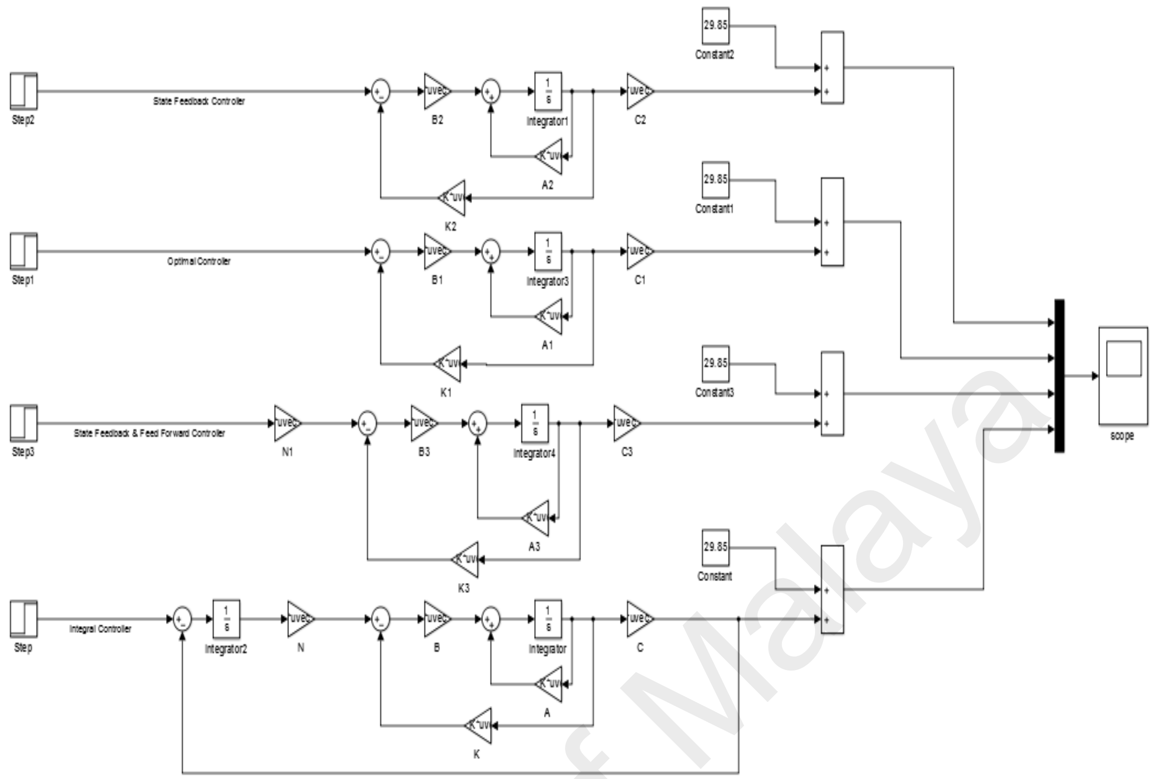


Figure 3.15: Comparison of modern controller

3.18.5 Full state observer

From Figure 3.16 show the combination of boost converter and full state observer in one block diagram. The values used in feedback control are estimated through the full state observer. For the output value measured in scope 1 must be similar or equal with the output value measured in scope 2.

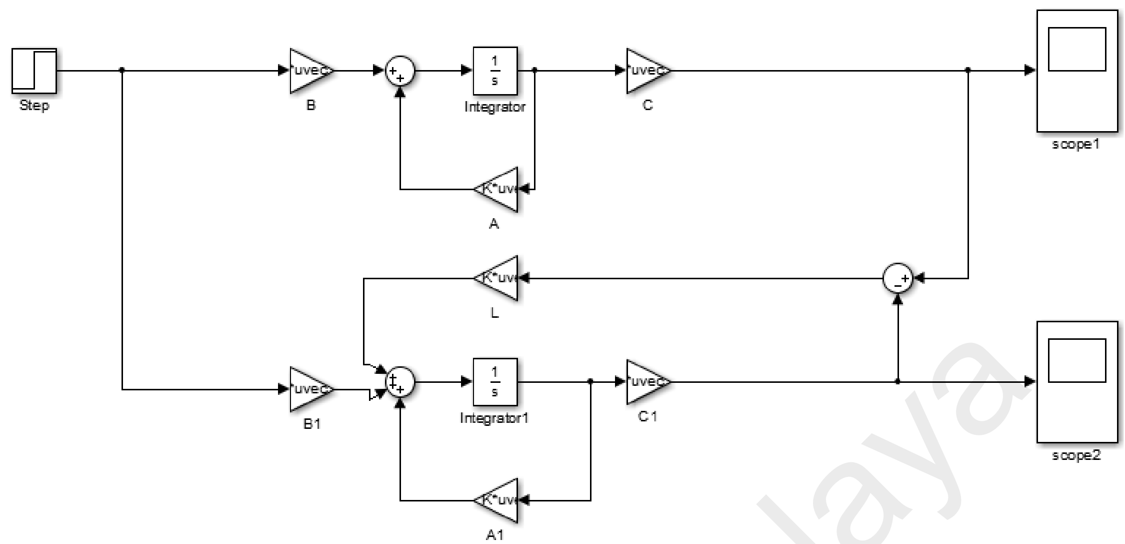


Figure 3.16: Full state observer

3.19 Summary

In the first section of this chapter referring to the flow chart show the steps of implementation for this research project. Flow chart also presented to summarize the flow including procedures taken place within this project. The first simulation involved photovoltaic modelling, maximum power point (MPPT) modelling with perturb & observation algorithm and boost converter modelling. These simulation to generate output voltage after through boost converter whereby the output voltage to get duty cycle and used in modern controller modelling as a constant voltage reference. The mathematical modellings are explained to verify the parameter applied in the system to meet project requirement. The boost converter designed and presented in steady-state form in order to check system controllability, observability and poles location while the state-space model must be derived. Value of gain, *L* used in observer design calculated by using former technique which value of gain, *K* used in controller design is calculated by using both pole placement method and optimal control method. However the feed forward gain, N and integral value calculated based on theory explained in previous chapter 2. All the parameter are placed in Simulation block diagram for analysis in controller and observer performance. Simulation result of controllers and observer will be discussed at following chapter.

CHAPTER 4
RESULT AND DISCUSSIONS

In this chapter, modelling simulation results using Matlab & Simulink software were analysed and discussed in details. It is divided into four subchapters. Firstly result from boost converter modelling for voltage output is presented and examined. Next, result from closed-loop system is evaluated and finally result from observer system. In this chapter presented result of boost converter modelling after through maximum power point tracking where the maximum voltage point is achieved and the closed-loop systems are examined in term of settling time, overshoot percentage and steady-state error. At the end of subchapter, the result of boost converter system observer has been analysed in term of different between output voltage from original boost system and observer system.

4.1 Introduction

The MPPT is the heart of this project which to determine the maximum operating point and give a gate signal or duty cycle to the boost converter. Boost converter would help to maintain the operating voltage at maximum power point. The maximum voltage point would be used in the modern controller systems as voltage reference for the evaluation. The boost converter graph without MPPT shows overshoot while for with MPPT no overshoot occurred. From Figure 4.1 shows the boost converter output result with and without MPPT. Afterwards Table 4.1 shows the analysis comparison values for power, voltage and current between with and without MPPT.

The boost converter output power, voltage and current values shows in Table 4.1 which the analysis comparison between with and without MPPT.

Table 4.1: Boost converter modelling results

Measurements	With MPPT	Without MPPT
Power, *Po*	8.192W	3.257W
Voltage, *Vo*	29.85V	18.05V
Current, *Io*	0.299A	0.181A

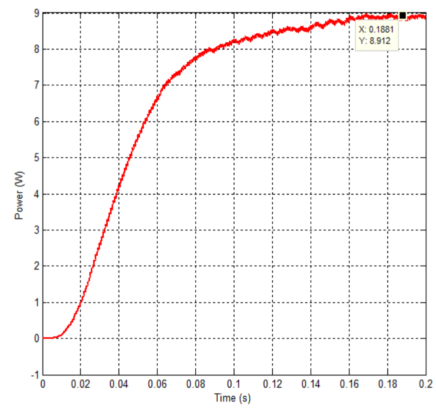
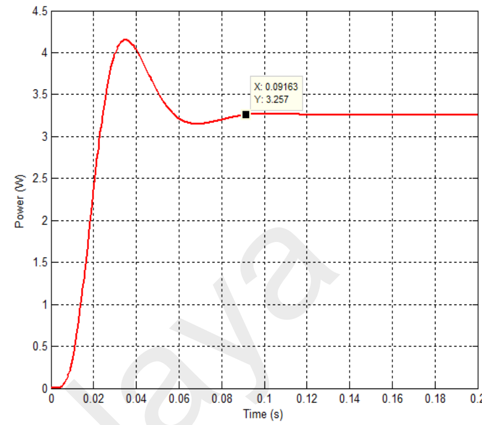
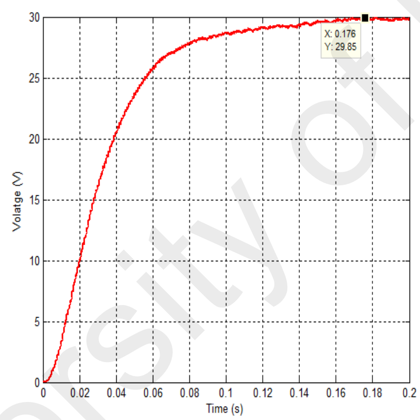
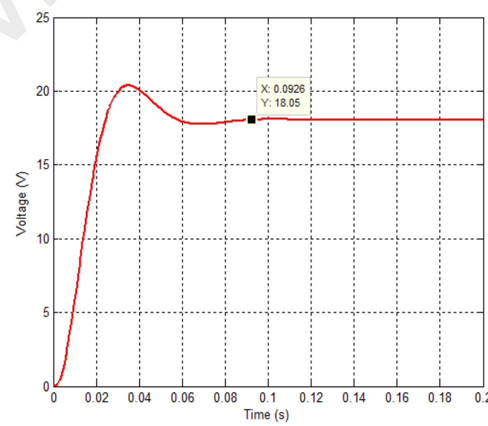
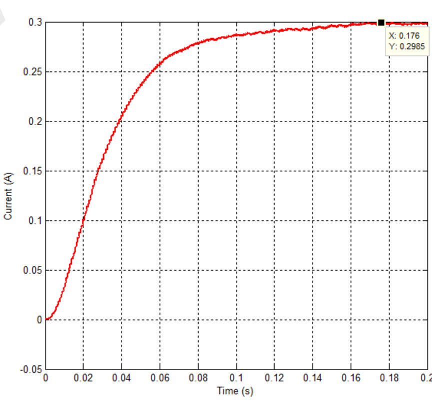
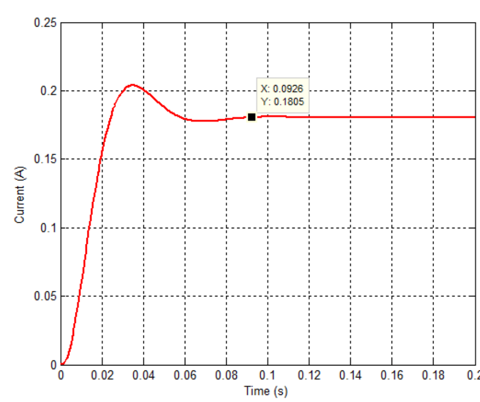
Measurements	Connection with MPPT	Connection without MPPT
Power		
Voltage		
Current		

Figure 4.1: Photovoltaic (PV) with and without MPPT boost converter system result

4.2 Response of boost converter closed-loop systems

Closed-loop converters are designed to maintain voltage output, *Vo* value if any changes happen at input, the output voltage received from boost converter modelling through MPPT system. Therefore for this research the analysis only perform at output voltage. The closed-loop evaluation consists with state feedback controller, state feedback with feed forward controller, integral controller and full state feedback observer. These controllers system are implemented and analysed respectively. Boost converter system design required parameter are listed in Table 4.2.

Table 4.2: Boost converter requirement parameter in the system

Output Voltage, *Vo*	29.85V
Input Voltage, *Vi*	14.55V
Inductor current, *iL*	0.58A

4.2.1 State feedback with pole placement technique

State feedback controller analysis can be implemented using two methods which pole placement technique and optimal control technique. The derivation of state feedback gain controller, *K* for simulation has been discussed on previous chapter referring to Figure 3.11. By applying pole placement technique, gain value for *K1* is inserted in *K* block diagram controller. Then followed with another gain value for *K2* and *K3*. Next page Figure 4.2 show result of gains which plotted at the same graph.

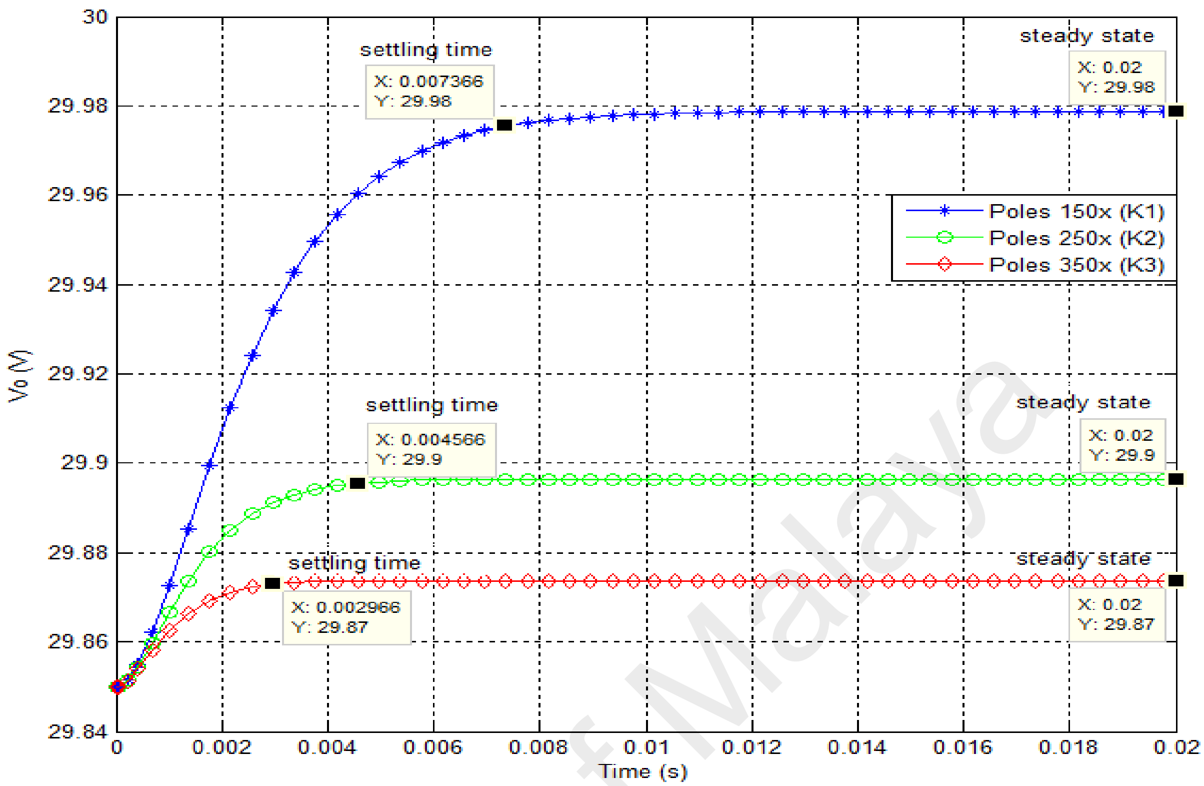


Figure 4.2: Result for pole placement technique

Table 4.3 is summarized results collected from Figure 4.2 as shown below.

Table 4.3: Analysis results from Figure 4.2

Pole location	Output voltage, *Vo*(V)	Settling time, *Ts*(sec)	Overshoot, (%)	Steady-state error, *Vess*(V)
Poles 150x (K1)	29.98	0.007366	0	0.13
Poles 250x (K2)	29.90	0.004566	0	0.05
Poles 350x (K3)	29.87	0.002966	0	0.02

Results achieved from three poles are evaluated to find the best compensated output voltage. The best compensated must be a controller that capable to produce 29.85V voltage output at steady state, fastest settling time, 0% overshoot and with minimum steady-state error. From Table 4.3 state feedback controller based on pole placement technique, *poles 350x* provide the best characteristics and the best compensated with shortest settling time 0.002966s, minimum steady-state error 0.02V and voltage output within expected voltage output 20.85V. From the analysis can be observed that steady-state values are improved when poles location are moved to the left half-plane in s-plane.

4.2.2 State feedback with optimal control technique

Referring from block diagram in Figure 3.12, the *K* value determine using Ricatti equation as calculated in previous subchapter 3.14. The simulation result with applying optimal controller shown in Figure 4.3.

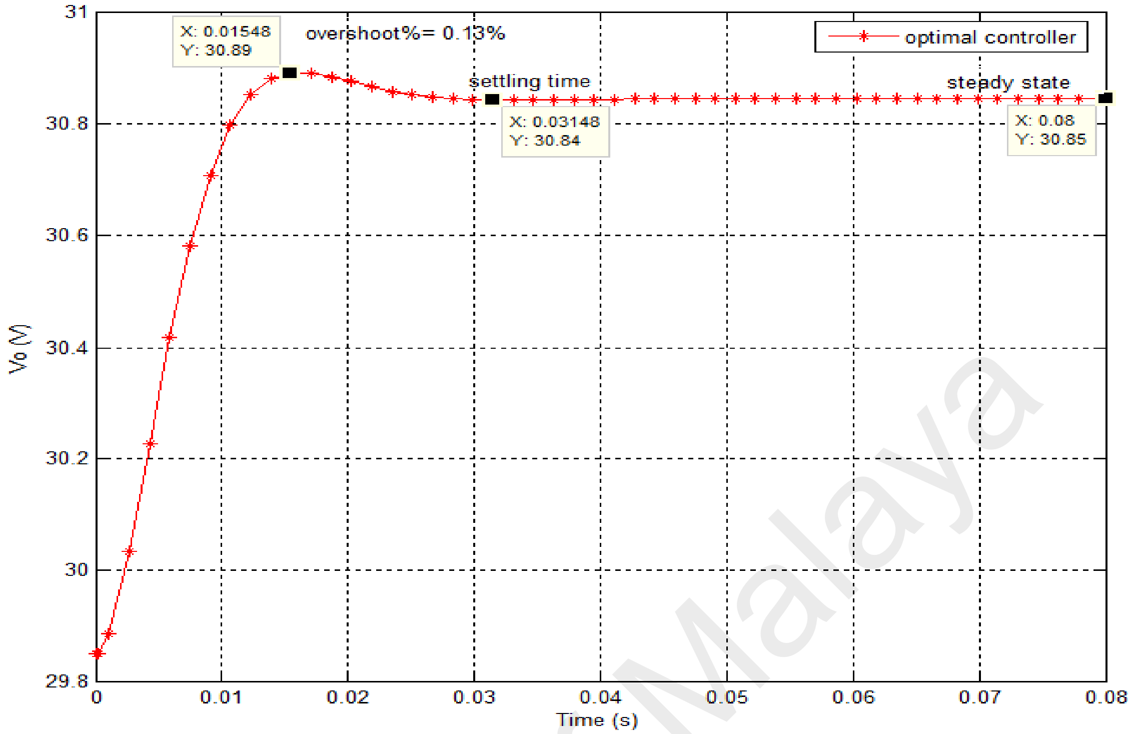


Figure 4.3: Result for optimal control technique.

From the graph above shown steady-state of output voltage, *Vo* is 30.84V while settling time, *Ts* is 0.03148s. Unfortunately, there is overshoot occurred at 0.01548s which is 0.13% and steady-state error is 1V.

4.2.3 State feedback with feed forward controller

Based on block diagram Figure 3.13, show the state feedback with feed forward controller. The *K* value chosen from *poles 350x* for this model, whereby the *N* value calculated in previous subchapter 3.15. The result of this simulation refer to Figure 4.4.

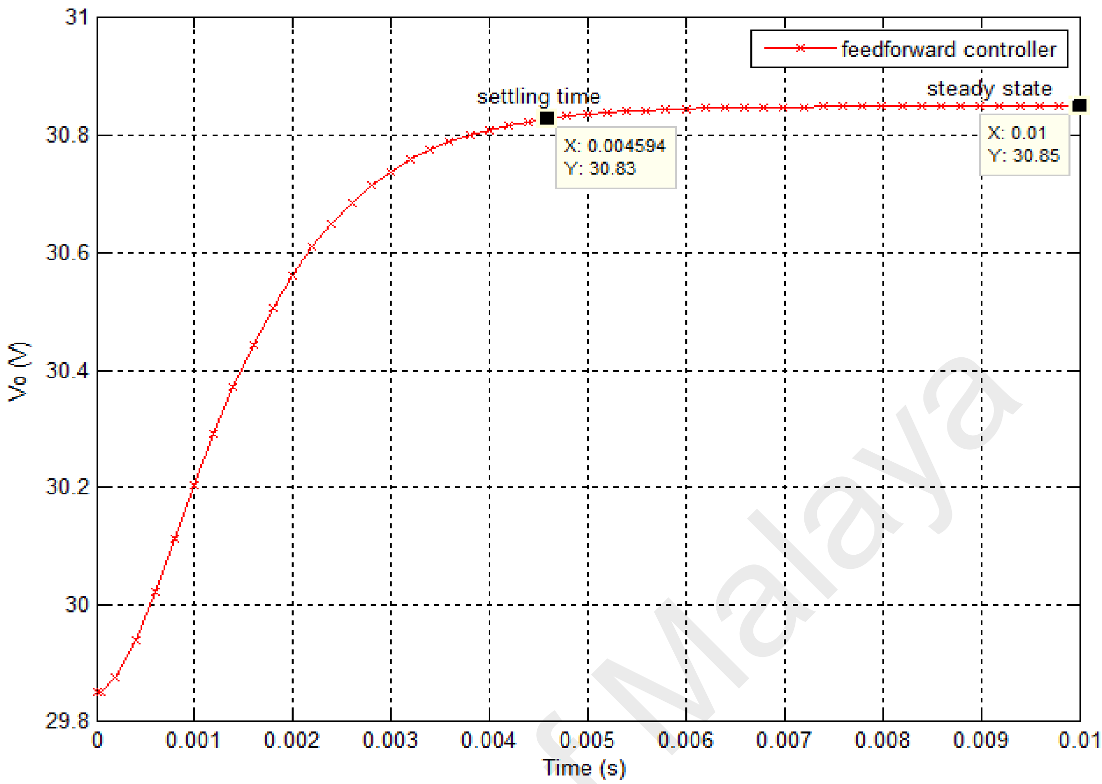


Figure 4.4: State feedback with feed forward controller result

From figure above can be observed that value of steady state output voltage increase to 30.83V from voltage reference 29.85V which additional 0.98V. However the additional 1V from desired output voltage is possible when compare between voltages output reference with 30.85V, whereby the additional gain was inserted at in front of the system and no overshoot observed at output controller. This controller have fastest settling time compared with optimal control technique which *Ts* at 0.004594s and *Ts* for optimal control at 0.03148s.

4.2.4 Integral controller

Based on block diagram Figure 3.14 show the integral controller, the new *K* value and *N* value have been calculated at previous subchapter 3.16. The simulation result of integral controller shown in Figure 4.5.

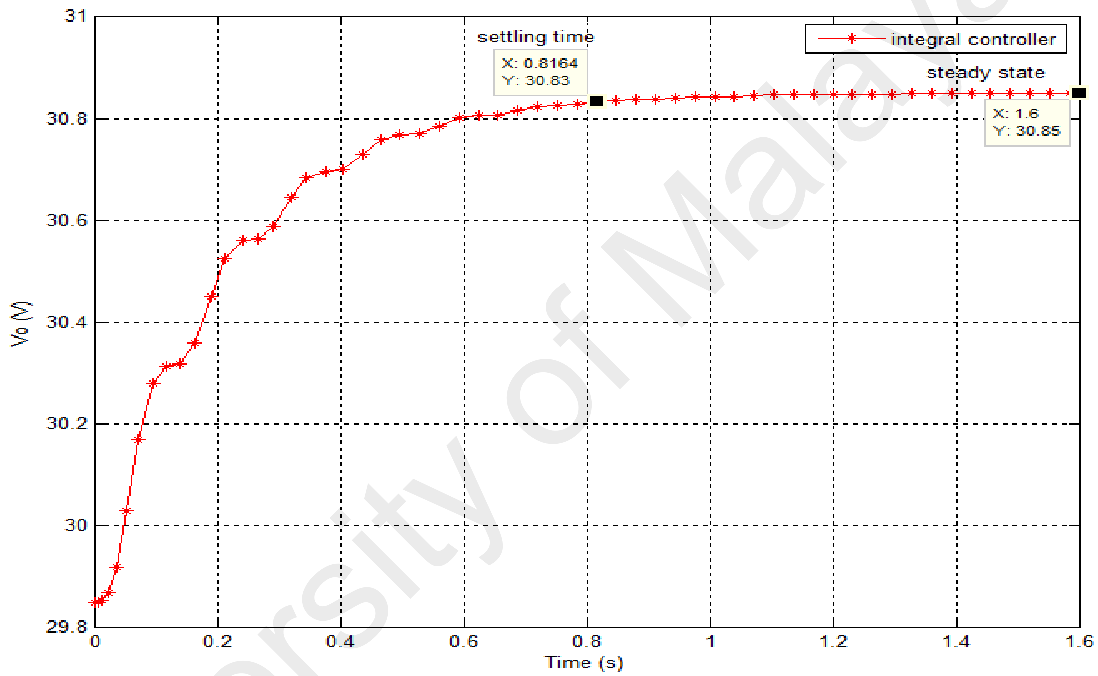


Figure 4.5: Result for integral controller

The integral controller result shows that the steady state of voltage output is 30.83V with settling time at 0.8164s. This slowest settling time compared to others modern controller. This controller also produced additional 1V steady state error with no overshoot occurred. From the graph also be seen that the signal was degraded during rise time.

4.2.5 Comparison between modern controllers

There are consists with four modern controller in this comparison analysis. Based on block diagram Figure 3.15 each controller presented at the same scope. The simulation result shown in Figure 4.6 below.

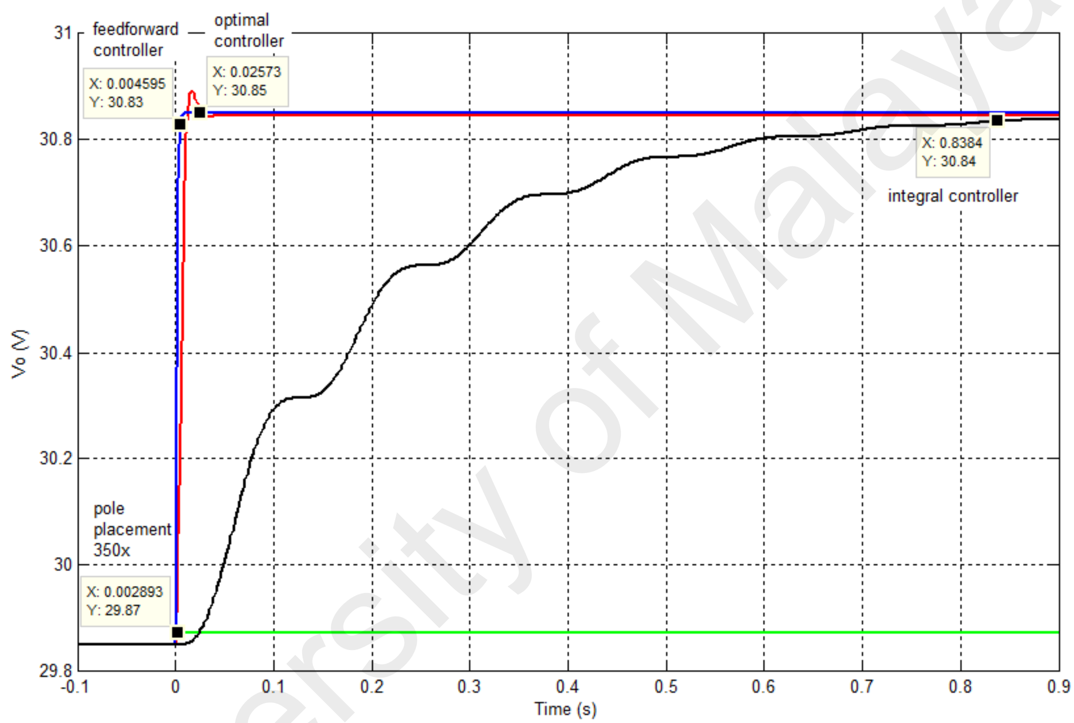


Figure 4.6: The comparison result of modern controller

From Figure 4.6 shows all controller achieved voltage output range between 29.89V until 30.85V. However the settling time, percentage of overshoot and steady error of the systems need to considered separately at next subchapter and referring to Table 4.4 shows the comparison between modern controllers.

4.2.6 Results summary for boost converter modern controller

Modern controller result summary referring from Figure 4.6 are presented at below Table 4.4. From the observation all last controller produced 1V steady state error, state feedback controllers with *poles 350x* produced the fastest settling time 0.002893s compared to others controller with no overshoot but 0.02V steady state error. Followed next controller state feedback with feed forward with settling time 0.004595s and no overshoot. Next controller which integral controller with settling time 0.8384s and no overshoot. Last controller which is optimal controller with settling time 0.02573s and 0.13% overshoot occurred.

Table 4.4: Summary result for modern controller

	State feedback (Pole placement) *Poles 350x*	State feedback (Optimal)	State Feedback with feed forward *Poles 350x*	Integral
Steady state *(V)*	29.87	30.85	30.85	30.85
Settling time, *Ts(sec)*	0.002966	0.03148	0.004594	0.8164
Overshoot *(%)*	0	0.13	0	0
Steady-state error *(V)*	0.02	1	1	1

4.3 Simulation result for boost converter with full state observer

Based on Figure 3.16 the observer analysis, the expected result for output observer system should be the same result with original boost converter system. The values of gain L has been calculated at previous subchapter 3.17 and inserted into block to ensure it is comparable to the system output. The matrix gain *L2* from Table 3.5 are preferred for this analysis. Figure below shows the simulation results from both original boost converter and observer system.

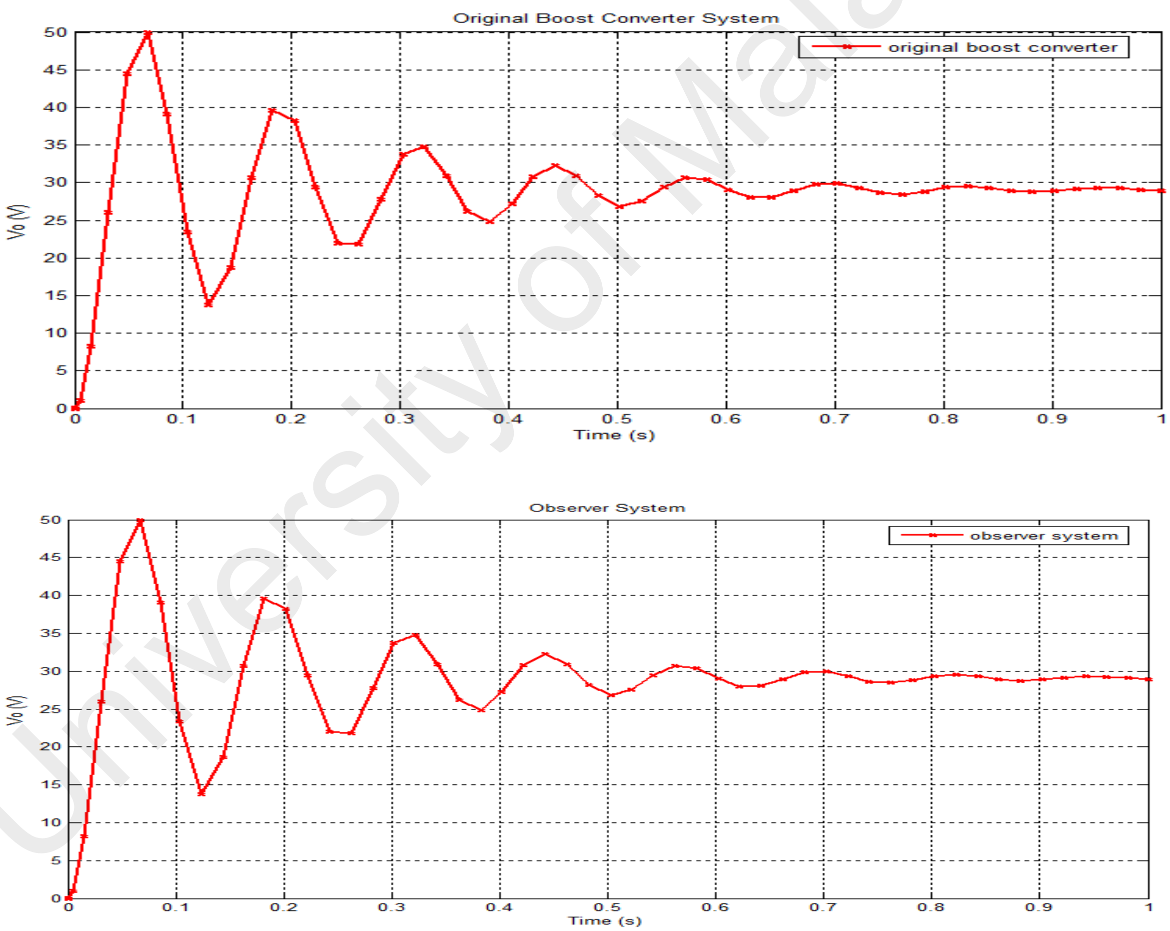


Figure 4.7: Boost converter open-loop response with full state observer

From Figure 4.7 can be conclude that this observer system is compatible to use as replacement for original system.

4.4 Summary

In this chapter referring to first subchapter shows the result of boost converter after through MPPT and the comparison of output voltage between with and without MPPT. The maximum output voltage used as a reference in closed-loop modern controller system. The closed-loop response, the full state feedback controller have been evaluated. State feedback with three poles locations are determined and compared the values of settling time, overshoot and steady state error which recorded in the table and evaluated. The same steps of evaluation are implemented at others modern controller called as optimal, integral and state feedback with feed forward controller. At the second last subchapter all the modern controller result have recorded into table for summarized the analysis. Finally, observer analysis has been perform and the result between observer and original boost converter systems are investigated.

CHAPTER 5
CONCLUSION

5.1 Conclusion

In this research, photovoltaic (PV), maximum power point tracking (MPPT) and boost converter modelling design have been explained in details. Afterwards the state model of boost converter and observer also have been explained and the implementation based on modern controller technique. The modern controller consists with state feedback with pole placement and optimal controller technique, integral controller and state feedback with feed forward controller technique. In this project the voltage supplies to controller provided by boost converter modelling which connected with MPPT and PV modelling. The input voltage through boost converter is 14.55V and the output voltage step up to 29.85V which under desired duty cycle 0.5. All the controllers evaluated using Matlab Simulink software tools. While state space averaging technique is used to find the matrix for simulation purpose inside Simulink block diagram. Principally, all three objectives have been achieved successfully. All the modelling including modern controller and observer were successfully built by using Matlab Simulink software.

From this research can conclude that closed-loop system is suitable to apply in modern controller for implemented in boost converter system. After evaluating all the modern controller results the best controller to be applied in boost converter system can determined, it is recommended to use state feedback and pole placement technique with *poles 350x* since it is produced fastest settling time at 0.002966s, 0% overshoot and smallest steady state error 0.02V on the output voltage. Next section is the recommendation to fulfill the final objective of this research.

5.2 Recommendation for further research

For expansion suggestion for next project in the future, this research can be implement on hardware model which the parameter values as acquired during simulation. For advice before assembling hardware parts, the researcher should perform circuit analysis using Matlab Simulink software or PSIM to evaluate the performance.

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