



Faculty of Engineering

**Design of a Digital Electronic Load Controller (ELC) Unit for Micro-Hydro
Power System**

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**Master of Engineering
2018**

Design of a Digital Electronic Load Controller (ELC) Unit for Micro-Hydro Power System

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A thesis submitted

In fulfilment of requirements for the degree of Master of Engineering

(Electronic Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2018

DECLARATION

The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature:

Name:

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Date:

DEDICATION

Dedicated to my beloved parents, family members, and friends.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude and appreciation to both of my supervisors, Dr Martin Anyi and Dr Lakshmanan A/L Gurusamy for their guidance, support, and patience during my master degree period. I would like to thank technicians Mr. Lawrence Macwell Sinin, Mr. Nasri Eli, and Mr. Abang Mohd Firdaus bin Abang Abdul Hamid for providing me all the assistances and instruments that I need for my experiment in the PCB laboratory. Furthermore, I would like to express my thank to my seniors Mr. Mohd Azlan bin Ismail, Mr. Amaranadha Reddy Manchuri, Ms. Chai Nee Ping, and Ms. Pang Lie Meng for listening to my problem and giving me encouragement and moral support. I also want to extend my thanks to my parents and my sisters for their continuous moral support, financial support, and encouragements to complete my research and thesis. Last but not least, my friends, especially Mr. Xia Young Ying, Ms. Leong Geok Teng and Mr. Liew Jak Cun who help me a lot throughout my master degree.

ABSTRACT

A micro-hydroelectric system, which is used for rural electrification, has a critical problem in that its output voltage is sensitive to load variation. The load variation causes the fluctuation of output voltage, and the electrical appliances could be malfunctioned due to low voltage and damaged due to overvoltage. Hence, an electronic load controller (ELC) is designed to maintain the output voltage at the nominal voltage of appliances by maintaining full load on the electrical generator. The criteria for an ELC used in rural micro-hydroelectric system should be simple and cost-effective in order to ensure the rural communities afford the system and able to support the ongoing maintenance cost. Therefore, this research proposed and presented a design of a simple and yet economical Arduino UNO based ELC system. The hardware implementation of the ELC, which included the calculation of component rating, was clearly demonstrated in this thesis. The control algorithm of the ELC was formulated by adopting the proportional-integral-derivative (PID) control concept. The digital implementation of PID control and the program code setup were also demonstrated in this thesis. The proposed ELC system was tested by using a motor-generator set, which is used to simulate the micro-hydroelectric system in the laboratory. First of all, the steady-state and transient behaviours of induction generator was studied. Then, the tuning effects of the three PID parameters proportional gain, integral gain, and derivative gain on the regulation of output voltage were investigated and analysed. During the PID tuning, it was found that there is no fix value for the time interval, which is included in the PID equations. In this research, tuning effect of the PID time interval was also investigated and studied, and the results showed that the ELC performed better by setting the time interval to its minimum value. By using the optimum values of PID parameters, the performance of the ELC was investigated using load variation test, and the results showed that the output voltage was kept

regulated at 240V despite the load variations. Lastly, a tuning guideline for the PID control in the ELC was developed based on the investigation of the tuning effects of the PID parameters.

Keywords: Electronic load controller, microcontroller, proportional-integral-derivative control, micro-hydroelectric system, rural community.

Reka Bentuk Unit Pengawal Beban Elektronik (ELC) Jenis Digital untuk Sistem Kuasa Mikro-Hidro

ABSTRAK

Sistem mikro hidroelektrik yang digunakan untuk elektrifikasi kawasan luar bandar mempunyai satu masalah kritikal, iaitu voltan keluarannya sensitif terhadap variasi beban. Variasi beban menyebabkan voltan keluaran tidak stabil. Akibatnya, peralatan elektrik berfungsi secara tidak normal akibat kurang voltan dan rosak akibat terlebih voltan. Oleh itu, pengawal beban elektronik (ELC) telah direka untuk mengekalkan voltan keluaran pada voltan nominal peralatan dengan mengekalkan beban penuh pada penjana elektrik. Kriteria untuk ELC yang digunakan dalam sistem mikro hidroelektrik luar bandar haruslah mudah dan kos efektif untuk memastikan masyarakat luar bandar mampu membeli sistem tersebut dan dapat menyokong kos penyelenggaraan yang berterusan. Oleh itu, penyelidikan ini telah mencadangkan dan membentangkan satu reka bentuk sistem yang tidak rumit dan ekonomik, iaitu ELC berasaskan Arduino UNO. Proses pembinaan litar ELC yang meliputi penghitungan nilai komponen jelas ditunjukkan dalam tesis ini. Algoritma kawalan ELC diformulasikan dengan menggunakan konsep kawalan kadaran-kamilan-terbitan (PID). Pelaksanaan kawalan PID secara digital dan persediaan kod program juga ditunjukkan dalam tesis ini. Sistem ELC yang dicadangkan telah diuji dengan menggunakan set motor dan penjana kuasa yang digunakan untuk mensimulasikan sistem mikro-hidroelektrik di makmal. Pertama sekali, tingkah laku penjana induksi mantap dan transien dipelajari. Kemudian, kesan penalaan daripada tiga parameter PID iaitu tambahan kadaran, tambahan kamilan, dan tambahan terbitan terhadap pengawalan voltan keluaran telah diselidiki dan dianalisis. Semasa penalaan PID, didapati tiada nilai yang tetap untuk selang

masa yang termasuk dalam kenyataan matematik PID. Dalam kajian ini, penalaan kesan selang masa PID juga diselidiki dan dikaji, dan hasilnya menunjukkan bahawa ELC berfungsi dengan lebih baik apabila nilai selang masa ditetapkan pada nilai minimum. Dengan menggunakan nilai optimum parameter PID, prestasi ELC diselidiki dengan menggunakan ujian variasi beban, dan hasilnya menunjukkan voltan keluaran tetap dikawal pada 240V walaupun beban berubah-ubah. Akhir sekali, panduan penalaan untuk kawalan PID dalam ELC juga disediakan berdasarkan penyiasatan kesan penalaan parameter PID.

Kata kunci: *Pengawal beban elektronik, mikropengawal, kawalan kadaran-kamilan-terbitan, sistem mikro hidroelektrik, masyarakat luar bandar.*

TABLE OF CONTENTS

	Page
DECLARATION	i
DEDICATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
ABSTRAK	vi
TABLE OF CONTENTS	viii
LIST OF TABLES.....	xiii
LIST OF FIGURES.....	xv
LIST OF ABBREVIATIONS	xviii
LIST OF SYMBOLS	xix
CHAPTER 1: INTRODUCTION	1
1.1 Introduction	1
1.2 Background	1
1.2.1 Electrification in Sarawak	2
1.2.2 Micro-Hydroelectric System	2
1.2.3 Drawback of Micro-Hydroelectric System.....	4
1.2.4 Mechanical Speed Governor	5
1.2.5 Electronic Load Controller (ELC).....	6
1.2.6 Criteria of ELC for Rural Application.....	7
1.2.7 The Need for Locally Designed ELC	8

1.3	Problem Statement	8
1.4	Objectives.....	10
1.5	Scopes	10
1.6	Thesis Outline	11
1.7	Summary	12
 CHAPTER 2: LITERATURE REVIEW		14
2.1	Introduction	14
2.2	Load Effect on Generator.....	14
2.3	Operation of ELC.....	16
2.4	Types of ELC	17
2.4.1	Phase Control.....	17
2.4.2	Binary-Weighted Load Control.....	18
2.4.3	Mark-Space Control	20
2.5	ELCs for Induction Generator (IG).....	21
2.5.1	Conventional Electronic Load Controller (CELC).....	22
2.5.2	Improved Electronic Load Controller (IELC).....	23
2.5.3	Decoupled Electronic Load Controller (DELC).....	25
2.6	Related Studies.....	26
2.6.1	Digitally Controlled ELCs.....	26
2.6.2	Control Algorithms for ELC	31
2.7	Proportional-Integral-Derivative (PID) Control	33
2.7.1	Proportional Mode.....	35
2.7.2	Integral Mode	36

2.7.3	Derivative Mode	36
2.7.4	Combination of Three Modes.....	37
2.8	Digital Implementation of PID Control	37
2.9	Summary	40
 CHAPTER 3: METHODOLOGY		42
3.1	Introduction	42
3.2	ELC Circuit Design.....	42
3.2.1	Identifications of Functions and Hardware	43
3.2.2	Complete ELC Design.....	44
3.3	Hardware Implementation.....	47
3.3.1	Voltage Sensor Module	47
3.3.2	Zero-Crossing Detection Circuit	48
3.3.3	Triac Circuit.....	50
3.3.4	Arduino UNO	52
3.3.5	Dump Load	53
3.4	Formulation of Control Algorithm.....	54
3.4.1	Main Algorithm	56
3.4.2	Interrupt Algorithm	59
3.5	Code Setup	59
3.5.1	Declaration of Variables.....	61
3.5.2	Setup() Function	64
3.5.3	Loop() Function.....	66
3.5.4	Trigger_Signal() Function	68

3.6	Software	69
3.6.1	Arduino Integrated Design Environment (IDE)	69
3.6.2	Proteus Virtual System Modelling (VSM)	70
3.6.3	National Instruments (NI) LabVIEW SignalExpress	71
3.7	Laboratory Setup	72
3.8	Laboratory Tests.....	75
3.8.1	Steady-State Analysis of IG	75
3.8.2	Transient Analysis of IG	76
3.8.3	PID Tuning	79
3.8.4	Load Variation Test	80
3.9	Summary	81
 CHAPTER 4: RESULTS AND DISCUSSION.....		83
4.1	Introduction	83
4.2	Steady-State Analysis of IG	83
4.3	Transient Analysis of IG	89
4.4	PID Tuning.....	91
4.4.1	Tuning of Proportional Gain.....	92
4.4.2	Tuning of Integral Gain	96
4.4.3	Tuning of Derivative Gain.....	99
4.4.4	Tuning of Time Interval	103
4.4.5	Summary of PID Tuning	106
4.5	Load Variation Test.....	108
4.6	PID Tuning with Less Overshoot.....	110

4.7	Summary	114
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS.....		117
5.1	Introduction	117
5.2	Conclusion	117
5.3	Contributions.....	119
5.4	Recommendations	120
5.4.1	Liquid Crystal Display (LCD) for Tuning.....	120
5.4.2	Directive PID Control.....	121
5.5	Summary	122
REFERENCES		123
APPENDICES.....		130

LIST OF TABLES

	Page
Table 2.1 Devices for digital control of ELC.....	29
Table 2.2 Reported algorithms and their control variables.	31
Table 2.3 The values of time interval that have been reported in literature.	33
Table 2.4 Tuning effect of K_p , K_i , and K_d	37
Table 3.1 Functions of used pins.	52
Table 3.2 List of program source code.	60
Table 3.3 Data and initial values of variables.	62
Table 3.4 Definitions of data types.	63
Table 3.5 Values and settings for PID tuning.	79
Table 4.1 Steady-state behaviour of IG with increasing consumer load.	84
Table 4.2 Steady-state behaviour of IG with decreasing consumer load.	86
Table 4.3 Steady-state behaviour of IG under increasing P_{CL} (smaller values).....	88
Table 4.4 Settling time of V_{out} of IG at the application and removal of load.....	91
Table 4.5 Transient responses of V_{out} for K_p values from 1 to 5 in step of 1.	94
Table 4.6 Transient responses of V_{out} for $K_p = 1.9, 2$, and 2.1	95
Table 4.7 Transient responses of V_{out} for K_i values from 1 to 5 in step of 1.....	98
Table 4.8 Transient responses of V_{out} for $K_i = 2.9, 3$, and 3.1	99
Table 4.9 Transient responses of V_{out} for K_d values from 10 to 50 in step 10.	101
Table 4.10 Transient responses of V_{out} for $K_d = 9, 10$, and 11	103
Table 4.11 Average values of V_{out} responses for $T_{interval} = 5\text{ms}, 30\text{ms}$, and 60ms	105
Table 4.12 Optimum values of PID parameters under different values of $T_{interval}$	106

Table 4.13	Tuning effects of K_p , K_i , K_d , and $T_{interval}$ on V_{out}	108
Table 4.14	Transient responses of V_{out} at application and removal of 240W load.	110

LIST OF FIGURES

		Page
Figure 1.1	Block diagram of micro-hydroelectric system basic setting.....	3
Figure 1.2	Load effect on generator V_{out} and f_{out}	4
Figure 1.3	Block diagram of micro-hydroelectric system connected with speed governor.	5
Figure 1.4	Block diagram of micro-hydroelectric system connected with ELC.....	6
Figure 2.1	Simple setup of a generator with armature reaction.	15
Figure 2.2	Block diagram of ELC system.....	16
Figure 2.3	Schematic diagram of phase control circuit.....	17
Figure 2.4	Phase control waveforms.	18
Figure 2.5	Schematic diagram of binary-weighted load control circuit.....	19
Figure 2.6	Dump Load variation.	19
Figure 2.7	Schematic diagram of mark-space control circuit.	20
Figure 2.8	Mark-space control waveforms.....	21
Figure 2.9	Schematic diagram of CELC.	23
Figure 2.10	Schematic diagram of IELC.....	24
Figure 2.11	Schematic diagram of DELC.	25
Figure 2.12	PIC18F252 microcontroller.	27
Figure 2.13	DS1104 R&D Controller Board.....	28
Figure 2.14	Panasonic PLC 14P.....	28
Figure 2.15	(a) Arduino UNO and (b) Outline of Arduino UNO.	30
Figure 2.16	Block diagram of PID control.....	34

Figure 2.17	Waveform characteristics of system output controlled by PID control.....	35
Figure 2.18	Integration of error.	38
Figure 2.19	Differentiation of error.	40
Figure 3.1	Block diagram of ELC in micro-hydroelectric system.	45
Figure 3.2	Schematic diagram of designed ELC.	46
Figure 3.3	Voltage sensor (TEC-AU1C5).	47
Figure 3.4	Zero-crossing events of AC voltage.	48
Figure 3.5	Schematic diagram of zero-crossing detection circuit.	48
Figure 3.6	Zero-crossing detection circuit board.	49
Figure 3.7	Schematic diagram of triac circuit.	50
Figure 3.8	Triac circuit board.	51
Figure 3.9	Used Arduino pins.	52
Figure 3.10	Schematic diagram of dump load.	53
Figure 3.11	Implementation of dump load.	54
Figure 3.12	Flow chart of ELC control algorithm.	55
Figure 3.13	Division of T_{delay} range into a number of sample.	57
Figure 3.14	Arduino IDE.	69
Figure 3.15	Proteus VSM.	70
Figure 3.16	LabVIEW SignalExpress Tektronix Edition.	71
Figure 3.17	Laboratory setup.	72
Figure 3.18	Block diagram of laboratory setup.	73
Figure 3.19	Screenshot from oscilloscope.	77
Figure 3.20	Import of signals from a file to LabVIEW SignalExpress.	77
Figure 3.21	Noise filtering.	78

Figure 3.22	Measurement of $t_{settling}$	78
Figure 3.23	AC 0-5A to DC 4-20mA current sensor (TEC-AI1B1).....	80
Figure 3.24	DC 4-20mA to 0-5VDC current-to-voltage converter (ASC201-V1.0).	81
Figure 4.1	Graph of V_{out} and I_{out} versus P_{CL} (increasing consumer load).	84
Figure 4.2	Graph of v and f_{out} versus P_{CL} (increasing consumer load).....	85
Figure 4.3	Graph of V_{out} and I_{out} versus P_{CL} (decreasing consumer load).....	87
Figure 4.4	Graph of v and f_{out} versus P_{CL} (decreasing consumer load).	87
Figure 4.5	Graph of V_{out} and I_{out} versus P_{CL} (actual) (increasing consumer load).	89
Figure 4.6	Transient waveforms of V_{out} of IG at the application of loads.....	90
Figure 4.7	Transient waveforms of V_{out} of IG at the removal of loads.	90
Figure 4.8	Transient waveforms of V_{out} for K_p values from 1 to 5 in step of 1.....	93
Figure 4.9	Transient waveforms of V_{out} for $K_p = 1.9, 2$, and 2.1	95
Figure 4.10	Transient waveforms of V_{out} for K_i values from 1 to 5 in step of 1.	97
Figure 4.11	Transient waveforms of V_{out} for $K_i = 2.9, 3$, and 3.1	99
Figure 4.12	Transient waveforms of V_{out} for K_d values from 10 to 50 in step of 10.....	100
Figure 4.13	Transient waveforms of V_{out} for $K_d = 9, 10$, and 11	102
Figure 4.14	Transient waveforms of V_{out} for $T_{interval} = 5\text{ms}, 30\text{ms}$, and 60ms	104
Figure 4.15	Transient waveforms of V_{out} for the three tuned gains.....	107
Figure 4.16	Transient waveforms of V_{out} and $I_{consumer}$ at application and removal of 240W load.....	109
Figure 4.17	Transient waveforms of V_{out} for extended investigation – Part 1.	111
Figure 4.18	Transient waveforms of V_{out} for extended investigation – Part 2.	113
Figure 5.1	LCD module for Arduino UNO.....	121

LIST OF ABBREVIATIONS

AC	Alternating Current
CC-VSI	Current-Controlled Voltage Source Inverter
CELC	Conventional Electronic Load Controller
DC	Direct Current
DELC	Decoupled Electronic Load Controller
DSP	Digital Signal Processor
ELC	Electronic Load Controller
EMF	Electromotive Force
ICSP	In-Circuit Serial Programming
IELC	Improved Electronic Load Controller
IG	Induction Generator
IGBT	Insulated Bipolar Gate Transistor
ISR	Interrupt Service Routine
MP	Micro-Hydroelectric Plant
PCC	Point Of Common Coupling
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Control
PWM	Pulse Width Modulation
SG	Synchronous Generator
STATCOM	Static Compensator
USB	Universal Serial Bus

LIST OF SYMBOLS

$D_{control_out}$	Output of Derivative Control
D_{error}	Derivative of Error
$e(t)$	Error (Real Time)
$error_{current}$	Current Error
$error_{derivative}$	Differentiation of Error
$error_{previous}$	Previous Error
$error_{sum}$	Summation of Error
E_{rr}	Error (Discrete Time)
E_{rr_sum}	Summation of Error
f_{out}	Output Frequency
$f_{nominal}$	Nominal Frequency
$I_{control_out}$	Output of Integral Control
$input_{current}$	Current Input
$input_{previous}$	Previous Input
I_{out}	Output Current
I_{out_max}	Maximum Current
K_d	Derivative Gain
K_i	Integral Gain
K_p	Proportional Gain
N_{sample}	Number of Sample
N_{total}	Total Sample
P	Power

$P_{consumer_load}$	Power of Consumer Load
$P_{control_out}$	Output of Proportional Control
P_{out_max}	Maximum Output Power
$PID_{control_out}$	Total Output of PID Control
$r(t)$	Set Value
R	Resistance
$t_{settling}$	Settling Time
$T_{current}$	Current Time
T_{delay}	Time Delay
$T_{elapsed}$	Elapsed Time
$T_{interval}$	Time Interval
$T_{previous}$	Previous Time
T_{sample}	Sample Time
$u(t)$	Control Variable
v	Rotational Speed
V_{LED}	LED Voltage
$V_{nominal}$	Nominal Voltage
V_{out}	Output Voltage
V_{out_max}	Maximum Output Voltage
$y(t)$	Feedback Value

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides an overview of this research. At first, it gives background information that helps to understand the application and importance of an electronic load controller (ELC) in a micro-hydroelectric system. The background information also explains the need for further research in ELC. Then, the problem statements are outlined with clear objectives. The scope of this research and the contents of onward chapters are also outlined at the end of this chapter.

1.2 Background

In this section, the electrification rate in Sarawak is firstly described for understanding the importance of a micro-hydroelectric system to rural electrification in Sarawak. The micro-hydroelectric system is then introduced generally. Its drawback and mechanical speed governor, which explain the need of an ELC, are also discussed. After that, a general introduction on the ELC is provided to describe its principle and functionality. Lastly, both the criteria of ELC for rural application and the need for locally designed ELC are described to explain the motivation of this research.

1.2.1 Electrification in Sarawak

Although the electrification of Sarawak has reached 94% in 2015, the remaining 6% of Sarawak areas are still without electricity coverage (“The Report: Malaysia 2016,” 2016). Those areas are usually situated in the remote rural heartlands of Sarawak, which have extremely rugged and challenging terrains. Moreover, the size of a rural community is usually small. Hence, the extension of electricity grids to those areas is challenging and uneconomical.

As a temporary solution for the convenience of everyday living, the rural communities in Sarawak employ diesel-powered generators for electricity supplies (Anyi, Kirke & Ali, 2010). The diesel generators solve the non-electricity problem; even so, they generate a lot of noise and pollution and require expensive diesel for operation that only can last for just a few hours.

After all, both grid extension and diesel generators would not provide a good solution for the problem. Hence, a different approach of generating electricity should be explored.

1.2.2 Micro-Hydroelectric System

Stand-alone and off-grid renewable energy technologies have become the preferred alternative solutions for rural electrifications. There are different types of renewable energy technologies, such as solar panel, wind turbine, hydroelectric plant, wave energy generator, and so on. However, with the high potential of micro-hydropower found in Sarawak, a micro-hydroelectric system can be considered as the most appropriate option for Sarawak

rural electrification. As reported in Borhanazad et al. (2013), the potential of micro-hydropower is estimated approximately to be 6717kW in Sarawak.

A micro-hydroelectric system has many advantages like renewable, clean, and reliable. Moreover, unlike a big-scale hydroelectric system, it does not need a costly, large dam that causes deforestation, submergence, and rehabilitation to the environment. Basically, a micro-hydroelectric plant consists of a forebay tank, a penstock, a turbine-generator set, a switchgear electrical box and a transmission line, as illustrated in Figure 1.1. The types of generator that can be used are synchronous generator (SG) or induction generator (IG).

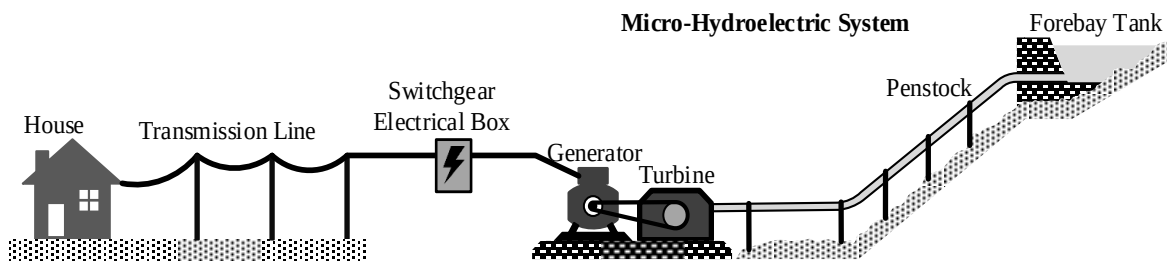


Figure 1.1: Block diagram of micro-hydroelectric system basic setting.

The operation of the micro-hydroelectric plant can be understood by referring to Figure 1.1 from right to left. At first, water is stored inside forebay tank. Through the penstock, the water is channelled to the turbine to rotate it. During the rotation, the turbine converts the water potential energy into mechanical energy. Simultaneously, the generator converts this mechanical energy into electrical energy to power the household appliances (referred as consumer loads). The electrical energy is transferred to the houses through the switchgear electrical box and the transmission line. With the fuses and circuit breakers inside, the switchgear box is actually used to protect and isolate the consumer loads.

1.2.3 Drawback of Micro-Hydroelectric System

The micro-hydroelectric systems solve the electricity problems in rural areas. However, the drawbacks like the fluctuation of the generator output voltage (V_{out}) and output frequency (f_{out}) due to load variations preventing their effective usage. This is due to the load effect on generator, which is further explained in Section 2.2.

As illustrated in Figure 1.2, a generator produces a nominal voltage ($V_{nominal}$, e.g. 240VAC) and a nominal frequency ($f_{nominal}$, e.g. 50Hz) when it spins at rated speed (e.g. 1500rpm) under no load condition (0% load). However, due to the load effect, the speed and hence the V_{out} and f_{out} drop below their standard values as the load increases from zero to full load (100% load). As a solution, the speed is first increased above its rated value to obtain the $V_{nominal}$ and $f_{nominal}$ at full load. This, on the other hand, causes the V_{out} and f_{out} to increase when the load is less than 100%. Moreover, the load consumption by consumer is not constant throughout the day. As a result, the V_{out} and f_{out} fluctuate during load variation, and there is a possibility for them to be out of their nominal ranges and damage the load.

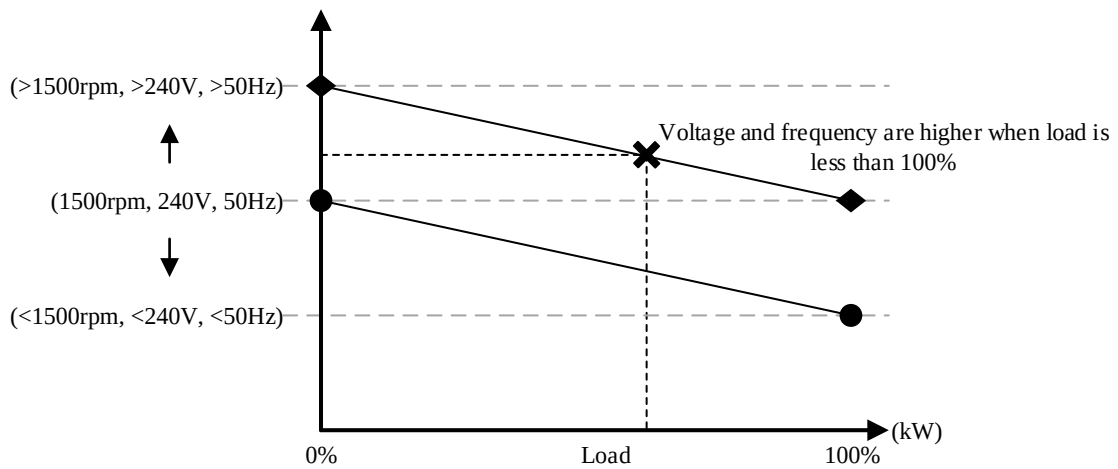


Figure 1.2: Load effect on generator V_{out} and f_{out} .

1.2.4 Mechanical Speed Governor

A mechanical speed governor is conventionally utilized to cope the fluctuation of V_{out} and f_{out} in a micro-hydroelectric system. It regulates the V_{out} and f_{out} by controlling the water flow through the turbine with a mechanical hydraulic valve (Harvey, Brown, Hettiarachi, & Inversin, 1993; Meier, 2001; Simões & Farret, 2014).

The speed governor provides the regulation at the input of turbine, as shown in Figure 1.3. It is installed at the penstock and near to the input of turbine. By detecting a rise in rotational speed (v) due to a decrease in consumer load, the water flow through the turbine is decreased by closing the valve. So that, the v is decreased, and hence the V_{out} and f_{out} are decreased. Oppositely, when the consumer load is increased and the v is decreased, the valve is opened to increase v so both the V_{out} and f_{out} are increased.

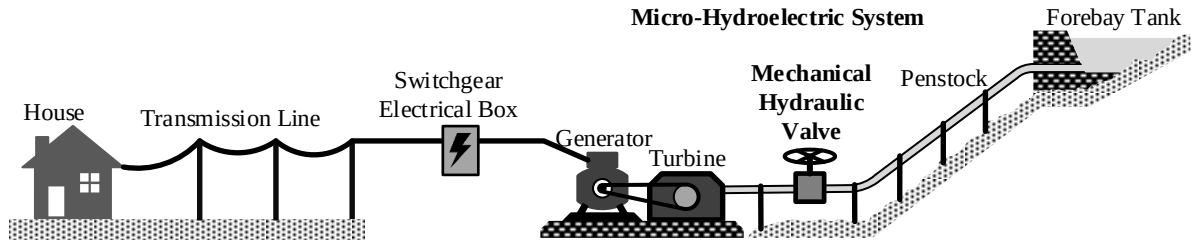


Figure 1.3: Block diagram of micro-hydroelectric system connected with speed governor.

However, a speed governor is complex and expensive as it involves numerous mechanical parts. Moreover, because of its large mechanical time constant, it is unable to react fast enough to the changes in V_{out} and f_{out} (Chilipi, Singh, Murthy, Madishetti, & Bhuvaneswari, 2014; Timorabadi, 2006; Yousef, Wahba, Yousef, & Sebakhy, 2010). Therefore, it also has low performance in the regulation of V_{out} and f_{out} .

1.2.5 Electronic Load Controller (ELC)

An electronic load controller (ELC) is an alternative for the speed governor. Unlike the speed governor, it regulates the V_{out} and f_{out} of a generator by maintaining the full load on the generator, known as load control method (Bokalders, 1991).

Again, unlike the speed governor, the control over the V_{out} and f_{out} is provided by the ELC at the output of generator, as show in Figure 1.4. By detecting V_{out} (or f_{out}), whenever the V_{out} is increased by a decrease in consumer load, the ELC increases the load on the generator by absorbing the excess power using an external load. Conversely, the power is released back to the consumer load when the V_{out} is dropped by an increase in consumer load. Further details of the operation of ELC are given in Section 2.3.

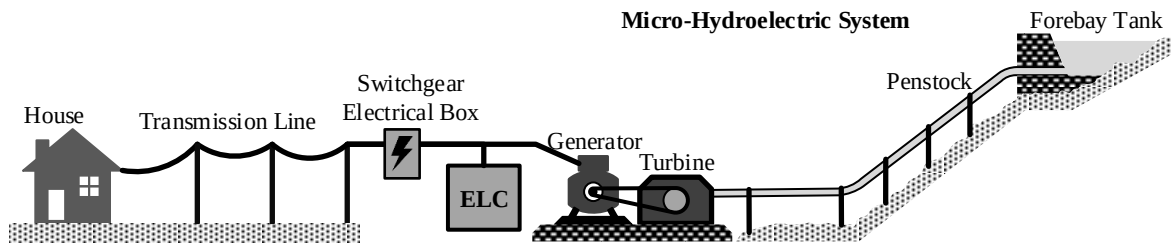


Figure 1.4: Block diagram of micro-hydroelectric system connected with ELC.

The replacement of the speed governor with the ELC simplifies the mechanical part of micro-hydroelectric system and reduces the installation and maintenance costs of the system. Besides that, the small electronic components in the ELC are more cost effective than the big and steel made mechanical parts. Electronic control also reacts faster than mechanical control. Therefore, the ELC is more simpler in control, faster in response, and

cheaper in cost as compared to the mechanical speed governor (Singh, Chelliah, & Agarwal, 2014).

1.2.6 Criteria of ELC for Rural Application

For rural application, the criteria for an ELC should be simple and cost-effective. As stated by Murthy et al. (1998), an ELC has moderate power quality with minimum possible circuit complications and minimum cost is the optimum solution for rural micro-hydroelectric system. This is to ensure that the rural communities afford for the system and able to support the ongoing maintenance cost.

The design or implementation of a control unit play an important role in reducing the design complication and development cost of an ELC. There are many types of modern control units available for designing the ELC. Some control units give flexibility in term of design but require further development of supporting circuit. Meanwhile, some control units are ready-made but come with limited features and expensive prices.

A simple control algorithm also contributes to the simplicity of ELC design. This is because a complex control algorithm requires more complex and costly circuitry as it involves more control parameters, even though it perform better. Furthermore, the tuning process becomes a more difficult task when more parameters are involved in the algorithm.

Therefore, researches will be needed to explore a simple and economic control unit and formulate a simple control algorithm for the ELC.

1.2.7 The Need for Locally Designed ELC

There is a significant need for a locally designed and manufactured ELC. This is because it may be easier to buy an imported ELC but may be not suitable for Malaysia context. Imported ELCs come with high cost due to currency exchange rate, and they are poorly supported after sale service. When breakdown occurs, the importation of service and parts takes too much time and money. This, in turn, causes unreasonable downtimes and black outs. Furthermore, a huge price will be required to pay the foreign experts to fly in and repair the faulty systems. Therefore, it is very important to have a locally available ELC.

1.3 Problem Statement

There are four problems are to be addressed and solved in this research. First of all, a micro-hydroelectric system has a critical problem in that its output voltage (V_{out}) is sensitive to load variation. Based on the description in Section 1.2.3, the V_{out} is dropped under or rose over the nominal voltage ($V_{nominal}$) of appliances if the load on generator is increased or decreased. The consumer loads may just malfunction or stop operate if the voltage is too low. However, overvoltage tends to cause the consumer loads to draw too much current and fail prematurely due to overheating.

Secondly, the digital control units of ELCs reported in literatures are considered to be not cost-effective and not user-friendly. As reported in Murthy et al. (2006), a microcontroller is used to realise the digital control in ELC. It is relatively inexpensive, and it provides flexibility in term of design. However, its use requires development of its supporting circuitries and programming tools, and hence, its use increases the design complication and cost of ELC. A digital signal processor (DSP) and a programmable logic

control (PLC) also have been proposed in Rajagopal & Singh (2010) and Kabalan et al. (2015) respectively for realising the digital control in ELC. Both DSP and PLC are ready-made systems. However, they are relatively expensive as compared to microcontroller, and they have fixed features for their implementation in designing an ELC.

Thirdly, the implementation of an advance control algorithm increases the complexities of circuitry and tuning process of an ELC. Complex control algorithms are implemented to provide more effective voltage and frequency regulation. Even though they perform better, their calculations involve too many parameters, which mean more sensing devices are required to provide input signals for the algorithms. For example, the implementations of $Icos\Phi$ (Rajagopal & Singh, 2010) and neural-network (Singh & Rajagopal, 2011) algorithms require eight input signals and eight sensors. Their circuitries also become complex in order to put all the devices together. Furthermore, the tuning process of algorithm becomes more difficult when the more parameters are involved.

Finally, limited study and experiment are conducted on the digital implementation of proportional-integral-derivative (PID) control in ELC. PID control has the considerable advantage in term of simplicity as it only involves three parameters: proportional gain (K_p), integral gain (K_i), and derivative gain (K_d). As reported in Yadav & Appan (2015), PID control performs better than the proportional-integral (PI) control that has been used to develop analogue or digital ELC. However, there is no specific documentation on how to implement PID control digitally as the control strategy of a digitally controlled ELC system. Plus, no clear information on the tuning effect of the PID parameters on the voltage regulation, and hence no specific instruction is provided on how to set the value for PID parameters in the ELC. Furthermore, it was discovered that there is no fix value for the time

interval, which is included in the PID equations. Again, no information is documented on the tuning effect of the time interval ($T_{interval}$) on the performance of the controlled system.

1.4 Objectives

Based on the problem statement, there are three identified objectives for this research. They are listed in brief as below:

- i. To design a cost effective digital ELC system using Arduino platform to regulate the V_{out} of a micro-hydroelectric system at 240V.
- ii. To formulate a simple control algorithm for ELC by using a digital implementation of PID control.
- iii. To investigate the tuning effect of K_p , K_i , K_d , and $T_{interval}$ of PID control on voltage regulation.

1.5 Scopes

There are three main focuses in this research. The first focus is on the hardware development of a digitally controlled ELC. In order to achieve the first objective with a simple and economic digital ELC, an Arduino platform is used in designing the system. This is achieved by implementing a low cost and user-friendly Arduino UNO microcontroller board as the control unit of the ELC. This also demonstrates the implementation of modern technology in the ELC system. Besides the control unit, the design of the power control circuit also contributes to the complexity and cost of the ELC. Therefore, a phase control method, which requires simple circuitry, is adopted in designing the power control circuit.

Secondly, the focus is on the formulation of a control algorithm for the ELC system. An advance and complex algorithm requires complex circuitry and difficult tuning process although it performs better as mentioned in Section 1.3. Hence, it is important to develop a simple control algorithm, and this is achieved by adopting the concept of PID control method. The PID control could be implemented easily without complex mathematical modelling and tuned manually without mathematical calculation. In this research the PID control is implemented digitally using the Arduino platform. Based on the algorithm, a program is written using the Arduino programming language, and it is loaded into the Arduino board.

Lastly, this research focuses on the analyses of the generator, the PID parameters, and the ELC. An induction generator (IG) is used in the experimental setup. A steady-state analysis of the IG is therefore conducted to understand how the steady-state values of rotational speed, output voltage, output current, and output frequency of the IG change during the increasing and decreasing of consumer loads. A transient analysis of the IG is also conducted to understand the transient response of the IG output voltage at the application and removal of consumer loads. Meanwhile, PID tuning is used to obtain the optimal values and the tuning effects of the PID gains. Lastly, the developed ELC is tested with load variations to assess its performance.

1.6 Thesis Outline

Chapter 2 discusses the theoretical aspects that lead to the implementation of ELC by explaining the load effect on generator. Then, the contents of this chapter is followed by the brief introduction of ELC and its different types and related researches, which helps to

justify the research gap for this research. The concept of PID control also explained in this chapter.

Chapter 3 shows the implementation of phase control method in designing the ELC circuit. The implementation of PID control method in the formulation ELC control algorithm also showed in this chapter. Furthermore, the hardware and software, which were used to develop the circuit and the program, are also explained in detail. This chapter also includes the explanations on the setups of program code and laboratory tests.

Chapter 4 presents the results obtained from the steady-state and transient analyses of IG, PID tuning, and voltage regulation. Based on the results, the steady-state and transient behaviour of IG towards the load change is determined. Additionally, the tuning effects of the four PID parameters, which includes the time interval, on the voltage regulation are analysed. The performance of the designed ELC circuit and program on the voltage regulation is also justified in this chapter.

Based on the results, conclusions are drawn for this research as given in Chapter 5. Discussions are also provided for the contribution of this research. Furthermore, based on the findings from the tests, two recommendations are provided to further improve the ELC.

1.7 Summary

This research is about solving the problem of voltage fluctuation in the micro-hydroelectric system by designing a digital ELC. At the same time, an attempt is made to reduce the cost of the ELC by implementing the system into the Arduino platform. A control algorithm based on PID control method is also formulated for the ELC. Furthermore, the

tuning effects of the PID gains (proportional gain, integral gain, and derivative gain) are investigated and analysed. The tuning effect of the PID time interval is also investigated since its setting process is no well documented in literature.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter begins with a brief introduction of load effect on generator, which helps to understand the fluctuation of output voltage (V_{out}) and output frequency (f_{out}) caused by the load variation. Then, the operation of the ELC is described to explain how it maintains V_{out} and f_{out} in detail. ELCs can be classified according to their power control methods, and the three common types are explained. One of the methods is adopted in designing the proposed ELC. Besides that, the types of ELCs improved for induction generator are described. The related studies such as digitally controlled ELCs and control algorithm for ELC are also discussed to justify the research gap for this research. Lastly, PID control, which is implemented as the control algorithm of ELC, is introduced in this chapter.

2.2 Load Effect on Generator

As mentioned in Section 1.2.3, the load effect causes the fluctuation of V_{out} and (f_{out}) of a generator during load variation. In detail, this effect is actually caused by a phenomenon called the armature reaction that happens in the generator (Meier, 2006). This phenomenon can be explained by using a simple setup of a generator illustrating the armature reaction, as shown in Figure 2.1. In the setup, the wire and the magnet represents the respective armature winding and field winding of an actual generator.

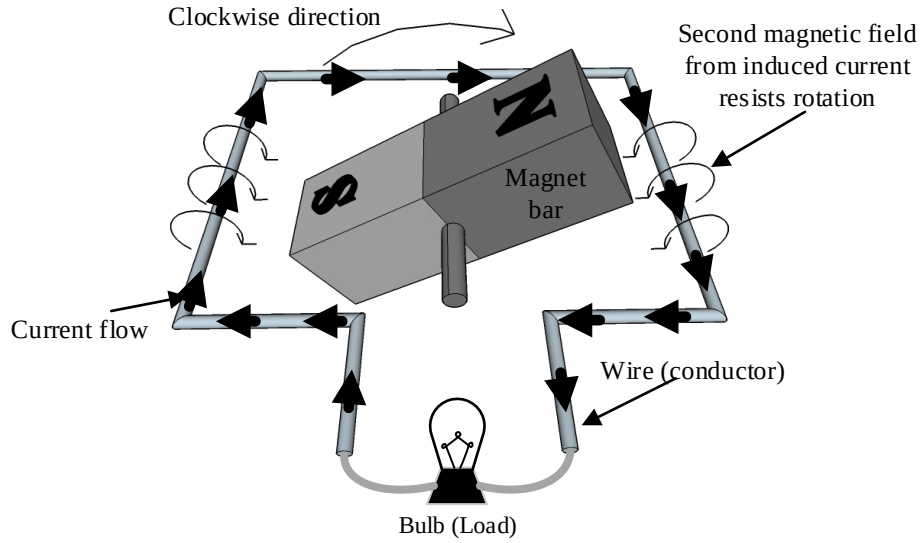


Figure 2.1: Simple setup of a generator with armature reaction (Meier, 2006).

What actually happens is, when the magnet bar spins relative to the wire, the main magnetic field from the magnet bar cuts the wire. As a result, an electromotive force (EMF) and hence current are induced in the wire. With a connected load, the current flows within the loop of wire. Then, a second magnetic field is immediately brought into existence in the space surrounding the wire by the flow of current. When same poles of two magnets are near each other, they will repel each other. Similarly, the main and second magnetic fields repel each other when they are interacting with each other. As an effect of the repulsion, the generator is slowed down, and hence the V_{out} and f_{out} are reduced (Meier, 2006).

It is important to emphasize that the repulsion effect is proportional to the amount of current drawn by the load or the output current (I_{out}) generated by the generator (Meier, 2006). Therefore, the V_{out} and f_{out} are further decreased if the load is further increased. Contrary, they are increased if the load is decreased. Furthermore, they are constant if the load is constant. These explain why the V_{out} and f_{out} fluctuate during load variation and why an ELC system is designed to maintain the load on generator.

2.3 Operation of ELC

An ELC system basically has a control unit, a power control circuit, a sensor, and an external load as shown in Figure 2.2. Based on the concept of feedback control, the change in consumer load is first measured. Practically, the change in consumer load is measured indirectly from the corresponding change in V_{out} (or f_{out}) by using a voltage (or frequency) sensor. Then, the measured V_{out} is fed into the control unit and compared with the nominal voltage ($V_{nominal}$) of electrical appliances. Immediately, the deviation of the measured V_{out} from the $V_{nominal}$ is estimated. According to the voltage deviation, an amount of power is absorbed by or released from the external load.

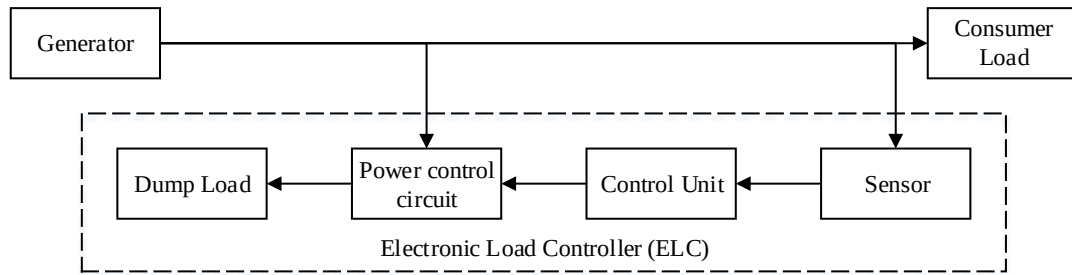


Figure 2.2: Block diagram of ELC system.

If a consumer load is switched off and the measured V_{out} is higher than the $V_{nominal}$, the excess power from the disconnected consume load is absorbed by the external load. Meanwhile, if a consumer load is switched on and the measured V_{out} is lower than the $V_{nominal}$, the absorbed power is released from the external load back to the consumer load. The amount of power to the external load is controlled by the power control circuit according to the voltage deviation. The external load is commonly called the dump load as it is where the extra power is “dumped”.

2.4 Types of ELC

ELCs can be categorized according to the types of power control method that adopted to control the amount of power to be transferred into the dump load. Phase control, binary-weighted load control, and mark-space control are the three most commonly used control methods (Smith, 1994; Smith, 1996). They are explained singularly hereafter.

2.4.1 Phase Control

Figure 2.3 shows a phase control circuit simply formed using a triac and a dump load, and they connect in series with the generator. The power delivered to the dump load is varied by adjusting the time delay (T_{delay}), which represents the delayed phase angle, applied before the triac is triggered for conduction in every half-cycle. As illustrated in Figure 2.4, T_{delay} is applied after a zero-crossing. During T_{delay} , the triac remains off, and hence no conduction for the input AC voltage. Once T_{delay} has elapsed, a voltage pulse is applied to trigger and turn on the triac. The triac then conducts for the remainder of the half-cycle. As a result, part of voltage is ‘chopped’ by the triac, and only a portion of input power is allowed to pass through the triac. Hence, the power to the dump load is varied.

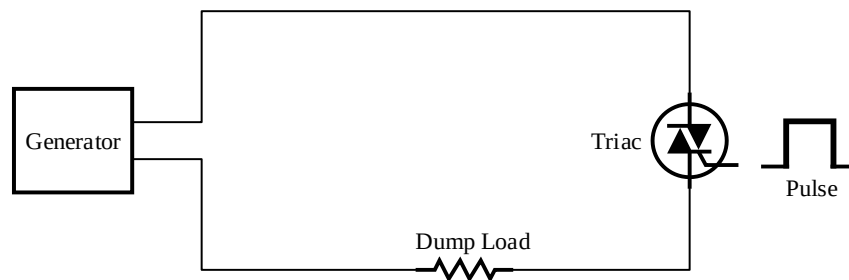


Figure 2.3: Schematic diagram of phase control circuit.

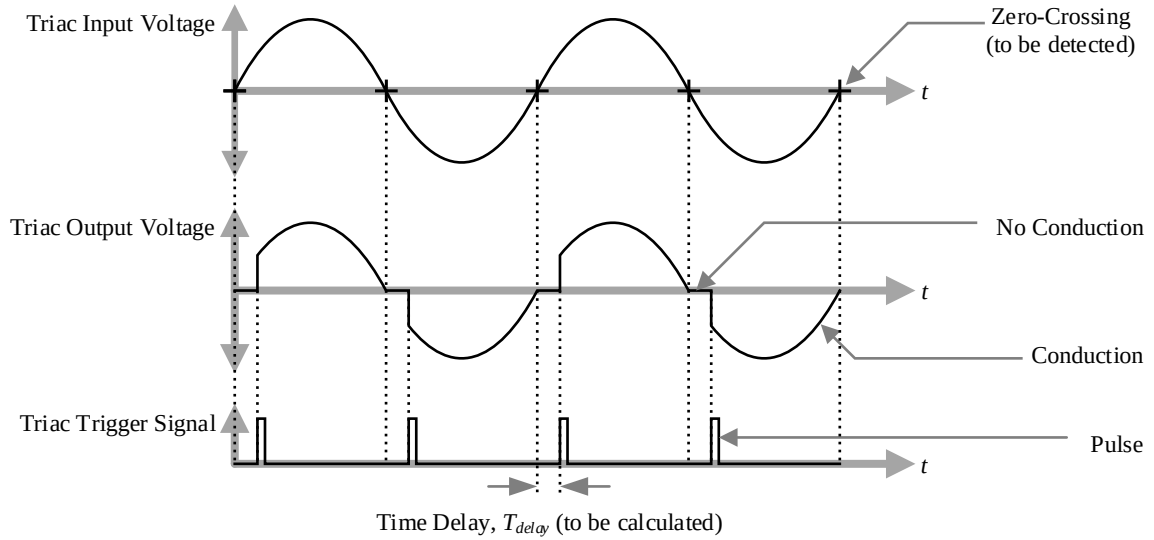


Figure 2.4: Phase control waveforms (Humphreys et al., 1991).

Phase control offers the simplest circuitry among the three methods, especially the driver circuit of triac. However, such approach is more suitable for synchronous generators (SGs) than induction generators (IGs) (Chan & Lubitz, 2016). This because it consumes reactive power that needed for the excitation in IG and de-rates the IG (Smith, 1994; Zobaa & Bansal, 2011). Moreover, it generates harmonic distortion that increases the heat in the generator windings.

2.4.2 Binary-Weighted Load Control

A binary-weighted load control varies the power to the dump load by using a group of loads (Melo, Rosa, & Ribeiro, 2013). The loads have different values of power consumption, and their values are binary weighted. Figure 2.5 shows an example of the binary-weighted load control circuit that consists of 3 triacs and 3 resistive dump loads. The triacs are used as on-off switches and labelled as S_1 , S_2 , and S_3 . While, the loads are in the

ratio of 1:2:4 and labelled as R_1 , R_2 , and R_3 . As shown in Figure 2.6, three different trigger signals are sent to the $S1$, $S2$ and $S3$ separately; high and low voltages are used to put the switches in on and off states respectively. By using different combinations of on-off states of three switches, the load can be varied from 0 to $7R$, in steps of R . As a result, the amount of power consumed by the dump load is varied, as indicated by the height of the bar.

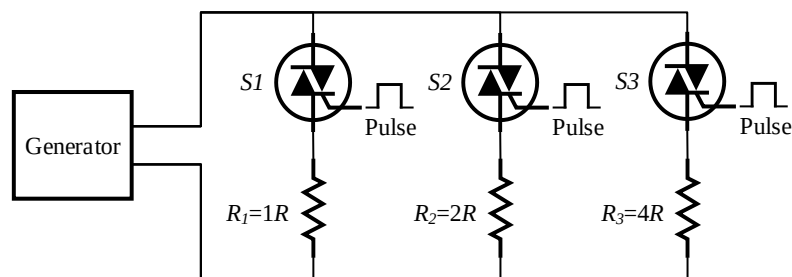


Figure 2.5: Schematic diagram of binary-weighted load control circuit (Smith, 1994).

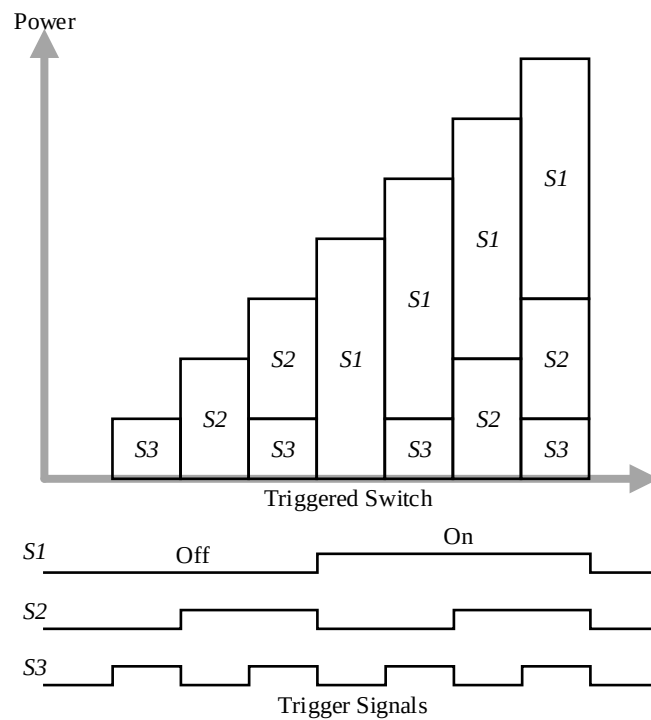


Figure 2.6: Dump Load variation (Smith, 1994).

As the operation of the binary weighted load control only involves on-off and no cutting of AC signal, it does not generate harmonic distortion (Rehman & Riaz, 2018) and demand reactive power. But a smooth control is not possible as the load exhibits a stepped characteristic (Simões & Farret, 2014). Furthermore, in order to get better resolution during control, more dump loads and complex circuitry are required. This causes the system to be bulky, prone to failure, and less reliable (Singh, Murthy, & Gupta, 2006).

2.4.3 Mark-Space Control

Unlike the other two methods, a mark-space control is applied on DC power instead of AC power. Figure 2.7 shows its circuit formed by using a rectifier, an insulated bipolar gate transistor (IGBT), and a dump load. As illustrated in Figure 2.8, the AC voltage from the generator is first converted into the DC voltage by using the rectifier. At the output of rectifier, the voltage is chopped by switching the IGBT on and off in a high frequency. The IGBT is switched on and off by high and low trigger voltages, respectively. By varying the on (mark) and off (space) times, which known as the mark-space ratio, the power dissipated in the dump load is varied (Smith, 1994). As it can be seen in Figure 2.8, the voltage through the IGBT is larger when the percentage of on-time is higher.

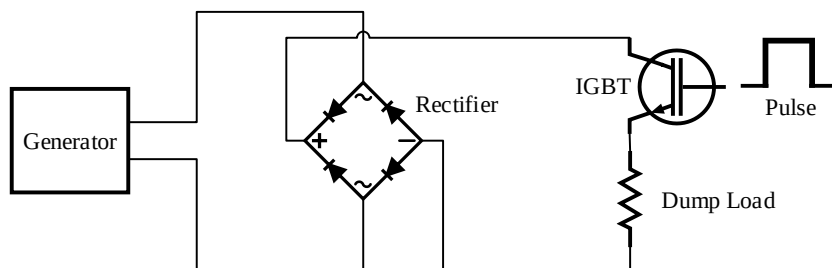


Figure 2.7: Schematic diagram of mark-space control circuit (Smith, 1994).

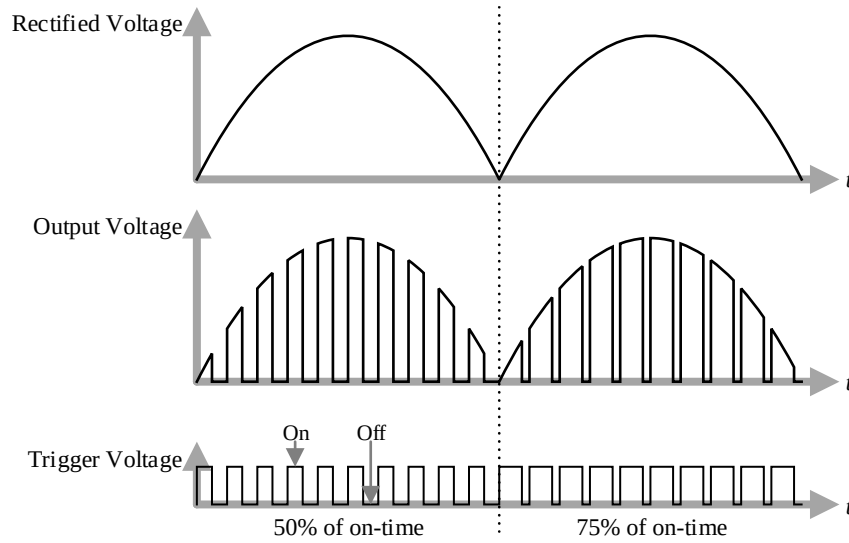


Figure 2.8: Mark-space control waveforms (Smith, 1994).

The mark-space control is very suitable to IG as it generates unity power factor dump load that does not consume reactive power. But, the uses of diode rectifier and IGBT still inject harmonic into the IG (Singh, Murthy, & Gupta, 2003). Consequently, similar to the negative effect of phase control, the IG gets hot easily.

2.5 ELCs for Induction Generator (IG)

An IG has extra advantages of absence of separate DC source for excitation and self-protection against short circuits as compared to an SG. However, the need of reactive power for excitation is the biggest disadvantage of an IG (Zobaa & Bansal, 2011). For an isolated micro-hydroelectric system, reactive power can only be supplied by capacitor banks. Therefore, reactive power supply is fixed and limited. Because of that, an extra demand of reactive power by a reactive load will cause insufficient reactive power for excitation and the consequential reduction of output power.

Hence, many researchers have reported in their literatures about the improvement of ELC design in order to make wider use of IG. ELC design is improved to compensate the demand of reactive power, along with further improvements of load balancing and harmonic elimination. This is because the unbalanced loading of a three-phase IG leads to the problems of extra power losses, excessive heating, insulation stress, and shaft vibrations (Jain, Sharma, & Singh, 2002). Also, the harmonic distortion tends to cause increase of temperature in generator winding, as mentioned in Section 2.4.

In the following subsections, together with the conventional ELC, two improved ELCs are introduced. It is noted that, the schematic diagrams used for explanations are simplified for easy understanding. From the explanations, it can be summarised that analogue proportional-integral (PI) controller in IC-3525 has been most commonly used as the control strategy of ELCs.

2.5.1 Conventional Electronic Load Controller (CELC)

A mark-space control based ELC is considered as the CELC for IG as it is most suitable for the IG, as reported in Section 2.4.3. CELCs have been reported in Mahato et al. (2010), Rathore & Singh (2016), Singh et al. (2005), and Singh et al. (2006). A single-phase CELC circuit is similar to that in Figure 2.7 while a three-phase CELC is shown in Figure 2.9. As it can be seen in Figure 2.9, a point of common coupling (PCC) is where an ELC system is connected in a micro-hydroelectric system.

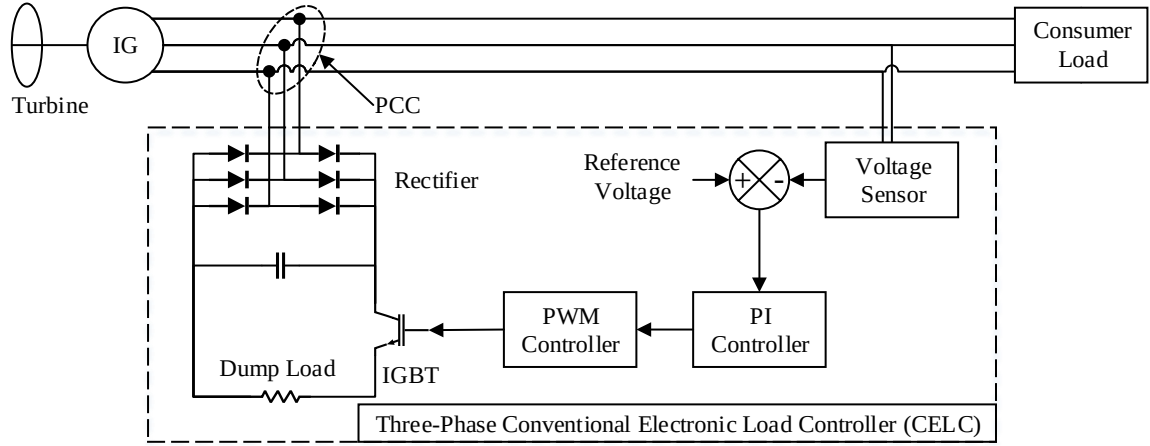


Figure 2.9: Schematic diagram of CELC (Singh et al., 2006).

The control strategy of CELC is based on the PI control (Singh et al., 2005). One phase of the IG voltage is rectified and sensed through a voltage sensor for feedback signal. The feedback signal is compared with reference voltage signal, and then the resultant error signal is fed to the PI controller. The output of the PI controller is compared with the saw-tooth carrier waveform in a pulse width modulation (PWM) controller to control the on-time of IGBT. Both the PI controller and PWM controller are realized by a PWM controller IC-3525.

The CELC able to provide regulation of V_{out} and f_{out} for a IG. However, it is expected to be used for the IG under resistive and balanced loading only.

2.5.2 Improved Electronic Load Controller (IELC)

IELCs have been proposed in Mishra & Tiwari (2017), Singh et al., 2003; Singh & Gaurav (2006); Singh et al. (2008), and Singh & Rajagopal (2009). An IELC circuit is shown in Figure 2.10. The power control circuit of IELC looks quite similar to that of CELC, but

the rectifier is replaced by a three-phase IGBT based current-controlled voltage source inverter (CC-VSI). Together with the capacitor, the CC-VSI is employed as a static compensator (STATCOM), which able to eliminates the harmonic, balance the load, and supply extra reactive power. The STATCOM also responsible for the voltage regulation. Meanwhile, the frequency regulation is taken over by the IGBT chopper and dump load.

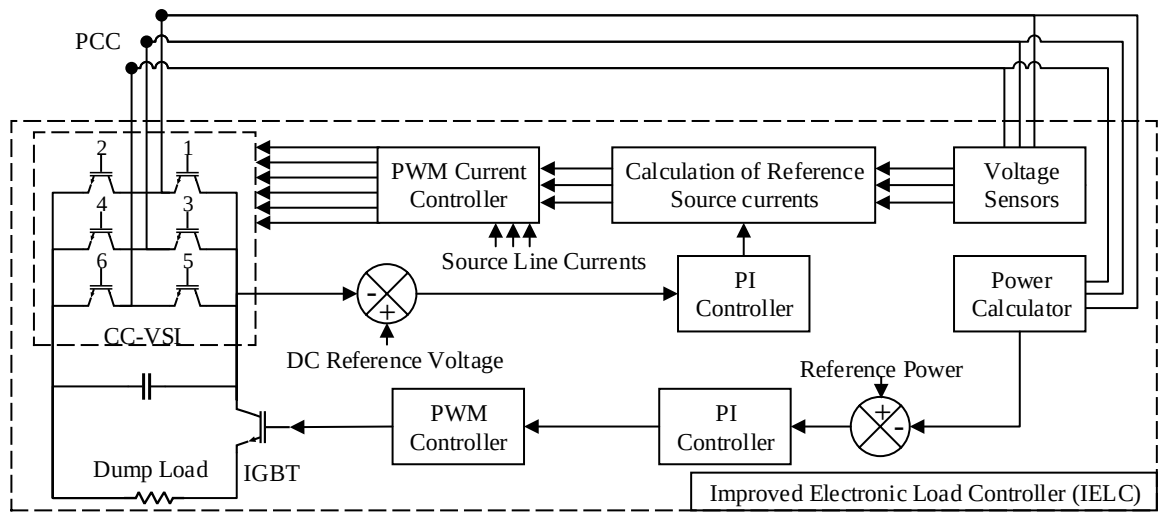


Figure 2.10: Schematic diagram of IELC (Singh & Rajagopal, 2009).

By using two independent control algorithms, the regulations of voltage and frequency are executed. The operation of IGBT chopper is similar to that of CELC. Meanwhile, the operation of the STATCOM is based on the controlling of source currents (Singh et al., 2003). It involves the calculation of total source reference currents that are compared with source line current. Inside the PWM controller, the current error signals are amplified and compared with the triangular carrier wave. If the amplified current error signal is equal to or greater than the triangular carrier wave, lower device of the inverter phase lag is turned on and upper device is turned off. If the amplified current error signal is equal to

or less than the triangular carrier wave, lower device of the inverter phase is turned off and upper device is turned on.

2.5.3 Decoupled Electronic Load Controller (DEL C)

A DELC is proposed to control the V_{out} and f_{out} in decoupled manner (Kasal & Singh, 2008; Kasal & Singh, 2008; Singh & Kasal, 2007; Singh, Rajagopal, Chandra, & Al-Haddad, 2010a). This is because, in the IELC, the continuous flow of dump power through the STATCOM tends to increase the rating of controller. In order to reduce overall rating of controller, the IGBT chopper and the dump load are detached from the STATCOM and put into a circuit that exactly the same to the CELC, as shown in Figure 2.11. Both the STATCOM and IGBT chopper operate exactly the same like the IELC.

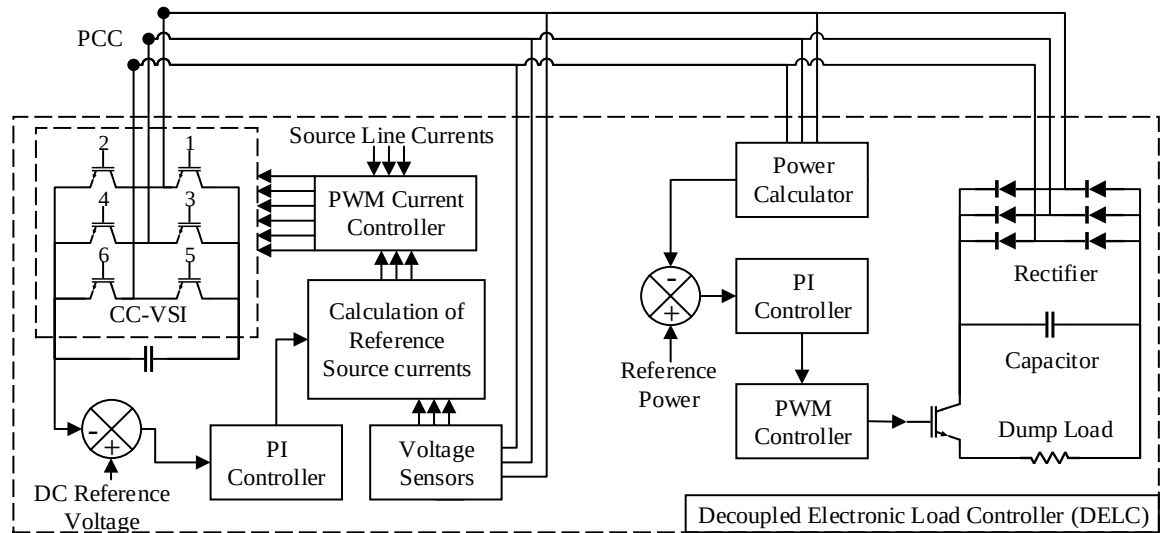


Figure 2.11: Schematic diagram of DELC (Singh et al., 2010a).

2.6 Related Studies

In this section, different digitally controlled ELCs reported in literature are reviewed to justify that the development cost of the system can be further reduced by using Arduino platform. For that purpose, the constraints of digital control devices used in the previous research and the advantage of using Arduino platform are identified and discussed. Besides that, the control algorithms for ELCs are reviewed to justify that the complexity of the system circuit can be decreased by using PID control method. From the reviews, it is understood that the complexity of an algorithm also contributes to complexity of the system circuit. Furthermore, the PID control is simple for implementation, but limited study for its implementation in the ELC.

2.6.1 Digitally Controlled ELCs

A further development of ELC is the conversion of analogue control to digital control. As described in Section 2.5, many developments of ELC are started with the use of analogue control. However, a digital control has many advantages over the analogue control. As reported in Murthy et al. (2008) and Murthy et al. (2006), digitally controlled ELC circuits are more compact, reliable, and cost effective for effective voltage regulation as compared to ELC with analogue control. In term of performance, digital control performs better with greater operational flexibility and faster response. The early development of digitally controlled ELC using AIM65 microcomputer has been reported in Kormilo & Robinson (1984). But, at that time, the system is considered bulky and expensive. With the advancement in digital technologies in the modern-day, more digitally controlled ELCs with different digital control devices have been reported in literature.

A microcontroller provides flexibility in designing the ELC circuit. However, in order to use the microcontrollers, more work need to be carried out in both hardware and programming. Figure 2.12 shows an example of microcontroller chip, i.e. PIC18F252 that costs RM26.50. In terms of hardware, power, timing, interfacing circuitry need to be developed for it to operate and interface with other devices. Meanwhile, in terms of programming, the user is required to buy an external hardware programmer or develop a programming circuit to put the program code into the microcontroller. These may increase the design complication and development cost and time.



Figure 2.12: PIC18F252 microcontroller (“PIC18F252 - Microcontrollers and Processors,” 2018).

Meanwhile, a digital signal processor (DSP) DS1104 that cost more than RM3000 is shown in Figure 2.13. DSPs have been used in implementing complex signal processing algorithms due to its intensive computational powers. For example, $\text{Icos}\Phi$ algorithm (Rajagopal & Singh, 2010) and neural-network algorithm (Singh & Rajagopal, 2011). However, an ELC should be a simple control scheme for rural application. Moreover, a simple control scheme could be achieved more economically using a microcontroller, which is developed specifically for general purpose applications.



Figure 2.13: DS1104 R&D Controller Board (“DS1104 R&D Controller Board - dSPACE,” 2018).

Unlike the previous two devices, a programmable logic controller (PLC) is a control device mainly for industrial application. Hence, it is robust enough to withstand the harsh conditions in the micro-hydroelectric plant. However, PLCs only operate in discrete logical systems. Thus, power control can only be toggled between on and off states and would be unable to implement functions like pulse width modulation (PWM). Besides that, the cost for a PLC is also higher as compared to a microcontroller. Figure 2.14 shows an example of PLC, PANASONIC PLC 14P that costs around RM700.



Figure 2.14: Panasonic PLC 14P (“PLC FP0R: New Standard for Compact PLCs Panasonic,” 2018).

Table 2.1 lists out the digital control devices that have been reported in literature to realize the digital controls in ELC systems. The table also summaries the constraints of the used devices.

Table 2.1: Devices for digital control of ELC.

Device	Types of ELC	Reference	Constraint
Microcontroller PIC18F252	• CELC	Murthy et al. (2006); Murthy et al. (2008)	They require extra cost and time for the developments of supporting and programming circuits.
Microcontroller PIC18F452	• Binary-weighted load control based ELC	Rehman & Riaz (2018)	
Microcontroller dsPIC30F6010	• CELC	Gao et al. (2014)	
Microcontroller Atmega32	• CELC	Sofian & Iyas (2011)	
Microcontroller Atmega328	• Binary-weighted load control based ELC	Rehman & Riaz (2018)	
Digital Signal Processor (DSP) DS1104	• IELC • DELC	Singh, et al. (2010b); Rajagopal & Singh (2011); Singh & Rajagopal (2011); Rajagopal et al. (2011); Chetana et al. (2012); Singh & Rajagopal (2012); Chilipi et al. (2014); Kalla et al. (2014)	They cost up to RM3000. The cost is relatively high for a rural application that prefers a simple and economic control scheme.
Digital Signal Processor (DSP) TMS320F28335	• IELC	Camargo (2016)	
Programmable Logic Controller	• Binary-weighted load control based ELC	Kabalan et al. (2015)	It cost up to RM700, and it only operates in discrete logical system.

An Arduino UNO in Figure 2.15 (a), on the other hand, is a more modern controller. It cost around RM100. As outlined in Figure 2.15 (b), its main components are an ATmega328P microcontroller, 14 digital input/output pins, 6 analogue-to-digital converter (ADC) pins, a 16Mhz quartz crystal, an universal serial bus (USB) connector, a 7-12VDC input power jack, an in-circuit serial programmer (ICSP) connector, a serial-to-USB circuitry, and a reset button. It has all the components and circuitries for operating and programing the microcontroller on a single board, and hence, it is ready for use. Besides that, the Arduino Integrated Development Environment (IDE) software is open source and free.

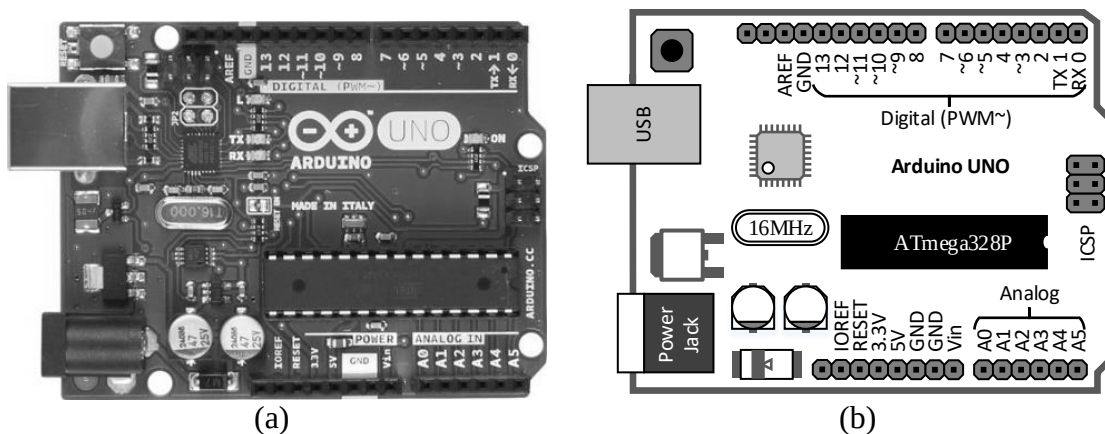


Figure 2.15: (a) Arduino UNO (“Arduino Uno Rev3,” 2018) and (b) Outline of Arduino UNO.

The cost of an Arduino UNO microcontroller board is relatively higher as compared to a microcontroller chip, but it saves the cost and time for the development of supporting circuit. Moreover, its cost is relatively lower as compared to DSP and PLC. Since the Arduino board is ready-made likes the DSP and PLC, hence it also has the same problem of fixed or limited features. As explained before, due to the fixed features of PLC, the PLC

operates only in on-off status and cannot perform function like PWM. The same problem may happen during the development of ELC using Arduino. Hence, the viability for the ELC to be implemented into the Arduino platform should be investigated.

2.6.2 Control Algorithms for ELC

Another advantage of digital control is its significant computational power and speed that allows the implementation of various and complex control laws. However, complex algorithms usually involve complex circuitry as they require more input signals and sensor devices. Table 2.2 shows the reported ELC algorithms and their numbers of current and voltage variables. From the number of variables involved in the algorithm, it could be justified that the number of sensors is high and hence high cost is involved in developing the ELC. As highlighted before, for rural application, the system must be simple and economical. Hence, it is recommended to keep the control algorithm as simple as possible.

Table 2.2: Reported algorithms and their control variables.

Algorithm	Reference	No. of Current Variable	No. of Voltage Variable
Discrete-Time Adaptive Control	Camargo et al. (2016)	6	4
Icos Φ Algorithm	Rajagopal & Singh (2010)	5	3
Neural-Network-Based Control	Singh & Rajagopal (2011)	5	3

As reported in Section 2.6 and 2.6.2, the PI control has been applied commonly in the development of ELC whether in analogue form using IC-3525 or in digital form using microcontroller. But Yadav & Appan (2015) proved the PID based ELC is faster than PI controllers by simulation. The simulated results show that the steady-state is attained in 0.26s using PID controller as compared to PI controller that attained in 0.29s.

As explained later in Section 2.7, the PID control only involve three parameters to be adjusted. Plus, controlled system shows good results in terms of response time and precision when these parameters are well adjusted (Godjevac, 2000). Another great thing is the implementation of PID control can be done without the development of a mathematical modelling of the controlled system, and its tuning can be done manually without involving mathematic calculation. This allows the PID tuning to be done easily on site based on the characteristics of micro-hydroelectric system.

However, limited study and experiment have been conducted on the digital implementation of PID control in ELC. There is no proper documentation available for setting the program codes that combine the PID equations with the commands for voltage regulation. Moreover, the exact tuning effects of the three PID gain parameters on the voltage regulation using ELC system are unknown. The significance of each gain parameter on the generator output voltage must be first identified in order to utilise the manual tuning method effectively in obtaining the optimum values of three gain parameters. Besides that, there is no clear information on setting the value of time interval ($T_{interval}$). As it can be seen later in Section 2.8, $T_{interval}$ is one of the variables of the PID equations, and its value controls the loop cycle rate of the control algorithm. Its value is no given in most of the literature, and Table 2.3 shows the values that have been used for $T_{interval}$ in literature. However, the used

values are not justified or explained. Moreover, the significance of $T_{interval}$ on the output voltage is also unknown.

Table 2.3: The values of time interval that have been reported in literature.

Reference	$T_{interval}$ (ms)
Melo et al. (2013)	13.3
Kalla et al. (2014)	40.0
Sofian & Iyas (2011)	50.0

2.7 Proportional-Integral-Derivative (PID) Control

A PID control is a feedback control strategy that prevents a system output value from being deviated from the desired system output value based on the combination of three control modes: a proportional mode, an integral mode, and a derivative mode as illustrate in Figure 2.16. Basically, it continuously calculates an amount of error, $e(t)$ as the difference between a set value, $r(t)$ and a feedback value, $y(t)$ measured from the system output (Janert, 2014), and the $e(t)$ is expressed as

$$e(t) = r(t) - y(t) \quad 2.1$$

Then, it applies adjustment to the control variable, $u(t)$, which is the sum of the outputs of the three control modes, to correct that error. This process goes on until the error equals to zero.

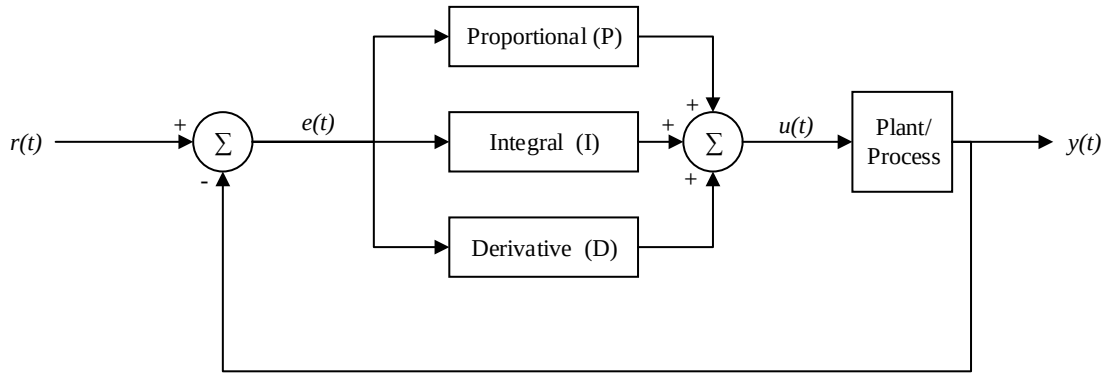


Figure 2.16: Block diagram of PID control (Janert, 2014).

The response of the controlled system by the PID control is quantified and justified by measuring four defined waveform characteristics: rise time (t_{rise}), percentage of overshoot (PO), settling time ($t_{settling}$), and steady-state error (e_{ss}) (“PID Theory Explained - National Instruments,” 2018), as shown in Figure 2.17. The four waveform characteristics are defined as following:

- i. Rise time, t_{rise} is the amount of time the system takes to go from 10% to 90% of steady-state, or final, value.
- ii. Percentage of overshoot, PO is the amount that the system output overshoots the final value, expressed as a percentage of the final value.
- iii. Settling time, $t_{settling}$ is the time required for the system output to settle within a certain percentage of the final value.
- iv. Steady-state error, e_{ss} is the final difference between the system output and the set point.

On the following subsections, the three control modes are described singularly with their equations and tuning effects on the waveform characteristics.

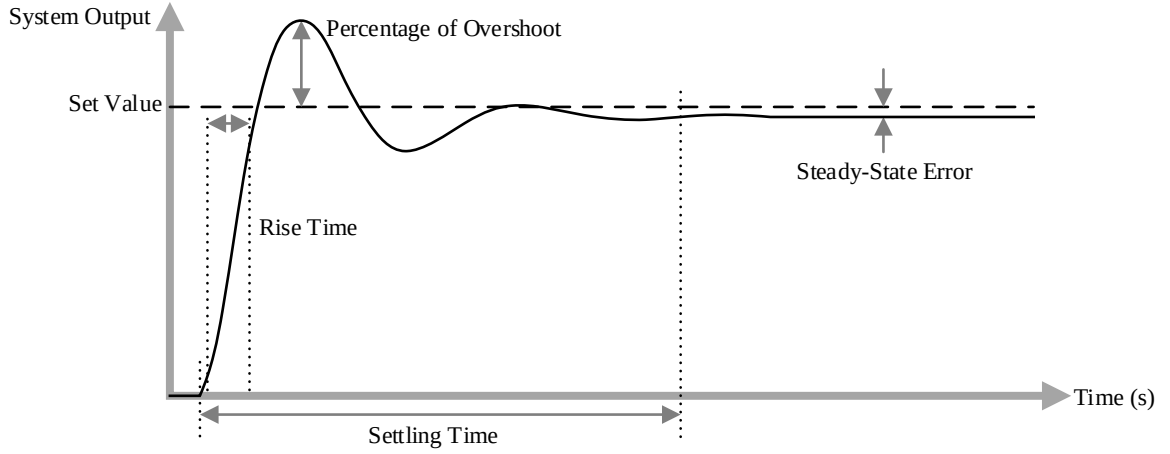


Figure 2.17: Waveform characteristics of system output controlled by PID control (“PID Theory Explained - National Instruments,” 2018).

2.7.1 Proportional Mode

The proportional control produces an output $P_{control_out}(t)$ that is proportional to the $e(t)$. According to Janert (2014), it is expressed as

$$P_{control_out}(t) = K_p e(t) \quad 2.2$$

where K_p is the proportional gain.

In general, increasing K_p will reduce the e_{ss} of system output. However, too high a value for K_p will cause the system output to overshoot and oscillate. If the K_p is further increased, both the PO and the oscillations will become larger. Consequentially, the performance of system turns to be unstable before the e_{ss} is eliminated. Therefore, the e_{ss} will never become zero if only the proportional control is used.

2.7.2 Integral Mode

The integral control reacts proportionally to the integral of the error. By referring to Janert (2014), its output $I_{control_out}(t)$ is given by

$$I_{control_out}(t) = K_i \int e(t) dt \quad 2.3$$

where K_i is the integral gain.

Once the integral control is added to the proportional control, the residual e_{ss} from the utilization of proportional control is full eliminated, and a set value is reached. The higher the value of K_i , the faster the set value could be reached. But the tendency for the system output to overshoot and become unstable is higher if the K_i is set too high.

2.7.3 Derivative Mode

The derivative control is used to calculate the rate of change of the error based on the equation

$$D_{control_out}(t) = K_d \frac{de(t)}{dt} \quad 2.4$$

where $D_{control_out}(t)$ is the derivative control output and K_d is the derivative gain according to Janert (2014).

A proportional-integral (PI) control is satisfactory to control a system. However, the implementation of derivative control helps to reduce PO and oscillation that resulted from the PI control. Again, if the K_d is set too high, the derivative control can have tendency to result an unstable system that will never reach a stable state.

2.7.4 Combination of Three Modes

A PID control is formed by combining the three control modes: P control, I control, and D control. According to Janert (2014), its final output $u(t)$ is then given by

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad 2.5$$

The tuning effect of each gain can be summarized as in Table 2.4 (Das, Chakraborty, Ray, & Bhattacharjee, 2012). However, the correlation may not be correct, because K_p , K_i , and K_d are dependent of each other. The table can be used as a reference for the determining the values for K_p , K_i , and K_d . Noted that, in determining the absolute values for the three parameters of the PID control, the first step is to determine the performance requirements of system or the characteristics of the system that needs to be improved.

Table 2.4: Tuning effect of K_p , K_i , and K_d .

Gain	Rise Time, t_{rise} (ms)	Percentage of Overshoot, PO (%)	Settling Time, $t_{settling}$ (ms)	Steady-State Error, e_{ss} (V)
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

2.8 Digital Implementation of PID Control

The proportional control can be implemented directly into the digital control by employing equations outlined in Section 2.7.1, but not for integral and derivative controls as

they involve the integration and differentiation of the error respectively. There is no specific function for both the integration and differentiation in the programming of the Arduino UNO. But they can be applied by understanding that the integration and differentiation are the calculations of the area under a curve and the slope of a curve, respectively.

Based on integration, the area under a curve can be calculated approximately by adding the areas of many small rectangles under the curve, and the area of each rectangle is calculated by length $\times$ width. Hence, in digital PID control, the integration of error is an accumulation of the error (length) multiplied with the $T_{interval}$ (width) from time to time as shown in Figure 2.18, and it is expressed as

$$error_{sum} = (error_{sum} + error) \times T_{interval} \quad 2.6$$

where $error_{sum}$ is the summation of error (Anderson & Cervo, 2013). Based on equation 2.3, $I_{control_out}$ is expressed as

$$I_{control_out} = K_i \times error_{sum} \quad 2.7$$

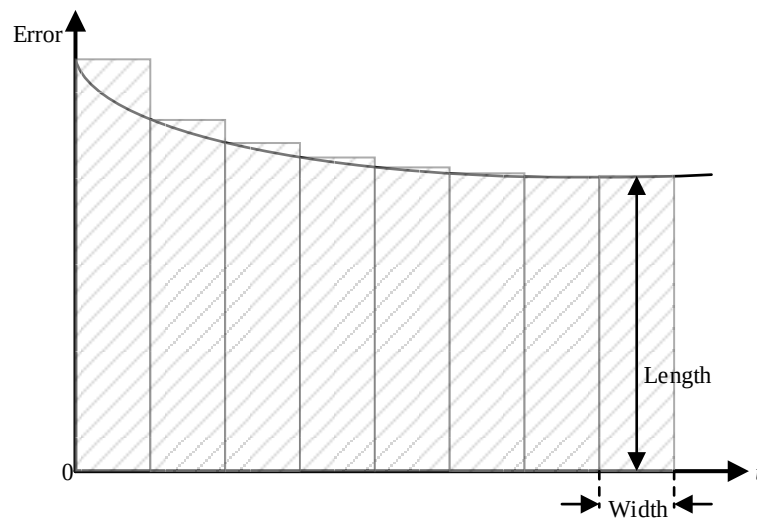


Figure 2.18: Integration of error.

On the other hand, the differentiation can be computed by obtaining the slope between two points on a curve by dividing the change in y-axis with the change in x-axis as shown in Figure 2.19. The variable at the x-axis can be either the input signal (feedback signal) or the computed error. According to Anderson & Cervo (2013), based on that concept, the differentiation is applied on the error by the equation as follow:

$$error_{derivative} = (error_{current} - error_{previous}) \div T_{interval} \quad 2.8$$

Or

$$error_{derivative} = (input_{current} - input_{previous}) \div T_{interval} \quad 2.9$$

where $error_{derivative}$ is the differentiation of error, $error_{current}$ is the current or the latest computed error, $error_{previous}$ is the previously computed error, $input_{current}$ is the current value of input signal, and $input_{previous}$ is the previous value of input signal. In some case, equation 2.9 is used instead of equation 2.8. This is because the error has greater perceived change, and thus a higher slope will be added to the final output of the PID controller (Anderson & Cervo, 2013). Thus, based on the expression in equation 2.4, the expression for output of the derivative control is:

$$D_{control_out} = K_d \times error_{derivative} \quad 2.10$$

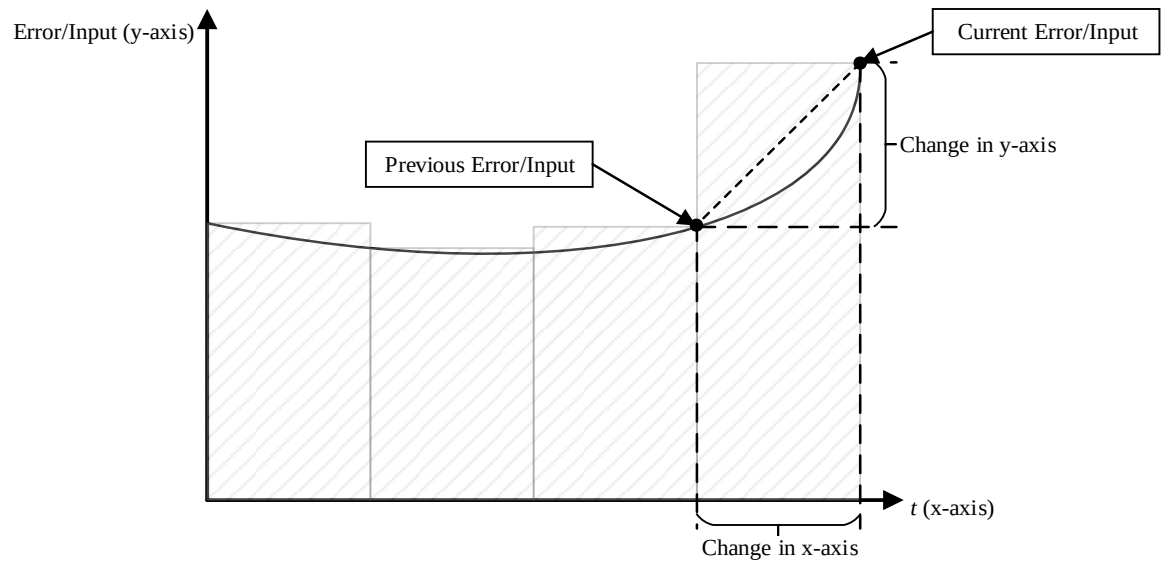


Figure 2.19: Differentiation of error.

2.9 Summary

The load effect on generator is the reason why the output voltage (V_{out}) and output frequency (f_{out}) fluctuate during load variation and why an ELC system is designed to maintain the load on generator. The most three common types of ELCs are phase control based ELC, binary-weighted load control based ELC, mark-space control based ELC. The ELCs have been improved to compensate the demand of reactive power for excitation in an induction generator. A further development of ELC is the conversion of analogue control to digital control. By reviewing different digitally controlled ELCs reported in literature, it is justified that the development cost of a digital ELC can be further reduced by using Arduino platform. Besides that, the control algorithms for ELCs are reviewed, and it is justified that a simple algorithm such as proportional-integral-derivative (PID) control is more applicable for an ELC. This is because advance algorithms are complex and require development cost as more input signals and hence more sensors are utilized. However, limited study and

experiment have been conducted on the digital implementation of PID control in ELC. Therefore, it is important to have a research to implement the ELC in to the Arduino platform and to development a PID control based algorithm for the ELC.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methods used in designing the proposed ELC system. The ELC circuit is designed based on the phase control method. Meanwhile, the control algorithm of the ELC is formulated based on the PID control concept. The following sections explain the implementation of the ELC concept, which includes the process of ELC circuit design, choice of hardware, formulation of program algorithm, and program code setup. This chapter also includes the subtopics on the software used for design and analysis, the laboratory setup and the laboratory test procedures.

3.2 ELC Circuit Design

The proposed ELC system must be kept simple and economical for rural off-grid application as described in Section 1.2.6. Overvoltage that will lead to the damage of the appliances is the main concern in this research. The nominal voltage ($V_{nominal}$) of appliances in Malaysia is 240VAC. With these in mind, an Arduino UNO based ELC system is proposed to regulate the output voltage (V_{out}) of a micro-hydroelectric system at 240VAC.

In the first step of design and implementation, the required functions of the proposed ELC for voltage regulation are determined. Subsequently, based on these functions, suitable components and modules are selected to be used in the design. Lastly, all parts are connected

together to complete a fully functioning ELC design. It is noted that, the ELC is designed to handle a generator with a maximum output power (P_{out_max}) of 3kW and a maximum output voltage (V_{out_max}) of 500VAC.

3.2.1 Identifications of Functions and Hardware

The ELC has three main functions to perform the voltage regulation. Firstly, the ELC must be able to monitor and measure the changes in consumer load. As explained in Section 2.2, the load change causes changes in both V_{out} and f_{out} . Thus, either one could be used to measure the variation of consumer load indirectly. Since the controlling mechanism is done prior to V_{out} , hence a voltage sensor is used to measure and convert the V_{out} into a range of DC value, which is readable by the microcontroller system.

The second function is to absorb the excess power that results from a disconnected consumer load and to release the power back when a consumer load is connected. In order to perform this function, a power control circuit is needed to control the amount of power to be delivered to the dump load. As explained in Section 2.4.1, the phase control has the simplest circuitry as compared to the binary-weighted load control and mark-space control. Hence, it is adopted in this research to design the power control circuit. This method varies the power delivered to the dump load by adjusting the time delay (T_{delay}) of triac trigger signal.

Then, the third function is to execute a control algorithm for the regulation of V_{out} . The key point here is to formulate a control strategy that determines how the ELC reacts to the change in V_{out} . For that purpose, a PID control is conceived as the control algorithm for the ELC, and it is realized digitally with an Arduino UNO. The PID control is employed to

compute the deviation of V_{out} from the $V_{nominal}$. Then, based on the combination of P, I, and derivative D control modes, it computes and adjusts the value of T_{delay} of the triac trigger signal, which defines the amount of power delivered to the dump load, until the V_{out} is corrected to the $V_{nominal}$. The implementation of the PID control is further explained in Section 3.4.

Therefore, the ELC implemented in this research is consisting mainly of a voltage sensor, an Arduino UNO board loaded with PID control based program, a phase control circuit, and a 3kW resistive dump load. Figure 3.1 shows a block diagram showing how the ELC is attached on the micro-hydroelectric system output line. As seen from the diagram, wires are channelled from the main transmission line to the voltage transducer and phased control circuit. The Arduino UNO is connected to the voltage sensor and phase control circuit. The dump load is connected on the other side of the phase control circuit.

3.2.2 Complete ELC Design

Besides the main parts of the ELC, a 240VAC-24/12VDC double channel voltage converter and a three-pin toggle switch are added to complete the ELC system. The voltage converter is used to supply 24VDC and 12VDC to the voltage transducer and Arduino UNO, respectively. Meanwhile, the toggle switch is used to start and stop the main program in the Arduino. A complete design of ELC is illustrated in the schematic diagram in Figure 3.2. As it can be seen, the phase control circuit is actually consisting of a zero-crossing detection circuit and a triac circuit. Also, the exact connection between the 3kW dump load and the consumer load is in parallel. A more detail information for the hardware is provided in Section 3.3.

Micro-Hydroelectric System

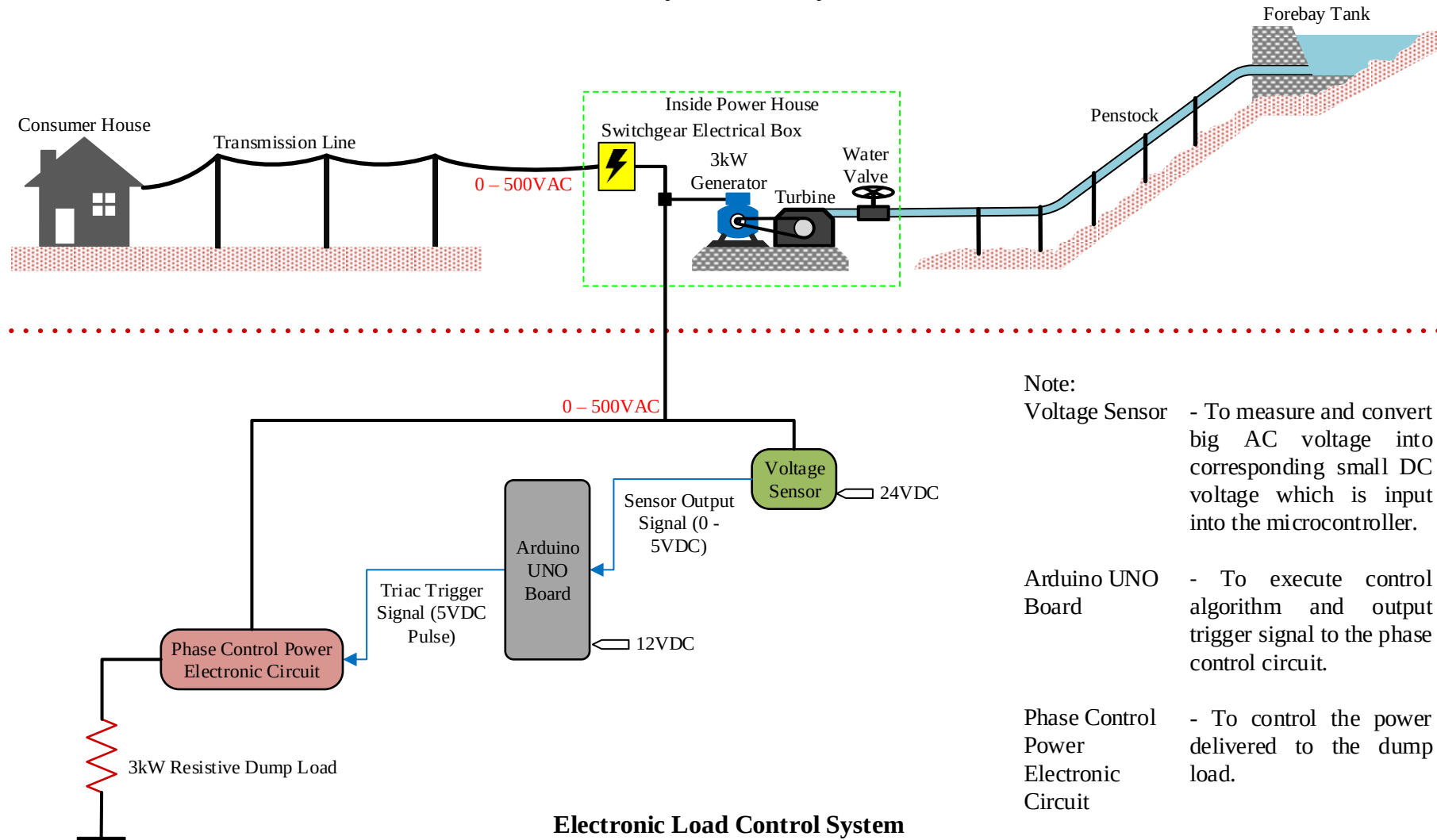


Figure 3.1: Block diagram of ELC in micro-hydroelectric system.

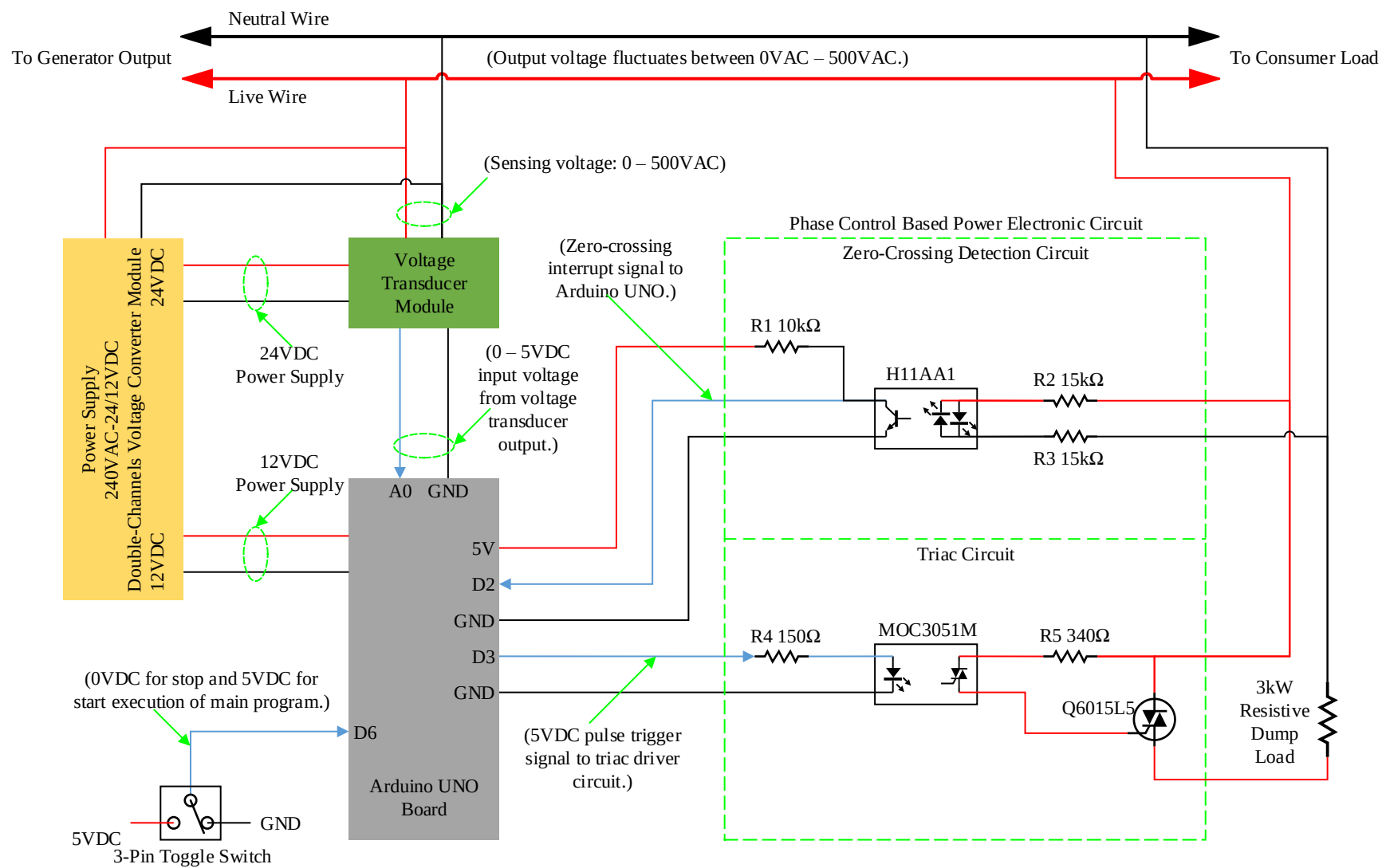


Figure 3.2: Schematic diagram of designed ELC.

3.3 Hardware Implementation

In the designed ELC, besides the phase control circuit and dump load, other parts of the ELC system are implemented by using modules. As mentioned in Section 3.2.2, the phase control circuit consists of the zero-crossing detector and triac driver circuits, and both the circuits are designed based on the rating of triac. In the following subsections, explanations are given to all the used components, circuits, and modules.

3.3.1 Voltage Sensor Module

A TEC-AU1C5 voltage sensor module, which is shown in Figure 3.3, converts an AC voltage in a range of 0VAC to 500VAC into a DC voltage in a range of 0VDC to 5VDC. It is used to allow the Arduino microcontroller to measure the value of V_{out} , which is in AC and greater than 5V. The V_{out} in term of DC value from the sensor output is expressed as:

$$V_{out}(DC) = V_{out}(AC) \div 500VAC \times 5VDC \quad 3.1$$

This equation will be used in Section 3.5.1.



Figure 3.3: Voltage sensor (TEC-AU1C5).

3.3.2 Zero-Crossing Detection Circuit

A zero-crossing detection circuit is used to generate a 5V pulse for every time the AC voltage crosses the zero volts, as shown in Figure 3.4. The waveforms in generated by using Proteus 8 software. The 5V pulse signal is sent to an interrupt pin of Arduino board for synchronizing the triac trigger signal with the zero-crossing events of AC voltage. The circuit is implemented by utilising a H11AA1 optocoupler IC (Integrated Circuit), as shown in the schematic diagram in Figure 3.5.

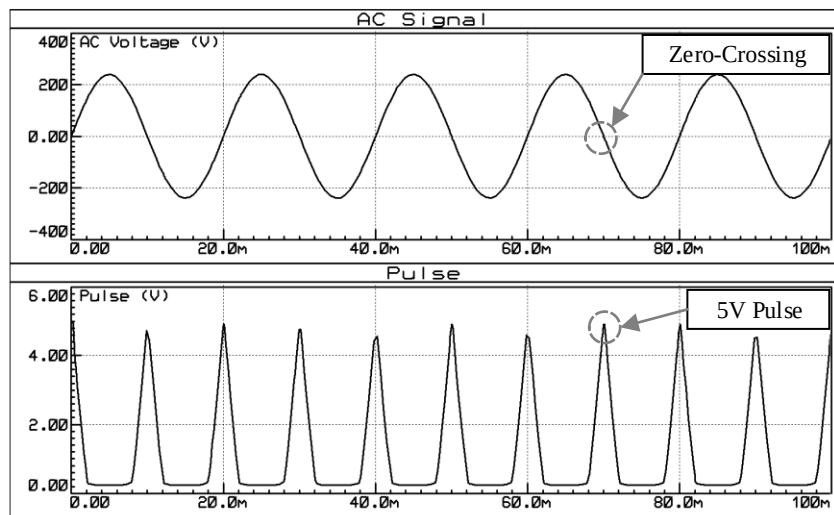


Figure 3.4: Zero-crossing events of AC voltage.

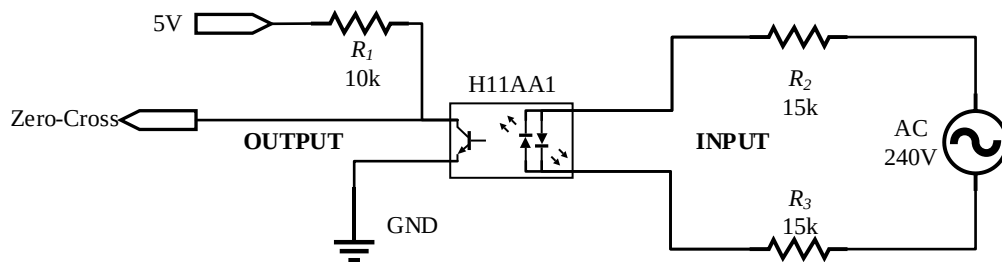


Figure 3.5: Schematic diagram of zero-crossing detection circuit.

The H11A1 is a bi-directional input optically coupled isolator consisting of two infrared LEDs coupled to a NPN phototransistor, and Appendix B shows its datasheet. Its output is connected to a 5V external voltage supply via a 10k Ω pull-up resistor (labelled R_1). Meanwhile, its input is connected to two current limiting resistors (labelled R_2 and R_3). The R_2 and R_3 resistors restrict the current through the LEDs to be 16mA, which is within the nominal value of current for driving the LED. By referring to Appendix B, the forward voltage of one LED is 1.5V. Thus, the values of R_2 and R_3 resistors are calculated as:

$$R_2 = R_3 = (240V - 1.5V) \div 16mA \approx 15k\Omega$$

Since the two resistors are connected directly to the AC power, hence they must be implemented by using power resistors. The power dissipation (P) of each resistor is calculated as:

$$P = 16mA \times (240V - 1.5V) \approx 3.8W$$

In order to increase the robustness of the circuit, a higher value of 5W is selected as the power rating of each of the resistors (R_2 and R_3). Figure 3.6 shows the hardware implementation of the zero-crossing detection circuit.

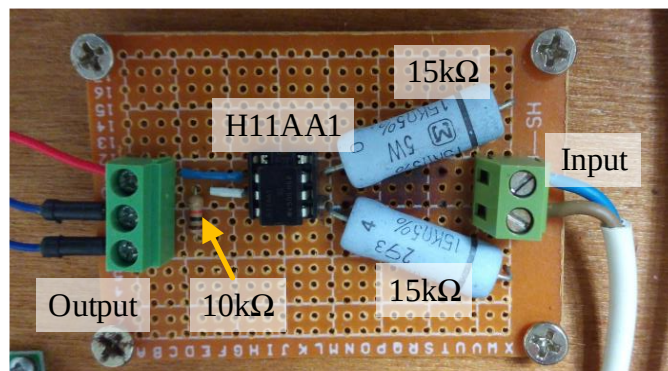


Figure 3.6: Zero-crossing detection circuit board.

3.3.3 Triac Circuit

Figure 3.7 shows the schematic diagram of a triac circuit developed in this research. The circuit consists of a triac and a driver circuit. The triac is responsible for chopping the AC voltage in every half-cycle. Meanwhile, the triac driver circuit is used to turn on and turn off the triac. At the same time, the driver circuit provides isolation between the low-power microcontroller and the high-power triac for safety.

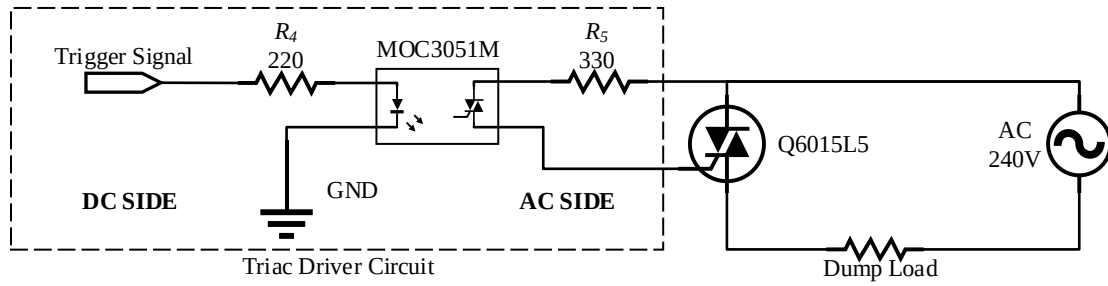


Figure 3.7: Schematic diagram of triac circuit.

The rating of the triac is selected according to the maximum voltage (V_{out_max}) and maximum output current (I_{out_max}) of the generator. As mentioned in Section 3.2, the P_{out_max} and V_{out_max} of the generator are 3kW and 500V, respectively. Thus, when the V_{out} is constantly at 240V, the value of I_{out_max} is calculated as:

$$I_{out_max} = 3\text{kW} \div 240\text{V} = 12.5\text{A}$$

Again, in order to increase the robustness of the circuit, a 600V/15A triac (Q6015L5) is used in the triac circuit. The datasheet of the triac is included in Appendix C.

At the meantime, the triac driver circuit is implemented by using a MOC3051M IC, which is a random-phase optocoupler consisting of an infrared LED coupled with a triac based detector. The DC side of IC receives a 5V pulse signal from the Arduino via a resistor labelled R_4 , which is use to set the current into the LED to be 15mA. With the forward voltage of 1.5V across the LED (according to Appendix D), the value of R_4 is calculated as:

$$R_4 = (5V - 1.5V) \div 15mA = 233\Omega$$

Meanwhile, at the AC side of the IC, another resistor labelled R_5 is used to limit the current into the detector to be 1A. The value of R_5 is calculated as:

$$R_5 = 240\sqrt{2}V \div 1A \approx 340\Omega$$

Based on the commercially available resistors, 220Ω and 330Ω resistors are used as R_4 and R_5 resistors, respectively. Power ratings selected for R_4 and R_5 resistors are 0.5W and 2W, respectively. Power resistor is not used in the AC side of the triac driver circuit since the power dissipation at R_5 resistor is very small. This is because the triac carries the current away as soon as the current through the optocoupler and R_5 resistor reaches the trigger current of the triac gate. Figure 3.8 shows the hardware implementation of the triac circuit.

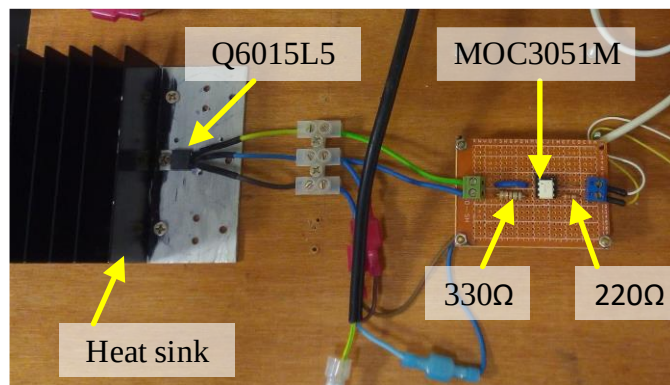


Figure 3.8: Triac circuit board.

3.3.4 Arduino UNO

The features of Arduino UNO have been discussed in Section 2.6. Its uses in the ELC system are to receive signals, execute control algorithm, and produce output signals. The pins used to perform the tasks are pins A0, 2, 3, 5, 6, and 7 as shown in Figure 3.9, and their functions are listed in Table 3.1.

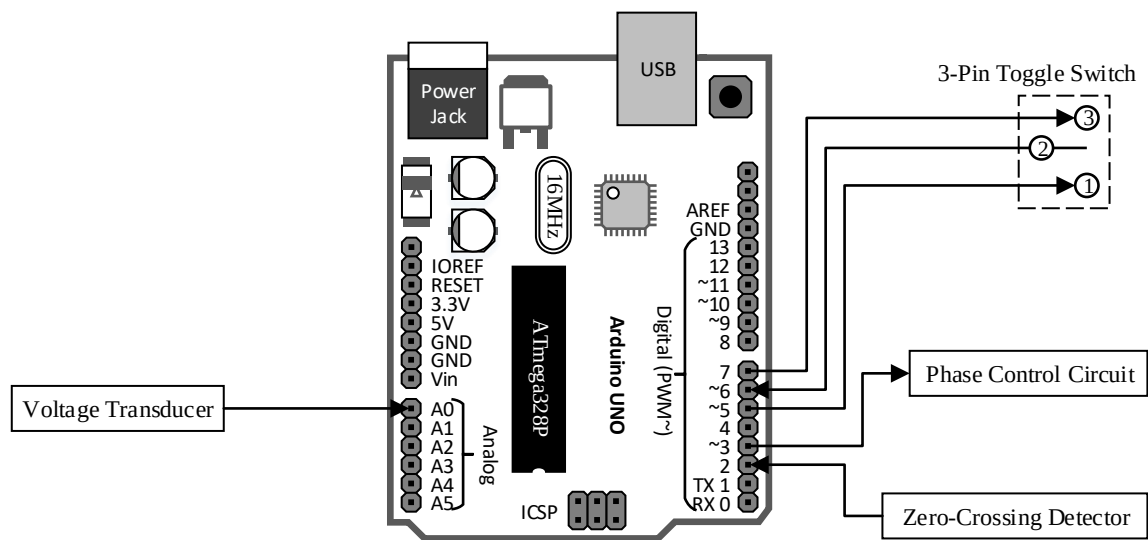


Figure 3.9: Used Arduino pins.

Table 3.1: Functions of used pins.

Pin	Function
A0	To receive V_{out} (DC) from the voltage sensor.
2	To receive 5V pulse signal from the zero-crossing detection circuit.
3	To output trigger signal to triac drive circuit.
5	To output 5V to the pin 1 of toggle switch.
6	To receive trigger signal from the pin 2 of toggle switch.
7	To output 0V to the pin 3 of toggle switch.

It is noted that the DC voltage at the analogue pin A0 is converted into an integer between 0 and 1023 by the on-board analogue-to-digital converter (ADC). The value of V_{out} in term of integer is expressed as:

$$V_{out}(\text{integer}) = (V_{out}(\text{DC}) \div 5\text{VDC}) \times 1023 \quad 3.2$$

3.3.5 Dump Load

A dump load is used to consume the excess power resulting from disconnected consumer loads. It must have a power absorbing capacity equal to (or slightly greater than) the power rating of the generator in order to consume all the power produced by the generator during no load condition. In this research, the ELC is designed to handle a 3kW power. However, a 500W of dump load is used instead of a 3kW dump load due to the limitation that will explained in Section 3.7. The 500W dump load is formed by using five light bulbs with each has 100W nominal power. The light bulbs are connected in parallel as shown in Figure 3.10. One end is connected to the triac terminal and another is connected to the neutral wire. Figure 3.11 shows the dump load implementation.

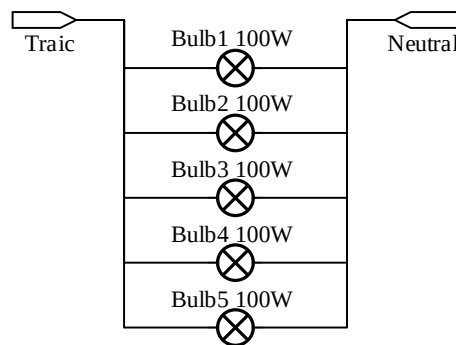


Figure 3.10: Schematic diagram of dump load.

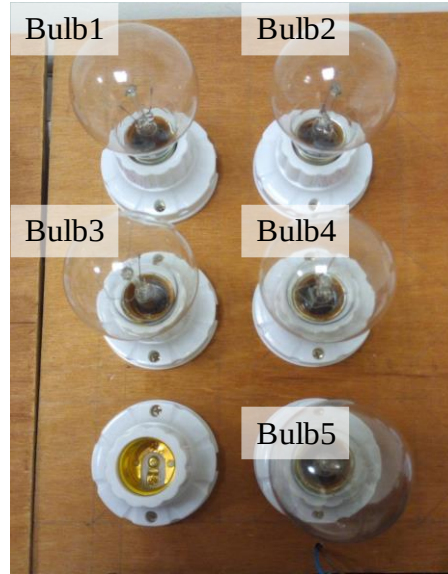


Figure 3.11: Implementation of dump load.

3.4 Formulation of Control Algorithm

The full load on the generator must be maintained in order to maintain the V_{out} constant at the nominal voltage ($V_{nominal}$) of appliances in Malaysia, which is 240V. This requires the ELC to continuously measure the V_{out} from the voltage sensor through the pin A0 and generate triac trigger signal to the triac circuit through pin 3. Based on the PID control concept, every measured value of V_{out} is responded by calculating its deviation from the value of $V_{nominal}$. Then, the deviation is reduced by adjusting the value of time delay (T_{delay}) of the triac trigger signal. T_{delay} acts as the control variable of PID control, and it controls the amount of power delivered to the dump load. The desired value of T_{delay} is calculated by using the PID equations. Based on these ideas, a control algorithm for the ELC system is formulated and presented in Figure 3.12. The control algorithm consists of a main algorithm for calculating the value of T_{delay} and an interrupt algorithm for generating the triac trigger signal.

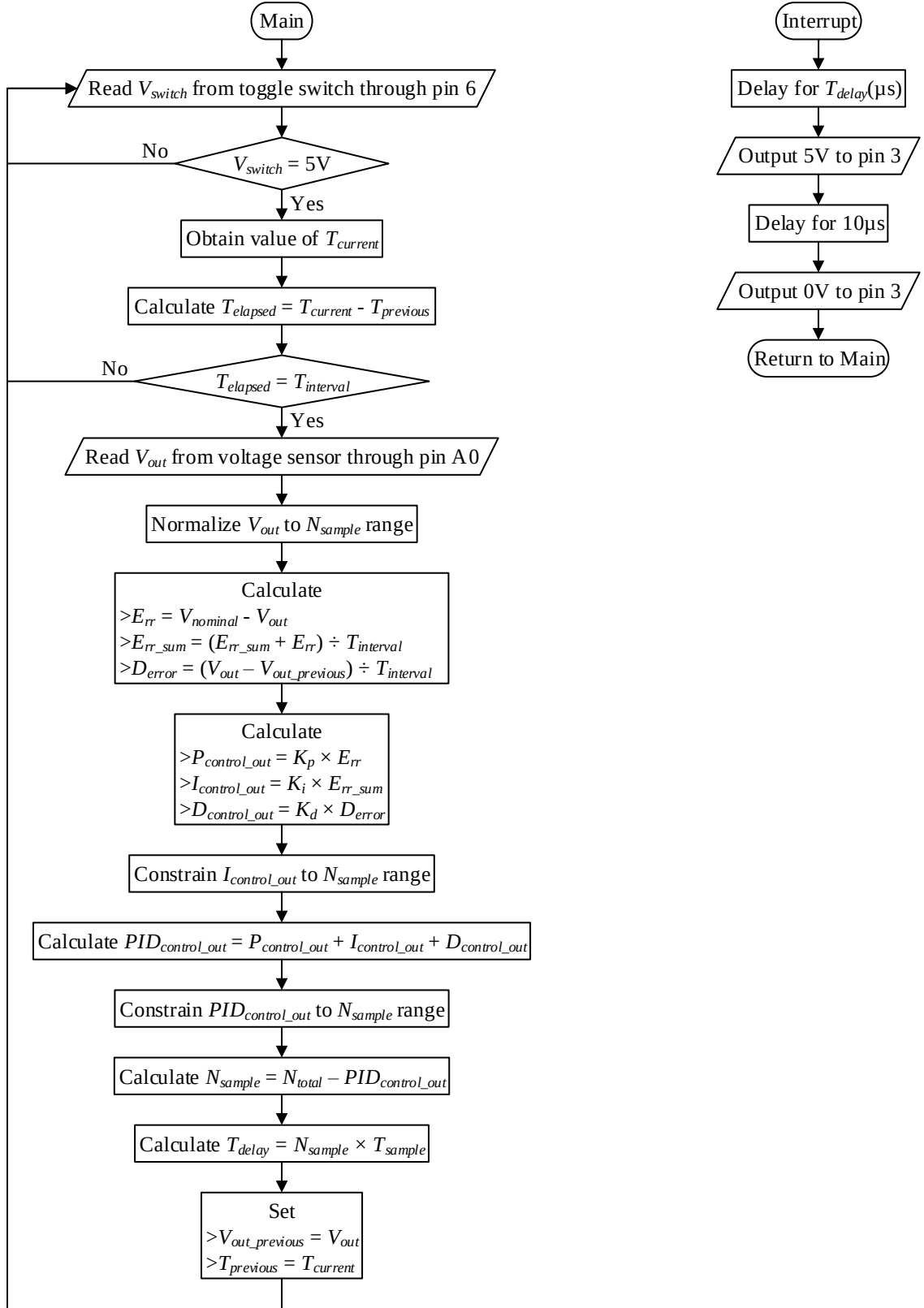


Figure 3.12: Flow chart of ELC control algorithm.

3.4.1 Main Algorithm

The main algorithm is where the measurement of V_{out} and calculation of T_{delay} are carried out repeatedly. At first, the V_{switch} , which is the voltage signal from the toggle switch, is checked whether it is 0V or 5V at pin 6. The algorithm stops the voltage regulation if V_{switch} is 0V, and this allows the algorithm to be in standby mode while waiting for the settings of micro-hydroelectric system to be done. If the V_{switch} is 5V, the algorithm moves to next step by obtaining the value of current time ($T_{current}$) from the Arduino internal clock. Then, the elapsed time ($T_{elapsed}$), which is the amount of time that has passed since the last the time the algorithm calculated T_{delay} . The $T_{elapsed}$, is calculated as:

$$T_{elapsed} = T_{current} - T_{previous} \quad 3.3$$

where $T_{previous}$ is the time when the previous T_{delay} is calculated. If the value of $T_{elapsed}$ is greater than or equal to the value of time interval ($T_{interval}$), the algorithm will start the calculation of T_{delay} . This ensure the V_{out} is constantly read and responded at a fixed time interval.

The main algorithm starts the calculation of T_{delay} by reading the value of V_{out} (DC) from the output of voltage sensor through the pin A0. It is noted that, the V_{out} (DC) is directly converted into an integer between 0 and 1023 by the Arduino on-board ADC. Then, the value of V_{out} (integer) is normalized to the range of control variable. The range of control variable should be the range of T_{delay} , which is from 0s to half-period of AC voltage. However, in order to increase the speed of response of the algorithm, the range of T_{delay} is divided into a number of sample (N_{sample}) with a sample time (T_{sample}), as shown in Figure 3.13. The value of T_{delay} is later calculated using the N_{sample} . Hence, the V_{out} (integer) is normalized to the range of N_{sample} , which is from zero to total sample (N_{total}).

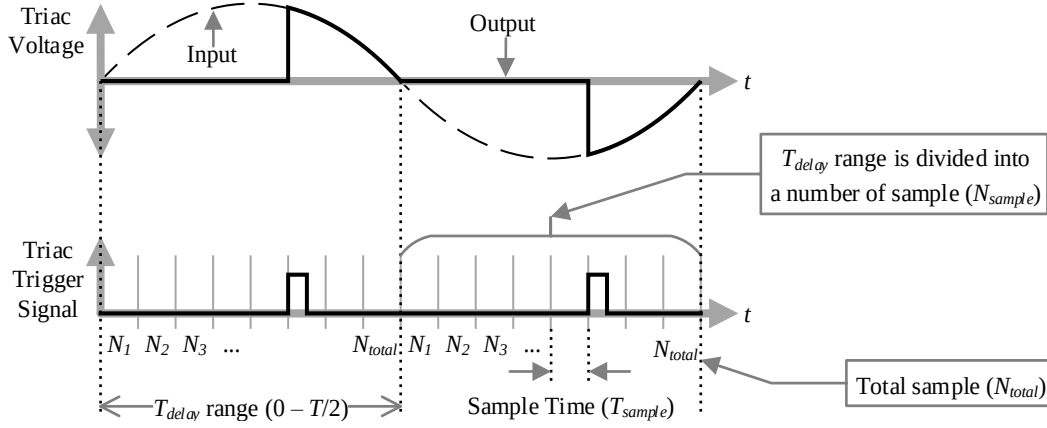


Figure 3.13: Division of T_{delay} range into a number of sample.

After that, the algorithm continuous with the calculations of errors for the proportional (P) control, integral (I) control, and derivative (D) control modes using the following equations (expressed based on the equations in Section 2.8):

$$E_{rr} = V_{nominal} - V_{out} \quad 3.4$$

$$E_{rr_sum} = (E_{rr_sum} + E_{rr}) \div T_{interval} \quad 3.5$$

$$D_{error} = (V_{out} - V_{out_previous}) \div T_{interval} \quad 3.6$$

where E_{rr} is error (the amount of deviation of V_{out} from $V_{nominal}$), E_{rr_sum} is accumulation of error, D_{error} is derivation of error, and $V_{previous}$ is the previous value of V_{out} . Sequentially, the outputs of the three control modes are calculated by using the equations:

$$P_{control_out} = K_p \times E_{rr} \quad 3.7$$

$$I_{control_out} = K_I \times E_{rr_sum} \quad 3.8$$

$$D_{control_out} = K_d \times D_{error} \quad 3.9$$

where $P_{control_out}$ is proportional control output, $I_{control_out}$ is integral control output, $D_{control_out}$ is derivative control output, K_p is proportional gain, K_i is integral gain, and K_d is derivative gain. The value of $I_{control_out}$ is constrained to the range of N_{sample} . If $I_{control_out}$ is less than zero, the $I_{control_out}$ will be set to zero; if $I_{control_out}$ is greater than N_{total} , the $I_{control_out}$ will be set to N_{total} . Then, the total output of PID control ($PID_{control_out}$) is calculated as:

$$PID_{control_out} = P_{control_out} + I_{control_out} + D_{control_out} \quad 3.10$$

Similar to $I_{control_out}$, the value of $PID_{control_out}$ is constrained to the range of N_{sample} .

After that, based on the calculated value of $PID_{control_out}$, the T_{delay} is calculated by using the equations:

$$N_{sample} = N_{total} - PID_{control_out} \quad 3.11$$

$$T_{delay} = N_{sample} \times T_{sample} \quad 3.12$$

Before, the calculation of T_{delay} , the value of N_{sample} is first calculated by subtracting the calculated value of PID_{out} from the value of N_{total} . This is because the direct multiplication of $PID_{control_out}$ and T_{sample} results the amount of time which the triac is on, but T_{delay} is the amount of time for the triac to be off as explained in Section 2.4.1. Therefore, the equation 3.11 is executed before the equation 3.12. Before the main algorithm back to its beginning, the values of V_{out} and $T_{current}$ used in the calculation are stored as previous output voltage ($V_{out_previous}$) and previous time ($T_{previous}$), as shown in equations below:

$$V_{out_previous} = V_{out} \quad 3.13$$

$$T_{previous} = T_{current} \quad 3.14$$

3.4.2 Interrupt Algorithm

The interrupt algorithm is used to generate and output the triac trigger signal to the pin 3, which connecting with the triac circuit. The execution of interrupt algorithm is triggered by the 5V pulses (interrupt signal) from the zero-crossing detection circuit. Therefore, at the same time, the algorithm allows the synchronization of the start of T_{delay} with the zero-crossing events of AC voltage. When the algorithm detects a 5V pulse at pin 2 (used as interrupt pin), a delay as long as T_{delay} (calculated from the main algorithm) is applied to keep the triac at off state. Subsequently, once T_{delay} is elapsed, a 5V pulse is output to pin 3 to turn on the triac. Then, the algorithm delays for $10\mu s$. After that, the 5V is removed by outputting 0V to pin 3, so that the triac is back to off state for the next 5V pulse (next zero-crossing event).

3.5 Code Setup

Based on the formulated control algorithm, a source code of ELC program is written by using Arduino programming language, as listed line by line in Table 3.2. The codes can be divided into declaration of variables, a `setup()` function, a `loop()` function, and a `Trigger_Signal()` function, which are explained in the following subsections.

Table 3.2: List of program source code.

Line	Code
1	<code>unsigned long</code> Telapsed, Tcurrent, Tprevious = 0, Tinterval = 10;
2	<code>float</code> Vout, Vout_previous, Vnominal = 92.0, Cnormalising = 5.173;
3	<code>float</code> Pcontrol_out, Icontrol_out, Dcontrol_out, PIDcontrol_out;
4	<code>float</code> Err, Err_sum, Derror, Kp = 2, Ki = 3, Kd=10;
5	<code>int</code> Tdelay, Tsample = 45, Nsample = 0, Ntotal = 140;
6	<code>int</code> sw5V_pin = 5, sw_pin = 6, swGND_pin = 7, trigger_pin = 3, voltSensor_pin = A0;
7	
8	<code>void</code> setup()
9	{
10	<code>pinMode</code> (sw5V_pin, <code>OUTPUT</code>);
11	<code>pinMode</code> (sw_pin, <code>INPUT</code>);
12	<code>pinMode</code> (swGND_pin, <code>OUTPUT</code>);
13	<code>pinMode</code> (trigger_pin, <code>OUTPUT</code>);
14	<code>digitalWrite</code> (sw5V_pin, <code>HIGH</code>);
15	<code>digitalWrite</code> (swGND_pin, <code>LOW</code>);
16	<code>attachInterrupt</code> (<code>digitalPinToInterrupt</code> (2), Trigger_Signal, <code>RISING</code>);
17	}
18	
19	<code>void</code> Trigger_Signal()
20	{
21	<code>delayMicroseconds</code> (Tdelay);
22	<code>digitalWrite</code> (trigger_pin, <code>HIGH</code>);
23	<code>delayMicroseconds</code> (10);
24	<code>digitalWrite</code> (trigger_pin, <code>LOW</code>);
25	}
26	
27	<code>void</code> loop()
28	{
29	<code>if</code> ((<code>digitalRead</code> (sw_pin)) == <code>HIGH</code>)
30	{
31	Tcurrent = <code>millis</code> ();
32	Telepased = (Tcurrent – Tprevious);
33	<code>if</code> (Telapsed >= Tinterval)
34	{
35	Vout = <code>analogRead</code> (voltSensor_pin) / Cnormalise;
36	Err = Vnominal - Vout;
37	Err_sum = (Err_sum + Err) / Tinterval;
38	Derror = (Vout – Vout_previous) / Tinterval;
39	Pcontrol_out = Kp * Err;
40	Icontrol_out = Ki * Err_sum;
41	Dcontrol_out = Kd * Derror;
42	Icontrol_out = <code>constrain</code> (Icontrol_out, 0, Ntotal);
43	PIDcontrol_out = Pcontrol_out + Icontrol_out + Dcontrol_out;
44	PIDcontrol_out = <code>constrain</code> (PIDcontrol_out, 0, Ntotal);
45	Nsample = Ntotal – PIDcontrol_out;
46	Tdelay = Nsample * Tsample;
47	Tprevious = Tcurrent;
48	Vout_previous = Vout;
49	}
50	}
51	}

3.5.1 Declaration of Variables

The program code starts with the declaration of variables, where data types, names, and values are given to the variables. Variables are created to store intermediate values used in the calculation of T_{delay} and pin numbers, and they are declared using the following codes:

```
unsigned long Telapsed, Tcurrent, Tprevious = 0, Tinterval = 10;

float Vout, Vout_previous, Vnominal = 92.0, Cnormalising = 5.173;

float Pcontrol_out, Icontrol_out, Dcontrol_out, PIDcontrol_out;

float Err, Err_sum, Derror, Kp = 2, Ki = 3, Kd=10;

int Tdelay, Tsample = 45, Nsample = 0, Ntotal = 140;

int sw5V_pin = 5, sw_pin = 6, swGND_pin = 7, trigger_pin = 3, voltSensor_pin = A0;
```

The data stored in the variables are listed in Table 3.3.

As it can be seen in the codes, unsigned long, float, and int data types are used in the variable declaration, and their definitions are listed in Table 3.4. The unsigned long data type is used for the variables $T_{elapsed}$, $T_{current}$, $T_{previous}$, and $T_{interval}$, which involve in the calculation of time. Variable $T_{current}$ is used to accumulate the time running in the Arduino. In order to avoid program crashing due to overflow of variable $T_{current}$ in a short time, unsigned long data type is used to allow a total time accumulation of 50 days. All variables involved in PID equations are declared with float data type as the PID tuning involves numbers with decimal places. Meanwhile, int data type is applied for variables T_{delay} , T_{sample} , N_{sample} , and N_{total} , which are used in the calculation of time delay involving integer number. Similarly, int data type is given to the variables storing the pin numbers as each pin is assigned with integer number.

Table 3.3: Data and initial values of variables.

Variable Name	Data Stored	Initial Value
Telapsed	Elapsed time, $T_{elapsed}$	-
Tcurrent	Current time, $T_{current}$	-
Tprevious	Previous time, $T_{previous}$	0
Tinterval	Time interval, $T_{interval}$	10
Vout	Output voltage, V_{out}	-
Vout_previous	Previous output voltage, $V_{out_previous}$	-
Vnominal	Nominal voltage, $V_{nominal}$	92.0
Cnormalising	Normalising constant, $C_{normalising}$	5.173
Err	Error, E_{rr}	-
Err_sum	Sum of error, E_{rr_sum}	-
Derror	Derivation of error, D_{error}	-
Pcontrol_out	Output of proportional control, $P_{control_out}$	-
Icontrol_out	Output of integral control, $I_{control_out}$	-
Dcontrol_out	Output of derivative control, $D_{control_out}$	-
PIDcontrol_out	PID total output, $PID_{control_out}$	-
Kp	Proportional gain, K_p	2
Ki	Integral gain, K_i	3
Kd	Derivative gain, K_d	10
Tdelay	Time delay, T_{delay}	-
Tsample	Sample Time, T_{sample}	45
Nsample	Number of sample, N_{sample}	0
Ntotal	Total sample, N_{total}	140
sw5V_pin	Digital pin 5	5
sw_pin	Digital pin 6	6
swGND_pin	Digital pin 7	7
trigger_pin	Digital pin 3	3
voltSensor_pin	Analogue pin A0	A0

Table 3.4: Definitions of data types.

Data type	Definition
float	Variables that store numbers that have a decimal point and range from -3.4028235E+38 to 3.4028235E+38.
int	Variables that store whole numbers range from -32,768 to 32,767.
unsigned long	Variables that has extended size and store nonnegative whole numbers range from 0 to 4,294,967,295.

Table 3.3 also showed that some variables are assigned with initial values. The values assigned to variables $T_{interval}$, K_i , K_p , and K_d are not absolute, and their values are obtained from the experimental analyses. The variable $T_{previous}$, which records the time when T_{delay} is calculated, is set to zero as the T_{delay} is yet to be calculated at the start of the program. The variable N_{sample} is also set to zero in order to keep the triac at off state at the start of the program. A value of 140 is set to the variable N_{total} . There is no absolute value for the variable, and it can be any value as long as the value is appropriate. Based on the value of N_{total} and generator frequency, the T_{sample} is calculated by using equation:

$$T_{sample} = ((10^6 \div 2f) - 10) \div N_{total} \quad 3.15$$

where f is frequency. The generator implemented in the experiment has a frequency of 80Hz.

Thus, the value of T_{sample} is:

$$T_{sample} = ((10^6 \div (2 \times 80)) - 10) \div 140 = 45\mu s$$

At the meantime, the variable $C_{normalising}$, which is used to normalise the value of $V_{out}(\text{integer})$ into the range of N_{sample} , is calculated as:

$$C_{normalising} = V_{out_max}(\text{integer}) \div N_{total} \quad 3.16$$

Before that, the maximum output voltage (V_{out_max}) in term of integer is calculated by using equations 3.1 and 3.2:

$$V_{out_max}(\text{integer}) = 354\text{V} \div 500\text{V} \times 1023 = 724$$

Then, the value of $C_{normalising}$ is:

$$C_{normalising} = 724 \div 140 = 5.173$$

Lastly, the $V_{nominal}$ is calculated by converting 240V into an integer and later normalised using $C_{normalising}$ as follow:

$$V_{nominal}(\text{integer}) = 240\text{V} \div 500\text{V} \times 1023 \approx 491$$

$$\text{Normalised } V_{nominal}(\text{integer}) = 491 \div 5.173 = 94$$

Thus, $V_{nominal}$ is set to 94.

3.5.2 Setup() Function

The digital pins on the Arduino board can behave either as input or output pins. Those modes must be configured for the pins before being used to read (input) or write (output) digital values. A setup() function is a block of code where the pin modes are configured by using the built-in pinMode(pin number, mode) function as shown in the codes below:

```
void setup()  
  
{  
  
  pinMode(sw5V_pin, OUTPUT);  
  
  pinMode(sw_pin, INPUT);
```

```

pinMode(swGND_pin, OUTPUT);

pinMode(trigger_pin, OUTPUT);

digitalWrite(sw5V_pin, HIGH);

digitalWrite(swGND_pin, LOW);

attachInterrupt(digitalPinToInterrupt(2), Trigger_Signal, RISING);

}

```

The pins named sw5V_pin, sw0V_pin, and trigger_pin are configured as output pins, while pin named sw_pin is configured as input pin. It is noted that, a pin named voltSensor_pin is not included in the configuration of pin mode as analogue pins are input pins by default.

In the same block of code, the sw5V_pin and swGND_pin are configured to output 5V and 0V respectively using a built-in digitalWrite(pin, value) function. The value in the function is set to HIGH for 5V and LOW for 0V (ground). The two pins are used as alternative 5V and 0V signals to the toggle pins switch due to limited 5V and GND (ground) pins on the Arduino board.

As described in Section 3.4.2, an interrupt pin is used to synchronize the starts of the T_{delay} with zero-crossing events in the generation of trigger signal. Hence, an interrupt pin is configured by using an built-in attachInterrupt(digitalPinToInterrupt(pin number), function name, mode) function. There are 3 arguments in the function. The first argument configures the pin 2 as an interrupt pin. The second argument sets the Trigger_signal() function as an Interrupt Service Routine (ISR), and this function is to be called when a zero-crossing point is detected. Lastly, the third argument defines the interrupt should be triggered when the voltage at pin 2 rises from 0V to 5 V.

3.5.3 Loop() Function

A loop() function does precisely what its name suggests, and loops consecutively, allowing the program to change and respond. This is where the instructions for the main algorithm are located, as shown in the codes below:

```
void loop()  
  
{  
  
  Instructions for main algorithm...  
  
}
```

An if statement block is used to check a certain condition has been met or not, and if so, it executes the code within its block. Based on the formulated main algorithm, there are two conditions need to be checked before the calculation of T_{delay} . Hence, there are two blocks of if statement in the loop() function, as shown in the codes below:

```
if ((digitalRead(sw_pin)) == HIGH)  
  
{  
  
  Tcurrent = millis();  
  
  Telepased = (Tcurrent – Tprevious);  
  
  if (Telapsed >= Tinterval)  
  
  {  
  
    Calculation of Tdelay... ...  
  
  }  
  
}
```

The first if statement is used to check whether the value of sw_pin is HIGH or not by using ‘==’ (equal to) operator. The value of sw_pin is obtained by using a built-in digitalRead(pin)

function, which is used specifically to read the value from a digital pin that is either HIGH (5V) or LOW (0V). The second if statement is inside the first if statement, and it is used to check whether the value of $T_{elapsed}$ is greater than or equal to $T_{interval}$ or not by using the ' $\geq$ ' (greater than or equal to) operator. The value of $T_{elapsed}$ is obtained by using equation 3.3. Before that, a built-in millis() function is used to obtain the latest time of the Arduino internal clock, and the returned value is assigned to $T_{current}$.

All the codes for calculating the T_{delay} are located in the second if statement block, and they are shown in the following codes:

```
Vout = analogRead(voltSensor_pin) / Cnormalise;
Err = Vnominal - Vout;
Err_sum = (Err_sum + Err) / Tinterval;
Derror = (Vout - Vout_previous) / Tinterval;
Pcontrol_out = Kp * Err;
Icontrol_out = Ki * Err_sum;
Dcontrol_out = Kd * Derror;
Icontrol_out = constrain(Icontrol_out, 0, Ntotal);
PIDcontrol_out = Pcontrol_out + Icontrol_out + Dcontrol_out;
PIDcontrol_out = constrain(PIDcontrol_out, 0, Ntotal);
Nsample = Ntotal - PIDcontrol_out;
Tdelay = Nsample * Tsample;
Tprevious = Tcurrent;
Vout_previous = Vout;
```

In order to calculate the T_{delay} , the analogue $V_{out}(DC)$ from the voltage sensor to voltSensor_pin is read by using a built-in analogRead(pin) function, which reads the value

input voltage from the specified analogue pin and maps the value map input voltages between 0 and 5 volts into integer values between 0 and 1023. Then, the value is directly normalised and assigned to variable V_{out} . After that, the following codes are written based on equations 3.3 to 3.14. The modifications are done by replacing the ‘ $\times$ ’ symbol and ‘ $\div$ ’ symbol with ‘*’ operator and ‘/’ operator respectively in the program code.

3.5.4 Trigger_Signal() Function

A Trigger_Signal() function block is created for the generation of trigger signal. The codes inside the function are:

```
void Trigger_Signal()
{
    delayMicroseconds(Tdelay);
    digitalWrite(trigger_pin, HIGH);
    delayMicroseconds(10);
    digitalWrite(trigger_pin, LOW);
}
```

In the function, an amount of delay equal to T_{delay} in the unit of μs is generated by using a built-in `delayMicroseconds(integer)` function. Then a 5V is output to the `trigger_pin` so the triac is switched on for conduction by using the `digitalWrite(pin, value)` function. Again, another delay about $10\mu\text{s}$ is put into the program so that the 5V last for $10\mu\text{s}$. After that, again, `digitalWrite(pin, value)` function is used to output 0V to the `trigger_pin`.

3.6 Software

An Arduino Integrated Design Environment (IDE), a Proteus Virtual System Modelling (VSM), a National Instruments (NI) LabVIEW SignalExpress are the three pieces of software that were used in this research, and they are explained hereafter.

3.6.1 Arduino Integrated Design Environment (IDE)

As shown in Figure 3.14, an Arduino IDE is open-source-software that used to write code and upload control programs to Arduino microcontroller boards. The environment is written in Java and based on Processing and other open-source software. The Arduino IDE supports both C and C++ programming languages for programming the microcontrollers.



Figure 3.14: Arduino IDE.

3.6.2 Proteus Virtual System Modelling (VSM)

The Proteus virtual system modelling (VSM) is a combination of SPICE circuit simulation, animated components, and microprocessor models to facilitate the simulation of complete microcontroller based designs, as shown in Figure 3.15. The software allows the execution of program code like a real chip, and it enables the interaction between program running on a microcontroller and any analogue or digital electronics connected to it.

Hence, Proteus VSM allows the ELC circuit design to be developed and tested before the construction of a physical prototype. The software also helps to test and verify the program code developed.

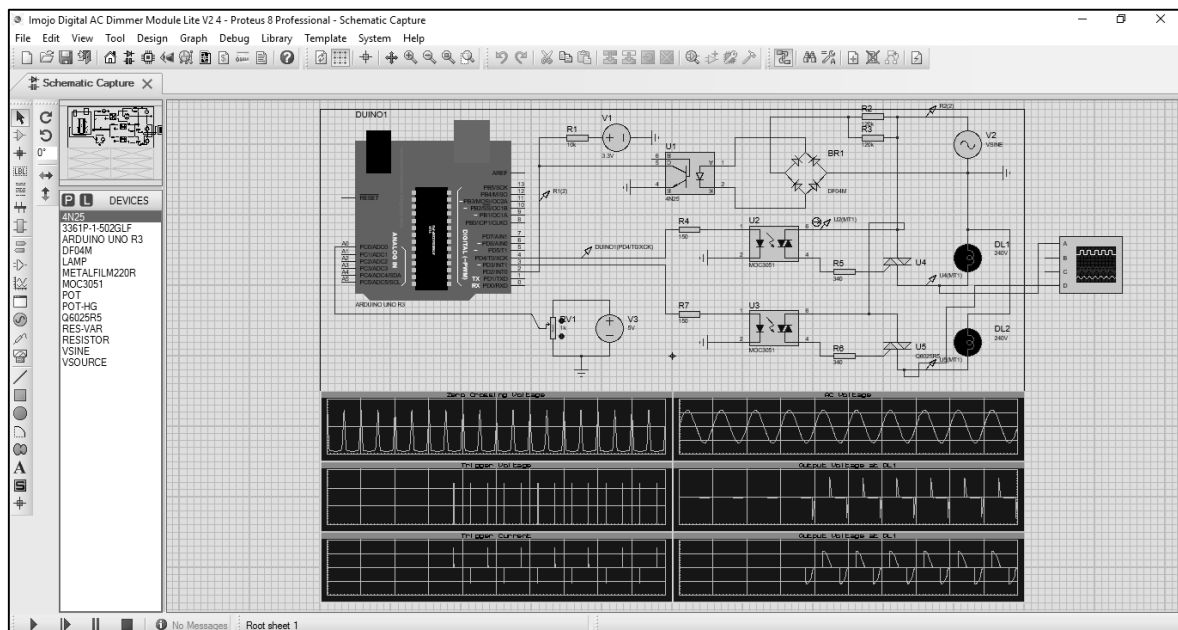


Figure 3.15: Proteus VSM.

3.6.3 National Instruments (NI) LabVIEW SignalExpress

LabVIEW SignalExpress Tektronix Edition is a fully interactive measurement acquisition, analysis, and documentation software, as shown in Figure 3.16. It includes Universal Serial Bus (USB) plug-and-play automatic configuration and connectivity with Tektronix Instruments. Hence, by connecting a Tektronix instrument to a PC through a USB cable, the software can automatically detect the instrument and takes control of the oscilloscope or arbitrary/function generator and acquire or generate signals immediately.

However, in practical, a delay occurs between the displayed data on oscilloscope and recorded data in the computer. As an alternative, this software acquires the waveform data using a Universal Serial Bus (USB) flash drive. Its application is further explained in Section 3.8.2.

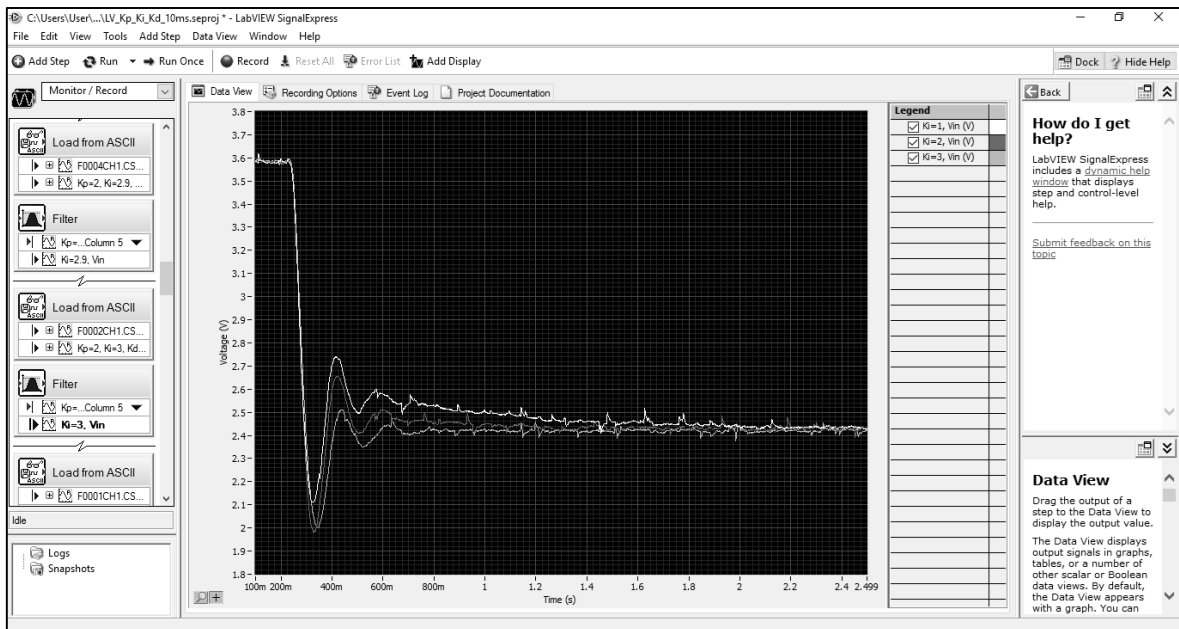


Figure 3.16: LabVIEW SignalExpress Tektronix Edition.

3.7 Laboratory Setup

Figure 3.17 shows a setup for laboratory tests. The setup consists of a motor-generator set, a motor speed controller, a digital multimeter, an oscilloscope, a tachometer, switches, and light bulbs. A block diagram of the laboratory setup is shown in Figure 3.18. It is noted that, the ELC in this research is designed to regulate the output voltage of a synchronous generator (SG) with a maximum power of 3kW and a frequency of 50Hz. However, due to the limited research facilities, an induction generator (IG) with a maximum power of 460W and a frequency of 80Hz is used for testing the ELC during the experimental tests. The induction generator has a maximum voltage of 354VAC.

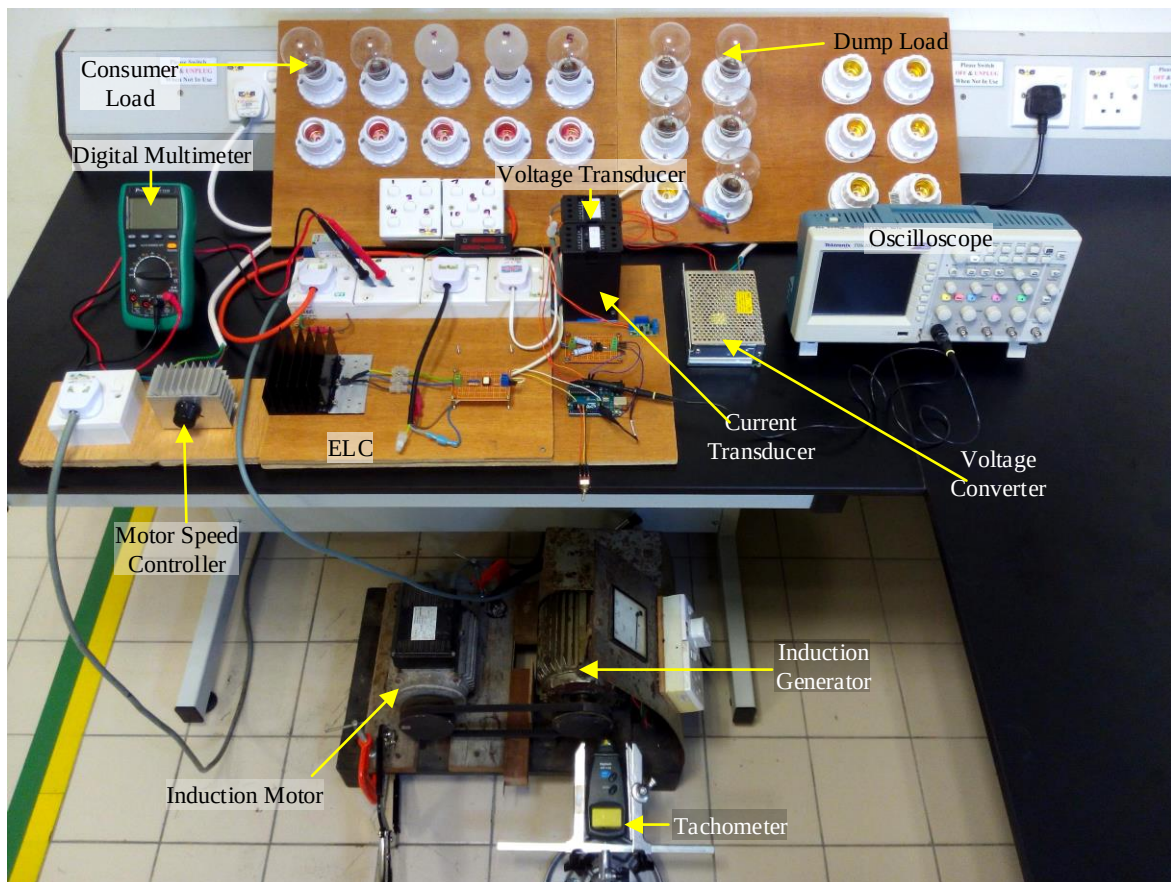
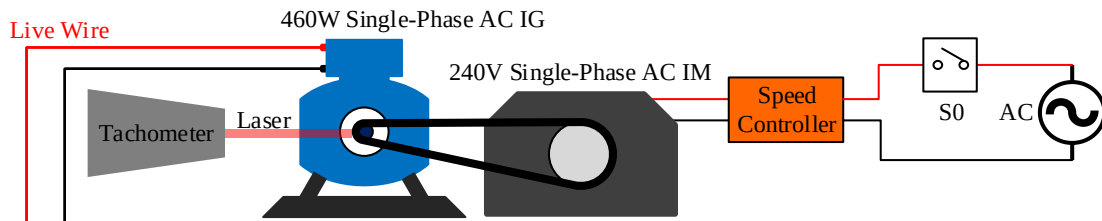


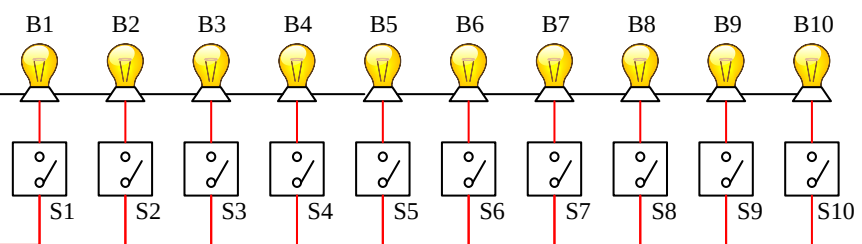
Figure 3.17: Laboratory setup.

Section 1: Micro-hydro Power System



Neutral Wire

Section 2: Consumer Load



Section 3: Electronic Load Controller (ELC) System

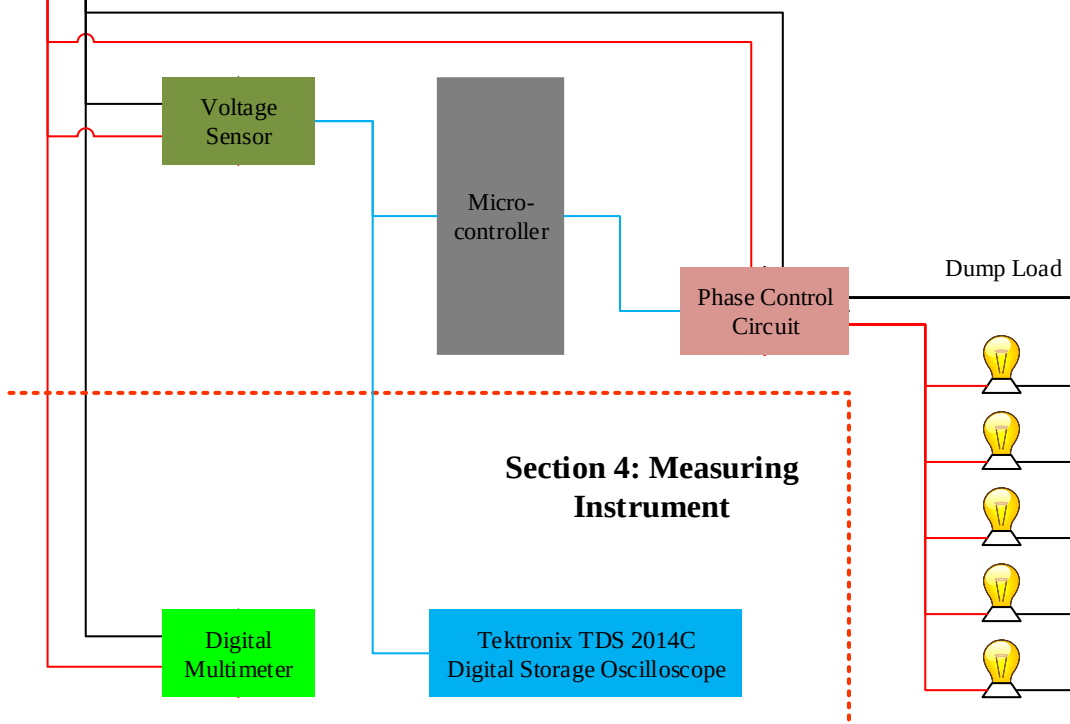


Figure 3.18: Block diagram of laboratory setup.

As it can be seen in Figure 3.18, the setup could be divided into four sections: (1) micro-hydroelectric power system, (2) consumer load, (3) ELC system, and (4) measuring instruments.

In the first section, a 240V single-phase AC induction motor (IM) and a 460W single-phase AC IG are set to mimic the turbine-generator set in micro-hydroelectric system. A 240V AC power is supplied to the IM through a switch and a motor speed controller, which is used to vary the rotational speed of the IM.

The second section has the setup for simulating the variation of consumer load. In the setup, 10 bulb holders connected in parallel to the output terminals of the IG. Each bulb is connected in series with its own switch. Depending on the types of tests, different numbers of light bulb are installed into the bulb holders. The consumer load on the generator is then varied by switching the bulbs on or off.

The third section is where the designed ELC system is installed. Both of its voltage sensor and phase control circuit are connected in parallel to the output terminals of the IG.

Lastly, in the fourth section, measuring instruments are prepared to obtain data for analyses. A digital multimeter is used to measure the output voltage (V_{out}), output current (I_{out}), and output frequency (f_{out}) of the IG. A digital storage oscilloscope is used to obtain the transient waveforms of V_{out} . Besides that, a digital photo laser tachometer is used to measure the rotational speed (v) of the IG, and it is illustrated in the first section of the block diagram as it is used near the IG's shaft.

3.8 Laboratory Tests

By using the laboratory setup, steady-state and transient analyses of IG, PID tuning, and load variation test are conducted, and the procedure for each test is explained in the following subsections. It is noted that, in the tests, the quantity of consumer load is expressed in term of power and labelled as P_{CL} .

3.8.1 Steady-State Analysis of IG

A steady-state analyses of IG is conducted to understand how the steady-state values of rotational speed (v), output voltage (V_{out}), output current (I_{out}), and output frequency (f_{out}) of IG change during the increasing and decreasing of consumer loads. The steady-state value of a system response variable is the constant value achieved by the variable after the system responded to a change in the system input.

Data is first obtained for the IG with increasing consumer load. The IM is switched on to its maximum speed. Then, by using six pieces of 100W light bulbs, the consumer load (P_{CL}) on the IG is increased in step of 100W starting from no load condition. For each connected consumer load, the steady-state values of the four response variables (v , V_{out} , I_{out} , and f_{out}) are measured and recorded. After that, results are obtained for the IG with decreasing consumer load by removing the light bulbs one by one. The steady-state analysis of the IG with increasing consumer load is repeated for another set of load, which consists of one 15W, two 40W, two 60W, and two 100W light bulbs. The data obtained are used to identify the relationship between the V_{out} and the increasing load.

3.8.2 Transient Analysis of IG

A transient analysis of IG is conducted to understand the transient response of IG's V_{out} at the application and removal of consumer load. A transient response is the momentary response of a system output to a change in the system input from a steady-state. During the transient response, the system output varies and dies out with time to reach a new steady-state.

In this experiment, four pieces of 100W light bulbs are used to form different amount of loads: 100W, 200W, 300W, and 400W. Then, each amount of load is applied to the IG under load condition, and then, the load is removed from the IG. For each load change, the transient waveform of V_{out} is recorded by using the oscilloscope. As an example, Figure 3.19 shows an oscilloscope screenshot of a V_{out} waveform generated during the connection of first 100W load on the IG. The recorded transient waveforms of V_{out} are analysed by using the LabVIEW SignalExpress software. This is done by first saving the data of waveforms from oscilloscope to files (.CSV) on a USB flash drive. The .CSV file type is a file that contains ASCII text strings that list the time (relative to the trigger) and amplitude values for each of the 2500 waveform data points. After that, the files are transferred into the PC. Then, the waveforms are loaded in the software by using the *Load from ASCII* function, as shown in Figure 3.20. Also, by using the *Filter* function in the software, the waveforms are filtered to reduce the noise generated from the voltage sensor, as shown in Figure 3.21.

By using the obtained waveforms and the cursors in the software, the settling time ($t_{settling}$) of V_{out} , which is the time required for the V_{out} to reach its steady-state value after a load change, are measured by putting the first cursor at the instant that load connected or disconnected and the second one at the steady-state value, as shown in Figure 3.22.

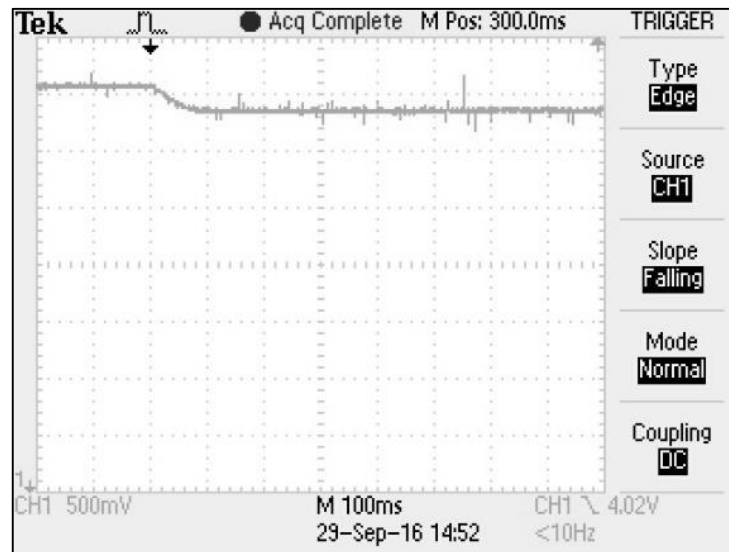


Figure 3.19: Screenshot from oscilloscope.

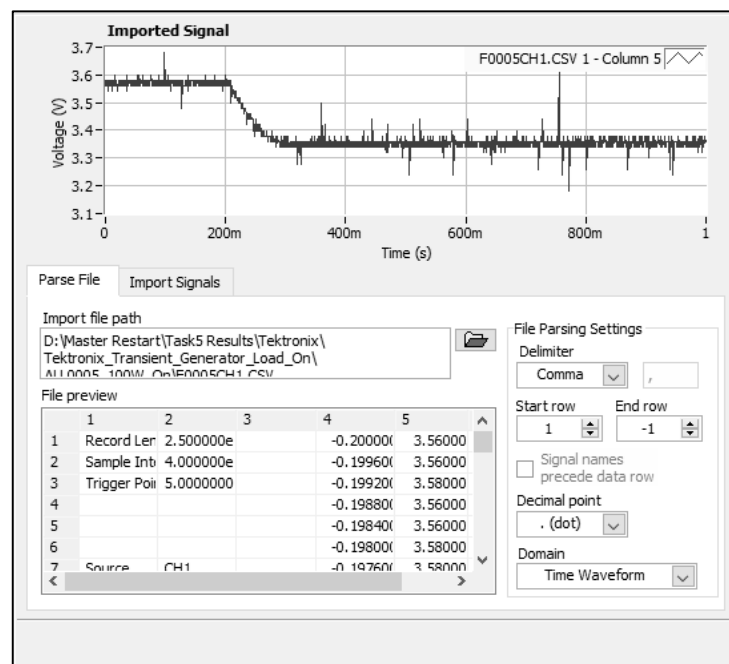


Figure 3.20: Import of signals from a file to LabVIEW SignalExpress.

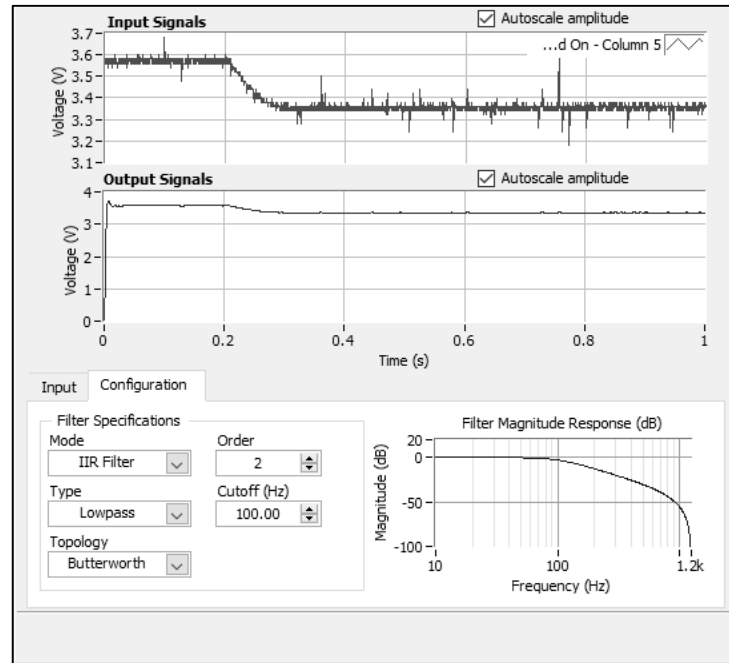


Figure 3.21: Noise filtering.

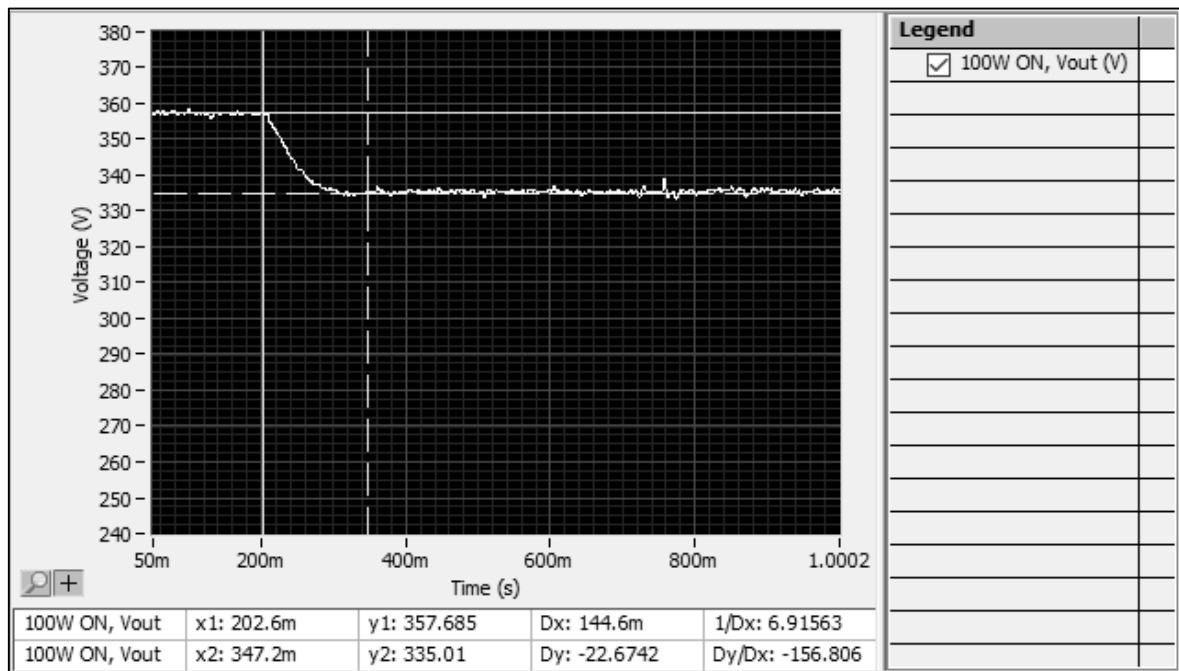


Figure 3.22: Measurement of t_{settling} .

3.8.3 PID Tuning

A PID tuning is a process that adjusts the values of PID control parameters (K_p , K_i , and K_d) to optimum values for the desired control response. Since guideline yet to be existed, it is assumed that fast ELC response is important during the voltage regulation. Hence, the control parameters are tuned to have a transient response with shortest $t_{setling}$. By implementing trial and error method, the parameters are tuned sequentially from K_p to K_i , and then to K_d . And, the optimum value of each parameter is obtained by testing the values and using the settings as shown in Table 3.5.

Table 3.5: Values and settings for PID tuning.

Parameter	Value		Setting
	1 st Set	2 nd Set	
K_p	1, 2, 3, 4, and 5	$K_p^* \pm 0.1$	$K_i = 0; K_d = 0; T_{interval} = 10\text{ms}$
K_i	1, 2, 3, 4, and 5,	$K_i^* \pm 0.1$	$K_p = K_p^{**}; K_d = 0; T_{interval} = 10\text{ms}$
K_d	10, 20, 30, 40 , and 50	$K_d^* \pm 1$	$K_p = K_p^{**}; K_i = K_i^{**}; T_{interval} = 10\text{ms}$
(*) – Selected number from 1 st set numbers; (**) – Selected number from 2 nd set numbers			

For every test, the variables K_p , K_i , and K_d in the program code are set according to Table 3.5, and the program is then loaded into the Arduino UNO. Once the program is ready, the IM is turned to drive the IG at maximum speed. Then, the toggle switch is switched from 0V to 5V to start the voltage regulation program under no consumer load condition. By using similar procedures in Section 3.8.2, the transient waveforms of V_{out} are obtained for all the tested values. Then, t_{rise} , PO , $t_{setling}$, and e_{ss} are measured for each waveform. By comparing the measured data, an optimum value is selected for each parameter.

In this research, $T_{interval}$ is included into the PID tuning in order to identify its optimum value. This is done by obtaining three sets of K_p , K_i , and K_d values tuned under three different values of $T_{interval}$, which are 5ms, 30ms, and 60ms. For each set of K_p , K_i , and K_d , five samples of V_{out} waveforms are obtained. At the same time, t_{rise} , PO , $t_{settling}$, and e_{ss} are measured and recorded for the five waveforms, and their average values are calculated and recorded. Lastly, the optimum value of $T_{interval}$ is selected by comparing the average values of t_{rise} , PO , $t_{settling}$, and e_{ss} obtained for the three sets of K_p , K_i , and K_d .

By using the optimum values of K_p , K_i , K_d , and $T_{interval}$ values obtained from the PID tuning, the load application and load removal are used for the assessment of performance of the proposed ELC. For that purpose, a current sensor and a current-to-voltage converter as shown in Figure 3.23 and Figure 3.24, respectively, are used to indicate the power consumption of the consumer load on the oscilloscope. The current sensor is first used to measure the current signal. Then, the current signal is converted to voltage signal by using current-to-voltage converter.

Figure 3.23: AC 0-5A to DC 4-20mA current sensor (TEC-AI1B1).

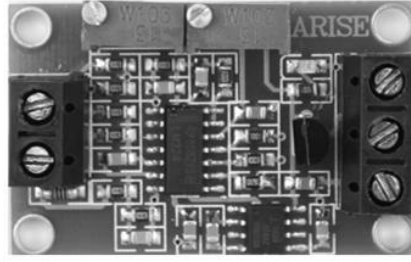


Figure 3.24: DC 4-20mA to 0-5VDC current-to-voltage converter (ASC201-V1.0).

Initially, the IM is powered to rotate the IG for electricity generation. Under no load condition, the output voltage of the IG is regulated by using the ELC. Then, a 240W load switched on, therefore connected to the IG. Then, the 240W load is switched off and disconnected from the IG. Again, by using the similar procedure in Section 3.8.2, the transient waveforms are obtained for that two situations. Also, t_{rise} , PO , $t_{settling}$, and e_{ss} are measured and recorded.

3.9 Summary

The proposed digital ELC consists mainly of a voltage sensor, an Arduino UNO board loaded with PID control based program, a phase control circuit, and a 3kW resistive dump load. It operates by continuously measuring the output voltage (V_{out}) from the voltage sensor and generate triac trigger signal to the triac circuit. Based on the PID control concept, every measured value of V_{out} is responded by calculating its deviation from the value of the nominal voltage ($V_{nominal}$), which is 240V for Malaysia. Then, the deviation is reduced by adjusting the value of time delay (T_{delay}) of the triac trigger signal. T_{delay} acts as the control variable of PID control, and it controls the amount of power delivered to the dump load. The desired value of T_{delay} is calculated by using the PID equations. The ELC is tested by using

a laboratory setup, which consists of a motor-generator set, a motor speed controller, a digital multimeter, an oscilloscope, a tachometer, switches, and light bulbs. By using the laboratory setup, steady-state and transient analyses of IG, PID tuning, and load variation test are conducted.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides all the results of the laboratory tests conducted in this research. First of all, the steady-state and transient behaviours of the induction generator (IG) under increasing and decreasing consumer loads are discussed. Next, justifications are provided for the tuning effects of the four PID parameters. A summary is also provided for the PID tuning. Then, the overall performance of the designed ELC is analysed based on the results from load variation test. Another PID tuning with less overshoot, which is conducted to improve the ELC performance and draw up a guideline for the PID tuning in ELC, is also reported here.

4.2 Steady-State Analysis of IG

Table 4.1 shows the data obtained from the steady-state analysis of the IG with increasing consumer load. Based on the data, a graph of output voltage (V_{out}) and output current (I_{out}) versus consumer load (P_{CL}) is plotted as shown in Figure 4.1. Another graph of rotational speed (v) and output frequency (f_{out}) versus P_{CL} is also plotted using the data, as shown in Figure 4.2.

Table 4.1: Steady-state behaviour of IG with increasing consumer load.

P_{CL} (W)	v (rpm)	f_{out} (Hz)	V_{out} (V)	I_{out} (A)
0	2607	86.40	354.6	0.00
100	2570	84.86	333.3	0.45
200	2541	83.49	309.8	0.96
300	2515	82.26	282.6	1.42
400	2506	81.58	253.8	1.80
500	2518	81.56	210.6	2.08
600	2689	0.00	0.007	0.06

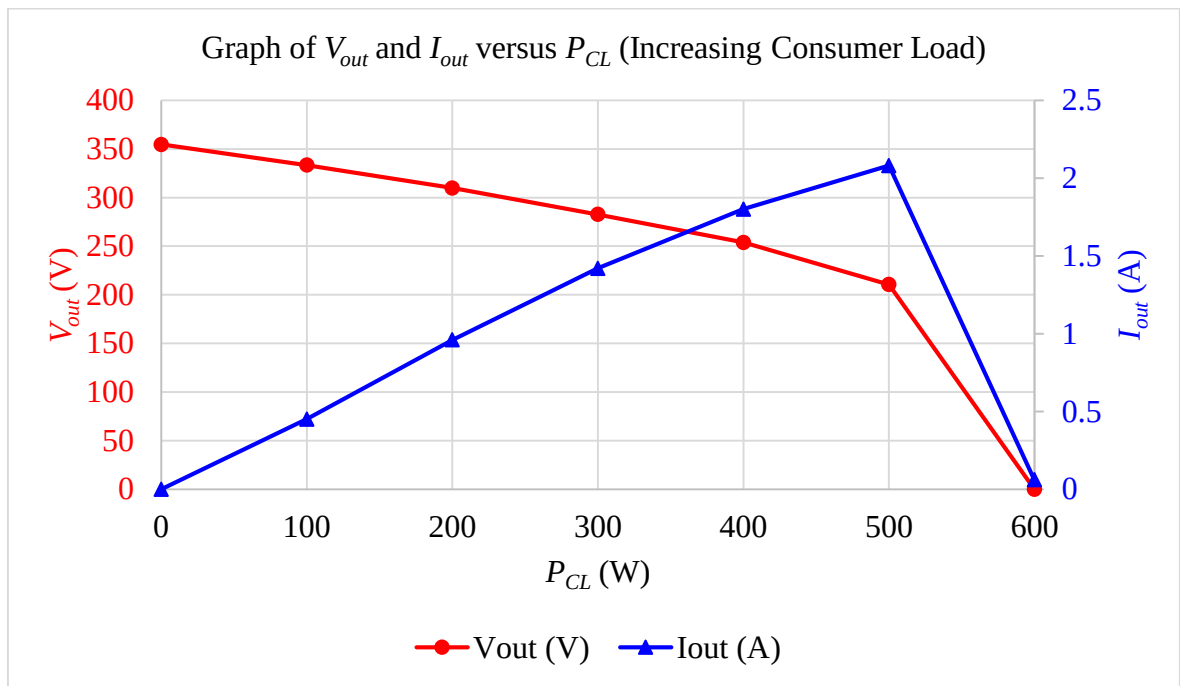


Figure 4.1: Graph of V_{out} and I_{out} versus P_{CL} (increasing consumer load).

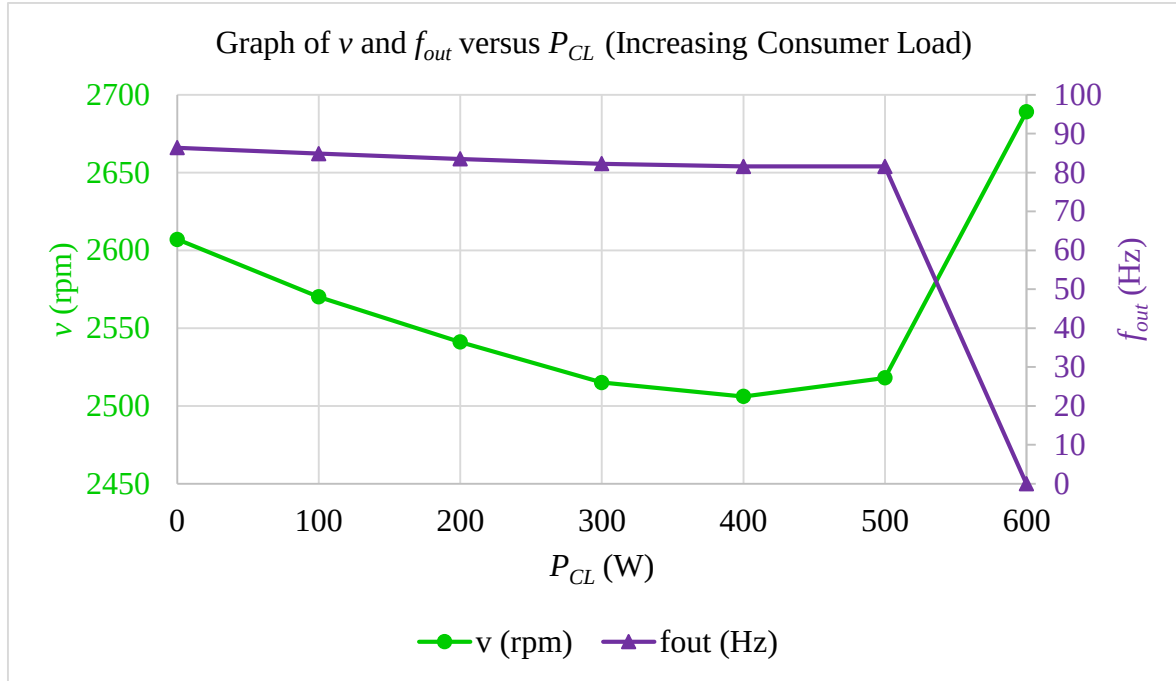


Figure 4.2: Graph of v and f_{out} versus P_{CL} (increasing consumer load).

It can be seen from Figure 4.1 and Figure 4.2, the values V_{out} and f_{out} were highest when there was no load connected to the IG. By referring to the top highlighted row in Table 4.1, under $I_{out} = 0A$ (no load condition) and $v = 2607rpm$ (maximum rotational speed), the IG produced a maximum V_{out} of 354.6V and a maximum f_{out} of 86.40Hz. When a 100W of consumer load was switched on and drew 0.45A from the IG, the variables v , V_{out} , and f_{out} dropped to 2570rpm, 333.3V, and 84.86Hz, respectively. The three variables were further decreased when more consumer loads were connected to the generator and more output currents were drawn from the generator. This is due to the load effect on the generator as explained in Section 2.2.

Since the IG has a maximum output power of 460W, hence it was overloaded when the consumer load was rose up to 500W. As it can be seen in the bottom highlighted row in Table 4.1, the values of V_{out} and f_{out} still followed the previous trend whereby the V_{out} and

f_{out} were further decreased as the consumer load was increased from 400W to 500W. However, the variable v was increased to 2518rpm, and this indicates that the excitation voltage of the IG became weaker.

When the IG was further overloaded with total 600W load, all the values of V_{out} , I_{out} , and f_{out} dropped significantly and nearly to zero. This is because excessive load causes the excitation to collapse (Smith, 1994). Consequently, the IG was rotating without the electromagnetic field at the rotor and loosely at a speed of 2689rpm, which was the higher than the rotational speed of IG under no load condition.

Table 4.2, on the other hand, shows the data obtained from the steady-state analysis of IG with decreasing consumer load. A graph of V_{out} and I_{out} versus P_{CL} and a graph of v and f_{out} versus P_{CL} for the case of decreasing consumer load are also plotted as shown in Figure 4.3 and Figure 4.4, respectively.

Table 4.2: Steady-state behaviour of IG with decreasing consumer load.

P_{CL} (Rated) (W)	v (rpm)	f_{out} (Hz)	V_{out} (V)	I_{out} (A)
500	2516	81.34	210.1	2.08
400	2506	81.37	253.1	1.80
300	2515	82.17	282.9	1.42
200	2541	83.33	308.9	0.96
100	2570	84.69	332.8	0.45
0	2604	86.16	354.1	0.00

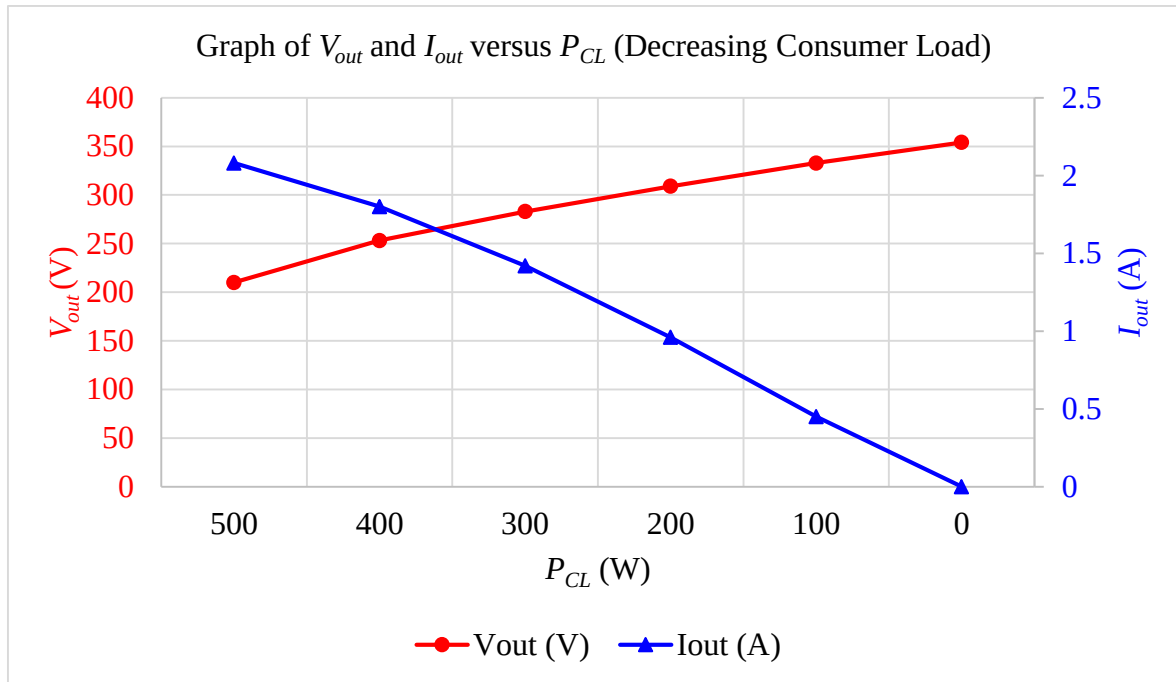


Figure 4.3: Graph of V_{out} and I_{out} versus P_{CL} (decreasing consumer load).

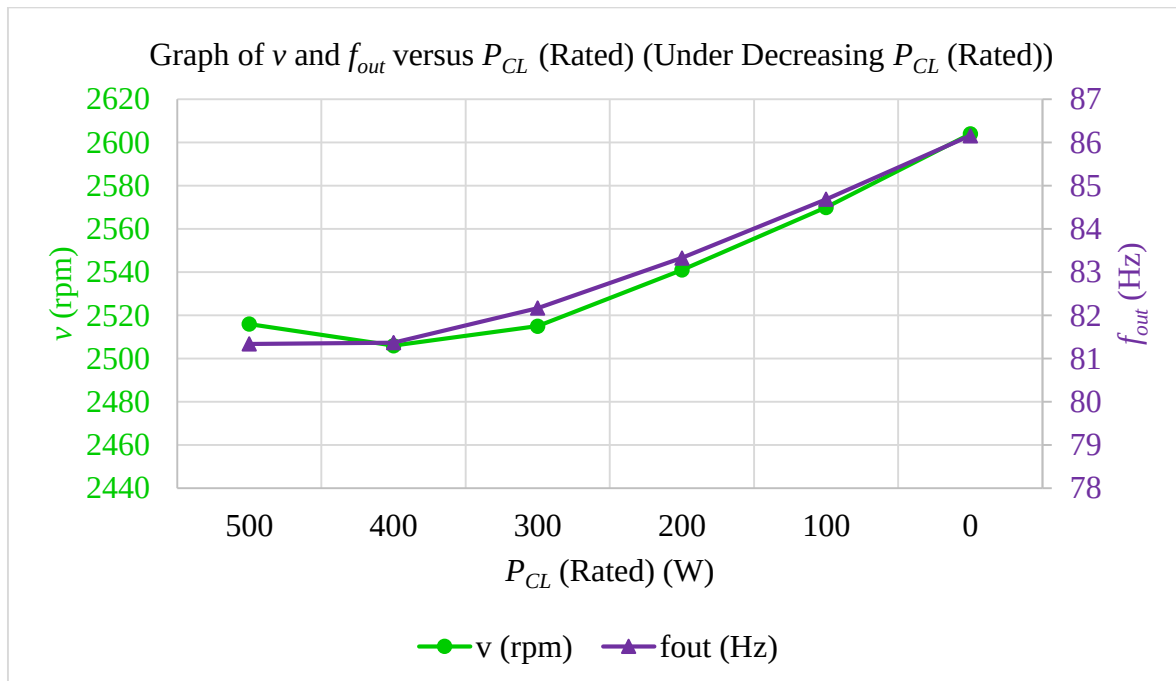


Figure 4.4: Graph of v and f_{out} versus P_{CL} (decreasing consumer load).

Conversely, the variables v , V_{out} , and f_{out} were increased as the consumer load on the IG was reduced from 500W to 0W and the I_{out} decreased from 2.08A to 0A, as illustrated in Figure 4.3 and Figure 4.4. By comparing the data in the two highlighted rows, the variable v at 500w load was higher than that at 400W. Again, the generator showed the sign of overloaded when it was connecting with 500W load. The data obtained in Table 4.2 are nearly the same with that in Table 4.1 but in different order. This is because the repulsion effect is proportional to the amount of current drew by the load as mentioned in Section 2.2.

Table 4.3 presents another set of data obtained from another steady-state analysis on the IG using the another set of consumer load, which was formed using different values of load. Based on the data in the table, another graph of V_{out} and f_{out} versus P_{CL} (actual) is plotted, as shown in Figure 4.5. This time, P_{CL} (actual), which is the actual power of the consumer load calculated using the V_{out} and I_{out} , is used as the value of x-axis. Before this, the used P_{CL} is the nominal power of the used light bulb.

Table 4.3: Steady-state behaviour of IG under increasing P_{CL} (smaller values).

P_{CL}	v (rpm)	f_{out} (Hz)	V_{out} (V)	I_{out} (A)	P_{CL} (Actual) (W)
0	2606	86.47	354.6	0.00	0.0
100	2570	84.88	333.4	0.49	163.4
200	2540	83.57	309.7	0.99	306.6
260	2522	82.77	294	1.25	367.5
320	2512	82.28	278.3	1.51	420.2
360	2508	81.85	265.5	1.68	446.0
400	2504	81.49	251.9	1.82	458.5
415	2502	81.38	239.9	1.93	463.0

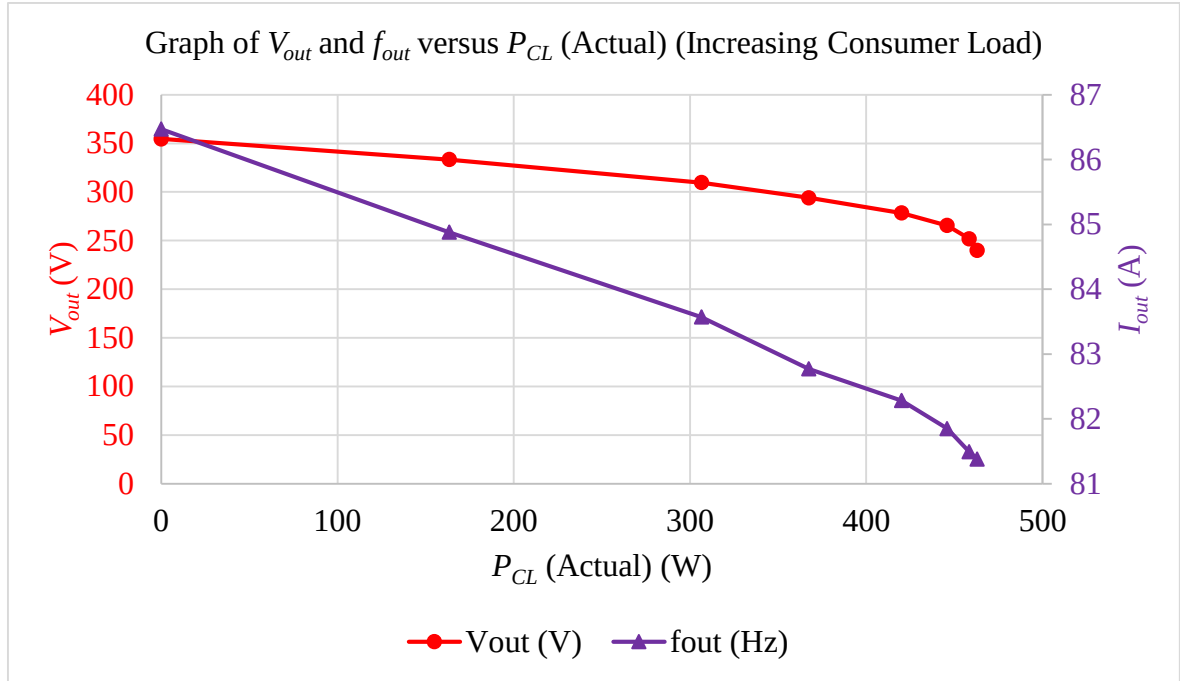


Figure 4.5: Graph of V_{out} and I_{out} versus P_{CL} (actual) (increasing consumer load).

Figure 4.5 clearly shows the relationship between V_{out} and load variation and the relationship of V_{out} and load variation. V_{out} is not directly proportional P_{CL} . Similarly, f_{out} is not directly proportional P_{CL} . Furthermore, the change in f_{out} is corresponding to the change in V_{out} . This is because both the V_{out} and f_{out} are influenced by rotational speed of the generator. Therefore, the regulation of V_{out} is equal to the regulation f_{out} .

4.3 Transient Analysis of IG

Figure 4.6 and Figure 4.7 illustrate the transient waveforms of V_{out} at the application and removal of consumer load, respectively. Table 4.4 shows the $t_{settling}$ of V_{out} measured from the waveforms of both conditions.

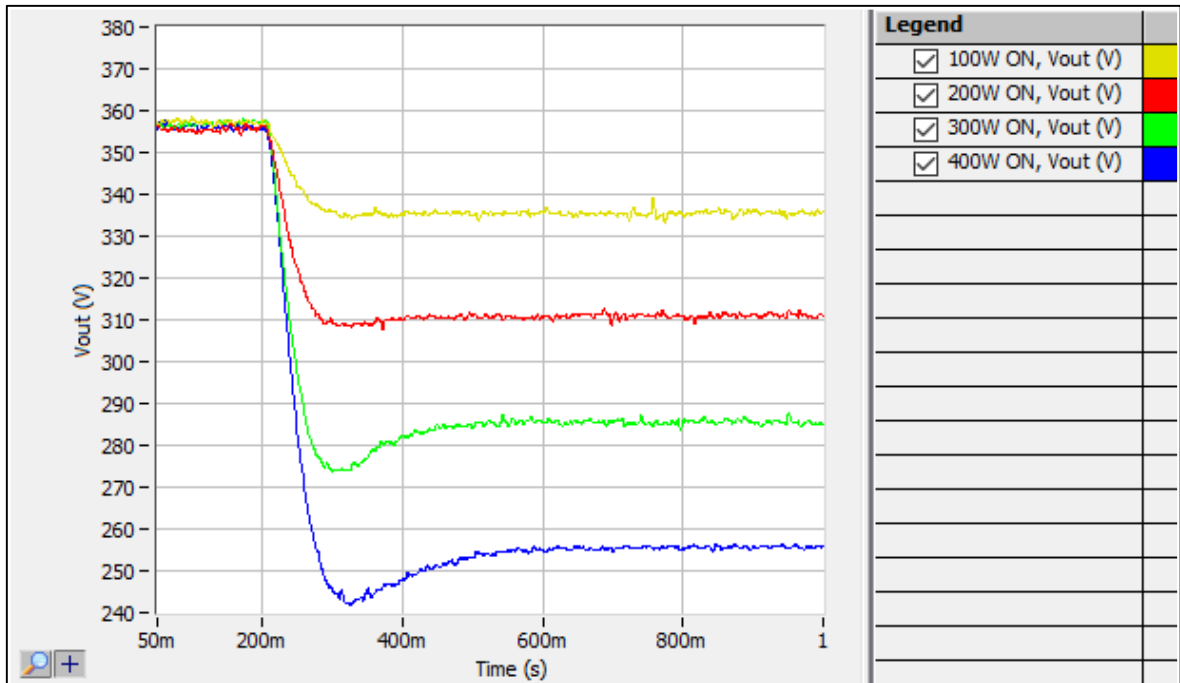


Figure 4.6: Transient waveforms of V_{out} of IG at the application of loads.

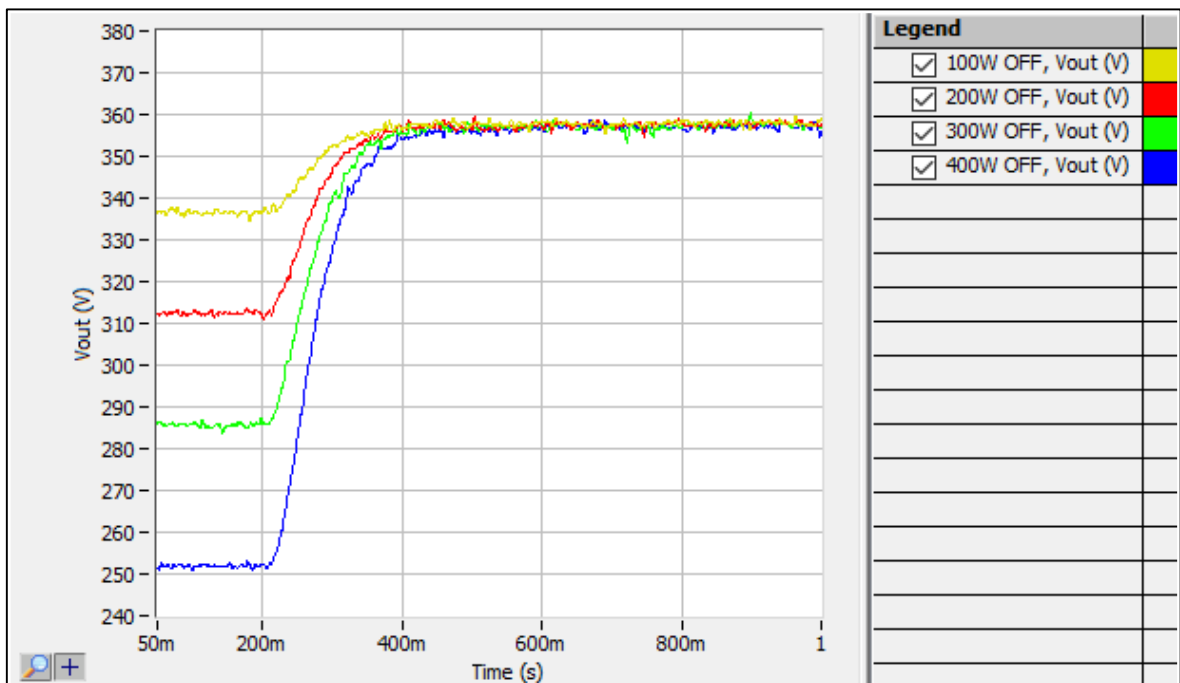


Figure 4.7: Transient waveforms of V_{out} of IG at the removal of loads.

Table 4.4: Settling time of V_{out} of IG at the application and removal of load.

Consumer Load (W)	$t_{settling}$ (ms)	
	Application	Removal
100W	144.4	184.4
200W	208.8	195.6
300W	306.4	213.2
400W	386.4	230.8

It was observed that the durations of voltage transients increased for both conditions. During the application of consumer load, the settling time ($t_{settling}$) increased from 144.4ms to 386.4ms. Meanwhile, $t_{settling}$ increased from 184.4ms to 230.8ms during the removal of consumer load. Also, longer time is needed for the V_{out} to reach its steady-state value during load connection than that during load disconnection. It is also observed that V_{out} overshoot more when more loads were added to the IG output.

4.4 PID Tuning

From the steady-state analysis of IG, it was identified that the V_{out} is nonlinearly proportional to P_{CL} . In fact, PID control unable to perform optimally when dealing with a nonlinear system. Despite that, it still can perform sub-optimally in a nonlinear system if it is tuned properly. In this research, the PID control was tuned based on the voltage regulation of the IG under no load condition, which is the worst case of loading condition. As observed in Figure 4.6, the V_{out} of the IG responded with large negative overshoot and long $t_{settling}$ when it was loaded with nearly maximum load under no load condition.

The trial and error method was applied to tune the PID gains as it did not require any complex mathematical modelling and simulation. Also, it might allow the tuning process to be easily and practically conducted on site, the users themselves. This method will become relatively easy once the significance of each PID gain on the IG output is identified. Hence, the results from PID tunings are not just for obtaining the optimal values of the gain but also provide a study on the tuning effects of the PID gains on the IG output voltage.

4.4.1 Tuning of Proportional Gain

Figure 4.8 shows the transient waveforms of V_{out} for K_p values from 1 to 5 in step of 1. Table 4.5 listed the measured rise time (t_{rise}), percentage of overshoot (PO), settling time ($t_{settling}$), and steady-state error (e_{ss}) of the transient response of V_{out} for each K_p value. It is noted that, the K_i and K_d tunings were deactivated by setting $K_i = 0$ and $K_d = 0$ during the K_p tuning.

As it can be seen in Figure 4.8, with $K_p = 0$, $K_i = 0$, and $K_d = 0$, the regulation of V_{out} was not performed by the ELC, and the V_{out} was at its maximum value of 354V. Hence, a straight line (in yellow colour) was laid near to 360V and far away from the line of $V_{nominal}$ (240V). Once the K_p tuning was started by giving it a value of 1, the ELC worked as a proportional controller and regulated the V_{out} to 290V. The transient response of V_{out} during regulation behaved more likely as a damped sinusoidal signal. As K_p was further increased, the deviation of steady-state of V_{out} waveform from the line of $V_{nominal}$ became smaller. This showed that the positive effect of K_p tuning in reducing the steady-state error (e_{ss}) of V_{out} . Based on the data in Table 4.5, e_{ss} was reduced from 49V to 23V as K_p was increased from 1 to 4. Therefore, e_{ss} was decreased as K_p was increased.

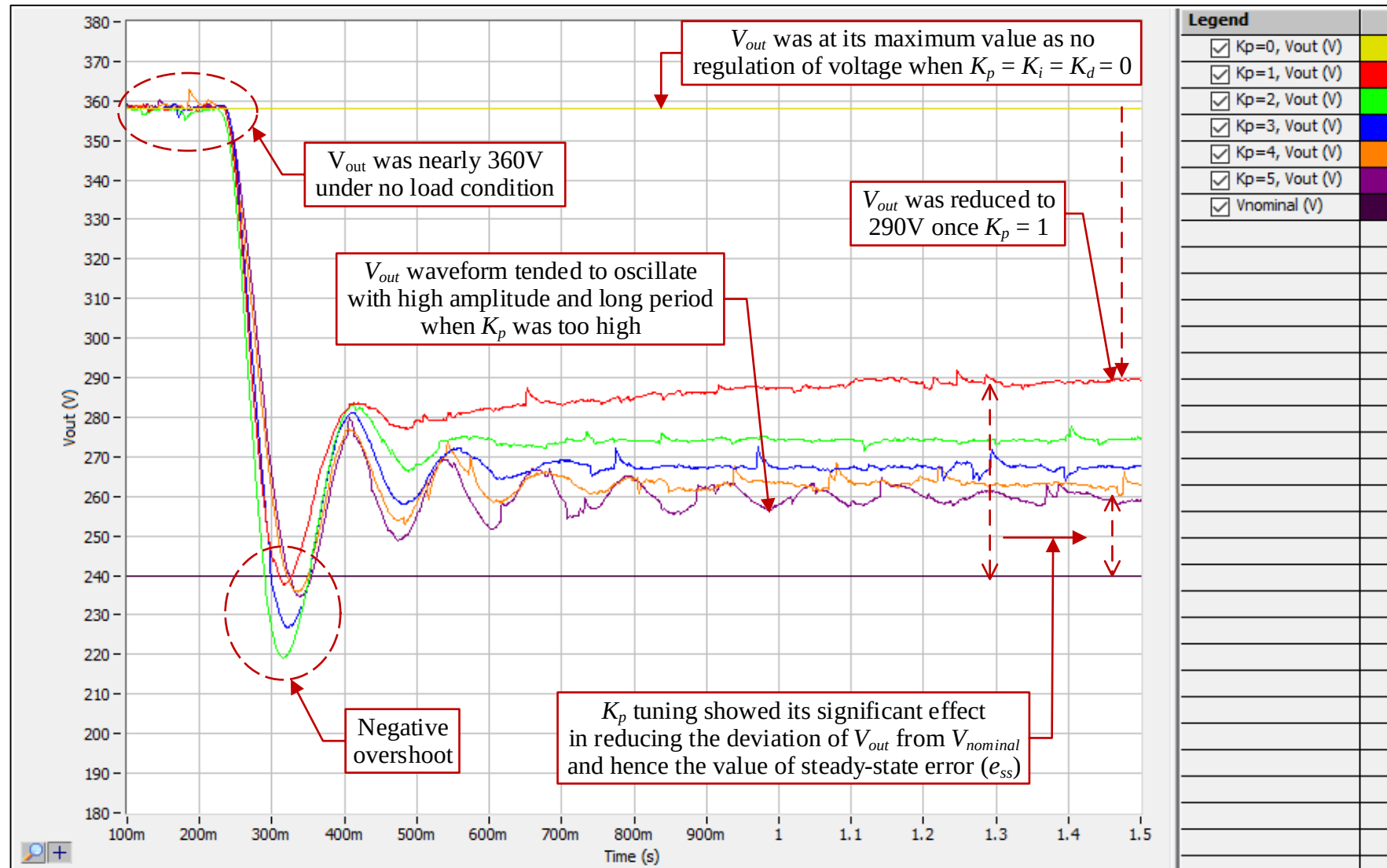


Figure 4.8: Transient waveforms of V_{out} for K_p values from 1 to 5 in step of 1.

Table 4.5: Transient responses of V_{out} for K_p values from 1 to 5 in step of 1.

K_p	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
1	27	17.98	1282	49
2	30	20.06	476	34
3	38	15.20	534	27
4	47	10.21	681	23
5	-	-	-	-

However, the amplitude and period of oscillation of the V_{out} waveform became larger when K_p was set too high. When $K_p = 5$, the V_{out} waveform was oscillating nonstop beyond the recording time of 2.5s used in the oscilloscope. Moreover, it was also observed that the operation of IM-IG set became unstable with too much vibration. Hence, obviously K_p could not go beyond the value of 4, and e_{ss} could not be further reduced to 0. No measurement was recorded for $K_p = 5$ in Table 4.5 since the waveform for $K_p = 5$ had no steady-state. As mentioned in Section 2.7, the transient response are measured based on the steady-state value.

The increase of K_p from 1 to 4 also increased the value of t_{rise} from 27ms to 47ms, and t_{rise} was changed proportionally to K_p . The percentage of overshoot (PO) was changed in an up-and-down manner. The value of PO was first increased from 17.98% to 20.06% when K_p went up from 1 to 2, and then it was dropped down to 10.21% when K_p was increased to 4. Oppositely, the change in settling time ($t_{settling}$) was in a down-and-up manner. The value of $t_{settling}$ was dropped significantly from 1282ms to 476ms when K_p was increased from 1 to 2. Then, the $t_{settling}$ had higher values of 534ms and 681ms for $K_p = 3$ and $K_p = 4$.

As mentioned in Section 3.8.3, the PID gains were assumed to be tuned for obtaining a fast transient response of V_{out} with small $t_{settling}$. Based on the data obtained, the answer for

the optimal value of K_p was obviously to be 2 as t_{settling} was the smallest when $K_p = 2$. Figure 4.9 shows the verification of K_p tuning using decimal numbers, and the responses were measured and recorded in Table 4.6. The results confirmed that 2 is the most suitable value for K_p as the other two values had higher T_{settling} .

As highlighted in Table 4.5, there was a significant finding where the V_{out} waveform with shortest t_{settling} possessed the highest value of PO .

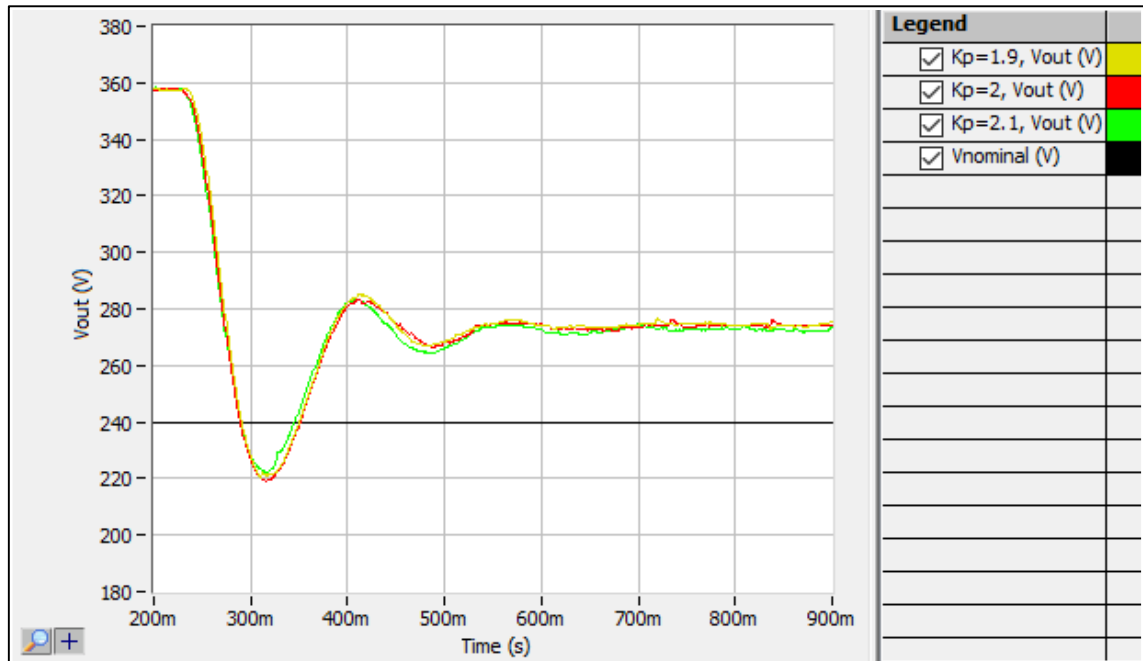


Figure 4.9: Transient waveforms of V_{out} for $K_p = 1.9$, 2, and 2.1.

Table 4.6: Transient responses of V_{out} for $K_p = 1.9$, 2, and 2.1.

K_p	t_{rise} (ms)	PO (%)	t_{settling} (ms)	e_{ss} (V)
1.9	28	19.38	494	35
2	30	20.06	476	34
2.1	30	18.75	506	32

4.4.2 Tuning of Integral Gain

In the K_i tuning, K_p was set to 2 (obtained from previous K_p tuning) and K_d was maintained at 0, and the ELC operated as a proportional-integral (PI) controller. All the transient waveforms and responses of V_{out} obtained from the K_i tuning are shown in Figure 4.10 and Table 4.7, respectively. The V_{out} waveform obtained from the K_p tuning was attached into Figure 4.10 as the waveform for $K_i = 0$ (in yellow colour) wherein the K_i tuning was yet to be activated. It was observed that the steady-state of the V_{out} waveform for $K_i = 1$ (in red colour) was laid near by the line of $V_{nominal}$. This clearly showed the tuning effect of K_i in minimising the value of e_{ss} . According to Table 4.7, the residual e_{ss} of 34V from the K_p tuning was significantly reduced to 3.33V when K_i was set to 1. As K_i was further increased to 5, e_{ss} was further decreased to 1.80V. Hence, as the K_i increased, the e_{ss} was decreased. The K_i tuning contributed to the significant reduction of e_{ss} . Theoretically, K_i tuning should fully eliminate e_{ss} as explained in Section 2.7.2. However, the data showed that e_{ss} was not eliminated but minimised.

Figure 4.10 also showed the oscillation period of the V_{out} waveform was reduced by the K_i tuning. Thus, the time required for V_{out} to reach its steady-state value was reduced. The value of $t_{settling}$ was changed in a down-and-up manner during K_i tuning. As K_i was increased from 1 to 3, the $t_{settling}$ was decreased from 1873ms to 572ms. Then, for the onward values of K_i , the $t_{settling}$ was increased from 572ms to 637ms. Therefore, it was very obvious that the optimum value of K_i was 3 as 572ms was the smallest value obtained for $t_{settling}$ during the K_i tuning.

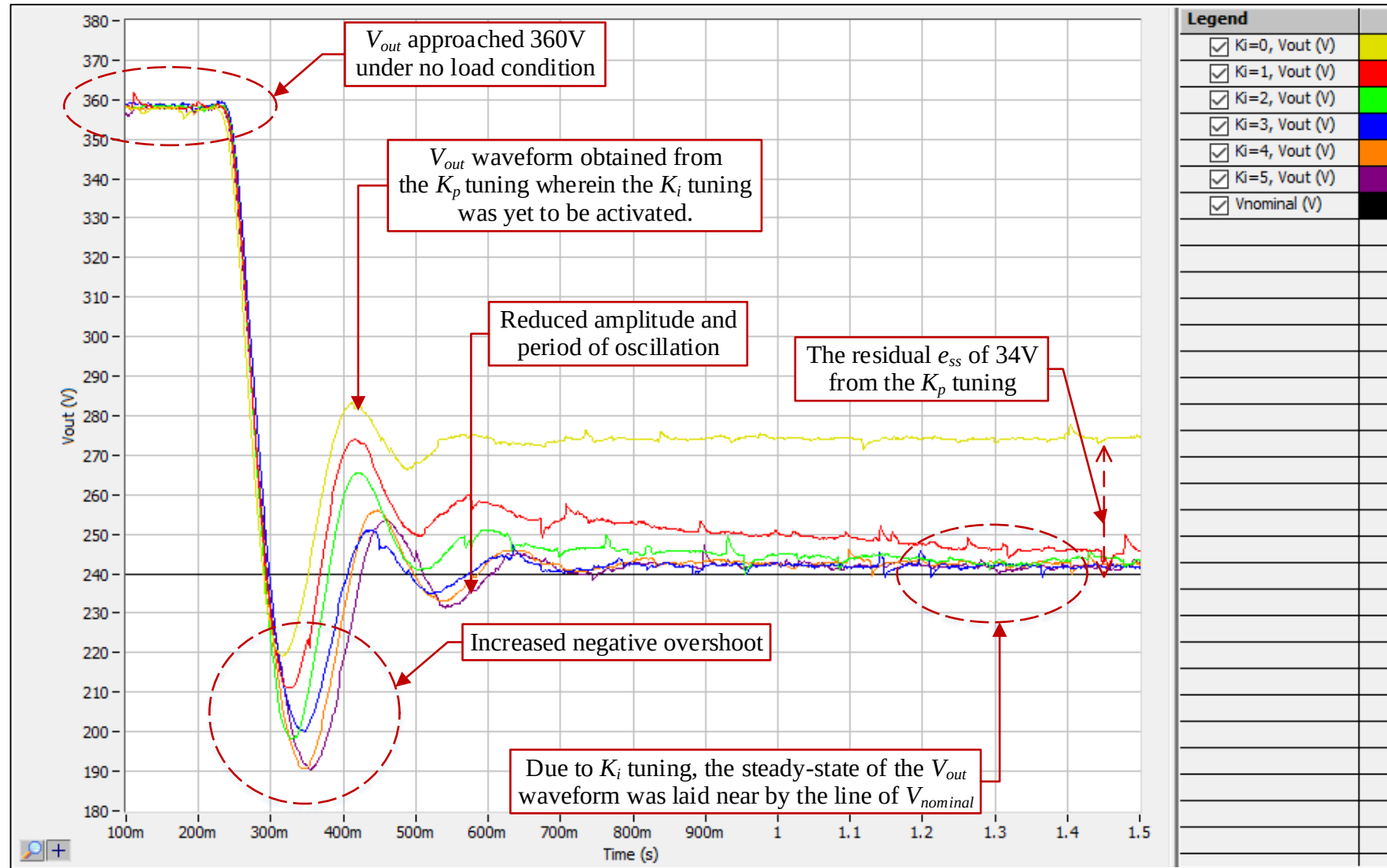


Figure 4.10: Transient waveforms of V_{out} for K_i values from 1 to 5 in step of 1.

Table 4.7: Transient responses of V_{out} for K_i values from 1 to 5 in step of 1.

K_i	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
1	37.80	13.20	1837	3.33
2	35.68	18.49	983	3.10
3	40.78	17.35	572	2.55
4	39.10	21.44	619	2.38
5	40.69	21.27	637	1.80

It was also observed that the shape of the waveforms did no change much throughout the K_i tuning, and they were more likely shifted down and toward the line of $V_{nominal}$. The K_i tuning did not help much in decreasing the overshoot. As a result, the amplitude of the negative overshoot over the line of $V_{nominal}$ was increased, as it can be seen in Figure 4.10. The data in Table 4.7 also showed PO was 13.20% when $K_i = 1$ and became 21.27% when $K_d = 5$. There is no definite trend to describe the change in PO . Though, there is significant difference between the value of PO for small K_i and that for large K_i . Therefore, the value of K_i should be minimised in order to minimised the value of PO .

Similar to the change in PO , the change in t_{rise} had no definite trend, and its value could be minimised by the minimum value of K_i . As presented in Table 4.7, the values of t_{rise} were below 38ms when $K_i = 1$ and $K_i = 2$, and they were about 40ms when $K_i = 3$, $K_i = 4$, and $K_i = 5$. The value of 3 was verified using smaller value, and again 3 was the suitable value for K_i as it can be seen in Figure 4.11 and Table 4.8. In the K_i tuning, it was also found out that waveform with the shortest $t_{settling}$ possessed the highest value of t_{rise} .

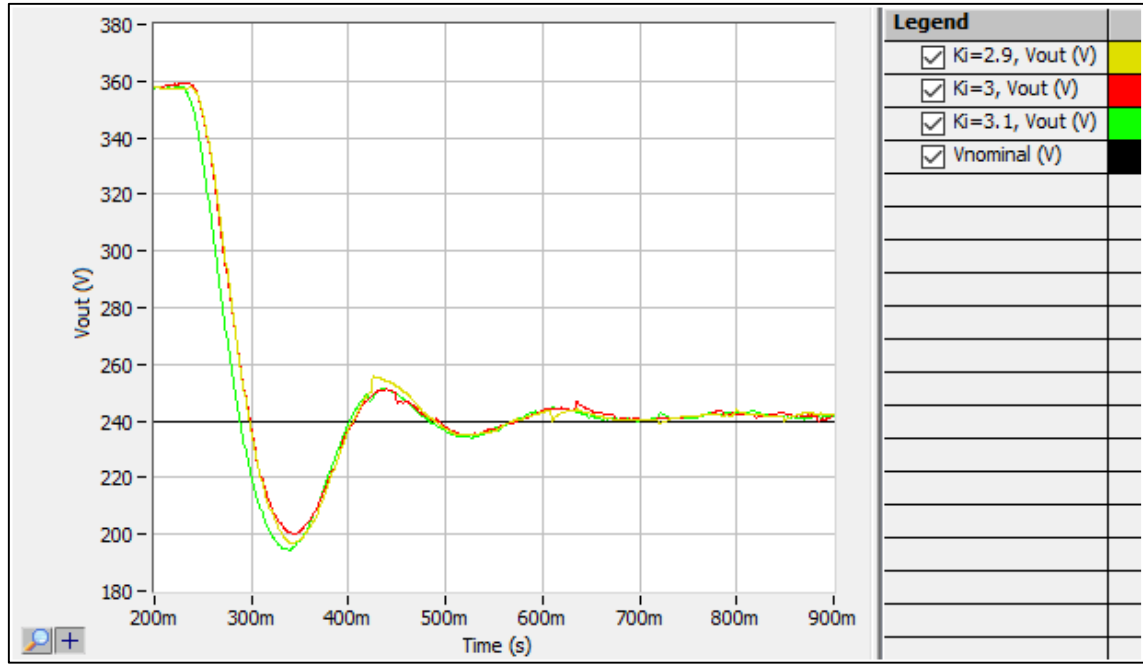


Figure 4.11: Transient waveforms of V_{out} for $K_i = 2.9, 3,$ and 3.1 .

Table 4.8: Transient responses of V_{out} for $K_i = 2.9, 3,$ and 3.1 .

K_i	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
2.9	39.41	18.57	705	1.97
3	40.78	17.35	572	2.04
3.1	39.41	19.38	611	1.51

4.4.3 Tuning of Derivative Gain

In this final tuning process, the derivative (D) control mode was activated to form a complete PID control. With K_p and K_i were set to 2 and 3, K_d tuning started from 10 as it only gave significant effect on the V_{out} response with that value. Figure 4.12 shows the transient waveforms of V_{out} for K_d values from 10 to 50 in step of 10 . Table 4.9 shows the transient response of V_{out} for each K_d value.

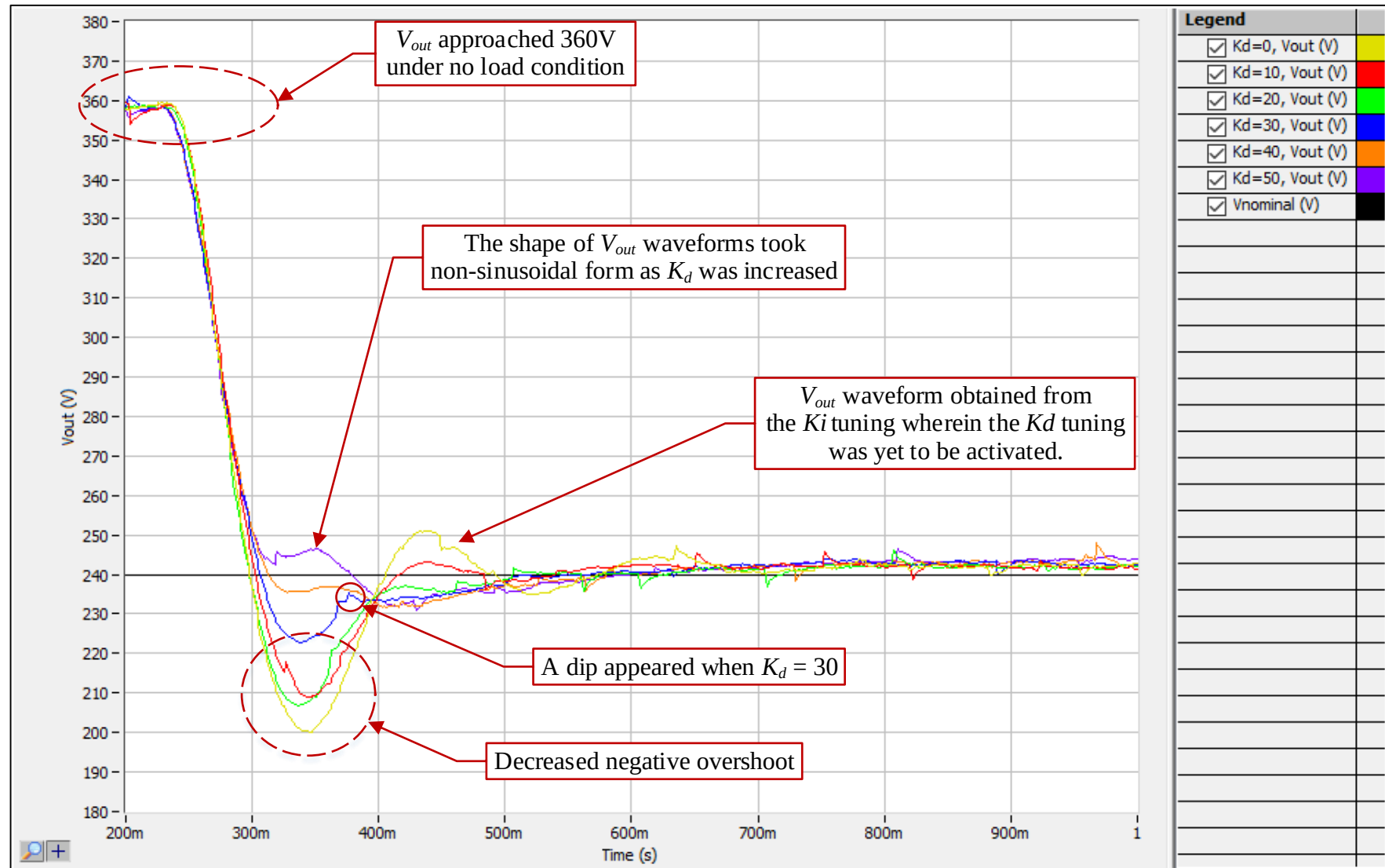


Figure 4.12: Transient waveforms of V_{out} for K_d values from 10 to 50 in step of 10.

Table 4.9: Transient responses of V_{out} for K_d values from 10 to 50 in step 10.

K_d	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
10	43.45	13.42	338	1.49
20	40.18	14.39	423	1.69
30	50.44	8.16	457	2.72
40	51.99	4.50	486	2.93
50	51.68	4.79	545	3.70

The yellow coloured waveform in Figure 4.12 was obtained from previous tuning process with $K_d = 0$ wherein the K_d tuning was deactivated. By comparing all the V_{out} waveforms obtained from the K_d tuning with the white coloured waveform, it is clearly observed that the amplitude of oscillation of the V_{out} waveform was significantly reduced by the K_d tuning. Furthermore, same thing happened to amplitude of the waveform overshoot, and this also showed that the K_d tuning contributed in reducing the overshoot. By referring to Table 4.9, $PO = 13.42\%$ when $K_d = 10$ and $PO = 4.79\%$ when $K_d = 50$, hence the K_d tuning decreased value of PO . However, the change in PO was not proportional to the change in K_d , and no definite trend for describing the change in PO during K_d tuning. Despite that, the data concluded that the value of K_d should be increased if the value of PO need to minimised.

It was also observed that the shape of V_{out} waveforms took non-sinusoidal form as K_d was above 10. Furthermore, a dip appeared on the V_{out} waveform for $K_d = 30$ (in blue colour). The dip in the waveform was immediately followed by a small drop then gradually became incline. When $K_d = 50$, the V_{out} waveform was unsmooth and no longer in sinusoidal form, as indicated by the purple coloured line.

The effect of K_d tuning on the other three waveform characteristics t_{rise} , $t_{settling}$, and e_{ss} could not be clearly observed from Figure 4.12. However, the data showed that the K_d tuning caused negative effect on the three waveform characteristics by increasing their values. As K_d was increased from 10 to 50, t_{rise} increased from 43.45ms to 51.68ms with an indefinite trend. The value of K_d should be decreased if the value of t_{rise} need to minimised. On the other hand, $t_{settling}$ was increased from 338ms to 545ms and e_{ss} was increased from 1.49V to 3.70V, as K_d was increased from 10 to 50. Both changes in $t_{settling}$ and e_{ss} were proportional to the change in K_d .

Since the value of $t_{settling}$ was higher for all the tested values of K_d above 10, hence the value of 10 was selected as the optimum value of K_d . The value of 10 is verified by tuning K_d with the value of 9 and 11. The Figure 4.13 shows transient waveforms of V_{out} for K_d values from 9 to 11 in step of 1. Table 4.10 shows the measured waveform characteristics.

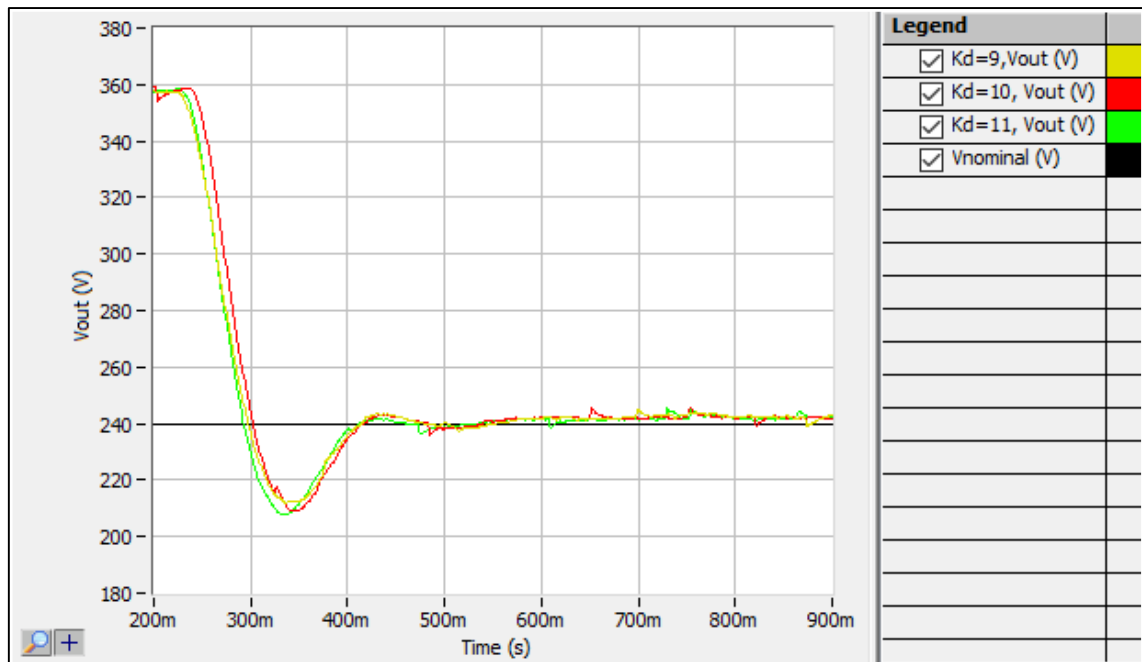


Figure 4.13: Transient waveforms of V_{out} for $K_d = 9, 10$, and 11 .

Table 4.10: Transient responses of V_{out} for $K_d = 9, 10$, and 11 .

K_d	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
9	47.69	12.76	361	2.52
10	43.45	13.42	338	1.49
11	42.71	13.91	351	1.53

From the results in Table 4.10, the waveform for $K_d = 10$ again had the smallest value of $t_{settling}$. This confirmed the 10 should be the optimum value for K_d . In the K_d tuning, it was also found out that waveform with the shortest $t_{settling}$ possessed the smallest e_{ss} .

4.4.4 Tuning of Time Interval

By referring to Section 3.4.1, the time interval ($T_{interval}$) is one of the variable in the PID equations, but its value is uncertain. Therefore, the tuning of $T_{interval}$ was included in the PID tuning in order to investigate its effect on t_{rise} , PO , $t_{settling}$, and e_{ss} of the transient response of V_{out} . This was done by obtaining different sets of the K_p , K_i , and K_d values under different values of $T_{interval}$. The value of 5ms was the minimum value of $T_{interval}$, and this value depends on processor speed of the implemented microcontroller. Hence, 5ms was the first value used for $T_{interval}$ tuning. In order to clearly identify how the value of $T_{interval}$ influences the V_{out} response, another two values 30ms (six times the value of 5ms) and 60ms (twelve times the value of 5ms) were used for the $T_{interval}$ tuning. Figure 4.14 presents the transient waveforms of V_{out} for $T_{interval} = 5\text{ms}$, 30ms, and 60ms. Table 4.11 shows the average values of transient responses of the V_{out} for $T_{interval} = 5\text{ms}$, 30ms, and 60ms.

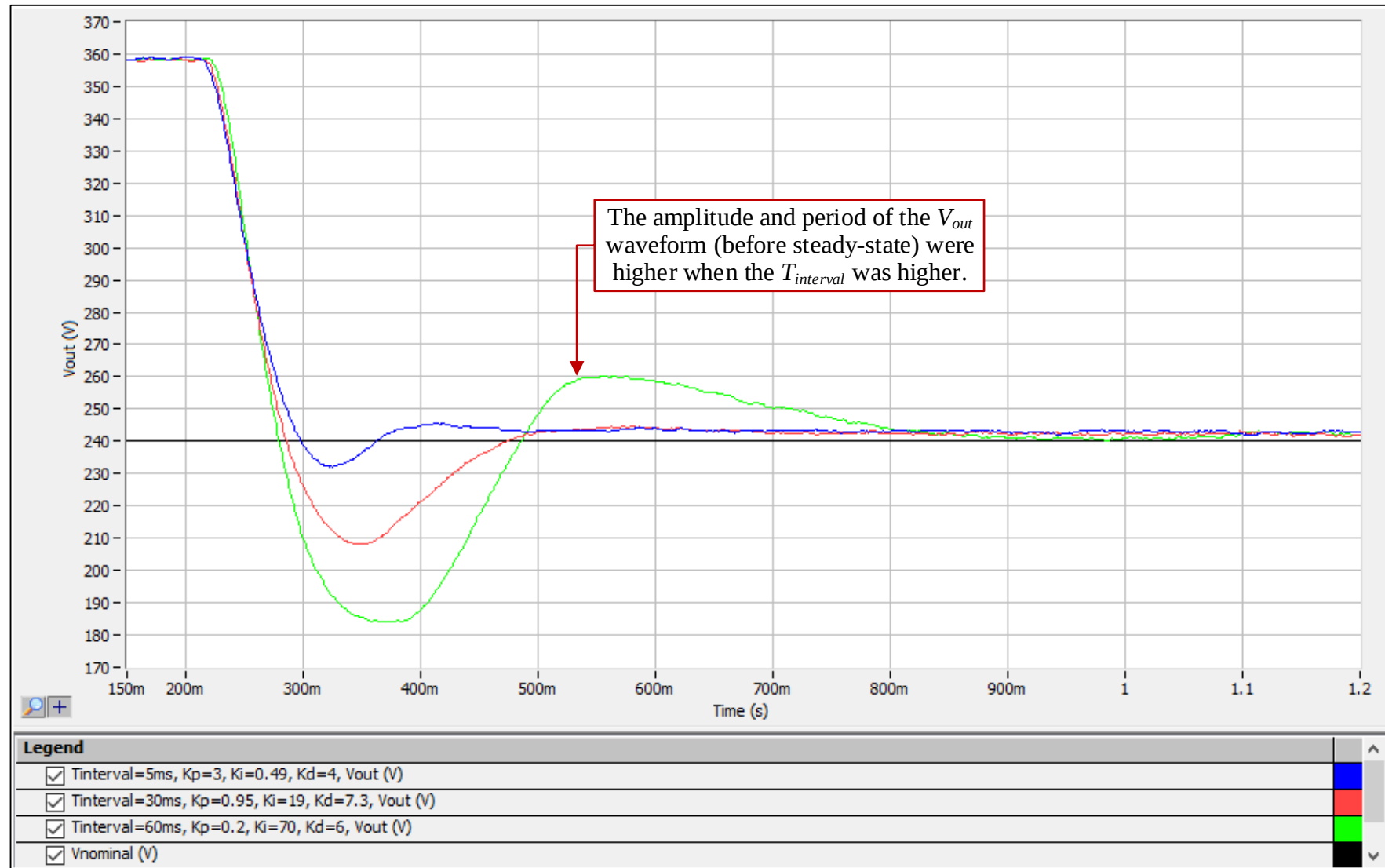


Figure 4.14: Transient waveforms of V_{out} for $T_{interval} = 5\text{ms}$, 30ms , and 60ms .

Table 4.11: Average values of V_{out} responses for $T_{interval} = 5\text{ms}$, 30ms , and 60ms .

$T_{interval}$ (ms)	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
5	57	5.34	354	1.75
30	46	12.78	585	2.16
60	37	24.03	913	2.48

It is noted that, five V_{out} waveforms were obtained for each setting of $T_{interval}$, and they are documented in Appendix A. Appendix A also shows the values of t_{rise} , PO , $t_{settling}$, and e_{ss} measured and recorded for all the acquired waveforms.

As it can be seen in Figure 4.14, the amplitude and period of oscillation of the green coloured V_{out} waveform was the largest as compared to the other two V_{out} waveforms. That waveform was obtained from PID tuning under $T_{interval} = 60\text{ms}$. It was seeming to be the increase in $T_{interval}$ caused the increase in the overshoot and the time required to reach the steady-state. The data in Table 4.11 clearly shows that the values of PO , $t_{settling}$, and e_{ss} were increased by the increase in $T_{interval}$. However, the tuning of $T_{interval}$ showed positive effect to V_{out} by decreasing the value of t_{rise} . By interpreting the data in Table 4.11 from below to above, the decrease of the $T_{interval}$ causes the decreases of PO , $t_{settling}$, and e_{ss} . Therefore, the value of $T_{interval}$ should be minimised. This investigation helped to conclude that the more frequent the ELC system monitors and responds to the change of the V_{out} , the better the performance of the voltage regulation.

In order to achieve the same performance requirement of short settling time, different optimum values were used for K_p , K_i , and K_d when they are tuned under different values of $T_{interval}$, as listed in Table 4.12. By referring to the data in the table, it can be observed that

the pattern of tuning the PID parameters under values of $T_{interval}$. The value of K_d needed to be smaller for larger value of $T_{interval}$. On the other hand, both the K_i , and K_d needed to be larger for larger value of $T_{interval}$.

Table 4.12: Optimum values of PID parameters under different values of $T_{interval}$.

$T_{interval}$ (ms)	Optimum Value		
	K_p	K_i	K_d
5	3	0.49	4
30	0.95	19	7.3
60	0.2	70	6

4.4.5 Summary of PID Tuning

Based on all the results obtained for PID tuning, it can be concluded that the K_p tuning contributed mainly to the reduction of e_{ss} of V_{out} response. However, it could not reduce the e_{ss} to 0 as the further increment of K_p caused the V_{out} to oscillate. Besides, the K_p tuning was never meant to be used for eliminating the e_{ss} as explained in Section 2.7.1. Meanwhile, the K_p tuning also reduction to the values of PO and $t_{settling}$, but the changes in PO and $t_{settling}$ were non-proportional to the change in K_p .

On the other hand, the K_i tuning was mainly for the further reduction of e_{ss} of V_{out} response towards the 0V. According to Table 2.4 in Chapter 2, supposed that the e_{ss} is eliminated by the K_i tuning. However, from the final tuning of PID, the value obtained for the e_{ss} was equalled to 1.49V. It also contributed in reducing the $t_{settling}$ but with an indefinite trend. Meanwhile, it increased t_{rise} and PO with indefinite trend.

The K_d tuning was very useful in reducing the PO of V_{out} response. However, it causes an increase in the $t_{settling}$ of V_{out} response, which supposedly to be an decrease if based on the theory in Table 2.4 in Chapter 2. It also caused incensements in t_{rise} and e_{ss} .

From the PID tuning too, it is found out that the waveforms for the subsequent tuned K_i and K_d exhibited similar shape as that of the first tuned K_p . As can be seen by putting the three waveforms together in Figure 4.15. Hence, the tuning of K_p influences the following tunings of K_i and K_d . Also, results in Table 4.7 shows PID controller performed better than PI controller in the application of voltage regulation.

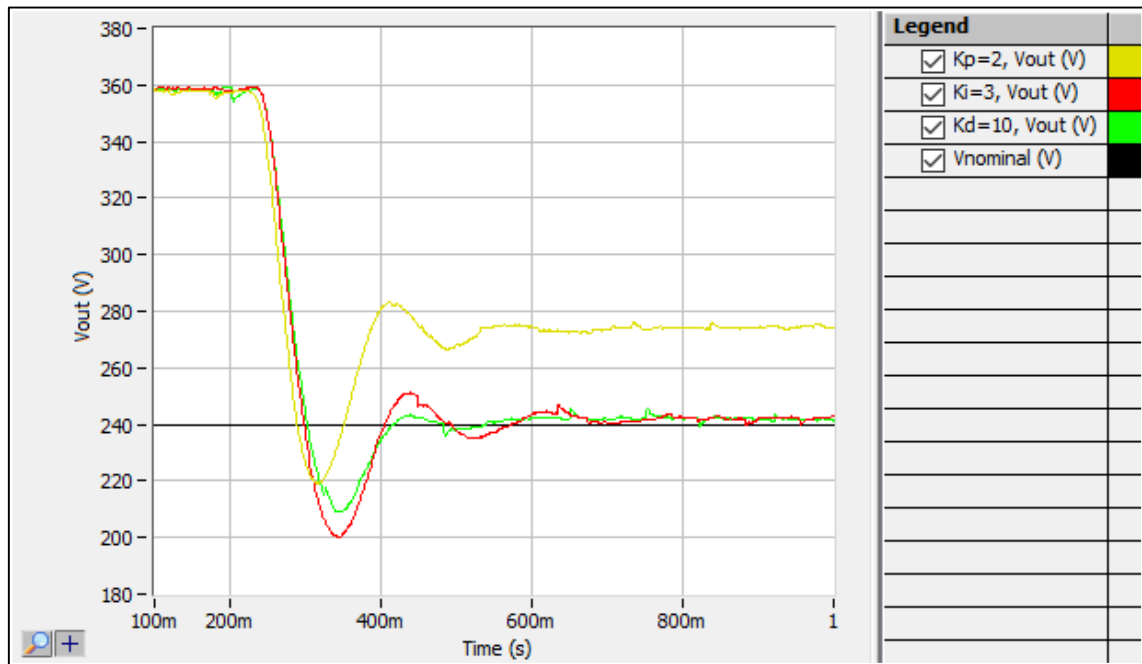


Figure 4.15: Transient waveforms of V_{out} for the three tuned gains.

Lastly, the $T_{interval}$ tuning increased the values of PO , $t_{settling}$, and e_{ss} , and it decreased the value of t_{rise} . Table 4.13 summarises the tuning effects of K_p , K_i , K_d and $T_{settling}$.

Table 4.13: Tuning effects of K_p , K_i , K_d , and $T_{interval}$ on V_{out} .

Tuning	Rise Time, t_{rise} (ms)	Percentage Overshoot, PO (%)	Settling Time, $t_{settling}$ (ms)	Steady-State Error, e_{ss} (V)
K_p	Increase	Decrease	Decrease	Decrease
K_i	Increase	Increase	Decrease	Decrease
K_d	Increase	Decrease	Increase	Increase
$T_{interval}$	Decrease	Increase	Increase	Increase

4.5 Load Variation Test

By using the optimal values of PID parameters $K_p = 2$, $K_i = 0.8$, $K_d = 5$, and $T_{interval}$ obtained from the PID tuning, the ELC system loaded with the PID control based program was tested with the application and removal of 240W consumer load. The transient waveforms of output voltage (V_{out}) and current of consumer load ($I_{consumer}$) resulted from the test are shown in Figure 4.16. The transient responses of V_{out} are shown in Table 4.14.

As illustrated in Figure 4.16, initially, the V_{out} of the IG was regulated by the ELC system nearly at 240V under no load condition ($I_{consumer} = 0$). When a 240W consumer load was applied to the IG at 250ms, $I_{consumer}$ waveform was suddenly increased from 0A to 1A (represented by 40V). The sudden increase in load on the IG was caused a sudden 20.09% of negative overshoot on the V_{out} waveform. However, within a duration of 464ms, the V_{out} was regulated back to nearly 240V. Then, at 750ms, the consumer load was removed from the IG, and $I_{consumer}$ was decreased to 0A. Consequently, the IG was under no load condition, and the V_{out} was overshoot positively above 10.99% of 240V. Again, the V_{out} was stabilised back to 240V within 583ms.

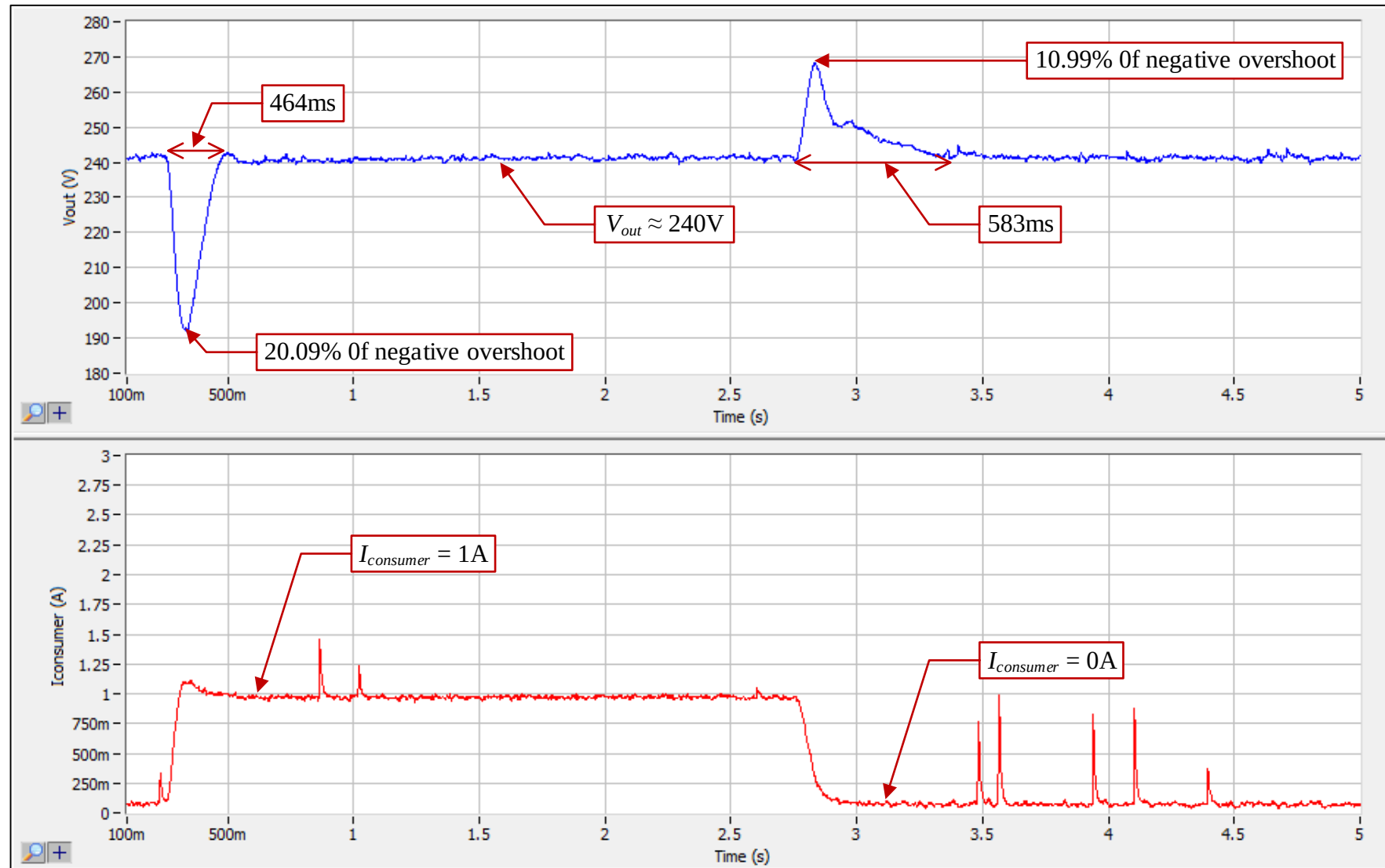


Figure 4.16: Transient waveforms of V_{out} and $I_{consumer}$ at application and removal of 240W load.

Table 4.14: Transient responses of V_{out} at application and removal of 240W load.

Consumer Load	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
240W Load ON	20.09	464	1.86
240W Load OFF	10.99	583	2.77

From Figure 4.16, it was observed that the regulated V_{out} was a little bit above 240V. This was due to the steady-state error (e_{ss}) about 3V resulted from the PID tuning. This issue could be easily solved by adjusting the value of $V_{nominal}$ in the ELC program code. In fact, there is no exact 240V power supply. The tolerance voltage of Malaysians' appliances was ranged from 240V + 6% (254V) to 240V – 10% (216V). Hence, it is not a problem if the value of V_{out} is a little bit more than 240V.

Overall, the results above implied that the ELC developed in this research had successfully regulated the output voltage of the IG nearly at 240V despite the load variations.

4.6 PID Tuning with Less Overshoot

During the regulation of V_{out} , it was observed that the lights bulbs flickered as the V_{out} was oscillating and overshooting negatively and positively. The flickering lights were irritating to the eyes. Hence, the PO of V_{out} should be the characteristic that need to be improved instead of the $t_{settling}$ of V_{out} . Besides that, the number of oscillation should be reduced too. In other words, stability is more important than short transient thereby the process of PID tuning was conducted again to minimize the PO. The waveforms obtained are shown in Figure 4.17.

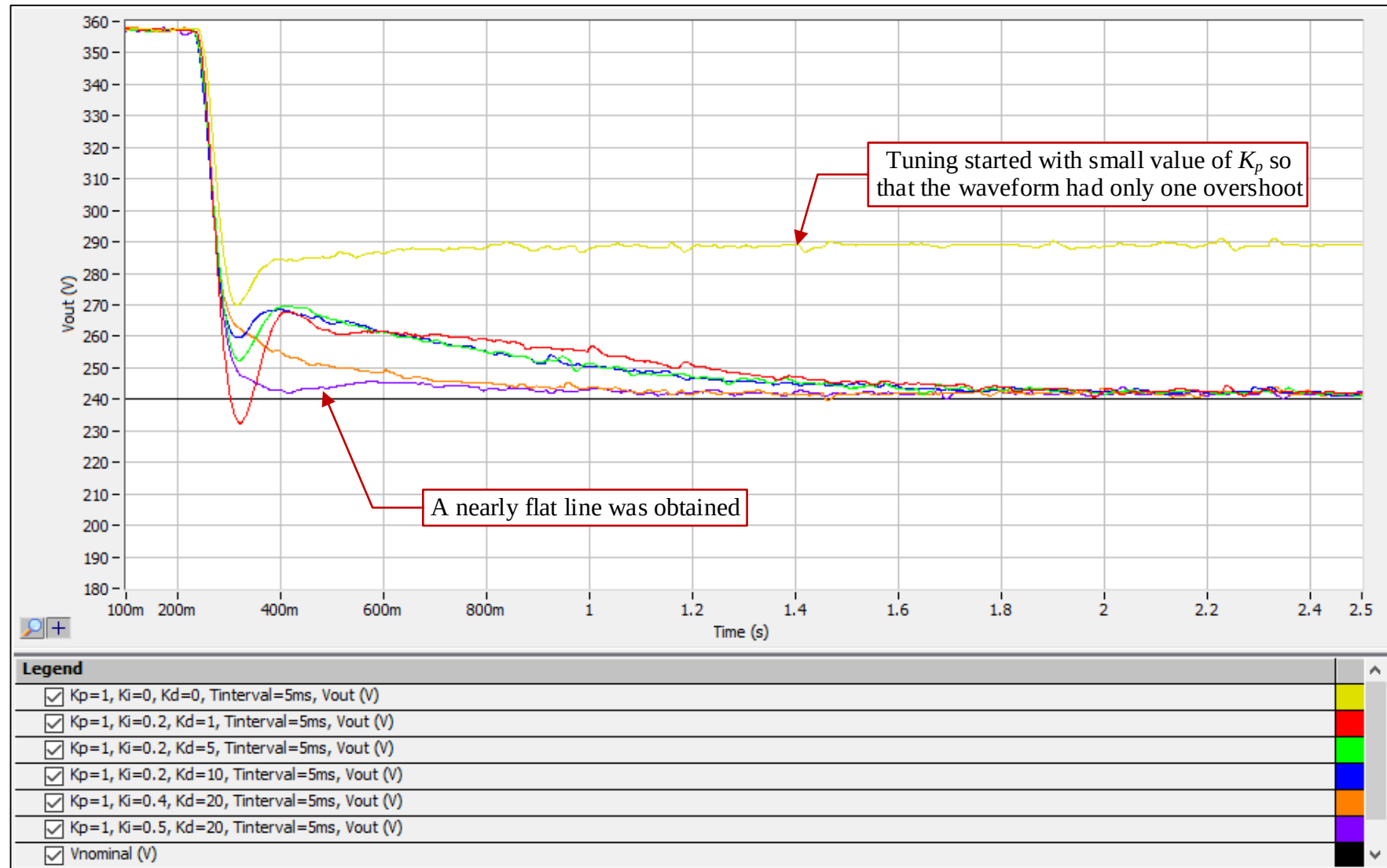


Figure 4.17: Transient waveforms of V_{out} for extended investigation – Part 1.

In this investigation, the PID tuning was fully based on the observation on the shapes of the V_{out} waveforms obtained without the data analyses of the transient response of V_{out} . Based on the findings in Section 4.4, the effect of K_p tuning on the voltage waveform will be inherited to the following K_i and K_d tunings, especially the number of oscillation. The V_{out} waveform tended to have one negative overshoot when the value of K_p was small. Thus, as the first step of tuning, the K_p was tuned so that the transient waveforms of V_{out} had one negative overshoot. Then, as a second step, the values of K_i and K_d were tuned interchangeably (instead of sequentially) until a nearly flat waveform was obtained.

By referring to Figure 4.17, the first step was completed by setting $K_p = 1$, and $K_i = 0$, and $K_d = 0$, and the waveform obtained was coloured in yellow. With the value of K_p fixed at 1, K_i and K_d were set randomly to 0.2 and 1, respectively, and the obtained waveform (in red colour) overshoot the black line ($V_{nominal}$) and required about 2s to reach its steady-state. Hence, for the next two steps the K_i was fixed at 0.2 and the K_d was tested with 5 and 10. As a result, the overshoot was reduced significantly (see green and blue coloured waveforms), but yet the waveforms still took long time to reach the steady state. Because of that, the K_i was increased to 0.4, and at the same time, the K_d was increased to 20 in order to reduce the resultant overshoot. Consequently, a smooth curvy orange line was obtained. Lastly, an attempt was carried out to reduce the curvy part and $t_{setling}$ by increasing the K_i . The waveform resulted (in purple colour) was a nearly flat line without overshoot. Hence, the tuned PID had $K_p = 1$, $K_i = 0.5$, and $K_d = 20$ under $T_{interval} = 5\text{ms}$.

The obtained PID gains was further tested by changing K_d to 15 and K_i to 0.6 separately, as shown in Figure 4.18. From the results, when $K_d = 15$, the turning point of the waveform became shaper. Meanwhile, when $K_i = 0.6$, the waveform overshoot the $V_{nominal}$ line. Still, the previously obtained PID gains possessed the most smoothest waveform.

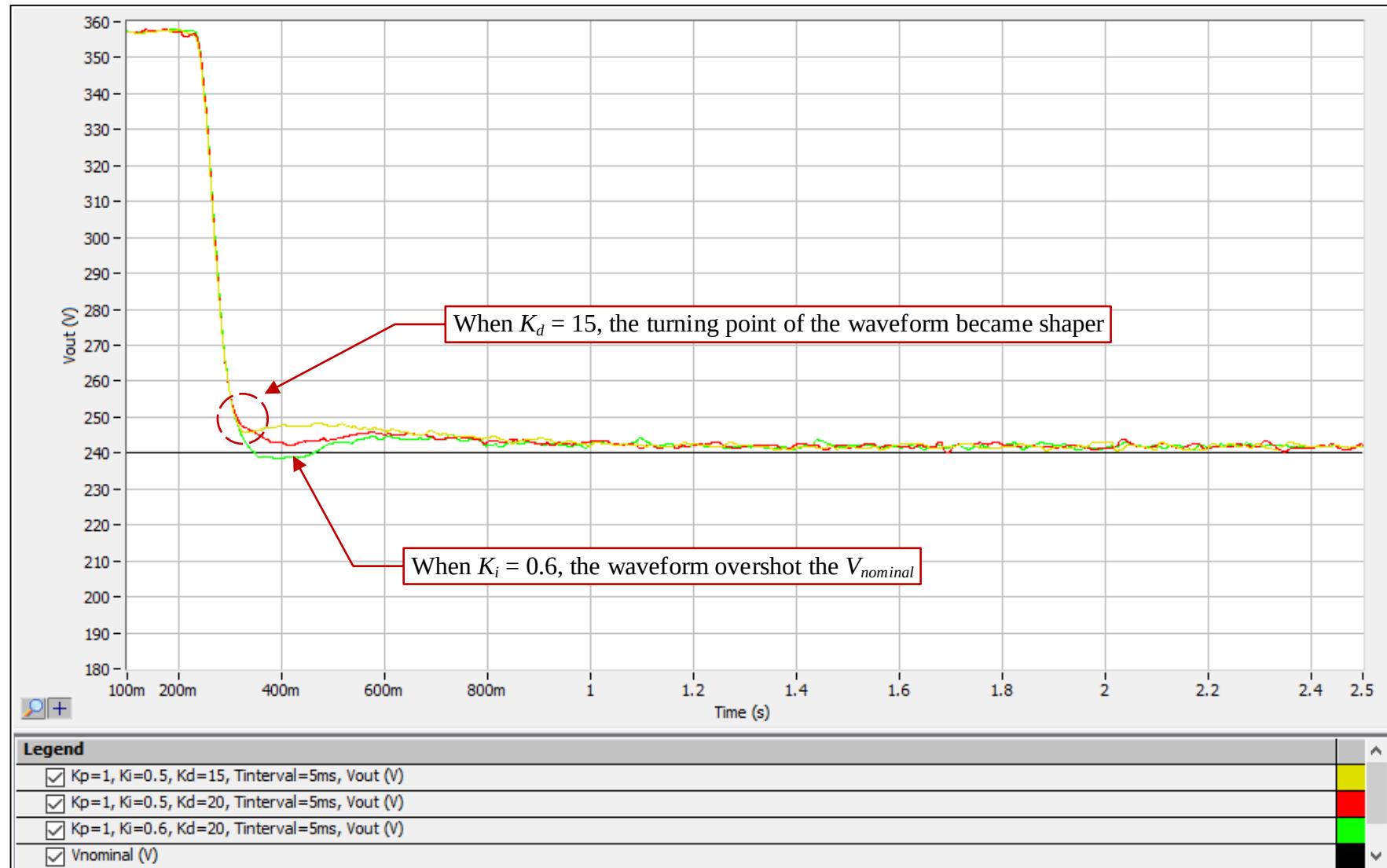


Figure 4.18: Transient waveforms of V_{out} for extended investigation – Part 2.

Based on the results and experiences acquired from this second PID tuning, it could be drawn up a guideline to tune the PID control of the ELC system. The tuning steps are as following:

- i. Set K_p with a small value about 1 and obtain the V_{out} waveform.
- ii. Set K_i and K_d with small values randomly and obtain the V_{out} waveform.
- iii. Set K_i with a higher value to reduce the settling time of the V_{out} waveform.
- iv. Set K_d with a higher value to reduce the overshoot of the V_{out} waveform.
- v. Repeat steps 3 and 4 interchangeably until a nearly flat line is obtained.

In the first step, K_p is given with a small value about 1 in order to obtained a response with only one negative overshoot. Secondly, both K_i and K_d are set randomly with any small values in order to reduce V_{out} to nearly 240V. Then, by observing on the shape of the V_{out} waveform, third step is conducted to shift down the negative overshoot and to reduce the time required for the V_{out} waveform to reach its steady-state. Next, fourth step is conducted to reduce the overshoot resulted from the third step. Third and fourth steps are repeated interchangeably so that the tuning effects of K_i and K_d are not overdone on the V_{out} waveform. Of course, if K_i and K_d are over tuned, their values can be reduced in order to get the desire V_{out} waveform. Lastly, both third and fourth steps are repeated until a nearly flat line similar to the red line in Figure 4.18 is obtained.

4.7 Summary

Steady-state and transient analyses were conducted on the induction generator (IG). From the steady-state analysis, the results showed that the changes in both output voltage

(V_{out}) and output frequency (f_{out}) are not directly proportional to the change in the power of consumer load (P_{CL}). Furthermore, the change in f_{out} is corresponding to the change in V_{out} , and hence, the regulation of V_{out} is equal to the regulation f_{out} . Meanwhile, the transient analysis of IG showed that longer time is needed for the V_{out} to reach its steady-state value during load connection than that during load disconnection. It is also observed that V_{out} overshoot more when more loads were added to the IG output.

Besides that, PID tuning was conducted to obtain the optimum values and tuning effects of the PID parameters: proportional gain (K_p), integral gain (K_i), derivative gain (K_d), and time interval ($T_{interval}$). The K_p tuning contributed mainly to the reduction of steady-state error (e_{ss}) of V_{out} response. It also reduced the values of percentage of overshoot (PO) and settling time ($t_{settling}$). On the other hand, the K_i tuning helped to further reduce e_{ss} towards 0V. It also contributed in reducing the $t_{settling}$ but the rise time (t_{rise}) and PO were increased by the K_i tuning. The K_d tuning was very useful in reducing the PO of V_{out} response. However, it causes increases in $t_{settling}$, t_{rise} , and e_{ss} of V_{out} response. Lastly, the $T_{interval}$ tuning increased the values of PO , $t_{settling}$, and e_{ss} , and it decreased the value of t_{rise} .

By using the optimal values of PID parameters $K_p = 2$, $K_i = 0.8$, $K_d = 5$, and $T_{interval}$ obtained from the PID tuning, the ELC system loaded with the PID control based program was tested with the application and removal of 240W consumer load. The results from the test implied that the ELC developed in this research had successfully regulated the output voltage of the IG nearly at 240V despite the load variations.

Lastly, another PID tuning was conducted to achieve a V_{out} response with less overshoot, and a new guideline for tuning the PID parameters was established. As the first step of tuning, K_p was tuned so that the transient waveforms of V_{out} had one negative

overshoot. Then, as a second step, the values of K_i and K_d were tuned interchangeably (instead of sequentially) until a nearly flat waveform was obtained.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This final chapter concludes all the results, findings and achievements obtained from this research. The contributions of this research are also discussed. Lastly, two recommendations derived based on the results are discussed for future development of ELC systems. One is inclusion of Liquid Crystal Display (LCD) for monitoring and tuning activities and another one is the use of directive PID control.

5.2 Conclusion

The first objective was successfully achieved with the Arduino based ELC that able to maintain the output voltage at 240V. The digital ELC proposed in this research was successfully implemented into the Arduino platform, and the overall ELC circuit was significantly simplified due to the use of Arduino UNO microcontroller board. As seen in the schematic diagram in Figure 3.2, the circuitry is much simpler and a lot of money and time can be saved due to this. The Arduino microcontroller system has most of the important components of a complete ELC, like analogue pin and built-in ADC to read voltage sensor and interrupt pin to synchronize the triac trigger signal with the zero-crossing events. Also, it showed satisfactory performance with its 16Mhz quartz crystal that allowed the designed program code to be executed within 5ms. This contributes to fast response of the ELC system. By using the designed ELC incorporating with the designed control program, the V_{out} of IG

was regulated nearly to 240V despite the variation of consumer load. This was proven by the waveforms obtained in Figure 4.16 at the application and removal of 240W consumer load. Although, a steady-state error (e_{ss}) less than 3V still exists in the regulated V_{out} , but this issue could be easily solved out as described in Section 4.5. The results also showed that within 0.6s the voltage was able to be recovered from the fluctuated voltage back to 240V. This proved that the designed circuit and program were applicable for voltage regulation of an induction generator. Hence, the first objective was achieved.

Meanwhile, the second objective was achieved with the formulated control algorithm using the concept of proportional-integral-derivative (PID) control method. The PID control method was modified and adopted specifically as the control strategy of the ELC designed in this research. The PID control showed its simplicity during its implementation and tuning process. In this research, it was implemented without involving mathematical modelling, and its tuning process only involves three parameters. Furthermore, its tuning process was done manually without any complex mathematical calculation. The results from experiments also showed that the control strategy was not only able to maintain the V_{out} closed to 240V, but also had control on the rise time (t_{rise}), settling time ($t_{settling}$), percentage of overshoot (PO), and steady-state error (e_{ss}) of the V_{out} response.

Lastly, the third objective was achieved with the documented tuning effects of PID parameters. The tuning effects of proportional gain (K_p), integral gain (K_i), derivative gain (K_d), time interval ($T_{interval}$) of the PID control were clearly identified and summarised in Table 4.13. The table could be used as reference for tuning the PID control in the ELC. The results from the $T_{interval}$ tuning confirmed that its optimum value is equal to its minimum value, which depends on the processing speed of a microcontroller. Besides that, the PID tuning results proved that the PID control performed better than PI control. Furthermore, it

was discovered that a stable IG output voltage (less oscillation) is more important than short transient (small $t_{settling}$) in the IG-ELC system. Based on the results and experiences from the PID tuning, a guideline was drawn up to tune the PID control of the ELC system.

5.3 Contributions

First of all, a simple and locally designed ELC circuit was obtained from this research. By using the knowledge and skills in developing the ELC, inexpensive, fast service and support can be provided to the rural communities once the system fails. The failure on the circuitry of the ELC system cannot be avoided after long and continuous operation hour under harsh operating conditions like high humidity, dust, and dirt in the MP. When failure is happened to the system, very much money and time are needed to import foreign experts and parts if an imported ELC is used, as mentioned in Section 1.2.7. On the other hand, local experts can be hired to repair the faulty system, and this reduces the overall cost of operation and maintenance of local made ELC system. This can reduce financial burden for rural communities, which have low income.

A practical PID control program code for the application for ELC system to regulate the rural community's micro-hydroelectric system was created. A proper explanation on how to implement the PID control as the control strategy of the ELC system is provided in Section 3.4. This includes the way the integration and differentiation were applied by using the concepts of the area under a curve and the slope on a curve. Also, how the PID control was used to calculate the T_{delay} . Furthermore, the design of the program algorithm was clearly illustrated by the flow chart in Figure 3.12. Then, step by step the setup of source code of the program was explained. It could be used as a guide line on writing the program for a

digitally controlled ELC. This code also could be used as reference for further development of future ELC research.

A guide line on tuning the ELC on site was developed in this research. Tuning was needed to obtained suitable value for the three parameters as the three parameters decided the behaviour of the output of the controlled system. Remember that the characteristic of every MP is different. Furthermore, the parameters have to be changed if different type or rating of generator is used. As mentioned in (Anderson & Cervo, 2013), the tuning of the PID control should follow the sequence of K_p , K_i , and K_d . From the results in Section 4.6, with the K_p , fixed value the tuning of the K_i and K_d should go alternately. Here, also, proved that manual tuning is a practical way for the rural communities to tune their ELC system.

5.4 Recommendations

Firstly, the ELC designed in this research is recommended for voltage regulation of a synchronous generator with fixed excitation only. Based on the findings in the PID tuning and voltage regulation, there are two recommendations that can be considered to make the system easier to tune and performs better.

5.4.1 Liquid Crystal Display (LCD) for Tuning

It is a great advantage that the manual tuning of PID control does not involve any mathematical equations. Also, the three parameters of PID control can be tuned by comparing the waveforms of a system output for different values of the three parameters as explained in chapter 4. While doing this research, a digital oscilloscope was used to capture

the waveforms. However, it is unpractical to bring along the oscilloscope to a micro hydro site for tuning. It will be a lot easier if the ELC system has its own LCD for displaying the output waveforms. Hence, it is hereby recommended to include a LCD module, similar to the one shown in Figure 5.1 to the microcontroller based ELC system.

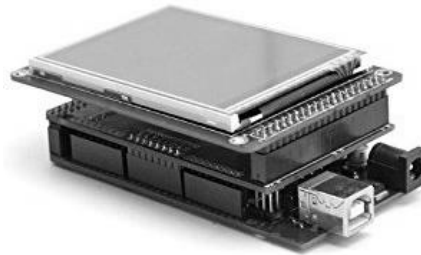


Figure 5.1: LCD module for Arduino UNO.

5.4.2 Directive PID Control

The data in Table 4.14 shows that the values of PO and $t_{settling}$ of the generator V_{out} responses were different at the application and removal of load. This shows that the IG has different behaviours for the two different load conditions. Hence, two set of PID parameters with different optimal values should be used. For example, set 1 for the application of load and set 2 for opposite one. Based on the equation 2.1 in Chapter 2, the calculated e_{ss} will have negative value as the V_{out} is more than V_{ref} at the application of load. On the other hand, it is positive if V_{out} is less than V_{ref} at the removal of load. By using if statement in the program code, the sign of the error is checked. Then, based on the sign of error, the PID parameters are applied.

5.5 Summary

The three objectives of this research were usefully achieved. The first objective was achieved with the Arduino based ELC that able to maintain the output voltage at 240V. The second objective was achieved with the formulated control algorithm using the concept of proportional-integral-derivative (PID) control method. Meanwhile, the third objective was achieved with the documented tuning effects of PID parameters. By achieving the three objectives, this research contributed a simple and locally designed digital ELC circuit. A practical PID control program code for the application for ELC system to regulate the rural community's micro-hydroelectric system was also created. This research also contributed a guide line for tuning the ELC on site was developed in this research. Lastly, two recommendations were suggested for future development. The first suggestion was to include a Liquid Crystal Display (LCD) for tuning. Secondly, it was suggested to formulate a directive PID control to handle the application and removal of loads differently.

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APPENDICES

Appendix A – Data of Time Interval Tuning

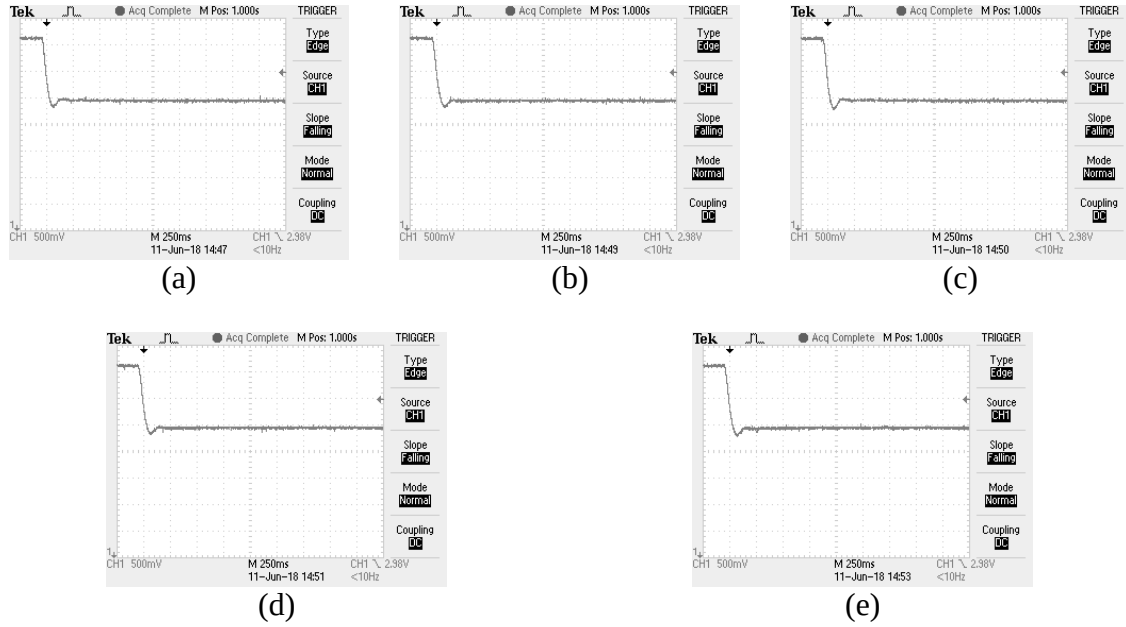


Figure A-1: V_{out} waveforms for $T_{interval} = 5\text{ms}$; (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, and (e) Sample 5.

Table A-1: Average t_{rise} , PO , $t_{settling}$, and e_{ss} of five V_{out} responses for $T_{interval} = 5\text{ms}$.

No. of Sample	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
1	53	4.75	355	1.70
2	58	4.71	354	1.67
3	57	6.43	357	1.80
4	59	4.65	351	1.77
5	58	6.17	351	1.81
Average	57	5.34	354	1.75

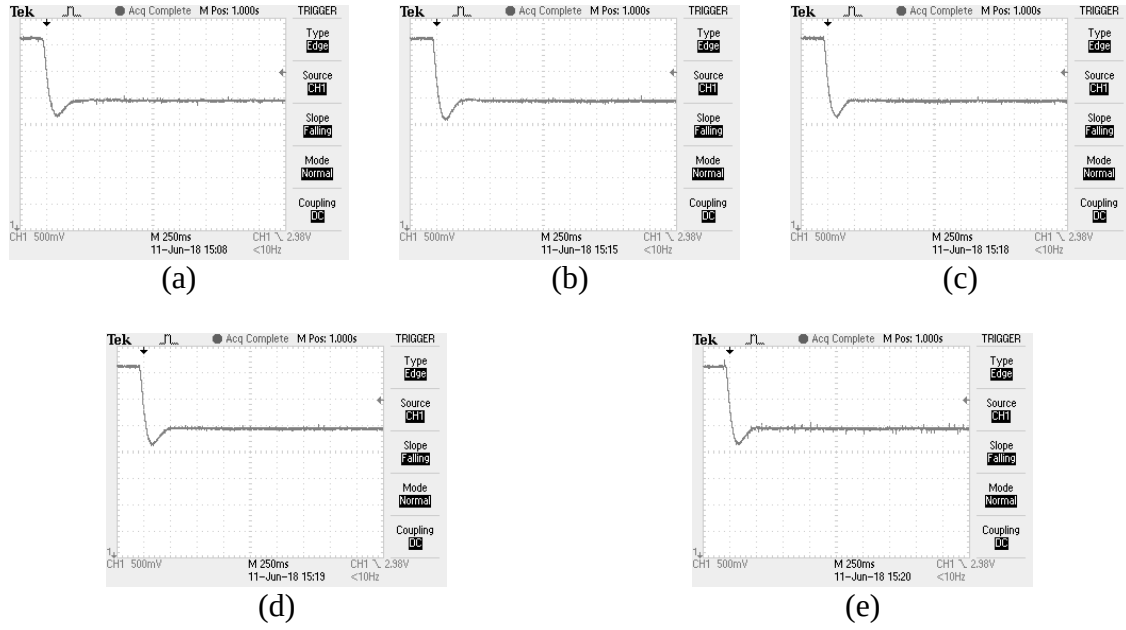


Figure A-2: V_{out} waveforms for $T_{interval} = 30\text{ms}$; (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, and (e) Sample 5.

Table A-2: Average t_{rise} , PO , $t_{settling}$, and e_{ss} of five V_{out} responses for $T_{interval} = 30\text{ms}$.

No. of Sample	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
1	53	12.00	583	2.16
2	44	14.32	583	2.23
3	43	12.54	589	2.29
4	46	12.83	586	2.01
5	44	12.23	583	2.11
Average	46	12.78	585	2.16

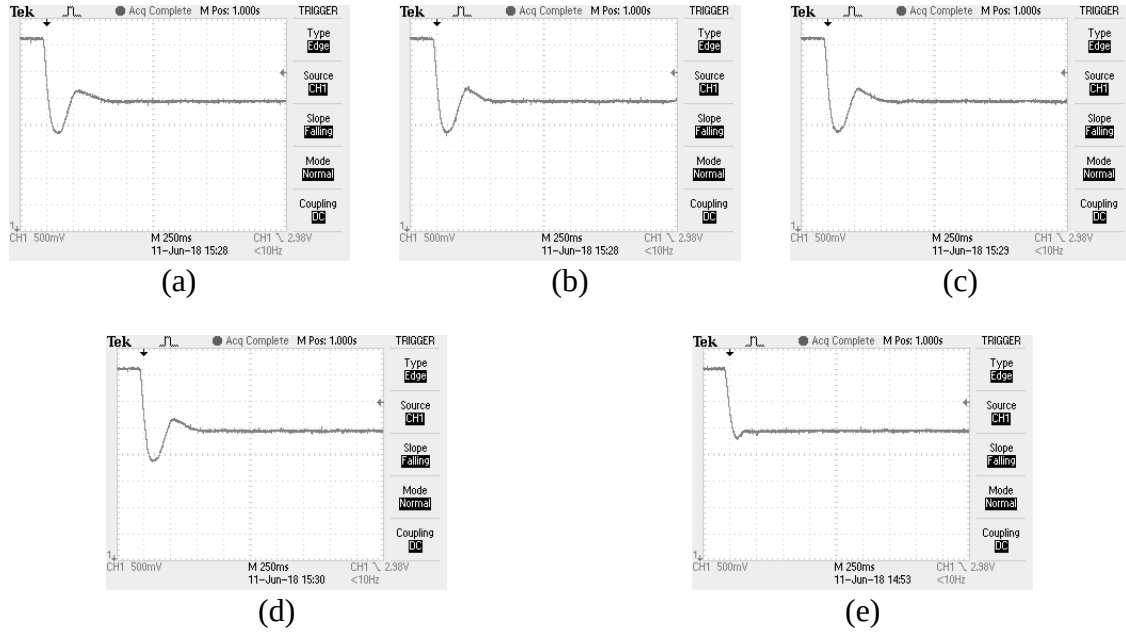


Figure A-3: V_{out} waveforms for $T_{interval} = 60\text{ms}$; (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, and (e) Sample 5.

Table A-3: Average t_{rise} , PO , $t_{settling}$, and e_{ss} of five V_{out} responses for $T_{interval} = 60\text{ms}$.

No. of Sample	t_{rise} (ms)	PO (%)	$t_{settling}$ (ms)	e_{ss} (V)
1	36	24.79	908	2.62
2	37	24.73	908	2.45
3	37	23.89	916	2.45
4	37	23.45	913	2.42
5	38	23.31	919	2.45
Average	37	24.03	913	2.48

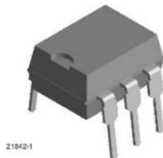
Appendix B – Datasheet of H11AA1 IC



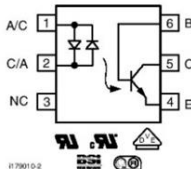
H11AA1

Vishay Semiconductors

Optocoupler, Phototransistor Output, AC Input,
with Base Connection



21862-1



0179010-2

FEATURES

- AC or polarity insensitive input
- Built-in reverse polarity input protection
- I/O compatible with integrated circuits
- Industry standard DIP package
- Isolation test voltage: 5300 V_{RMS}
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC



RoHS
COMPLIANT

APPLICATIONS

- Telephone line detection
- AC line motor
- PLC
- Instrumentation

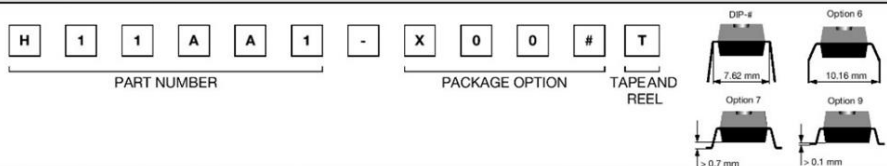
AGENCY APPROVALS

- UL1577, file no. E52744 system code H, double protection
- CSA 93751
- BSI IEC 60950; IEC 60065
- DIN EN 60747-5-2 (VDE0884)/DIN EN 60747-5-5 (pending), available with option 1
- FIMKO

DESCRIPTION

The H11AA1 is a bi-directional input optically coupled isolator consisting of two inverse parallel gallium arsenide infrared LEDs coupled to a silicon NPN phototransistor in a 6 pin DIP package. The H11AA1 has a minimum CTR of 20 %, a CTR symmetry of 1:3 and is designed for applications requiring detection or monitoring of AC signals.

ORDERING INFORMATION



AGENCY CERTIFIED/PACKAGE	CTR (%)
UL, cUL, BSI, FIMKO	≥ 20
DIP-6	H11AA1
DIP-6, 400 mil, option 6	H11AA1-X006
SMD-6, option 7	H11AA1-X007T ⁽¹⁾
SMD-6, option 9	H11AA1-X009T ⁽¹⁾
VDE, UL, cUL, BSI, FIMKO	≥ 20
DIP-6	H11AA1-X001

Note

- Additional options may be possible, please contact sales office.
- ⁽¹⁾ Also available in tubes; do not add T to end.

Document Number: 83608
Rev. 1.7, 23-Feb-11

For technical questions, contact: optocoupleranswers@vishay.com

www.vishay.com
1

H11AA1

Vishay Semiconductors Optocoupler, Phototransistor Output,
AC Input, with Base Connection



ABSOLUTE MAXIMUM RATINGS ($T_{amb} = 25\text{ }^{\circ}\text{C}$, unless otherwise specified)				
PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
INPUT				
Forward continuous current		I_F	± 60	mA
Power dissipation		P_{diss}	100	mW
Derate linearly from $25\text{ }^{\circ}\text{C}$			1.3	mW/ $^{\circ}\text{C}$
OUTPUT				
Power dissipation		P_{diss}	200	mW
Derate linearly from $25\text{ }^{\circ}\text{C}$			2.6	mW/ $^{\circ}\text{C}$
Collector emitter breakdown voltage		BV_{CEO}	30	V
Emitter base breakdown voltage		BV_{EBO}	5	V
Collector base breakdown voltage		BV_{CBO}	70	V
COUPLER				
Isolation test voltage (RMS)	Between emitter and detector, referred to standard climate $23\text{ }^{\circ}\text{C}/50\%\text{ RH}$, DIN 50014	V_{ISO}	5300	V_{RMS}
Creepage distance			≥ 7	mm
Clearance distance			≥ 7	mm
Comparative tracking index	per DIN IEC 112/VDE 0303, part 1	CTI	175	
Isolation resistance	$V_{IO} = 500\text{ V}$, $T_{amb} = 25\text{ }^{\circ}\text{C}$	R_{IO}	$\geq 10^{12}$	Ω
	$V_{IO} = 500\text{ V}$, $T_{amb} = 100\text{ }^{\circ}\text{C}$	R_{IO}	$\geq 10^{11}$	Ω
Storage temperature range		T_{stg}	-55 to $+150$	$^{\circ}\text{C}$
Operating temperature range		T_{amb}	-55 to $+100$	$^{\circ}\text{C}$
Lead soldering time at $260\text{ }^{\circ}\text{C}$		T_{sld}	10	s

Note

- Stresses in excess of the absolute maximum ratings can cause permanent damage to the device. Functional operation of the device is not implied at these or any other conditions in excess of those given in the operational sections of this document. Exposure to absolute maximum ratings for extended periods of the time can adversely affect reliability.

ELECTRICAL CHARACTERISTICS ($T_{amb} = 25\text{ }^{\circ}\text{C}$, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
INPUT						
Forward voltage	$I_F = \pm 10\text{ mA}$	V_F		1.2	1.5	V
OUTPUT						
Collector emitter breakdown voltage	$I_C = 1\text{ mA}$	BV_{CEO}	30			V
Emitter base breakdown voltage	$I_E = 100\text{ }\mu\text{A}$	BV_{EBO}	5			V
Collector base breakdown voltage	$I_C = 100\text{ }\mu\text{A}$	BV_{CBO}	70			V
Collector emitter leakage current	$V_{CE} = 10\text{ V}$	I_{CEO}		5	100	nA
COUPLER						
Collector emitter saturation voltage	$I_F = \pm 10\text{ mA}$, $I_C = 0.5\text{ mA}$	V_{CEsat}			0.4	V

Note

- Minimum and maximum values were tested requirements. Typical values are characteristics of the device and are the result of engineering evaluations. Typical values are for information only and are not part of the testing requirements.

CURRENT TRANSFER RATIO ($T_{amb} = 25\text{ }^{\circ}\text{C}$, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
DC current transfer ratio	$I_F = \pm 10\text{ mA}$, $V_{CE} = 10\text{ V}$	CTR_{DC}	20			%
Symmetry (CTR at $+10\text{ mA}$)/(CTR at -10 mA)			0.33	1	3	

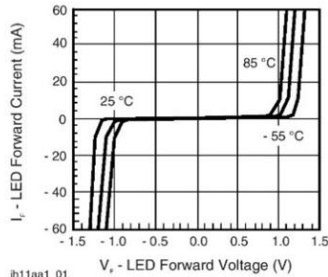
**TYPICAL CHARACTERISTICS** ($T_{amb} = 25^\circ\text{C}$, unless otherwise specified)

Fig. 1 - LED Forward Current vs. Forward Voltage

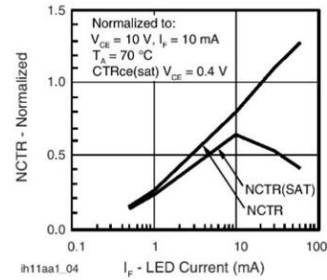


Fig. 4 - Normalized Non-Saturated and Saturated CTR vs. LED Current

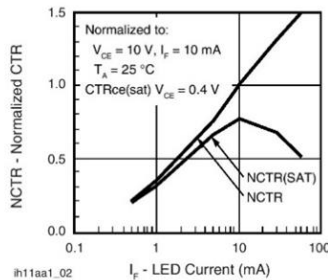


Fig. 2 - Normalized Non-Saturated and Saturated CTR vs. LED Current

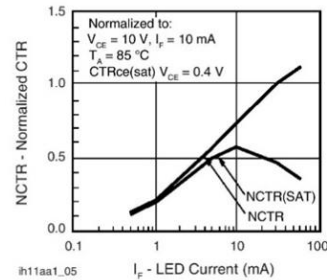


Fig. 5 - Normalized Non-Saturated and Saturated CTR vs. LED Current

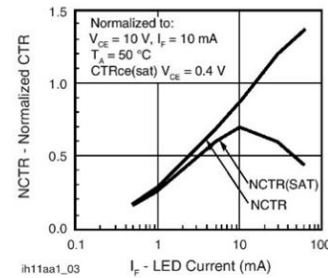


Fig. 3 - Normalized Non-Saturated and Saturated CTR vs. LED Current

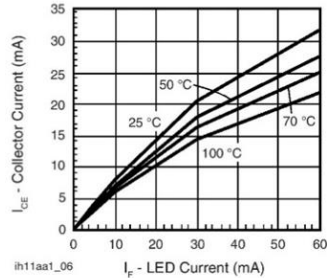


Fig. 6 - Collector Emitter Current vs. Temperature and LED Current

H11AA1

Vishay Semiconductors Optocoupler, Phototransistor Output,
AC Input, with Base Connection

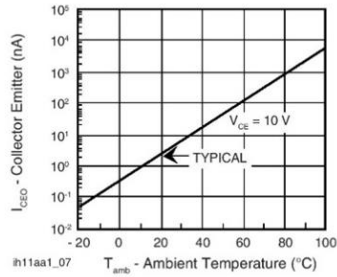


Fig. 7 - Collector Emitter Leakage Current vs. Temperature

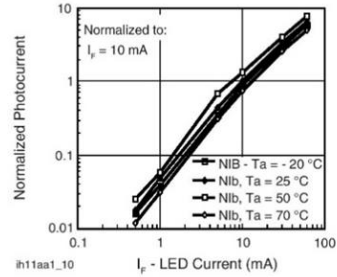


Fig. 10 - Normalized Photocurrent vs. LED Current

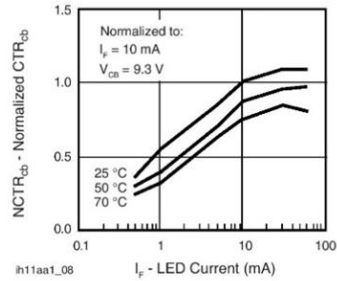


Fig. 8 - Normalized CTR_{cb} vs. LED Current and Temperature

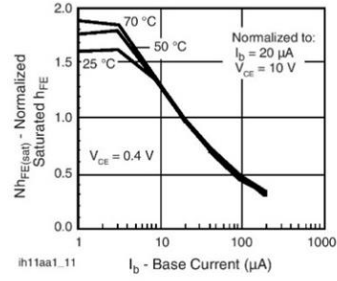


Fig. 11 - Normalized Saturated h_{FE} vs. Base Current and Temperature

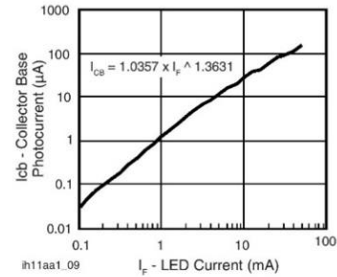


Fig. 9 - Collector Base Photocurrent vs. LED Current

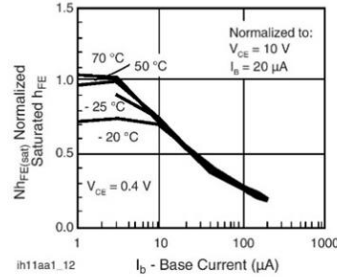
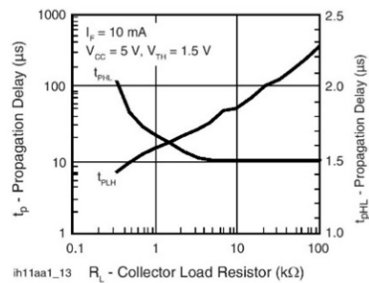


Fig. 12 - Normalized Saturated h_{FE} vs. Base Current and Temperature



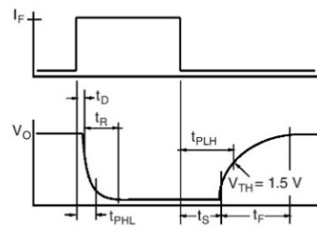
H11AA1

Optocoupler, Phototransistor Output, Vishay Semiconductors
AC Input, with Base Connection



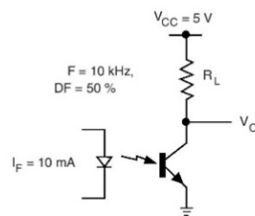
ih11aa1_13 R_L - Collector Load Resistor ($k\Omega$)

Fig. 13 - Propagation Delay vs. Collector Load Resistor



ih11aa1_14

Fig. 14 - Switching Waveform



ih11aa1_15

Fig. 15 - Switching Schematic

Appendix C – Datasheet of Q6015L5 TRIAC

Teccor® brand Thyristors
15 Amp Standard & 16 Amp Alternistor (High Commutation) Triacs

Littelfuse®
Expertise Applied | Answers Delivered

RoHS Qxx15xx & Qxx16xHx Series

Agency Approval

Agency	Agency File Number
	L Package : E71639

Main Features

Symbol	Value	Unit
$I_{T(RMS)}$	15 & 16	A
V_{DRM}/V_{RRM}	400 to 1000	V
$I_{GT(IQ1)}$	10 to 80	mA

Schematic Symbol

Description

15 Amp and 16 Amp bi-directional solid state switch series is designed for AC switching and phase control applications such as motor speed and temperature modulation controls, lighting controls, and static switching relays.

Standard type devices normally operate in Quadrants I & III triggered from AC line.

Alternistor type devices only operate in quadrants I, II, & III and are used in circuits requiring high dv/dt capability.

Features & Benefits

- RoHS Compliant
- Glass – passivated junctions
- Voltage capability up to 1000 V
- Surge capability up to 200 A
- Electrically isolated “L-Package” is UL recognized for 2500Vrms
- Solid-state switching eliminates arcing or contact bounce that create voltage transients
- No contacts to wear out from reaction of switching events
- Restricted (or limited) RFI generation, depending on activation point in sine wave
- Requires only a small gate activation pulse in each half-cycle

Applications

Excellent for AC switching and phase control applications such as heating, lighting, and motor speed controls.

Typical applications are AC solid-state switches, light dimmers, power tools, lawn care equipment, home/brown goods and white goods appliances.

Alternistor Triacs (no snubber required) are used in applications with extremely inductive loads requiring highest commutation performance.

Internally constructed isolated packages are offered for ease of heat sinking with highest isolation voltage.

Qxx15xx & Qxx16xHx Series

107

Revised: November 1, 2010 05:04 PM

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Specifications are subject to change without notice.
Please refer to <http://www.littelfuse.com> for current information.

Absolute Maximum Ratings — Standard Triac

Symbol	Parameter	Value	Unit
$I_{T(RMS)}$	RMS on-state current (full sine wave)	15	A
I_{TSM}	Non repetitive surge peak on-state current (full cycle, T_J initial = 25°C)	167	A
I_{GT}	Peak gate trigger current	2.0	A
$P_{G(AV)}$	Average gate power dissipation	0.5	W
T_{stg}	Storage temperature range	-40 to 150	°C
T_J	Operating junction temperature range	-40 to 125	°C

Note: xx = voltage, γ = sensitivity

Absolute Maximum Ratings — Alternistor Triac (3 Quadrants)

Symbol	Parameter	Value	Unit
$I_{T(RMS)}$	RMS on-state current (full sine wave)	16	A
I_{TSM}	Non repetitive surge peak on-state current (full cycle, T_J initial = 25°C)	167	A
I_{GT}	Peak gate trigger current	2.0	A
$P_{G(AV)}$	Average gate power dissipation	0.5	W
T_{stg}	Storage temperature range	-40 to 150	°C
T_J	Operating junction temperature range	-40 to 125	°C

Note: xx = voltage, γ = sensitivity

Electrical Characteristics ($T_J = 25^\circ\text{C}$, unless otherwise specified) — Standard Triac

Symbol	Test Conditions	Quadrant	Value	Unit
I_{GT}	$V_D = 12V$ $R_L = 60\ \Omega$	I – II – III	50	mA
V_{GT}		I – II – III	2.0	V
V_{GD}	$V_D = V_{DRM}$ $R_L = 3.3\ k\Omega$ $T_J = 125^\circ\text{C}$	I – II – III	0.2	V
I_H	$I_T = 100\text{mA}$	MAX.	70	mA
dv/dt	$V_D = V_{DRM}$ Gate Open $T_J = 125^\circ\text{C}$	MIN.	275	V/μs
$(dv/dt)_c$	$(di/dt)_c = 8.1\ \text{A/ms}$ $T_J = 125^\circ\text{C}$	MIN.	4	V/μs
t_{GT}	$I_G = 2 \times I_{GT}$ $PW = 15\ \mu\text{s}$ $I_T = 22.6\ \text{A(pk)}$	TYP.	4	μs

Electrical Characteristics ($T_J = 25^\circ\text{C}$, unless otherwise specified) — **Alternistor Triac (3 Quadrants)**

Symbol	Test Conditions	Quadrant	Qxx16xH2	Qxx16xH3	Qxx16xH4	Qxx16xH6	Unit	
I _{GT}	V _D = 12V R _L = 60 Ω	I – II – III	MAX.	10	20	35	80	mA
V _{GT}		I – II – III	MAX.	1.3				V
V _{GO}	V _D = V _{DRM} R _L = 3.3 kΩ T _J = 125°C	I – II – III	MIN.	0.2				V
I _H	I _T = 100mA		MAX.	15	35	50	70	mA
dv/dt	V _D = V _{DRM} Gate Open T _J = 125°C	400V	MIN.	200	350	475	925	V/μs
		600V		150	250	400	850	
		800V		100	200	350	475	
		V _D = V _{DRM} Gate Open T _J = 100°C		1000V	100	200	300	
(dv/dt) _c	(di/dt) _c = 8.6 A/ms T _J = 125°C		MIN.	2	20	25	30	V/μs
t _{gt}	I _G = 2 × I _{GT} PW = 15μs I _T = 22.6 A(pk)		TYP.	3	3	3	5	μs

Static Characteristics

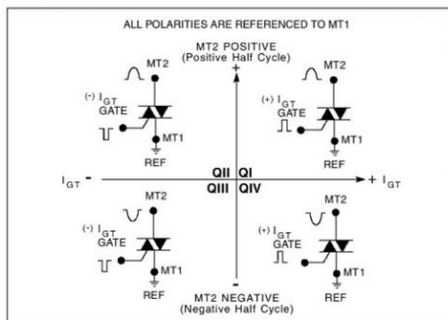
Symbol	Test Conditions			Value	Unit	
V_{TM}	15A Device $I_T = 21.2A$ $t_b = 380\mu s$			MAX	1.60	V
	16A Device $I_T = 22.6A$ $t_b = 380\mu s$					
I_{DRM} I_{RRM}	$V_D = V_{DRM} / V_{RRM}$	$T_J = 25^{\circ}C$	400-1000V	MAX	5	μA
		$T_J = 125^{\circ}C$	400-800V		2	mA
		$T_J = 100^{\circ}C$	1000V		3	

Thermal Resistances

Symbol	Parameter		Value	Unit
$R_{\theta(J-C)}$	Junction to case (AC)	Qxx15Ry Qxx15Ny Qxx16RHx Qxx16NHx	1.1	$^{\circ}\text{C/W}$
		Qxx15Ly Qxx16LHx	2.1	
$R_{\theta(J-A)}$	Junction to ambient	Qxx15Ry Qxx16RHx	45	$^{\circ}\text{C/W}$
		Qxx15Ly Qxx16LHx	50	

Note: xx = voltage; y = sensitivity

Figure 1: Definition of Quadrants



Note: Alternistors will not operate in QIV

Figure 2: Normalized DC Gate Trigger Current for All Quadrants vs. Junction Temperature

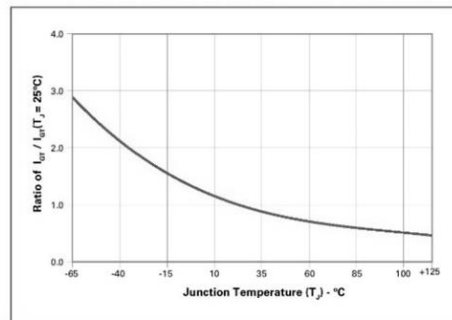


Figure 3: Normalized DC Holding Current vs. Junction Temperature

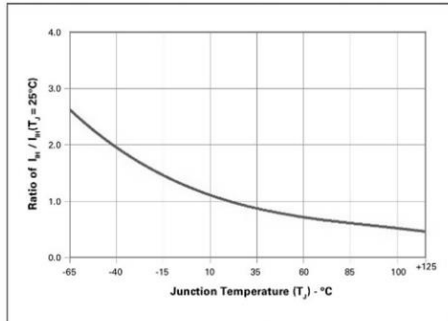


Figure 4: Normalized DC Gate Trigger Voltage for All Quadrants vs. Junction Temperature

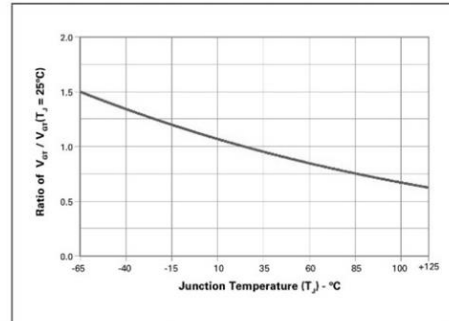


Figure 5: Power Dissipation (Typical) vs. RMS On-State Current

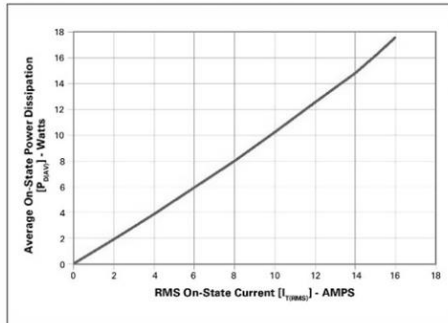


Figure 6: Maximum Allowable Case Temperature vs. On-State Current (15A devices)

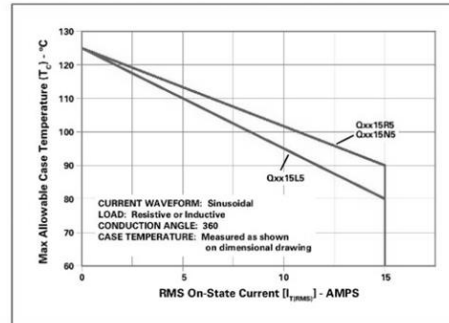


Figure 7: Maximum Allowable Case Temperature vs. On-State Current (16A devices)

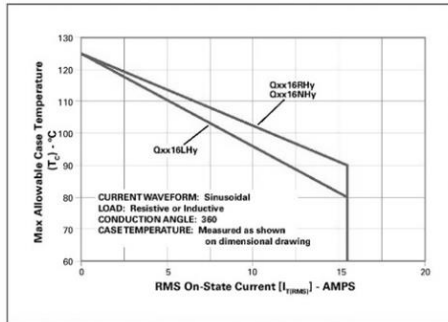


Figure 8: Maximum Allowable Ambient Temperature vs. On-State Current

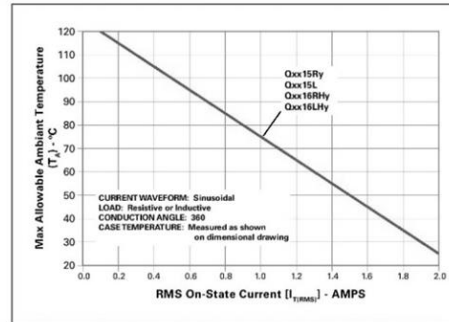


Figure 9: On-State Current vs. On-State Voltage (Typical)

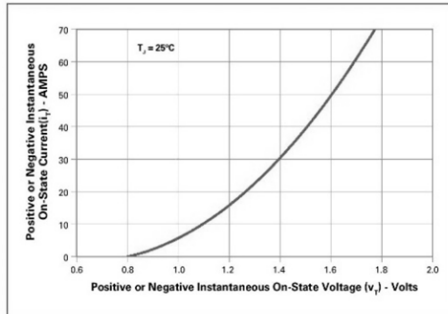
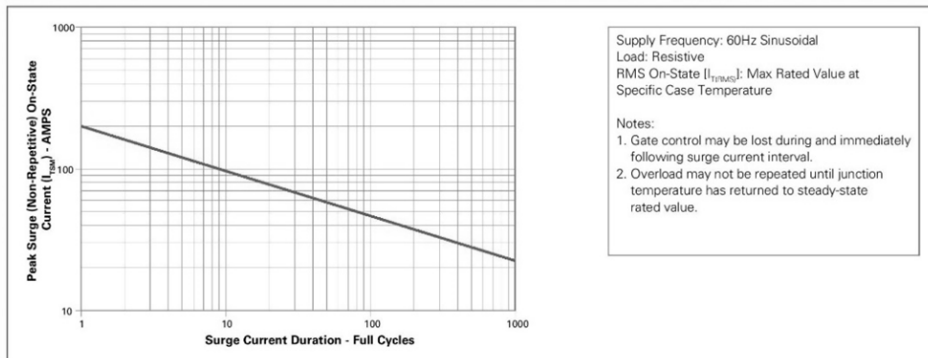
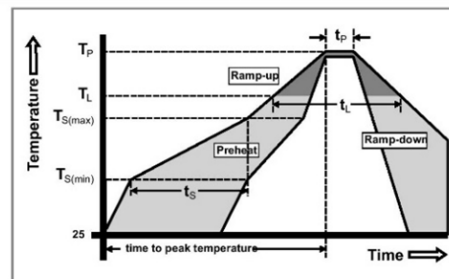


Figure 10: Surge Peak On-State Current vs. Number of Cycles



Soldering Parameters

Reflow Condition	Pb - Free assembly
Pre Heat	- Temperature Min ($T_{S(min)}$) 150°C
	- Temperature Max ($T_{S(max)}$) 200°C
	- Time (min to max) (t_p) 60 - 180 secs
Average ramp up rate (Liquidus Temp) (T_L) to peak	5°C/second max
$T_{S(max)}$ to T_L - Ramp-up Rate	5°C/second max
Reflow	- Temperature (T_L) (Liquidus) 217°C
	- Temperature (t_L) 60 - 150 seconds
Peak Temperature (T_p)	260 ± 5°C
Time within 5°C of actual peak Temperature (t_p)	20 - 40 seconds
Ramp-down Rate	5°C/second max
Time 25°C to peak Temperature (T_p)	8 minutes Max.
Do not exceed	280°C



Appendix D – Datasheet of MOC3051M IC



September 2015

MOC3051M, MOC3052M 6-Pin DIP Random-Phase Triac Driver Optocoupler (600 Volt Peak)

Features

- Excellent I_{FT} Stability—IR Emitting Diode Has Low Degradation
- 600 V Peak Blocking Voltage
- Safety and Regulatory Approvals
 - UL1577, 4,170 VAC_{RMS} for 1 Minute
 - DIN EN/IEC60747-5-5

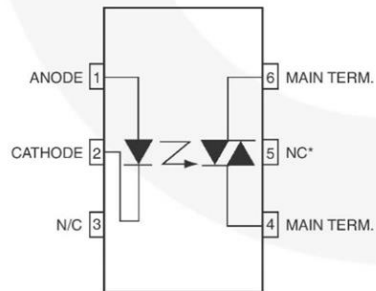
Applications

- Solenoid/Valve Controls
- Lamp Ballasts
- Static AC Power Switch
- Interfacing Microprocessors to 115 V_{AC} and 240 V_{AC} Peripherals
- Solid State Relay
- Incandescent Lamp Dimmers
- Temperature Controls
- Motor Controls

Description

The MOC3051M and MOC3052M consist of a GaAs infrared emitting diode optically coupled to a non-zero-crossing silicon bilateral AC switch (triac). These devices isolate low voltage logic from 115 V_{AC} and 240 V_{AC} lines to provide random phase control of high current triacs or thyristors. These devices feature greatly enhanced static dv/dt capability to ensure stable switching performance of inductive loads.

Schematic



*DO NOT CONNECT
(TRIAC SUBSTRATE)
Figure 1. Schematic

Package Outlines

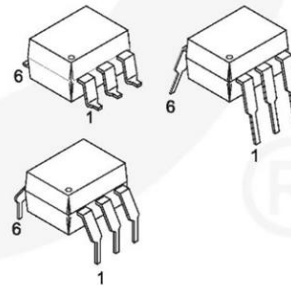


Figure 2. Package Outlines

Safety and Insulation Ratings

As per DIN EN/IEC 60747-5-5, this optocoupler is suitable for "safe electrical insulation" only within the safety limit data. Compliance with the safety ratings shall be ensured by means of protective circuits.

Parameter	Characteristics
Installation Classifications per DIN VDE 0110/1.89 Table 1, For Rated Mains Voltage	I–IV
Climatic Classification	40/85/21
Pollution Degree (DIN VDE 0110/1.89)	2
Comparative Tracking Index	175

Symbol	Parameter	Value	Unit
V_{PR}	Input-to-Output Test Voltage, Method A, $V_{IORM} \times 1.6 = V_{PR}$, Type and Sample Test with $t_m = 10$ s, Partial Discharge < 5 pC	1360	V_{peak}
	Input-to-Output Test Voltage, Method B, $V_{IORM} \times 1.875 = V_{PR}$, 100% Production Test with $t_m = 1$ s, Partial Discharge < 5 pC	1594	V_{peak}
V_{IORM}	Maximum Working Insulation Voltage	850	V_{peak}
V_{IOTM}	Highest Allowable Over-Voltage	6000	V_{peak}
	External Creepage	≥ 7	mm
	External Clearance	≥ 7	mm
	External Clearance (for Option TV, 0.4" Lead Spacing)	≥ 10	mm
DTI	Distance Through Insulation (Insulation Thickness)	≥ 0.5	mm
R_{IO}	Insulation Resistance at T_S , $V_{IO} = 500$ V	$> 10^9$	Ω

Absolute Maximum Ratings

Stresses exceeding the absolute maximum ratings may damage the device. The device may not function or be operable above the recommended operating conditions and stressing the parts to these levels is not recommended. In addition, extended exposure to stresses above the recommended operating conditions may affect device reliability. The absolute maximum ratings are stress ratings only. $T_A = 25^\circ\text{C}$ unless otherwise specified.

Symbol	Parameters	Value	Unit
Total Device			
T_{STG}	Storage Temperature	-40 to +150	$^\circ\text{C}$
T_{OPR}	Operating Temperature	-40 to +85	$^\circ\text{C}$
T_J	Junction Temperature Range	-40 to +100	$^\circ\text{C}$
T_{SOL}	Lead Solder Temperature	260 for 10 seconds	$^\circ\text{C}$
P_D	Total Device Power Dissipation at 25°C Ambient	330	mW
	Derate Above 25°C	4.4	$\text{mW}/^\circ\text{C}$
Emitter			
I_F	Continuous Forward Current	60	mA
V_R	Reverse Voltage	3	V
P_D	Total Power Dissipation at 25°C Ambient	100	mW
	Derate Above 25°C	1.33	$\text{mW}/^\circ\text{C}$
Detector			
V_{DRM}	Off-State Output Terminal Voltage	600	V
I_{TSM}	Peak Non-Repetitive Surge Current (Single Cycle 60 Hz Sine Wave)	1	A
P_D	Total Power Dissipation at 25°C Ambient	300	mW
	Derate Above 25°C	4	$\text{mW}/^\circ\text{C}$

Electrical Characteristics $T_A = 25^\circ\text{C}$ unless otherwise specified.**Individual Component Characteristics**

Symbol	Parameters	Test Conditions	Min.	Typ.	Max.	Unit
EMITTER						
V_F	Input Forward Voltage	$I_F = 10\text{ mA}$		1.18	1.50	V
I_R	Reverse Leakage Current	$V_R = 3\text{ V}$		0.05	100	μA
DETECTOR						
I_{DRM}	Peak Blocking Current, Either Direction	$V_{\text{DRM}} = 600\text{ V}$, $I_F = 0^{(1)}$		10	100	nA
V_{TM}	Peak On-State Voltage, Either Direction	$I_{\text{TM}} = 100\text{ mA peak}$, $I_F = 0$		1.7	2.5	V
dv/dt	Critical Rate of Rise of Off-State Voltage	$I_F = 0$ (Figure 13, at 400V)	1000			V/ μs

Transfer Characteristics

Symbol	DC Characteristics	Test Conditions	Device	Min.	Typ.	Max.	Unit
I_{FT}	LED Trigger Current, Either Direction	Main Terminal Voltage = $3\text{ V}^{(2)}$	MOC3051M			15	mA
			MOC3052M			10	
I_{H}	Holding Current, Either Direction		All		220		μA

Isolation Characteristics

Symbol	Characteristic	Test Conditions	Min.	Typ.	Max.	Unit
V_{ISO}	Input-Output Isolation Voltage ⁽³⁾	$f = 60\text{ Hz}$, $t = 1\text{ Minute}$	4170			VAC_{RMS}
R_{ISO}	Isolation Resistance	$V_{\text{I-O}} = 500\text{ V}_{\text{DC}}$		10^{11}		Ω
C_{ISO}	Isolation Capacitance	$V = 0\text{ V}$, $f = 1\text{ MHz}$		0.2		pF

Notes:

- Test voltage must be applied within dv/dt rating.
- All devices are guaranteed to trigger at an I_F value less than or equal to max I_{FT} . Therefore, the recommended operating I_F lies between maximum I_F (15 mA for MOC3051M, 10 mA for MOC3052M) and absolute maximum I_F (60 mA).
- Isolation voltage, V_{ISO} , is an internal device dielectric breakdown rating. For this test, pins 1 and 2 are common, and pins 4, 5 and 6 are common.

Typical Performance Curves

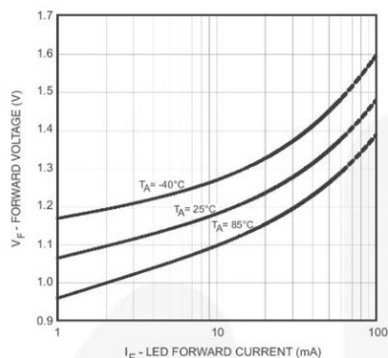


Figure 3. LED Forward Voltage vs. Forward Current

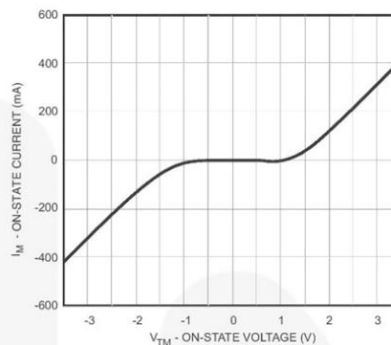


Figure 4. On-State Characteristics

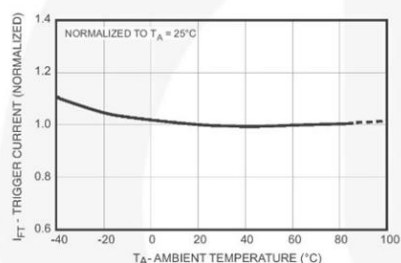


Figure 5. Trigger Current vs. Ambient Temperature

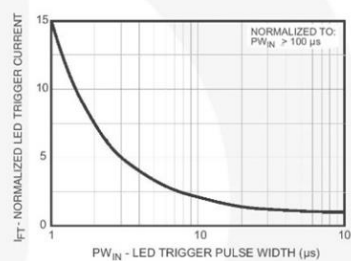


Figure 6. LED Current Required to Trigger vs. LED Pulse Width

I_F vs. Temperature (normalized)

Figure 5 shows the increase of the trigger current when the device is expected to operate at an ambient temperature below 25°C. Multiply the normalized I_{FT} shown on this graph with the data sheet guaranteed I_{FT} .

Example:

$T_A = 25^\circ\text{C}$, $I_{FT} = 10\text{ mA}$

I_{FT} at $-40^\circ\text{C} = 10\text{ mA} \times 1.1 = 11\text{ mA}$

Phase Control Considerations

LED Trigger Current versus PW (normalized)

Random Phase Triac drivers are designed to be phase controllable. They may be triggered at any phase angle within the AC sine wave. Phase control may be accomplished by an AC line zero cross detector and a variable pulse delay generator which is synchronized to the zero

cross detector. The same task can be accomplished by a microprocessor which is synchronized to the AC zero crossing. The phase controlled trigger current may be a very short pulse which saves energy delivered to the input LED. LED trigger pulse currents shorter than 100 μs must have an increased amplitude as shown on Figure 6. This graph shows the dependency of the trigger current I_{FT} versus the pulse width can be seen on the chart delay $t(d)$ versus the LED trigger current.

I_{FT} in the graph I_{FT} versus (PW) is normalized in respect to the minimum specified I_{FT} for static condition, which is specified in the device characteristic. The normalized I_{FT} has to be multiplied with the devices guaranteed static trigger current.

Example:

Guaranteed $I_{FT} = 10\text{ mA}$, Trigger pulse width $PW = 3\text{ }\mu\text{s}$

$I_{FT}(\text{pulsed}) = 10\text{ mA} \times 5 = 50\text{ mA}$

Minimum LED Off Time in Phase Control Applications

In Phase control applications one intends to be able to control each AC sine half wave from 0° to 180°. Turn on at 0° means full power and turn on at 180° means zero power. This is not quite possible in reality because triac driver and triac have a fixed turn on time when activated at zero degrees. At a phase control angle close to 180° the driver's turn on pulse at the trailing edge of the AC sine wave must be limited to end 200 μ s before AC zero cross as shown in Figure 7. This assures that the triac driver has time to switch off. Shorter times may cause loss of control at the following half cycle.

I_{FT} versus dv/dt

Triac drivers with good noise immunity (dv/dt static) have internal noise rejection circuits which prevent false

triggering of the device in the event of fast raising line voltage transients. Inductive loads generate a commutating dv/dt that may activate the triac drivers noise suppression circuits. This prevents the device from turning on at its specified trigger current. It will in this case go into the mode of "half waving" of the load. Half waving of the load may destroy the power triac and the load.

Figure 10 shows the dependency of the triac drivers I_{FT} versus the reapplied voltage rise with a V_p of 400V. This dv/dt condition simulates a worst case commutating dv/dt amplitude.

It can be seen that the I_{FT} does not change until a commutating dv/dt reaches 1000V/ μ s. The data sheet specified I_{FT} is therefore applicable for all practical inductive loads and load factors.

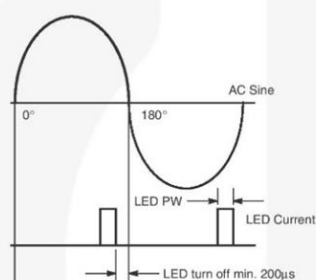


Figure 7. Minimum Time for LED Turn Off to Zero Cross of AC Trailing Edge

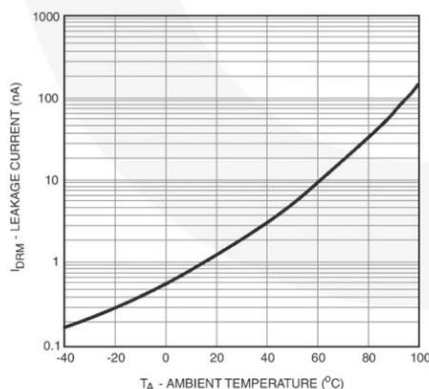


Figure 9. Leakage Current, I_{DRM} vs. Temperature

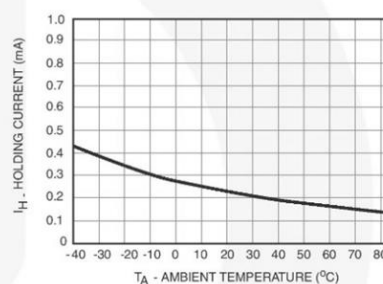


Figure 8. Holding Current, I_H vs. Temperature

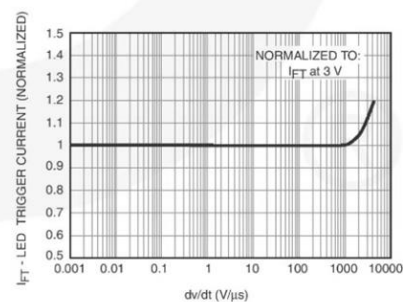


Figure 10. LED Trigger Current, I_{FT} vs. dv/dt

$t(\text{delay}), t(f)$ versus I_{FT}

The triac driver's turn on switching speed consists of a turn on delay time $t(d)$ and a fall time $t(f)$. Figure 12 shows that the delay time depends on the LED trigger current, while the actual trigger transition time $t(f)$ stays constant with about one micro second.

The delay time is important in very short pulsed operation because it demands a higher trigger current at very short trigger pulses. This dependency is shown in the graph I_{FT} vs. LED PW.

The turn on transition time $t(f)$ combined with the power triac's turn on time is important to the power dissipation of this device.

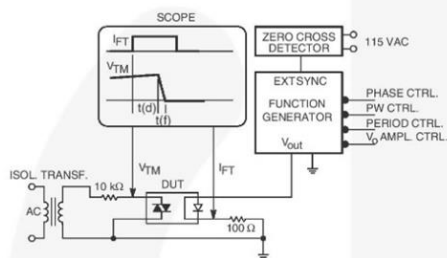


Figure 11. Switching Time Test Circuit

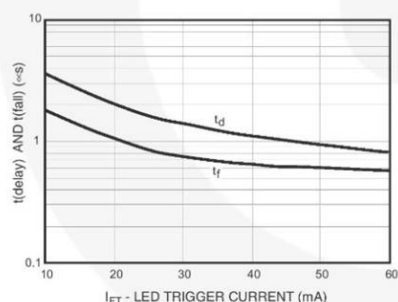


Figure 12. Delay Time, $t(d)$, and Fall Time, $t(f)$, vs. LED Trigger Current

1. The mercury wetted relay provides a high speed repeated pulse to the D.U.T.
2. 100x scope probes are used, to allow high speeds and voltages.
3. The worst-case condition for static dv/dt is established by triggering the D.U.T. with a normal LED input current, then removing the current. The variable R_{TEST} allows the dv/dt to be gradually increased until the D.U.T. continues to trigger in response to the applied voltage pulse, even after the LED current has been removed. The dv/dt is then decreased until the D.U.T. stops triggering. τ_{RC} is measured at this point and recorded.

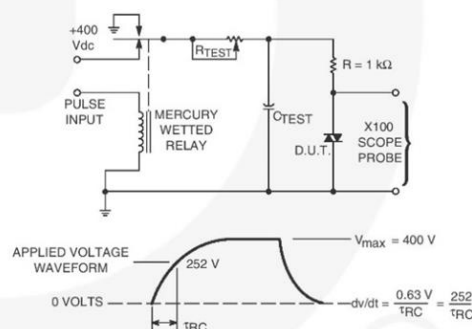


Figure 13. Static dv/dt Test Circuit

Applications Guide

Basic Triac Driver Circuit

The new random phase triac driver family MOC3052M and MOC3051M are very immune to static dv/dt which allows snubberless operations in all applications where external generated noise in the AC line is below its guaranteed dv/dt withstand capability. For these applications a snubber circuit is not necessary when a noise insensitive power triac is used. Figure 14 shows the circuit diagram. The triac driver is directly connected to the triac main terminal 2 and a series Resistor R which limits the current to the triac driver. Current limiting resistor R must have a minimum value which restricts the current into the driver to maximum 1 A.

$$R = V_p AC / I_{TM} \text{ max rep.} = V_p AC / 1 A$$

The power dissipation of this current limiting resistor and the triac driver is very small because the power triac carries the load current as soon as the current through driver and current limiting resistor reaches the trigger current of the power triac. The switching transition times for the driver is only one micro second and for power triacs typical four micro seconds.

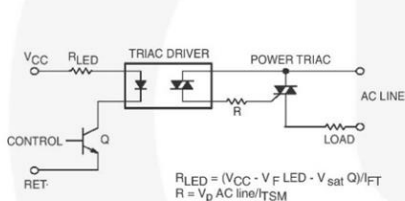


Figure 14. Basic Driver Circuit

Triac Driver Circuit for Noisy Environments

When the transient rate of rise and amplitude are expected to exceed the power triacs and triac drivers maximum ratings a snubber circuit as shown in Figure 15 is recommended. Fast transients are slowed by the R-C snubber and excessive amplitudes are clipped by the Metal Oxide Varistor MOV.

Triac Driver Circuit for Extremely Noisy Environments

As specified in the noise standards IEEE472 and IEC255-4.

Industrial control applications do specify a maximum transient noise dv/dt and peak voltage which is superimposed onto the AC line voltage. In order to pass this environment noise test a modified snubber network as shown in Figure 16 is recommended.

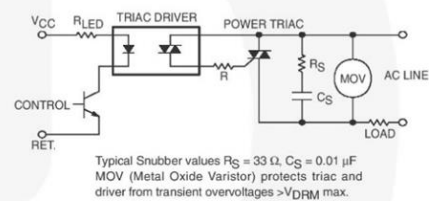


Figure 15. Triac Driver Circuit for Noisy Environments

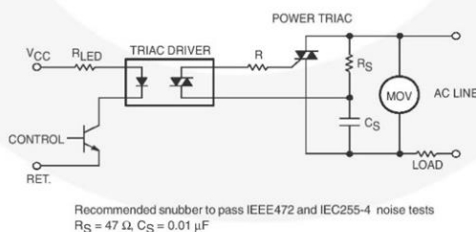


Figure 16. Triac Driver Circuit for Extremely Noisy Environments