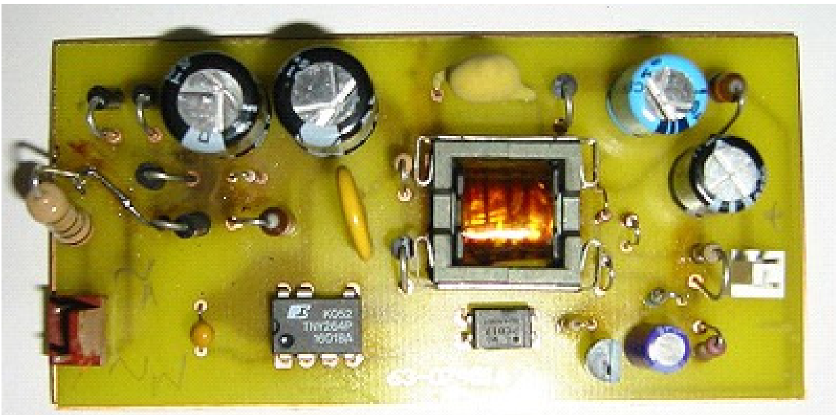
THE UNIVERSITY OF QUEENSLAND

School of Information Technology and Electrical Engineering

Low Profile Offline Switch Mode Power Supply

Submitted For The Degree Of Bachelor of Engineering In The Division Of Electrical Engineering



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29 October, 2003.

Professor Simon Kaplan,
The Head of School,
Department of Information Technology and Electrical Engineering,
University of Queensland,
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Dear Professor Kaplan,
In accordance with the requirements of the degree of Bachelor of Engineering in the division of Electrical Engineering, I present the following thesis entitled “Low Profile Switch Mode Power Supply”. This work was performed under the supervision of Mr. Richard Cocks.

I declare that the work submitted is my own, except as acknowledged in the text, and has not been previously submitted for a degree at the University of Queensland or any other institution.

Yours Sincerely,
Joel Wong

Acknowledgement

Although the completion of the thesis was a result of endless hours of individual hard work, it could not have happened without the help of several people. The author would like to take this chance to thank those who were involved.

Mr Richard Cocks the supervisor, for his guidance and his help for making the author discover a whole new way of working efficiently.

Dr Geoff Walker, for taking time off his busy schedule to set up and scrutinize the layout of the test equipments at the most crucial moment.

Mr EH Quek, **Mr YH Lek**, **Mr Colin Tuck**, **Mr Philip Wong** and **Mr Salil Chellappan** from Power Integrations, for providing valuable information to aid the author in the completion of the project.

Mr Paul Michaelis from Neosid, for providing technical support in the selection of materials for the construction of the transformer.

Mr Peter Allen the laboratory supervisor, for assisting the author with the testing of his circuits and ensuring a safe testing environment.

Mr Keith Bell and **Mr Denis Bill** , for sharing their expertise in selecting the appropriate components for the circuits.

Friends and **Family Members**, for their encouragement and moral support.

Abstract

The aim of this project was to produce a low cost Switch Mode Power Supply (SMPS) to power low energy embedded products. The module should be able to handle a wide range of input voltages and produce a steady output at 3 or 5 volts. In addition, the unit must produce power from 500mW to 2.5W with a maximum component height of 12.5mm.

Two power supplies with 5V outputs were constructed for this thesis. The first design was followed strictly to a pre-design circuit provided by the company Power Integrations. While the second design was a modified version of the first circuit with the intent to further reduce its standby power consumption.

The objectives of this project had been met as the final products had fulfilled all the specified parameters. This thesis gave a detail description of the steps that were taken to implement the power supplies and the several tests that were conducted to investigate the performance of the circuits.

With the completion of this project, I hope that the switch mode power supply could provide highly stable voltage conversion in several countries. As the modules were designed to handle a universal input voltage range, this goal could be achieved.

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Chapter 1 – Introduction

1.1 Problem Overview

All electronic appliances are required to be supplied with power to function. Battery is a popular choice for modules with lower power consumption or demand portability. On the other hand, AC mains are usually used to supply power to units that demand higher power. A switch mode power supply unit is normally employed to convert the AC mains voltage to a suitable voltage level for the appliance [1].

Due to the ever increasing advances in power supply design, they have led to a proliferation of power supplies which are much smaller and have higher efficiency. The purpose of this thesis is to investigate the switch mode technology and develop a low profile power supply which has a universal input voltage range. In addition, it must be able to generate an output of 3 or 5V.

1.2 Overview of Thesis

Throughout the rest of the thesis document, more information of switch mode power supply could be found. In addition, an intensive research was conducted to understand why certain components were used in the pre designed circuit and how the power supplies were developed and tested. The report had been divided into several chapters as follow:

Chapter 2 was devoted to provide the relevant background information which was required to construct the power supplies.

Chapter 3 specified the technical parameters needed for the products. The specification list was used to serve as guideline for the design progress.

Chapter 4 described the approach for developing the circuits and selecting their components. Although one of the final products was derived from a pre-designed circuit, a detail investigation was conducted to elaborate the rationale behind each selection.

Chapter 5 presented the methodology for constructing the transformer and selecting of its components.

Chapter 6 covered the various troubleshooting and tests that were conducted on the constructed circuits to determine their performance.

Chapter 7 described the evaluation of the circuits against the specifications stated in Chapter 3. From this assessment, the success of this thesis could be gauged.

Chapter 8 described some of the possible ways which could be implemented to improve the design of the power supplies.

Chapter 9 restated the objectives of the thesis, provided a summary of the important aspects of the document and closing statement regarding the design.

Chapter 2 - Literature Review

This chapter contained a large amount of relevant background information which was required to develop the power supplies. This included the advantages/disadvantages of switch mode power supply and its design topologies.

2.1 History of Switch Mode Power Supplies (SMPS)

Figure 2.1: Diagram of a mercury arc rectifier unit [2]

Switch mode power supplies were already developed in the beginning of the 1920s. The first switching power supplies used mercury-arc rectifiers and grid controlled mercury arc tubes. However, these mercury arc power supplies had limited commercialization due to some problems found in the switching devices used. They were namely poor efficiency, high cost, questionable reliability and high maintenance.

During the late1960s, these problems were overcome when the semiconductor industry developed a variety of high performance switching devices. The discovery of these switching devices became significant to power supplies and had a great impact on its industry. Their superior performance characteristics had allowed them to break into markets that had been unattainable for mercury arc. Nonetheless, it was only until the 1970s that SMPSs had been widely used [3].

2.2 Introduction to SMPS

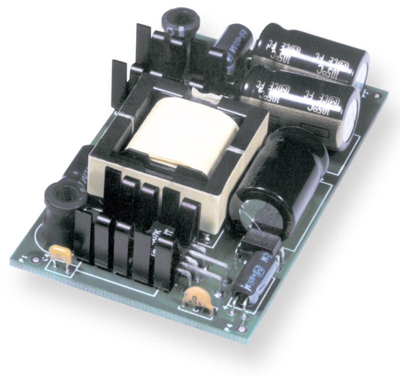

Figure 2.2: Diagram of a SMPS

A switch mode power supply can be classified as either an AC to DC or DC to DC converter in which the AC or DC input voltage is converted to the required DC output voltage. Both converters operate in very similar ways except that the AC input voltage of the AC to DC converter has to be rectified to a DC voltage first. After which, the two converters function very much the same way.

SMPS designs have several topologies (refer to chapter 2.7) but they are common in the fact that a DC current is turned on and off producing a pulsed waveform through an inductor or transformer (refer to chapter 5). The fundamental principle for the inductor topology is that current in an inductor cannot change instantaneously (based on Lenz's law). In most designs, the DC current passes through the primary side of the transformer when the switch is turned ON and the current has no path to continue when the switch is turned OFF. However, due to its inductive property the current cannot instantaneously, the energy that is previously built up in the transformer is transferred to the secondary side of the transformer. By introducing the necessary circuitries (rectification, clamp, feedback…etc) to the design, the converter can transform the input voltage from the mains to the desired output voltage on the secondary side of the transformer [4].

2.3 Principles of SMPS

Many appliances and circuits will not be able to function well if they do not receive a constant supply voltage. Such devices need a reliable power supply that provides a highly stable DC voltage despite the variations from input voltage of the power source.

With the ever-increasing demand for Switch Mode Power Supplies, a SMPS must be capable of carrying out the following tasks:

- Converting the input voltage from the mains to a suitable DC voltage for the electrical device.
- Rectifying the AC input voltage to DC output voltage.
- Filtering by smoothing the ripple of the rectified voltage.
- The DC voltage must be stable and independent of line and load variations.
- Providing isolation between the main line and the output of the power supply.
- The power supply must have high efficiency.
- Small in size.
- Low in cost.
- Must be able to handle a wide range of input voltage [5].

2.4 Advantages of SMPSs compared to Linear Power Supplies (LPSs)

Figure 2.3: Diagram of LPS (Left) and SMPS (Right)

The merits of using Switch Mode Power Supplies instead of Linear Power Supplies are with respect to efficiency, size and weight.

- Efficiency - In an ideal situation, the switching devices are fully on or fully off. Therefore, very little power is lost during the conversion and efficiency for SMPSs can exceed 85% (compared to LPSs which only 50-60%) [6].
- Size and weight – The transformer of a LPS normally uses pounds of silicon steel core to convert 60Hz input voltage to the required output voltage. On the contrary, SMPS rectifies the 60Hz input to DC and then "chops" the rectified voltage into a high frequency square waveform with a frequency from 10kHz to more than 1MHz. As the SMPS transformer operates in high frequency, the core required is typically ounces of ferrite. Therefore, SMPSs are a lot smaller and lighter than LPSs [7], [8].

2.5 Drawback of SMPSs

There are several benefits when using SMPSs which made them really attractive. However, their greatest weakness is the generation of Electromagnetic Interference (EMI). Due to the fact that SMPSs are switching its current constantly, they producing a lot more EMI compared to linear power supplies [1]. Proper designs must be introduced to the circuit to eliminate this noise so that it will not interfere with the performance of the power supply. In addition, SMPSs have more complicated circuitries to analyze and have a slower transient reaction compared to LPSs [9].

2.6 Two modes of SMPS operation

SMPS can operate in two modes:

- Continuous mode – The SMPS operates by starting a new cycle before the transformer core has used up all of its energy(flux) [4]. The inductor current never returns to zero in this mode [7].

- Discontinuous mode – The SMPS operates by starting a new cycle only when the transformer core has used up all of its energy(flux) [4]. The inductor current falls to zero in this mode [7].

2.7 SMPS Topologies

The word *topology* refers to "science of place". Two systems are considered as topologically similar if they are different only in the circuit elements that put together their branches. A SMPS comprises of a number of storage components and switches which are arranged in a topology such that the switches cyclically controls the transfer of power from the mains input to generate the required DC level at the output. In general, the storage elements are arranged in such a way that they form a filter to achieve a low output ripple voltage. The two basic topologies of SMPS are the buck converter and the boost converter. Many of the other topologies are derived from these two converters as they are considered topologically similar to either of the two converters [12]. Additionally, converters can be classified as non-isolated or isolated, depending on whether a transformer is used in the design [13]. In the following section, the principle operations of a few popular topologies are presented.

2.7.1 Buck Topology (Non-isolated)

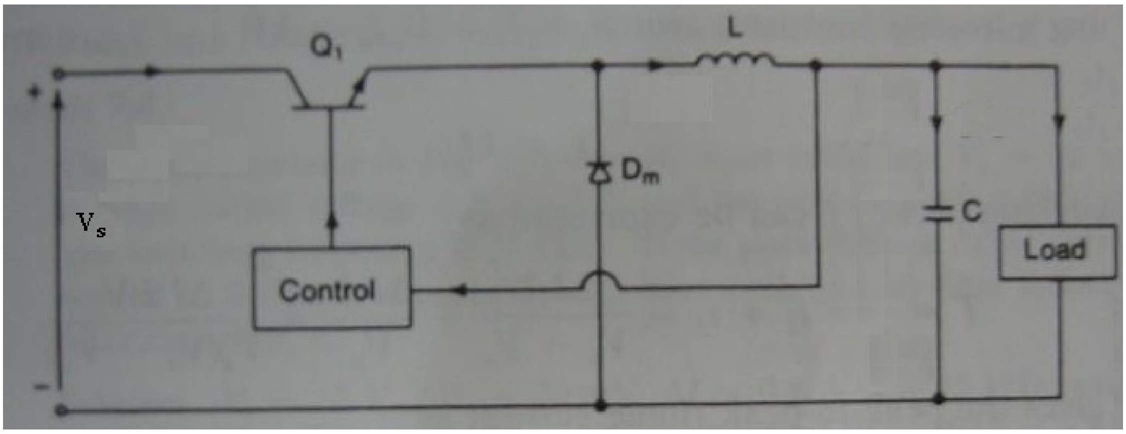

Figure 2.4: Circuit Diagram of a Buck Converter [3]

The buck converter operates as a step down converter where the output voltage is lower than the input voltage. The circuit functions in two modes. For the first mode, the transistor Q1 is switched on and the input current rises linearly when it passes through inductor L, capacitor C and the load. At the second mode, Q1 is switched off and the diode D_m conducts due to the energy stored in the inductor. The inductor current maintains its flow by passing through the inductor, capacitor, load the diode. The energy that is stored in the inductor is transferred to the load. The inductor current decreases until the transistor is switched on another time in the next cycle [3].

2.7.2 Boost Topology (Non-isolated)

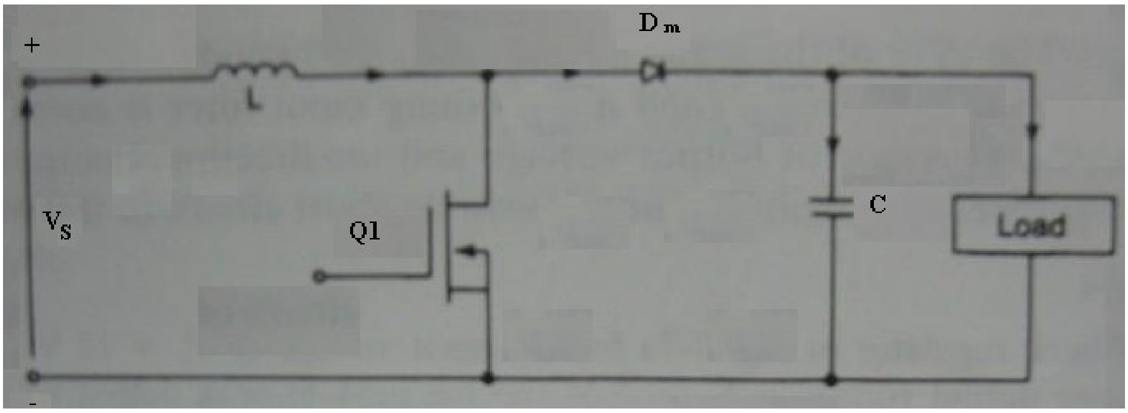

Figure 2.5: Circuit Diagram of a Boost Converter [3]

The boost converter operates as a step up converter where the output voltage is higher than the input voltage. Just like the previous topology, the boost converter functions in two modes. For the first mode, the transistor Q1 is switched on and the input current rises linearly when it passes through inductor L and transistor Q1. At the second mode, Q1 is switched off and the current which was flowing through the transistor maintains its flow by passing through the inductor, capacitor, load the diode $D_{m.}$ The energy that is stored in the inductor is transferred to the load. The inductor current decreases until the transistor is switched on another time in the next cycle [3].

2.7.3 Buck-Boost Topology (Non-isolated)

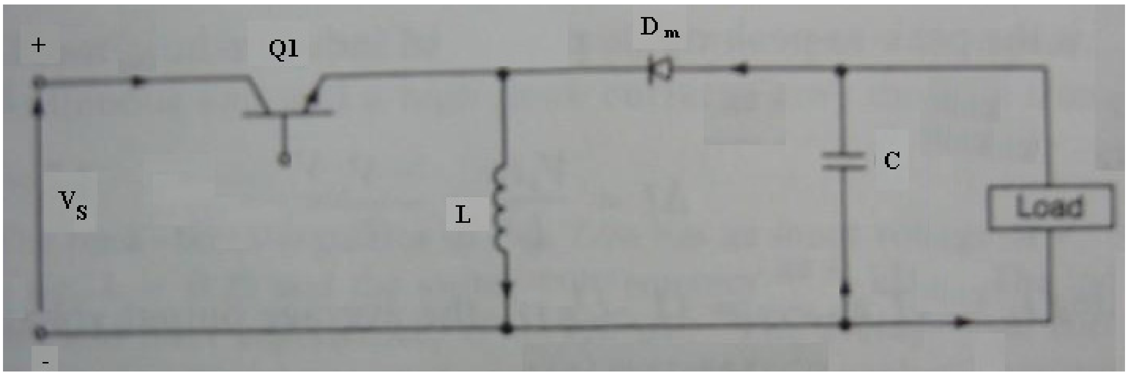

Figure 2.6: Circuit Diagram of a Buck-Boost Converter [3]

The buck-boost converter can either operate as a step down or step up converter where the output voltage can be lesser or larger than the input voltage. This circuit also functions on two modes. For the first mode, the transistor Q1 is switched on and the diode D_m is reversed biased. The input current rises linearly when it flows through the inductor and the transistor. At the second mode, Q1 is switched off and the current which was flowing through the inductor maintains its flow by passing through the inductor, capacitor, load the diode D_m. The energy that is stored in the inductor is transferred to the load. The inductor current decreases until the transistor is switched on another time in the next cycle [3].

2.7.4 Forward Topology (Isolated)

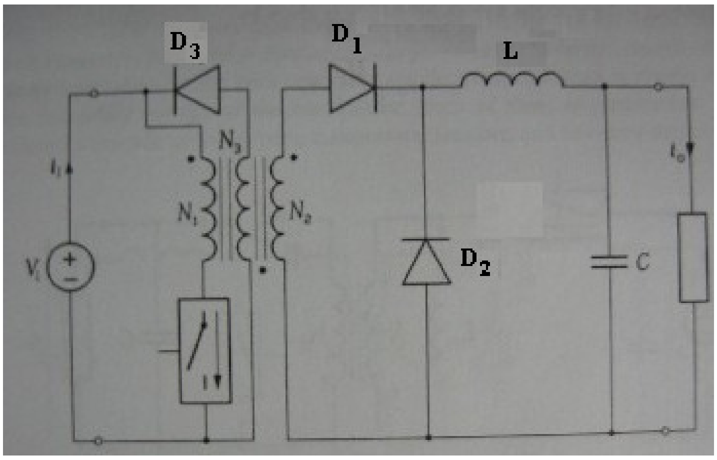

Figure 2.7: Circuit Diagram of a Forward Converter [11]

The forward converter is an isolated version of the buck converter [11]. This converter operates in three different states in each cycle. When the switch is turned on during the first state of the cycle, input current is passed through the transformer and the switch. By observing the dots on the transformer, it is shown that the polarity of the primary and the secondary windings is positive. As a result, current is able to pass through D1 (as it is forward biased), through the inductor, through the capacitor, through the load and through the secondary winding to finish its path. Energy is stored in the inductor and capacitor at this stage.

When the switch is turned off during the second state of the cycle, the output voltage falls and D1 becomes reverse biased. The inductor changes its polarity and sends current through the capacitor, through the load, through D2 and through the inductor to finish its path. Energy stored in the inductor is passed to the capacitor at this stage.
There is a net flux in the core and it must be reset at the completion of the first state to avoid saturation of the transformer [3]. To release the energy stored in the transformer, a third winding (also termed as *freewheeling winding*) is introduced to the transformer with a diode D3 connected in series [11]. The third state commences when the energy stored in the inductor has been transferred totally to the capacitor. At this stage, there is no active energy transfer and is termed as the *dead time*.

2.7.5 Flyback Topology (Isolated)

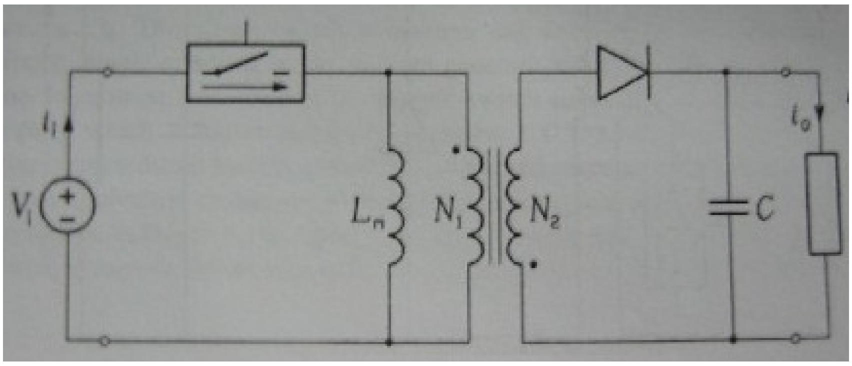

Figure 2.8: Circuit Diagram of a Flyback Converter [11]

The flyback converter is an isolated derivation of the buck-boost converter [12]. The magnetizing inductance, L_m, of the transformer takes on the role of the inductor in the buck-boost converter. However, the magnetizing inductance is an element of the equivalent circuit of a transformer and should not be considered as another component [11]. This converter operates in three different states in each cycle as well. When the switch is turned on during the first state of the cycle, input current is passed through the transformer and the switch. By observing the dots of the transformer, it is shown that the polarity of the transformer is inversed. Consequently, none of the current flows on the secondary side as the diode is reversed bias. Energy is stored in the gap (refer to chapter 5) of the transformer at this stage.

When the switch is turned off during the second state of the cycle, the input current on the primary side ceases its flows. Instead, the stored energy in the transformer is released to the capacitor and load resulting in a secondary current flow. In addition, this current also resets the core to zero flux bias.

During the final state, only the capacitor discharges to the load and there is no active energy transfer. At the completion of this state, the switch is turned on again and the process is repeated [3].

2.7.6 Push Pull Topology (Isolated)

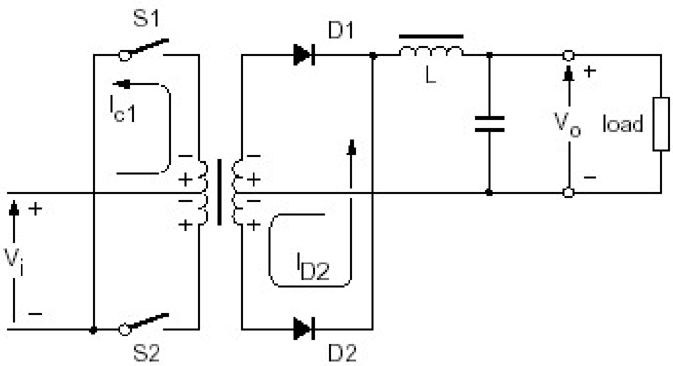

Figure 2.9: Circuit Diagram of a Push Pull Converter [13]

The push pull converter is another derivation of the buck converter which is an arrangement of two forward converters functioning in antiphase (Push Pull action) [13]. This topology operates by conducting switch 1(S1) and switch 2(S2) alternatively.

When S1 is closed, diode 2(D2) conducts and current is passed through the inductor(L) and flows into the load and capacitor. Energy is stored in the inductor at this time. When S1 is opened, the energy which is stored in the inductor is released into the load via diode 1(D1) and (D2) which are acting as freewheel diodes.

When S2 is closed, D2 stops conducting and D1 continues to conduct. Current is passed through the inductor(L) and flows into the load and capacitor. Energy is stored in the

inductor at this time. When S2 is opened, the energy which is stored in the inductor is released into the load via (D1) and (D2). The process is repeated for the next cycle [5].
Careful measures must be taken to make sure that the S1 and S2 close and open for an equal cycle. If not, the transformer will saturate when a DC voltage is supplied to the primary side of the transformer. Normally, an air gap is introduced to the transformer core to prevent this from happening.

Chapter 3 - Specifications

In order to meet the requirements which were set in chapter one, it would be necessary to specify the technical parameters needed for the products. The specification list would serve as guideline for the design progress and unnecessary parameters should not be included. Doing so would increase the price of the product and might affect their performance [5]. The specifications of the products were presented in the following section.

3.1 Wide Input Voltage Range

The products should have a universal range so that they could cater to different countries. Voltage level in different countries could range from 110-240Vac and the module should be designed to handle a wide input voltage range. A table showing a list of countries' voltages was attached under Appendice 11.1 [14].

3.2 Output Voltage Range

The output voltage should only have a +/- 10% variation of the nominal DC voltage (either 3 or 5V).

3.3 Output Voltage Regulation

As mentioned in chapter 2, most appliances would not be able to function well without a constant supply of voltage. Therefore, the power supplies should be designed to have a tight regulation on the output voltage and independent of line variations.

3.4 Isolation

Transformer coupling would be needed to isolate the output from the input. This is usually a requirement when operating from a 230 volt or 110 volt mains supply, to keep the mains voltages well apart from a low voltage load [1].

3.5 Simplified Design

Simplified design would cut down the numbers of component to be used which in turns reduce the cost of production.

3.6 Protection

As faults might inevitably happen during the usage of the power supply, it should be designed to guard against certain abnormal conditions. Some common forms of protections are:

a) Overvoltage Protection: In order to prevent the load from incurring any damages during an overvoltage condition, it would be normal to shut down the power supply when an overvoltage was sensed.
b) Overcurrent Protection: The power supply unit should be equipped with some form of current limit so that load current will fall within a safe limit if it reaches above a specified level.
c) Short Circuit Protection: This is similar to overcurrent protection except that a different circuit is normally used to shut down the power supply when a short circuit is detected at the output terminals [1].

3.7 Low Cost

Products should be produced at low cost due to the high market demand for low cost and high reliability modules.

3.8 Low Profile

As the power supply should be designed to be low in height so that it could easily be fitted into a slim enclosure. The module should not have a height of more than 12.5mm.

3.9 Low Power Output

Since these power supplies were supposed to power low energy products, it should be able to produce a low power output.

3.10 Energy Efficient

The no load power consumption of these units should be kept as low as possible to avoid wastage of energy.

3.11 EMI

As the switching frequency of the power supply rises, problems related to EMI increases [1]. Therefore, sufficient filtering circuitries should be included in the design to bring the EMI to an acceptable level.

3.12 Fusing

A fuse should be installed into the power supply to provide additional protection to guard against faulty conditions [5].

Chapter 4 – Hardware Implementation: Circuit

This chapter described the approach to develop the circuit and select its components. Despite the fact that one of the final products was derived from a pre-designed circuit, a detail investigation was conducted to elaborate the rationale behind each selection.

Selection of circuit and its components were based on the following requirements:

- Ability to take in a wide range of input voltage
- Provides isolation
- Simplified design
- Low cost
- Low profile
- Produce an output of either 3 or 5 volts

4.1 Key Features of Different Design Topologies

As Buck, Boost and Buck-Boost converters do not meet the isolation requirement, they were not taken into consideration during the selection. Only a tradeoff of Flyback, Forward and Push-Pull converter was presented.

4.1.1 Features of Flyback converter

- Isolation is provided between the input and the output with the use of a transformer.
- Voltage conversion is done by varying the “on” and “off” switching time and by the transformer turn ratio.
- Ideal for high voltage supplies.
- Energy is stored in the transformer before it is transferred to the capacitor and load [5].
- Flyback is a simple design with the lowest component count compared to other converters [11].

- It is suitable for low power applications (up to 100W) since the transformer is designed to endure a DC bias which is larger than the average input current [15], [12].
- As the output capacitor is charged only when the switch is "off", a higher output capacitor ripple current is produced than other converters.
- Energy is stored in the transformer and is driven in a single direction only. As a result, a larger transformer is required [13].

4.1.2 Features of Forward converter

- Isolation is provided between the input and the output with the use of a transformer.
- Voltage conversion is determined by the transformer turn ratio [5].
- Suitable for higher power applications and allows smaller transformer to be used compared to Flyback converter [11].
- Has higher efficiency compared to Flyback converter [16].

4.1.3 Features of Push-Pull converter

- Isolation is provided between the input and the output with the use of a transformer.
- Voltage conversion is determined by the transformer turn ratio.
- Has the highest efficiency among the 3 converters.
- Complicated circuit [5].
- As the converter increases two times the frequency of the ripple current in the output filter, the output ripple voltage is decreased.
- Since the transformer operates in two directions, a smaller transformer is used [13].

4.2 Selection of Design Topology

By comparing the features of the 3 converters, it is obvious that using a Flyback converter is a favorable choice for my application. The main factors which it possesses are:

- Isolation is provided between the input and the output.
- It is a simple circuit with low component count which results in overall low cost.
- It is suitable for low power application.

4.3 Application of Power Integrated Chip in SMPS

To develop a small and light SMPS, the use of an integrated chip is inevitable. Generally, the functions of regulation, protection, current limit and other circuitries are incorporated onto a single chip. Thus, the number of components required is greatly lessened and the design is simplified to a large extent.

4.4 Available Integrated Chips

Despite the fact that there are several integrated chips which were capable of performing the required tasks for my application, only 3 chips were considered in this section. They were namely TinySwitch II TNY264 (by Power Integrations), LinkSwitch LNK501 (by Power Integrations) and STARplug TEA152X (by Philips).

4.5 Selection of Integrated Chip

The performance of the 3 chips was comparable as they were built to operate with a wide range of input voltage (90 to 276Vac for TEA152X and 85 to 265Vac for both LNK501 and TNY264) and had built in protection circuitries. However, TNY264 was chosen due to the following reasons:

- A pre-designed 5V/2.5W output circuit was available for TNY264 which met the specified output voltage and power. Although LNK501 had a sample circuit design as well, the circuit was designed to function with an output of 5.5V and 2.75W. By using the software called “STARplug design wizard”, a circuit based on STARplug products could be generated by specifying the requirements. However, the schematic was not as comprehensive as the schematic provided by Power Integrations.

- Important transformer parameters which were needed for the construction of the required transformer could be generated with the use of software "PI Expert" (refer to chapter 5) for TNY264 but not LNK501.The program "STARplug design wizard" is capable of generating some transformer parameters but it did not specify the wire size of the primary and secondary winding.
- TNY264 could offer a tighter output regulation compared to LNK501.
- Evaluation Kit was available for Power Integration products but not STARplug.

4.6 Description of TinySwitch II TNY264

TNY264 is a 7 pin ON/OFF integrated control chip with a 700V MOSFET (to allow handling of input voltage of from 85Vac to 265Vac), high voltage switched current source, oscillator and temperature protection circuitry (set at a limit of 135 degree Celsius). The ON/OFF control method is a lot faster compared to a typical PWM (Pulse Width Modulation). This will allow a tight output regulation and superb transient response. It operates at 132kHz and is capable of performing auto-restart when faults such as short circuit or open loop occurs. On top of that, it has frequency jittering and line under voltage sense to monitor the line voltage [17].

4.7 Functions of TNY264 Pins

The pins of the TNY264 had different functions and the description of each pin was presented in the following section. Information for next segment was extracted from the application guide of TinySwitch II and more information of the chip can be found in Appendice 11.2 [17].

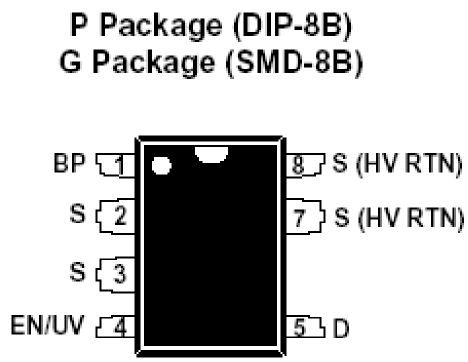

Figure 4.1: TinySwitch II Pin Configuration

4.7.1 Drain (D) Pin

This is the MOSFET drain connection which supplies internal operating current for accomplishing start-up and steady-state.

4.7.2 BYPASS (BP) Pin

This pin is meant for connecting a 0.1uF bypass capacitor externally for the 5.8V supply which is generated within the TinySwitch II. The 5.8V regulator charges the bypass capacitor every time the MOSFET is turned "Off". When the MOSFET is turned "ON", the TinySwitch II operates from the energy that is stored in the capacitor.

4.7.3 ENABLE/UNDER-VOLTAGE (EN/UV) Pin

This connection point serves two functions: enable input and line under-voltage sense. Switching MOSFET is managed by this pin under most load conditions and the switching operation stops when the current drawn from the pin exceeds 240uA. At near full load, the MOSFET will still continue to switch but at preset lower current limit. In addition, this pin is able to detect line under-voltage states through an external resistor connected to the DC line voltage. However, the line under-voltage is disabled when no external resistor is used on the pin.

4.7.4 SOURCE (S) Pin

The pin controls the circuit common and is internally connected output MOSFET source.

4.7.5 SOURCE (HV RTN) Pin

The purpose of this pin is for high voltage return and is connected to the output MOSFET source.

4.8 Description of 5V/2.5W circuit (First Circuit)

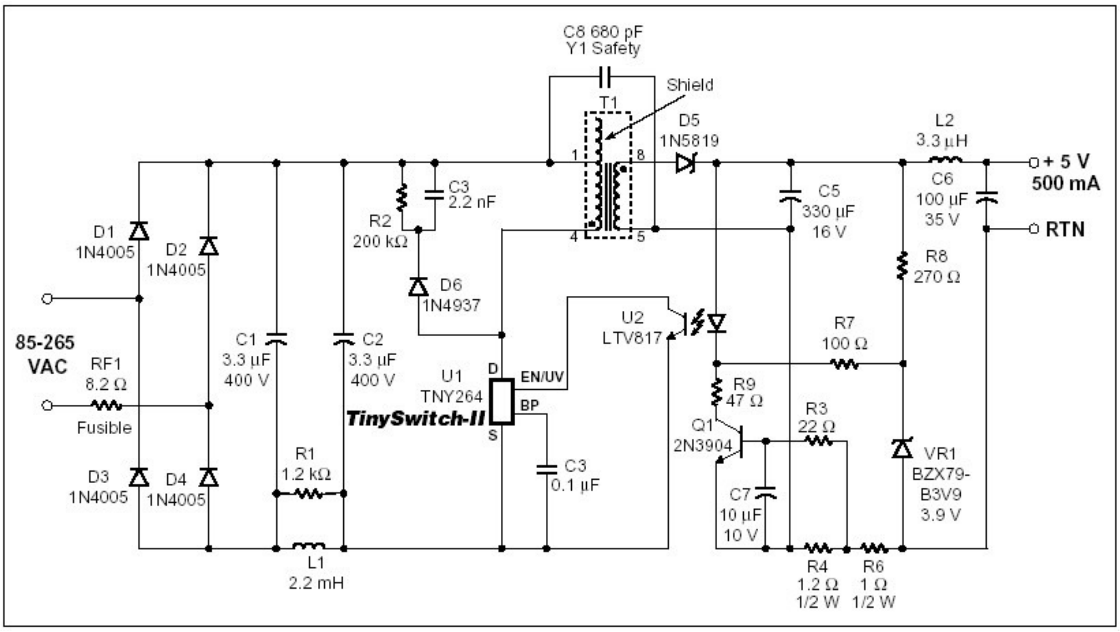

Figure 4.2: Schematic of the 5V/2.5W Circuit

The circuit had been divided into a few major parts for analysis in the following sections. Its schematic and PCB layout could be found in Appendice 11.3.

4.8.1 Fuse

A fusible resistor RF1 (8.2ohms/1W) was introduced into the power supply to provide more protection to guard against faulty conditions. Furthermore, RF1 was used in place of a fuse to cut cost and improve differential mode filtering [18].

4.8.2 Input Rectifier

Four 1N4005 silicon diodes (D1 to D4) were used to form a bridge rectifying circuit. The purpose of the rectifier was to convert the AC line voltage to a constant polarity DC voltage. A bridge rectifying configuration was employed as lower ripple will stay on the rectified voltage compared to other rectifying arrangements. In addition, the configuration allowed the use of a storage capacitor of a smaller capacitance value to be used [5].

At any instant, only two diodes are forward-biased and the other two are reverse-biased. D1 and D4 operate during the first half of the period while D2 and D3 operate during the second half of the period [19]. The forward-biased diodes had a voltage drop of 1.2V during the conduction time.

These diodes were selected as they have low voltage drop and high reverse voltage properties [19]. In addition, essential diodes rating such as average rectified forward-current limit, peak rectified forward-current limit and peak inverse-voltage (PIV) limit were considered during the selection [20]. For example, the stated PIV and current must not be exceeded as it may cause damage to the diode. 1N4005 have a rated PIV of 600V and is suitable to handle 265Vac from the mains.

4.8.3 Input Filter

As mentioned, SMPSs generate a lot of EMI due to their high switching frequency. The inductor (L1) formed a π filter in combination with capacitors, C1 and C2 which were used to bring the EMI of the circuit to an acceptable standard. A Y1 capacitor(C8) was also used to further reduce the interference [17].

There other types of filter configurations which could be applied to the circuit. Two of which were the T filter and L filter. However, π filter was chosen since it was known to be the most advantageous arrangement among all the filters [21].

Two important specifications for an inductor were its inductance and rated current. The rated current would designate the highest permissible current which might be applied across the component constantly. In general, the current rating comes down with increasing inductance for a given size. For this design, I had decided to use a 2.2mH suppression choke with a rated current of 80mA as L1 since the rating was suitable for the circuit. The resonances in the suppression choke were dampened with the use of resistor R1 [17].

The purposes of the capacitors were to filter the rectified voltage and accumulate enough energy to sustain a constant supply of voltage for the SMPS. A proper choice of the capacitors would supply the circuit with enough voltage to keep it operational even when there is a short term failure on the mains [5].

As the circuit was designed to take in a voltage of up to 265Vac, the C1 and C2 were rated at 400V. The rated voltage specified the maximum DC voltage and the peak ripple voltage level, which would be allowed to pass through the capacitor continuously [22]. The rating of the capacitor was chosen based on the table from application note 23.

Input Voltage	C_{in} (uF/watt)
100/115	2-3
230	1
Universal	2-3

Table 4.1: Selection Guide for Input Capacitor [23]

Since the output power of the circuit was rated at 2.5W and 2-3uF was required per watt, 6.6uF input capacitance is a reasonable choice for the circuit. As the capacitors were to be arranged in a π configuration, the input capacitance is split into two capacitors of 3.3uF each. In addition, electrolytic capacitors were selected for this application as they are low cost and small in size [24].

4.8.4 RCD Clamp Circuit

Flyback was known to possess another drawback of having huge transient voltage spikes at the drain pin of integrated chips. The leakage inductance (energy stored inside and between the flyback transformer windings) was the cause of these spikes and clamp/snubber circuits were used to manage the effects of the leakage inductance and enhance the performance of the circuit [25].

As the primary leakage inductance of the flyback converter was not involved in the transmission of energy from the primary to the secondary winding, the current generated within it had no path to flow during turn on of the MOSFET. Consequently, a voltage spike occurred and slowed down the transmission of the power from the primary to the secondary during the turn off time. The function of the clamp circuit was to limit the voltage spike on the TNY264 drain pin to a safe level during this period [17].

In this design, an RCD clamp was preferred over a snubber. Although both circuits served the same purpose, an RCD clamp was capable of producing higher efficiency for circuits which produces power of less than 3W. For this circuit, capacitor C3, resistor R2 and diode D6 made up the RCD clamp circuit [23].

During the turn off of the MOSFET, the primary current path of the flyback transformer was closed via C3 and D6. The moment the MOSFET was turned on, C3 was discharged through R2. At this instant, D6 was not conducting. If D6 was not used, there would be a huge current spike through the MOSFET every time it was turned on as C3 would reverse its charge. This would be very inefficient [5].

As high peak currents occur during the turn off period, C3 was chosen to deal with these currents as it has low ESR (Equivalent Series Resistance) and low inductance. The capacitance of C3 was also chosen to reduce the building up rate of the voltage at the drain pin [5]. To handle the peak current, the diode (1N4937) was selected as it has high current and fast recovery capabilities. The resistor used in the clamp circuit has low inductance property to prevent too much overshooting from taking place [25].

4.8.5 Transformer

The main functions of the transformer were to provide isolation between the mains and the output of the power supply and store energy. On top of that, it was used to convert the input voltage to the desired output voltage. The energy stored in the transformer would be able to deliver a high voltage if no secondary winding was used. Therefore, the purpose of the secondary winding was to decrease the primary voltage [26]. A shield winding has been included to further reduce the EMI conducted. As the transformer was a topic by itself, please refer to Chapter 5 for more details.

4.8.6 Output Rectifier

The purpose of diode D5 and capacitor C5 was to rectify the output pulses of the flyback transformer. The best diode for this function should have sufficient reverse voltage carrying capacity, minimum forward voltage drop and a fast reverse recovery time. To minimize losses, the switching rate of the diode was an important parameter which should be considered.

A 1N5819 Schottky diode was used in the design and was chosen for those reasons mentioned above. In addition, the diode was suitable for this application as the output voltage of the circuit was low (5 volts). For circuits with output voltage of more than 50V, epitaxial diodes would be a more suitable choice to perform the task [5].

The output capacitor C5 performed the tasks of storing energy and filtering. In general, variation of the output voltage was caused by the high frequency AC component found in the power supply and dynamic changes in the load current.

The characteristics of the output capacitor affect the size of the variations mentioned above. Two important parameters of the component are the equivalent series resistance (ESR) and equivalent series inductance (ESL). As a filtering capacitor, these two parameters influence the output ripple voltage of the capacitors.

As the circuit was based on a flyback topology, C5 should have a low ESR to manage the high rms current. Therefore, a capacitor with a low ESR of 0.72 ohms was adopted for this application. In addition, C5 was chosen to have a high capacitance of 330uF for its purpose of storage of energy [5].

4.8.7 Feedback

The output voltage regulation of the circuit was determined by the operation of the integrated chip, TNY264. The ENABLE pin sensed the difference between the output voltage and the specified voltage (5V). If the output voltage was lower than the specified value, the ENABLE pin would turn on.

The ENABLE pin was powered by the optocoupler U2 for this power supply which was made up of a photo transistor and a photo LED (Light Emitting Diode). The photo transistor was connected to the pins of TNY264 while the LED was connected through resistor R8 to voltage regulator diode VR1. If the output voltage went above the specified value, the LED would activate which in turn would stop the operation of the ENABLE pin. The output voltage of the circuit was obtained by the adding the voltage drop across these two components (LED and VR1) [17].

A diode (BZX79-B3V9) with a tolerance of 2% was chosen for VR1 since it could offer a tighter output voltage regulation compared to diodes with higher tolerance values. The optocoupler (PC817A) used in the design has a CTR from 80 to 160% which was ideal for this application. The CTR stands for Current Transfer Ratio which is the ratio of output current to input current (expressed in percentage) [27]. If the CTR was too high, the gain of the feedback loop would be too high and cause instability.

4.8.8 Constant Current (CC) Circuit

A constant current circuit was implemented to maintain the specified current level despite the variations from the input voltage and the load [28]. The V_{BE} of transistor Q1 was used to detect voltage across the resistor R4 which was used to detect current. Q1 would switch on and manage the loop by activating the LED of the optocoupler if the voltage drop of R4 went above the V_{BE} of transistor.

The use of resistor R6 was to provide enough voltage to operate the control loop even when the output reached 0V.On top of that, the voltage drop across R4 and R6 would be enough to keep the transistor and LED functional with the output shorted. During short circuit situations, the forward current obtained through the Zener diode VR1 could be high. Therefore, resistors R7 and R9 were employed to limit this current surge [17].

4.8.9 Output Filter

The output filter comprised of an inductor L2 and capacitor C6 which was employed to reduce the output ripple voltage and switching noise. A suppression choke was used as L2 and was selected in a similar manner as L1. It had a rated current of 900mA and would be able to handle the output current of the power supply. As the LC filter was not within the feedback control loop, the resonant frequency of the filter could be reduced to a low level [23].

4.9 Description of 5V/2.5W circuit with Bias Winding (Second Circuit)

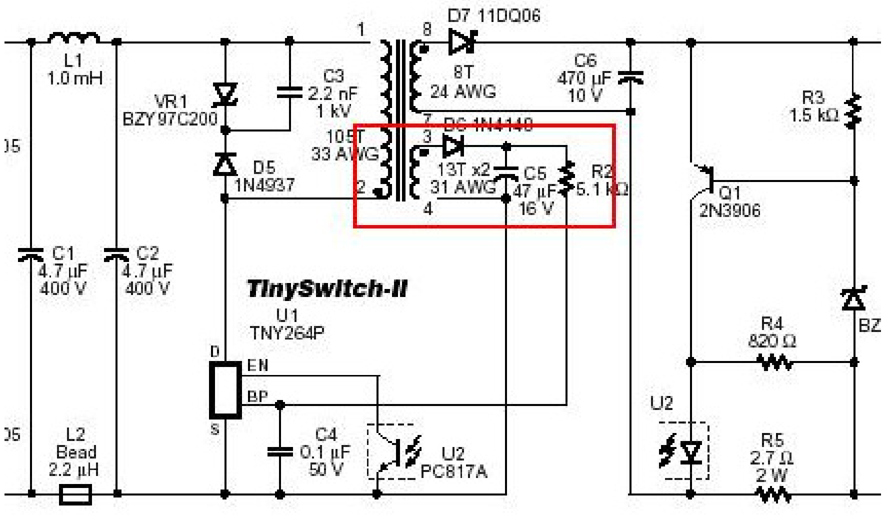

Figure 4.3: Partial Schematic of A Circuit With Bias Winding

This design was developed to reduce the no load power consumption of the existing design. The previous design was expected to have a no load power consumption of not more than 300mW. However, if the 3 component circuitry (together with a bias winding) shown in the red box were to be introduced to the original circuit. It should drastically reduce the standby power loss to less than 50mW.

When the bias winding was used, the internal circuitry of TNY264 would take its supply from the Bypass pin (via bias winding) and could greatly reduce the Standby loss. C5 was selected to extreme large value (47uF) so that the charge stored would be able to run with many switching cycle as to prevent the chip from taking the current from DC bulk capacitor (DC bus). The first circuit did not include a bias winding, so the design had a higher standby loss. Moreover, the chip would occasionally take the supply from the bus.

The design shown above was part of a schematic from DI-28 (Design Idea 28) provided by Power Integration [29]. Certain adjustments had to be made to the bias circuitry before it could be implemented on my circuit since DI-28 was designed to produce a different output. As my output winding for the first circuit was design to have only 4 turns, 13 turns of winding (as stated in schematic) will be too many for the bias circuitry. The bias winding turns had to be adjusted to get 10V output from the winding.

In order to produce 5V at the output of the first circuit, the transformer was designed to produce 6.6V. This was to make up for the voltage drop across the 0.5V voltage drop across the output rectifier and 1.1V voltage drop across the sense resistors (0.6V across R4 and 0.5V across R6). To get this 6.6V, 4 turns were used for the secondary winding. Therefore, the voltage per turn was 1.65V (dividing 6.6V by 4 turns). Consequently, 6 turns (dividing 10V by 1.65V) were required to get 10V at the bias winding [30].

The schematic of this circuit and its PCB layout could be found in Appendice 11.4. Besides the replacement of the shielding winding with the bias winding circuitry, this design still differed slightly from the first one as the Y1 capacitor (C8) was not in use as well.

Chapter 5 – Hardware Implementation: Transformer

To construct an appropriate transformer for the circuit, it would be necessary to have a good understanding of the magnetic component. In the following section, the methodology for constructing the transformer and selection of its components were presented.

5.1 Flyback Transformer

The main purpose of using a transformer in this application was to provide isolation between the main input and the output load for safety and reliability reasons. However, the transformer used in a flyback converter differed from a typical linear transformer. The key differences between a flyback transformer and a linear transformer were as followed:

- A flyback transformer is gapped and designed to stored energy. On the other hand, a linear transformer is ungapped and designed to transfer energy from its primary to secondary with minimal energy storage.
- The current of a flyback transformer will not flow in it primary winding and secondary winding simultaneously [31].
- As an air gap is introduced to the flyback transformer, its reluctance is normally larger than that of a linear transformer.
- Pulsed (rectangular) voltages are supplied to the primary side of a flyback transformer while sinusoidal voltages are supplied to a linear transformer [6].

5.2 Use of PI Expert (Transformer design software)

As my circuit was based on PI (Power Integrations) products, I had chosen to use the software "PI Expert (version.4.0.3.1)" to design my transformer. The purpose of this software was to simplify the tedious designing process of deriving essential transformer parameters needed for the construction. With the use of program, I had generated the necessary information (found in Appendix 11.5) for constructing a transformer to suit my circuit. Some of the design parameters were shown below and other design parameters could be found in Appendix 11.6 [32]:

- N_p – The number of turns required for the primary winding.
- AWG_p – The size of wire to be used on the primary winding.
- A_e – The effective cross sectional area of the core.
- AL_g – The effective inductance of the gap core.
- L_g – The gap length of the core.
- N_s – The number of turns required for the secondary winding.
- AWG_s – The size of wire to be used on the secondary winding.

Despite the fact that PI Expert had greatly shortened my transformer design process, I still need to investigate on the appropriate components (eg. the type of core material, core geometry, type of wires…etc) to match the generated results. The subsequent sections displayed the research I had conducted on each transformer component.

5.3 Transformer Core

The primary purpose of a transformer core was to supply the highest amount of magnetic coupling between the primary and secondary winding. Without the use of a core, very little magnetic flux would be produced by the primary couples with the secondary winding. By employing a core with higher permeability, more flux could be achieved which would in turn result in better coupling of the total flux. Furthermore, an appropriate selection of core properties could reduce the losses found in the transformer

[33]. The next few segments described some of the materials which I had come across when choosing the suitable core for my transformer.

5.4 Introduction to Ferrite

Soft ferrite cores are normally used in switch mode power conversion due to their desirable properties. They are attractive as they can be easily magnetized, have low power loss during conversion and have high saturation. Two popular combinations are Manganese Zinc (MnZn) and Nickel Zinc (NiZn).

Soft ferrites can be used in a different frequencies and it will be considered as ideal to achieve high permeability and low magnetic losses at high frequencies. Magnetic losses are termed as the deviation between the energy which is stored for the period of the application of a magnetic field and the energy recovered once the field has gone back to its original value.

In addition, ferrites have a much higher resistivities compared to magnetic alloys. Despite that, the eddy current found in the Manganese Zinc ferrite is considerable and may lead to high energy losses at high frequencies [33].

5.5 Different Grades of Ferrite and Its Applications

Selecting an appropriate ferrite grade would be important when constructing a transformer as it determined the power, saturation and inductive capabilities of the cores [34]. The next few paragraphs were some examples of common grade* of ferrites and its applications.

(* Note that various manufacturers may grade their ferrite differently from other companies although the compounds of the ferrite are exactly the same. For example, grade M25 from Siemens is the cross reference of grade 3D3 from Ferroxcube [35]. The data in the following segments is based on ferrite from the company, Neosid [36])

5.5.1 Grade F47

Material Type: Manganese Zinc Ferrite.

Properties: F47 belongs to a higher frequency power grade, has low losses and high saturation.

Application: Switch mode Power Supplies.

5.5.2 Grade F14

Material Type: Nickel Zinc Ferrite.

Properties: F14 has low losses at average frequency and high suppression impendence at high frequencies.

Applications: Radio frequency suppression, medium frequency and aerial rods.

5.5.3 Grade F16

Material Type: Nickel Zinc Ferrite.

Properties: F16 has low losses at high frequency.

Applications: Tuned circuits and aerial rods.

5.5.4 Grade F19

Material Type: Nickel Zinc Ferrite.

Properties: F19 has low losses at low frequency, average permeability and high resistance at high frequency.

Applications: Beads, cable suppressors and sleeves.

5.5.5 Grade P11

Material Type: Manganese Zinc Ferrite.

Properties: P11 has low loss factor, average permeability and high stability of inductance.

Applications: Filter networks and proximity.

5.6 Selection of Ferrite

By comparing the ferrite data from the Neosid Catalogue, I had decided to use F47 which belonged to a low loss and high saturation grade. In order to prevent the cores from saturation, the flux density in the smallest cross section area must not be greater than the saturation flux density of the ferrite. F47 had a saturation flux density between 350 to 470mT [13].

It had the ability to transfer energy with little power loss and would not be prone to saturation when it had to operate at high switching frequency. When a core became saturated it would cause the inductance to drop and would limit its ability to store energy. This is undesirable [34].

The rest of the ferrites belonged to other grades (eg. a radio frequency, electromagnetic capability, suppression grade…etc) that were unsuitable for a SMPS application.

5.7 Core Geometry

Most transformer cores comprise of two parts and come in various shapes and sizes. A suitable core must be used to meet the specified requirements and achieve optimum results for the power supply. This section described some common shapes of cores and was an excerpt from the website of Neosid [5].

5.7.1 EP Cores

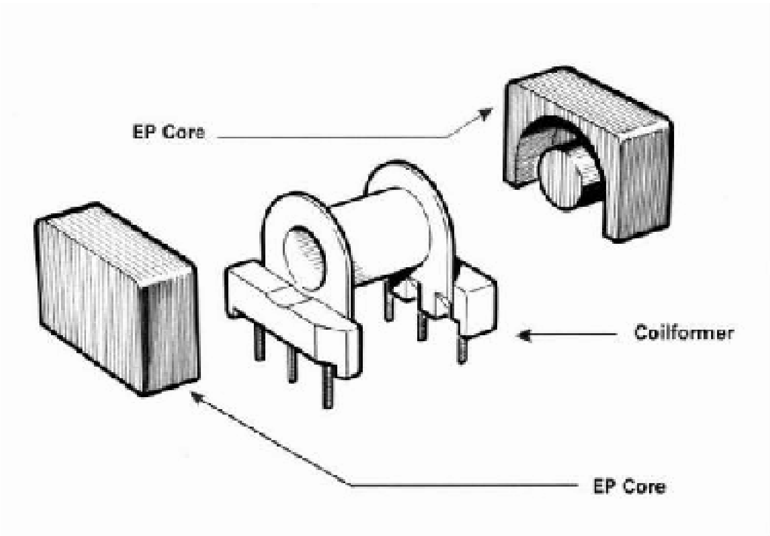

Figure 5.1: EP cores

EP cores are designed to be compact and low in height to meet designs with space constraint. As the winding is more or less enclosed by the cores, this design provides superb shielding from adjacent cores. These cores are assembled horizontally and were initially designed for applications like broadband, signal transmission and small power packing transformers. However, they are widely used as components in modern electronic due to their desirable properties. The available sizes for this core are EP7, EP10, EP13, EP17 and EP20 where the number denotes the major dimension of the core in mm. For example, core EP7 has a length of 7mm.

5.7.2 ETD Cores

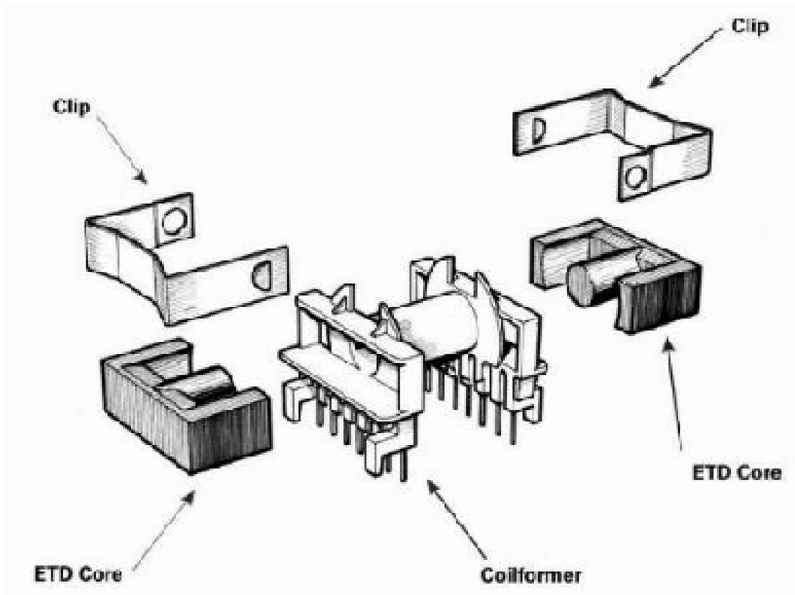

Figure 5.2: ETD cores

The ETD (Economical Transformer Design) core has a round center limb which results in low winding resistance, copper eddy losses and leakage inductance. Furthermore, the total cross sectional area of the two outer limbs of the ETD core is the same as the center limb permitting a constant flux distribution throughout the core. This will eliminate the localized “hot spots” that can worsen the performance of the transformer when operating at high flux levels and high frequencies. These cores have been designed for SMPS application and some available sizes are ETD 29, ETD 34, ETD 39, ETD 44 and ETD 49.

5.7.3 E Cores

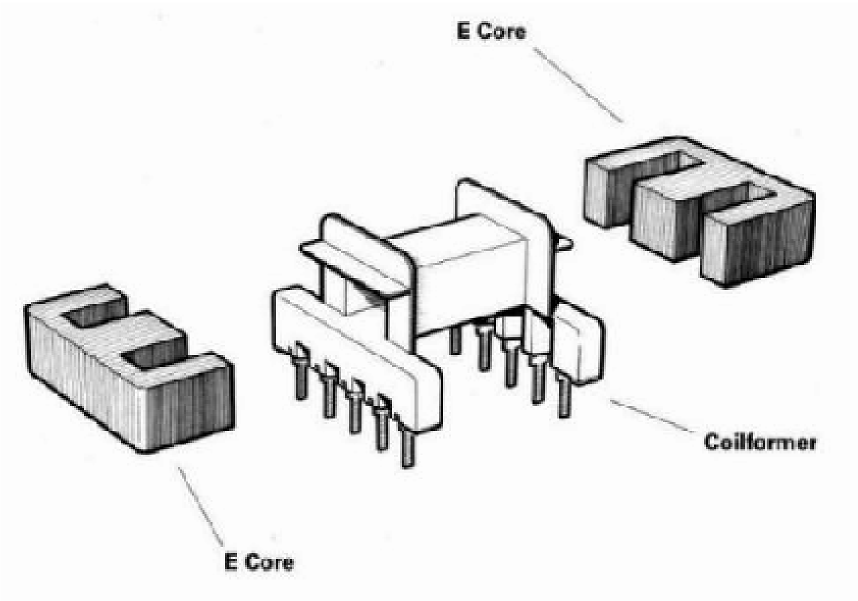

Figure 5.3: ETD cores

E cores were among the earliest cores that were developed and are comparatively simple to produce due their rectangular limbs. These cores are ideal for filters at low frequencies and power transformers. However, they are not appropriate for high frequency applications as the rectangular limb may result in winding resistance and higher leakage inductance. The available sizes are EE20, EE25, EE30, EE42, EE55 and EE65.

5.7.4 Toroid Cores

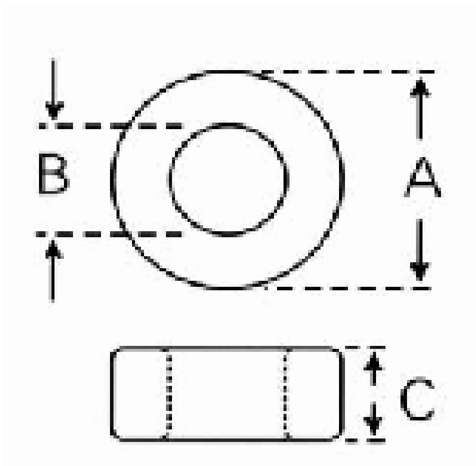

Figure 5.4: Toroid cores

Toroid core is only a one part design unlike the other shapes. The core has high permeability due to the lack of gap and high inductance resulting in fewer turns. In addition, this design has low leakage inductance and allows the huge bandwidths to be attained [33]. Two typical applications of toroids are RF suppression and common mode chokes.

5.7.5 RM Cores

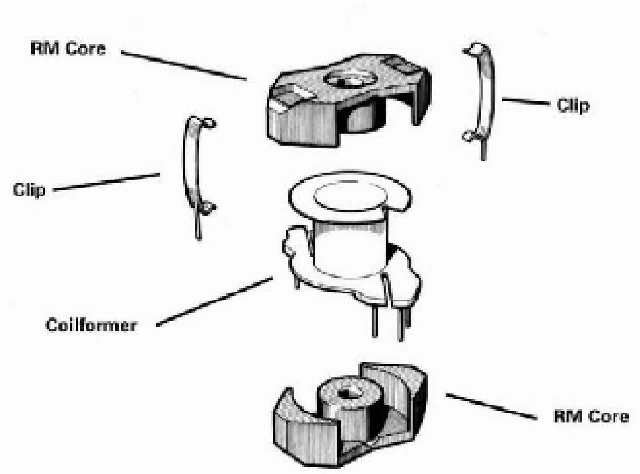

Figure 5.5: RM cores

RM (Rectangular modulus) cores are developed to meet the ease of winding and direct mounting onto a PCB. These cores can be produced with the absence of a center hole which will increase the AL value and cross sectional area. This will allow the core to be employed in power transformer applications. However, two major applications for this core shape are:

- Highly stable and low loss filter inductors
- Low distortion broadband transmission operating at low signal modulation

The available sizes are RM5, RM6, RM10 and RM12.

5.7.6 EFD Cores

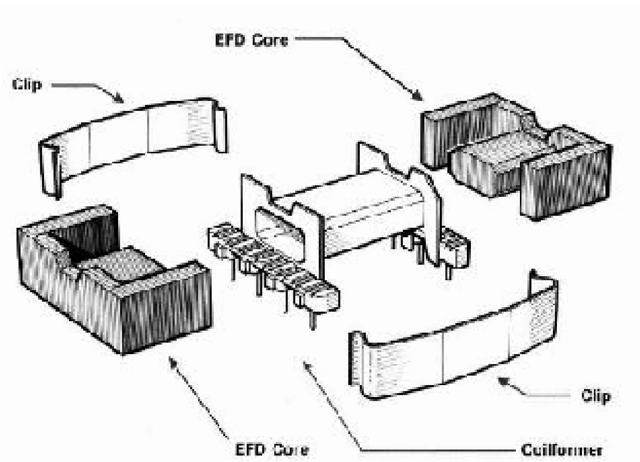

Figure 5.6: EFD cores

EFD (Economical Flat Design) cores are extremely low profile and superb throuput power when weigh against the rest of the cores. These properties made EFD cores extremely desirable for power transformer designs where space considerations are an important issue. The available sizes are EFD15, EFD20 and EFD25.

5.8 Selection of Core

By comparing the properties and applications of the various together with the results I had generated from PI Expert, I had decided to use EFD15. The results from the software suggested the use of EE13, but EE cores were obsolete and hard to come by. In addition, EFD15 was extremely low profile and had a height of approximately 8mm when mounted to the coil former.

5.9 Air Gap in Transformer

The purpose of using gapped cores was to lower the flux density of the core so that higher field strength would be required to saturate the core [13]. The bigger the air gap, the higher the peak inductor current would be required to saturate the core [12]. If a small air gap was used, the flux density in the gap would almost be the same as the ferrite. Generally, all the energy would be considered to be stored in the air gap since the magnetic field strength in the gap was a lot greater compared to the ferrite core.

With PI Expert, the calculated core should have a gapped core effective inductance of 139nH/T^2 and a gap length of 0.11mm. Based on F47 ferrite cores offered by Neosid, combining an ungapped core with a 0.1mm gapped core would produce 160nH/T^2. Therefore, two gapped cores with a measured 0.055mm gap size each are used to match the required gapped effective inductance during the construction of the transformer.

5.10 Winding the transformer

5.10.1 Wires

Insulated copper magnetic wires were normally used for winding transformers. During the selection of the suitable wires, the resistivity of the wire was an important parameter which should be considered. This was because it would determine the efficiency and the output voltage regulation of the transformer.

By using the software PI Expert, I had managed to derive the required wire size and turns for the primary and secondary windings. They were 98 turns of 35AWG Double Nyleze wire and 4 turns of Triple Insulated wire respectively.

These wires were purchased from an American company, MWS Wire Industries. Triple Insulated wire was equivalent to Triple Build Polyurethane Nylon (TPN) while Double Nyleze was Heavy Build Polyurethane Nylon (HPN). The term "Nyleze" meant Polyurethane Nylon insulation.

Polyurethane Nylon incorporated the magnet wire insulation property of polyurethane with the benefits of a nylon topcoat. The use of nylon allowed the insulation to have superb solvent resistance and thermal stability of the insulation is excellent. Moreover, the nylon enables the wire to be more stress resistant during the harsh winding process for transformer [37].

5.10.2 Winding Procedure

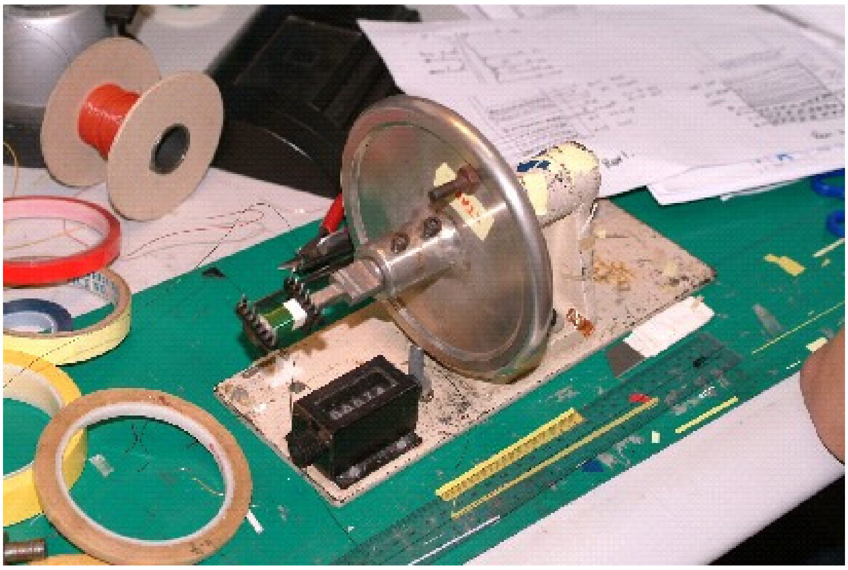

Figure 5.7: Hand Wheel

When it comes to winding of transformer for use with SMPS, it requires the wires dressing to be consistence and nicely put up. This requires a machinery like simple hand wheel (shown in figure 5.7) as it may be unlikely to achieve satisfactory results through winding by hand. If the wires are loosely wound, the leakage inductance would be very high and adversely affect the performance of the design [38].

Figure 5.8: Hand Winding

However, due to the absence of a winding machine in the workshop, I resorted to winding the transformer by hand. This was done winding the wires in a clockwise direction while securing the core with a mini flat head screwdriver (shown in figure 5.8). Additionally, insulation tape was used between primary layers to further reduce intra-winding capacitance and standby power loss [29].

5.10.3 Dot Notation

It is vital that the sense of various windings is identified as they determine the polarity of the windings with respect to each winding. Unfortunately, these markings are not standardized and may vary with different transformer designs [39]. Usually, windings of the same polarity have a dot indicated at their end pins to show their polarity [1]. However, the dots were stated on the start pins of each winding for my design. From figure 4.2, it was shown that dots were labeled on Pin 4 of the primary winding, Pin 1 of the shield winding and Pin 8 of the secondary winding.

Chapter 6 – Testing and Troubleshooting

In order to determine the functionalities of the product, certain tests should be conducted to check if product was performing as well as it should be. Basically, four different tests were performed. They are namely Output Regulation, Efficiency, Standby Power Consumption and Output Ripple. This chapter described the various tests that were carried during the testing/troubleshooting phase of the thesis. Some of the troubleshooting ideas were proposed by specialists whom the author had consulted and were acknowledged accordingly.

Before the commencement of each test, all the multimeters and the 1 ohm resistor (used in efficiency test) were tested for accuracy by methods suggested by the laboratory supervisor [40]. However, all the equipments were found to be highly accurate with very negligible error. The voltage meters were tested for error by shorting the two pins as shown in Appendice 11.7 in their respective mode (either AC or DC mode). On the hand, the ampere meters were tested for error by shorting another two pins as shown in Appendice 11.8. The 1 ohm resistor was tested with a 4 wires set up as shown in Appendice 11.9.

The errors found in the multimeters and the 1 ohm resistor were as follow:

Input voltage meter- 0.324mVac
Input ampere meter- 0.395mAac
Output voltage meter- 0.0009mV
Output ampere meter- 0.002mA
1 ohm resistor- 0.0042 ohm

6.1 Output Regulation

The first test performed on the switch mode power supply was to check the output regulation of the circuit. This test was done by using an Adjustable Variac (WF), an

Isolation Transformer (SAF PAK), an Analog AC Voltage Meter (A.J.William-Type P16), an Analog AC Ampere Meter (Weston-Model 155), two Digital Multimeters (Hewlett Packard-3478A) and a 50.5 ohm Variable Resistor. The following was a block diagram for the set up of this test [41]:

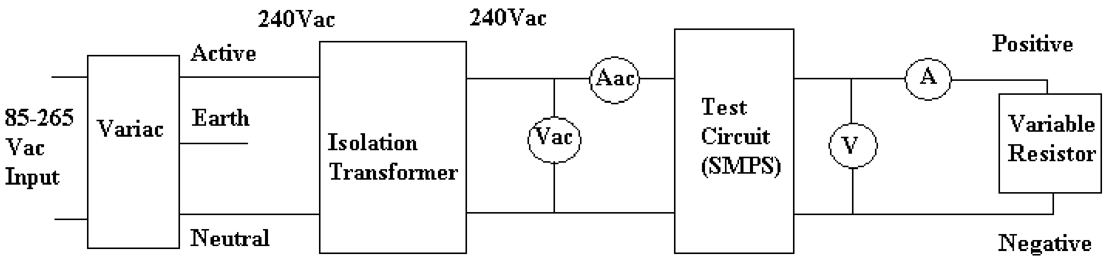

Figure 6.1: Output Regulation Test Layout

The purpose of each equipment was stated below:

- Variac- It was used to vary the input voltage from the mains
- Isolation Transformer- It was used to protect the mains and variac in case there was a fault in the circuit (eg. short circuit)
- Input Voltage and Ampere meters- They were used to measure the input voltage and current respectively
- Output Voltage and Ampere meters- They were used to measure the output voltage and current respectively
- Variable Resistor- It was used as a "dummy load" to simulate half load and full load conditions

The subsequent sections show the test results and the troubleshooting steps which were conducted after each result.

6.1.1 Measurement 1 (Output Regulation)

The circuit was tested at 3 load conditions, namely no load, half load and full load. The results were collected and presented in this section.

6.1.1.1 At no load (no load attached to circuit)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	5.06	0.009
160	5.07	0.009
200	5.08	0.009
240	5.08	0.009
265	5.08	0.009

Table 6.1 : Output Regulation At No Load (Measurement 1)

6.1.1.2 At half load (20 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.40	216.91
160	4.94	241.26
200	0.001-0.009	0-240
240	4.82	246.80
265	4.93	242.26

Table 6.2 : Output Regulation At Half Load (Measurement 1)

6.1.1.3 At full load (10 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	0.001-0.009	0-240
160	0.001-0.009	0-240
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.3 : Output Regulation At Full Load (Measurement 1)

6.1.1.4 Observation

The circuit was producing a constant output of 5.09 V for no load test. As for the half load test, the circuit was producing a constant voltage between 4.4 to 4.93V for almost the whole input range. However, when an input from 160Vac to 235Vac was fed into the circuit, the output voltage had a fluctuating value from 1 to 9mV. The circuit became unstable and had a fluctuating output voltage for the whole input voltage range.

6.1.1.5 Possible Cause(s)

The current limit circuit might be reacting with the voltage regulating circuit and vice-versa.

6.1.1.6 Proposed Solution

Resistor R8 was moved so that it was directly across the optocoupler LED. This would lower the gain of the optocoupler/zener combination and speed up the operation of the optocoupler when it turned off. If the situation did not improve, R3 should be increased to slow down the response time of the current limit until the circuit becomes stable [42].

6.1.2 Measurement 2 (Output Regulation)

The circuit was modified with the proposed solutions and was tested at 3 load conditions again. The results were collected and presented in this section.

6.1.2.1 At no load (no load attached to circuit)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	5.1	0.01
160	5.11	0.01
200	5.12	0.01
240	5.13	0.01
265	5.14	0.01

Table 6.4 : Output Regulation At No Load (Measurement 2)

6.1.2.2 At half load (20 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.51	219.61
160	4.90	239.34
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.5 : Output Regulation At Half Load (Measurement 2)

6.1.2.3 At full load (10 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	0.001-0.009	0-240
160	0.001-0.009	0-240
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.6 : Output Regulation At Full Load (Measurement 2)

6.1.2.4 Observation

The results did not show any improvement and were very similar to those in measurement 1. However, the circuit performed worse when R8 was moved directly across the optocoupler LED. The functioning range of the circuit at half load was limited to input voltage of up to 160Vac instead.

6.1.2.5 Possible Cause(s)

The effect of noise spikes might be interrupting the operation of TNY264.

6.1.2.6 Proposed Solution

A 1nF ceramic capacitor was soldered directly across the ENABLE pin and the SOURCE pin on the TNY264. This would reduce the noise spikes of the IC. Extra filtering could be achieved by connecting a 2k2 resistor in series with the connection from the optocoupler to the ENABLE pin on TNY264 [42].

6.1.3 Measurement 3 (Output Regulation)

R8 was put to its original position and the circuit was modified with the proposed solutions. It was tested at 3 load conditions again. The results are collected and presented in this section.

6.1.3.1 At no load (no load attached to circuit)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	5.1	0.01
160	5.11	0.01
200	5.11	0.01
240	5.12	0.01
265	5.13	0.01

Table 6.7 : Output Regulation At No Load (Measurement 3)

6.1.3.2 At half load (20 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.49	220.14
160	4.89	232.88
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.8 : Output Regulation At Half Load (Measurement 3)

6.1.3.3 At full load (10 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	0.001-0.009	0-240
160	0.001-0.009	0-240
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.9 : Output Regulation At Full Load (Measurement 3)

6.1.3.4 Observation

The results were almost identical to those in measurement 2 and there was no improvement.

6.1.3.5 Possible Cause(s)

The leakage in the constructed transformer might be affecting the overall performance of the circuit.

6.1.3.6 Proposed Solution

Reconstruct the transformer by employing “split” or “sandwich” winding. This arrangement would require half of the primary winding to be wound first, followed by the secondary winding and then the remaining half of the primary winding. This would allow a better coupling between the two windings and lower losses would incur. The shield winding was omitted for this design [5].

6.1.4 Measurement 4 (Output Regulation)

The circuit was introduced with the newly constructed transformer and was tested at 3 load conditions again. The results were collected and presented in this section.

6.1.4.1 At no load (no load attached to circuit)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.36	0.02
160	4.36	0.02
200	4.26	0.02
240	4.26	0.02
265	4.26	0.02

Table 6.10 : Output Regulation At No Load (Measurement 4)

6.1.4.2 At half load (20 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.16	202.48
140-155	0.001-0.009	0-240
160	4.12	201.34
200	4.12	200.50
240	4.13	200.91
265	4.14	201.17

Table 6.11 : Output Regulation At Half Load (Measurement 4)

6.1.4.3 At full load (10 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	0.001-0.009	0-240
160	0.001-0.009	0-240
200	0.001-0.009	0-240
240	0.001-0.009	0-240
265	0.001-0.009	0-240

Table 6.12 : Output Regulation At Full Load (Measurement 4)

6.1.4.4 Observation

The results showed great improvement for the half load test as the unstable range was only limited to voltage input of 140-155Vac. However, there was no improvement for the full test as the output values were still fluctuating. From the results, it was also observed that the output voltage had dropped to around 4.2V.

6.1.4.5 Possible Cause(s)

The transformer might be constructed wrongly and it might be due to the wrong phasing of the windings.

6.1.4.6 Proposed Solution

Reconstruct the transformer by reversing the winding direction of the secondary winding [30].

6.1.5 Measurement 5 (Output Regulation)

The circuit was introduced with the newly constructed transformer with the winding direction of secondary winding reversed and was tested at 3 load conditions again. The results were collected and presented in this section.

6.1.4.1 At no load (no load attached to circuit)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.98	0.01
160	4.98	0.01
200	4.98	0.01
240	4.98	0.01
265	4.98	0.01

Table 6.13 : Output Regulation At No Load (Measurement 5)

6.1.4.2 At half load (20 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (mA)
115	4.89	240.45
160	4.89	240.45
200	4.89	240.7
240	4.89	240.68
265	4.89	240.64

Table 6.14 : Output Regulation At Half Load (Measurement 5)

6.1.4.3 At full load (10 ohms)

Input Voltage (Vac)	Output Voltage (V)	Output Current (A)
115	4.76	0.45
160	4.76	0.45
200	4.77	0.46
240	4.78	0.46
265	4.80	0.46

Table 6.15 : Output Regulation At Full Load (Measurement 5)

6.1.4.4 Observation

The results showed that the circuit was producing an acceptable output voltage of between 4.76 to 4.98V. The output voltage deviation was less than 5% from the specified voltage which was extremely desirable.

6.1.4.5 Conclusion

From the recorded observations, they clearly indicate that it would be critical that the phasing of the transformer windings was correct to ensure flyback operation. Despite the fact that the windings were started on the correct pins, the polarity of the windings could be changed with the alteration of the winding direction. Therefore, it would be recommended to maintain the same direction (clockwise or anti clockwise) for all windings when constructing the transformer.

6.2 Efficiency Test

The next performance test that was conducted on the circuit was to check the efficiency of the power supply. Two different approaches were being carried out and the results of the two methods would be discussed in this section.

6.2.1 Measurement 1 (Efficiency)

The first layout was done by adding an additional Digital Watt and Phase Angle Meter (Red Phase Instruments-Model 632A) to the input side of the original layout. In addition, the input voltage and ampere meters were changed to Digital Multimeters (Hewlett Packard-3478A) for more accurate readings. The following was a block diagram for the set up of this test [40]:

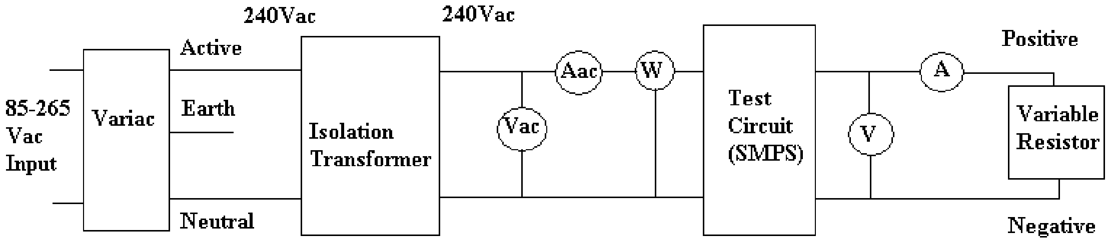

Figure 6.2: First Efficiency Test Layout

In order to determine the efficiency the circuit, the input power and the output power must be determined. The output power could easily be derived by multiplying the readings from the output voltage and ampere meters. To obtain the input power, one way would be to use an AC Watt Meter that was capable of reading the power accurately. However, the Watt Meter that was available in the laboratory did not have this function and was only able to produce an accurate phase angle,θ between the input voltage and current.

The method for deriving the input power with this layout was by applying the equation [43]:

$$P=VI \cos \theta$$

Where V was the AC Input Voltage, I was the AC Input Current and θ was the Phase Angle.

The efficiency could be derived be using the equation:

$$\eta = (\text{Output Power}/\text{Input Power}) \times 100\%$$

As there were results (from the Engineering Report) to compare with for the 9V evaluation circuit, it was used to test the reliability of this layout instead. The efficiency data was brought together at full load and was tabulated below:

6.2.1.1 (At full load)

Input Voltage (Vac)	Input Current (mA)	Phase Angle, θ (degree)	Output Voltage (V)	Output Current (A)	Input Power P=VI Cosθ (W)	Output Power (W)	Efficien-cy (%)
85.38	82.05	57	8.91	0.328	3.82	2.919	76.41
159.27	50.53	65.8	8.91	0.328	3.30	2.919	88.45
201.94	39.21	68.3	8.91	0.328	2.93	2.919	99.69
265.21	27.68	69.6	8.91	0.328	2.56	2.919	114.07

Table 6.16 : Efficiency Test At Full Load (Measurement 1)

6.2.1.2 Observation

From the results, it was shown that the efficiency of the circuit improved drastically with the increase of the input voltage which was unlikely. Moreover, the efficiency of this circuit according to this setup was between 76-114% which is impossible as the efficiency of any circuit can never exceed 100% in all cases. The expected efficiency of this circuit was between 71-76%.

6.2.1.3 Possible Cause(s)

Although the power factor was considered for this calculation, the collected data showed that the approach for calculating the efficiency was wrong. This setup might not be suitable for calculating the input power since the input current was a complex waveform.

6.2.1.4 Proposed Solution

Employ time domain multiplication by capturing the input voltage and current waveforms with an oscilloscope.

6.2.2 Measurement 2 (Efficiency)

The next layout was done by removing the Digital Watt and Phase Angle Meter and adding a Two Channel Digital Real Time Oscilloscope (Tektronix-TDS340). A 1ohm metal film resistor was used as well to allow the current waveform to be captured. The following was a block diagram for the set up of this test [41]:

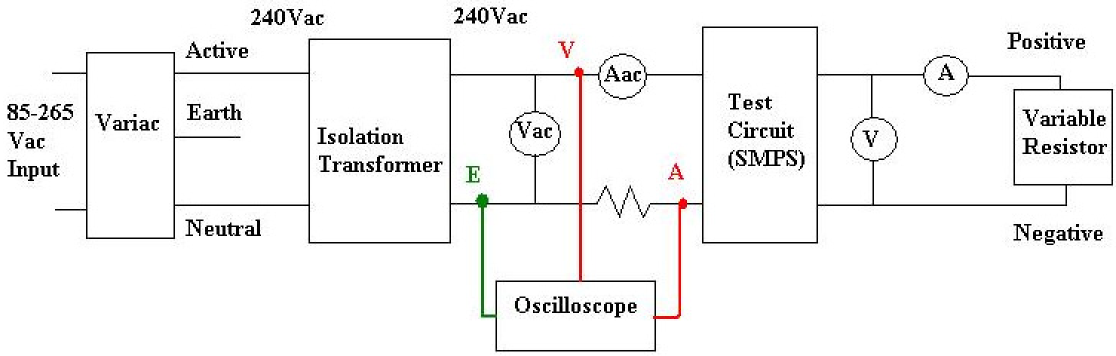

Figure 6.3: Second Efficiency Test Layout

The voltage and current waveforms could be captured at point V and point A respectively. Certain precautions must be taken when setting up this layout. The earth point (E) of the oscilloscope must be connected after the isolation transformer and not anywhere else. If it was connected at the neutral line before the isolation transformer, the results would be disastrous. As the equipments had different potentials, this action might cause the circuit breaker to trip and the SMPS to blow up [30]. A 10:1 probe must be used to obtain the voltage waveform instead of a BNC lead (1:1 probe). Otherwise, it would be impossible to display the voltage waveform within a reading range at high voltage and it might even damage the oscilloscope [41].

The method for deriving the input power of the circuit was by multiplying the voltage and current followed by getting the mean of the results. The mean would be the equivalent of the input power of the circuit. All these steps could be done by using the math functions found on the Tektronix Oscilloscope.

Once again, the 9V evaluation circuit was used to test the reliability of the setup. The circuit was tested at full load (27 ohms) and the results were presented in table 6.17.

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (A)	Mean (mVV)	Output Power (W)	Efficiency (%)
100.9	71.31	8.8	0.325	394	2.86	72.59
135.16	57.26	8.8	0.325	390	2.86	73.33
202.8	34.74	8.8	0.324	390	2.85	73.08
240.22	28.00	8.8	0.324	395	2.85	72.15
265.59	25.91	8.8	0.324	396	2.85	71.97

Table 6.17 : Efficiency Test At Full Load (Measurement 2)

The input power was derived from the Mean, where 394mVV was equivalent to 3.94W since a 10:1 probe was used for the voltage channel. The efficiency was obtained by using the formula:

$$\eta = (\text{Output Power}/\text{Input Power}) \times 100\%$$

An efficiency graph had been plotted for this circuit and was shown below:

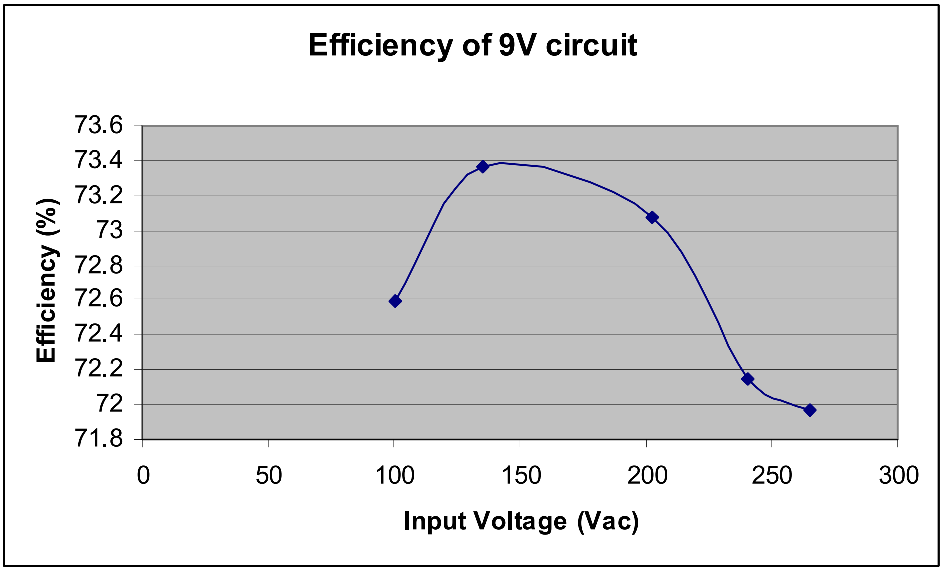

Figure 6.4: Efficiency Graph (Measurement 2)

WaveStar software was used to connect the Tektronix Oscilloscope to the PC. It was employed to capture the data from the oscilloscope and display the information on the monitor. Waveforms captured to the monitor were displayed with same scale and position as on the oscilloscope. The input waveforms of the 9V circuit at 240Vac and their resultant waveform (after time domain multiplication) were presented below:

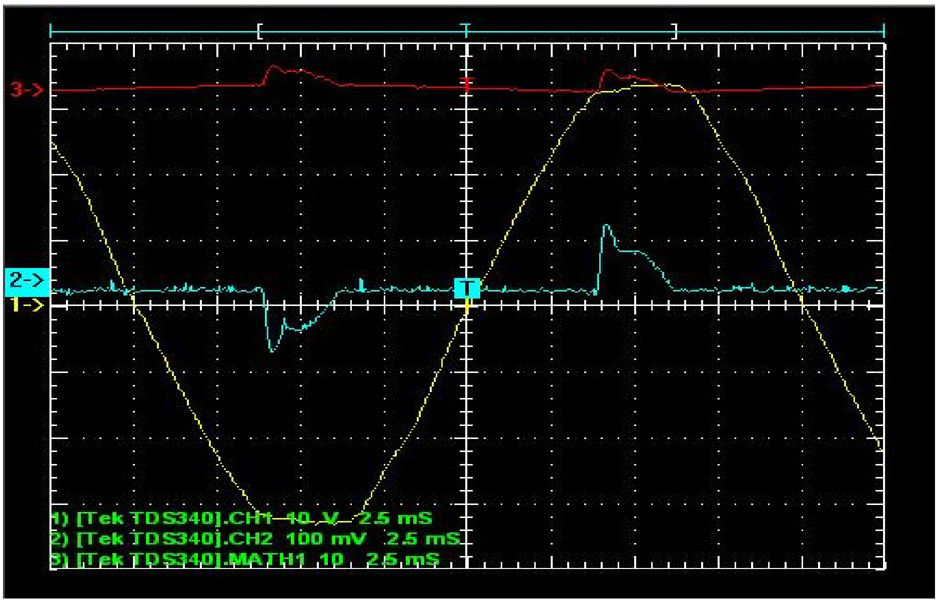

Figure 6.5: Input Waveforms (Measurement 2)

- Line 1(Yellow) represented the input voltage waveform
- Line 2(Blue) represented the input current waveform
- Line 3(Red) represented the resultant waveform after the multiplication of voltage and current waveforms

6.2.2.1 Observation

From the tabulated results, it was observed that the calculated efficiency was very close to the stated efficiency in the engineering report.

6.2.2.2 Conclusion

By comparing the results from the two different setups, it was obvious that the second setup was more a suitable method to derive the input power of the SMPS. The first setup would be suitable if both the current and voltage waveforms were sinusoidal. Since the test layout was proven to be reliable, the remaining circuits were tested with the same arrangement.

6.2.3 Measurement 3 (Efficiency)

The efficiency data of the constructed 5V circuit was collected at its full load condition (10 Ohms) and was presented in table 6.18.

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (A)	Mean (mVV)	Output Power (W)	Efficiency (%)
99.39	74.45	4.77	0.452	458	2.16	47.13
137.68	60.42	4.77	0.453	450	2.16	47.95
201.41	46.44	4.77	0.462	473	2.20	46.47
240.21	38.07	4.78	0.461	479	2.20	45.97
264.12	35.09	4.79	0.464	495	2.22	44.89

Table 6.18 : Efficiency Test At Full Load (Measurement 3)

An efficiency graph had been plotted for this circuit and was shown below:

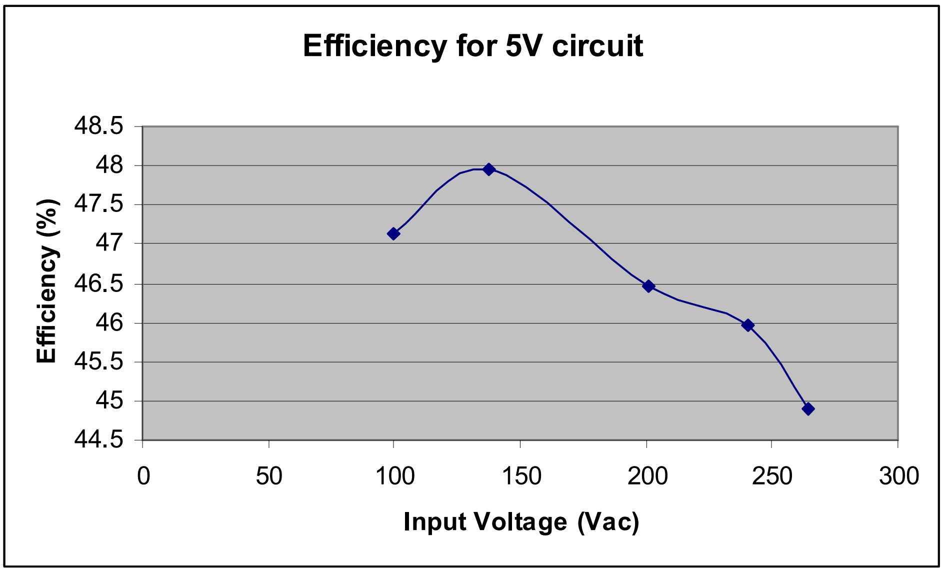

Figure 6.6: Efficiency Graph (Measurement 3)

The input waveforms of the circuit were captured with WaveStar software and were shown below:

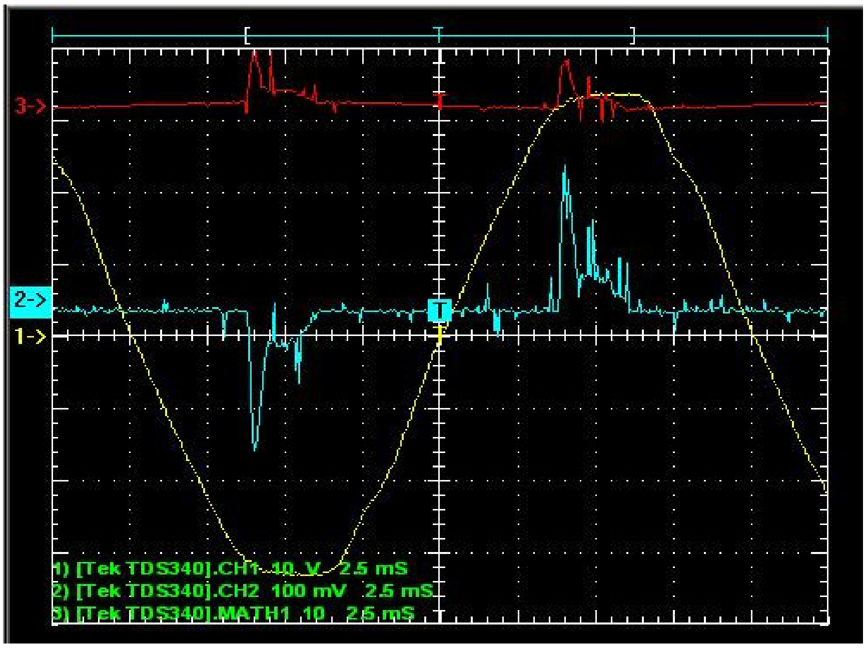

Figure 6.7: Input Waveforms (Measurement 3)

6.2.3.1 Observation

From the tabulated results, it was observed that the calculated efficiency was much lower than expected. The efficiency graph also showed that the efficiency was the highest at the input voltage of around 135Vac and it decreased with the increment of the input voltage. This was a typical phenomenon. The input current waveform was noticed to be slightly noisier compared to the 9V circuit as well.

6.2.3.2 Possible Cause(s)

The constant current (CC) circuitry might be interfering with the constant voltage circuitry and vice versa. The sense resistors used in the CC circuit to maintain it constant were dissipative since they were in the main current path. This might have affected the performance of the circuit and thus reducing its efficiency.

The components on the 5V circuit were placed much further apart compared to the 9V circuit. In addition, there were more components on the secondary side and the layout arrangement was very different. These factors might attribute to the noises found in the power supply [30].

6.2.3.3 Proposed Solution

Disable the CC circuit by shorting R4, R6 and removing R9. This was to check if there would be any efficiency improvement as the circuit would be operating in a constant voltage (CV) mode only.

6.2.4 Measurement 4 (Efficiency)

The CC circuit of the constructed 5V circuit was disabled and its efficiency data was collected at its full load condition (10 Ohms) and was presented in table 6.19.

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (A)	Mean (mVV)	Output Power (W)	Efficiency (%)
99.97	63.81	4.75	0.442	396	2.10	52.99
135.47	52.68	4.75	0.443	376	2.10	55.83
200.43	37.79	4.75	0.442	384	2.10	54.69
240.11	31.01	4.76	0.449	395	2.14	54.21
266.70	26.21	4.76	0.450	402	2.14	53.23

Table 6.19 : Efficiency Test At Full Load (Measurement 4)

An efficiency graph had been plotted for this circuit and was shown below:

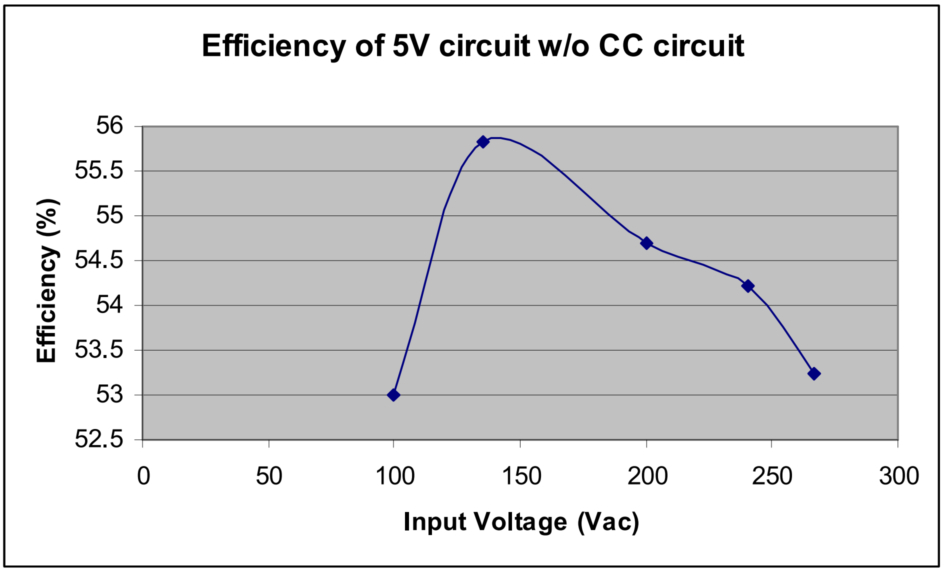

Figure 6.8: Efficiency Graph (Measurement 4)

The input waveforms of the circuit were captured with WaveStar software and were shown below:

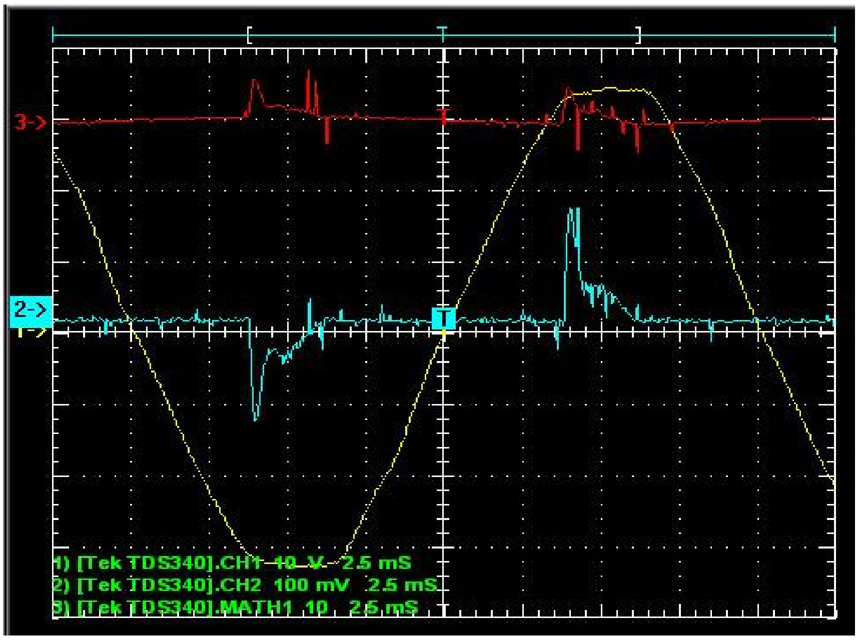

Figure 6.9: Input Waveforms (Measurement 4)

6.2.4.1 Observation:

The efficiency of the circuit was improved from 47% to 55% (improvement of approximately 8%). The components used in the CC circuit might have caused losses of the power supply. Consequently, the absence of this circuit had led to an improvement of the circuit efficiency. However, the efficiency of the circuit was still considered as rather poor compared to a typical SMPS.

6.2.4.2 Possible Cause(s)

The transformer coupling might be bad which led to a poor efficiency. In addition, certain components might be generating too much heat (hottest component would be dissipating the most power) and thus reducing the efficiency. There might also be a chance that the primary inductance of the transformer was too high due to the large number of primary winding [5].

6.2.4.3 Proposed Solution

Employ the “split” winding technique to improve the coupling between the windings of the transformer [5]. Nonetheless, the number of winding turns had to be re-calculated to obtain the suitable transformer ratio. When winding the transformer, the wires should be wound as tightly and neatly to minimize leakage (thus improving efficiency).

Check the temperature of all components and ensure that the sufficient ground plate was made available for heat dissipation of key components like TNY264. If not, area of the ground plate should be increased and tracks which appeared to be thin should be thickened. This was because thin tracks in the circuit could lead to power loss as well.

A lower primary inductance could produce a transformer with higher efficiency. This could be achieved by reducing the numbers of turns in both windings. Although this would lead a better efficiency, the load regulation of the output would be compromised [5].

6.2.4.4 Conclusion

By comparing the efficiency results of the two circuits, it was shown that certain components in the circuit might contribute to power loss and hence worsened the efficiency. It was also important to construct a proper transformer to ensure good coupling between the windings. The proposed solutions were believed to be able to solve the issues of poor efficiency. However, further troubleshooting could not be carried out due to time constraint.

6.2.5 Measurement 5 (Efficiency)

The efficiency data of the constructed 5V circuit with a bias winding was collected at its full load condition (10 Ohms) and was presented in table 6.20.

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (A)	Mean (mVV)	Output Power (W)	Efficiency (%)
99.55	72.27	4.79	0.472	424	2.26	53.36
134.78	59.80	4.79	0.471	405	2.26	55.86
200.73	44.32	4.79	0.473	408	2.26	55.45
239.69	33.91	4.80	0.474	419	2.28	54.43
264.02	29.86	4.80	0.476	429	2.28	53.17

Table 6.20 : Efficiency Test At Full Load (Measurement 5)

An efficiency graph had been plotted for this circuit and was shown below:

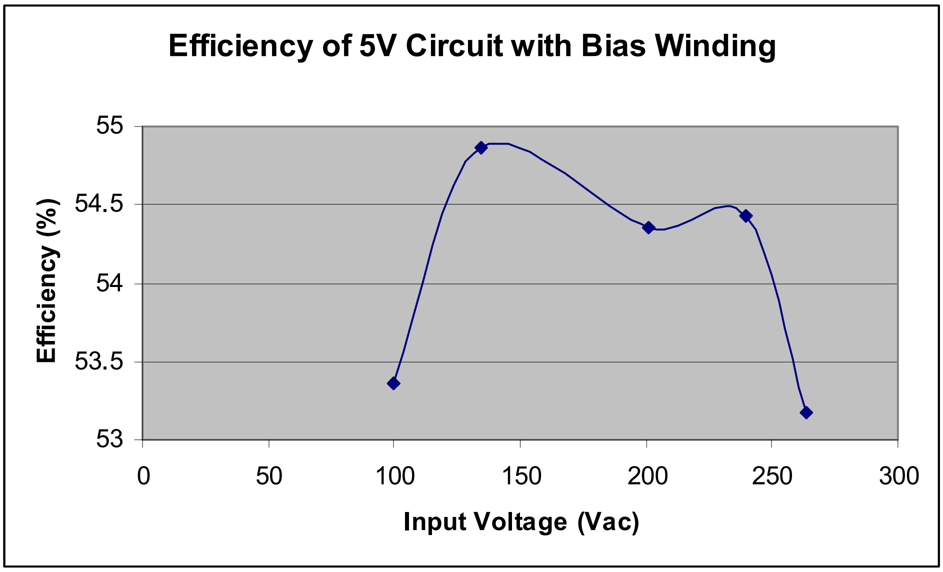

Figure 6.10: Efficiency Graph (Measurement 5)

The input waveforms of the circuit were captured with WaveStar software and were shown below:

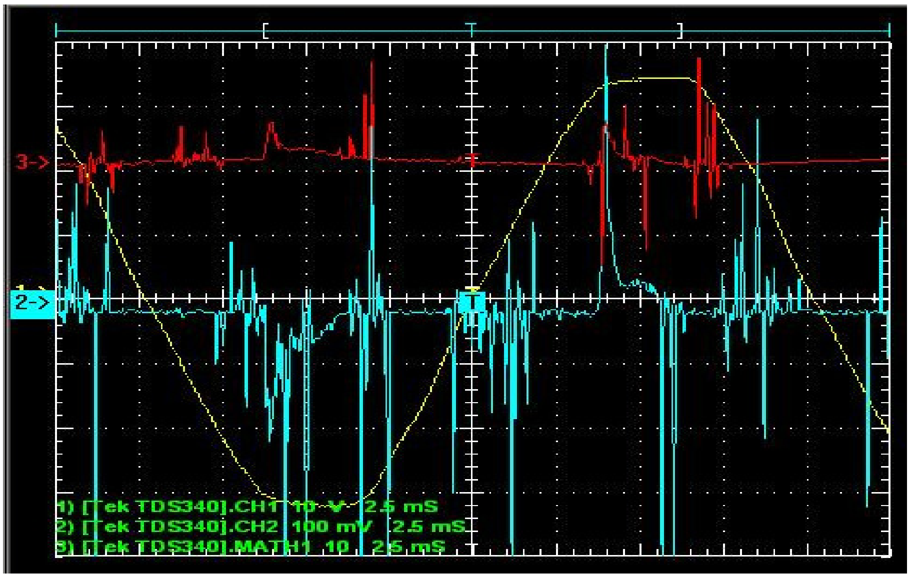

Figure 6.11: Input Waveforms (Measurement 5)

6.2.5.1 Observation

The efficiency of this bias winding circuit was about the same as the previous measurement and managed to produce a constant output voltage and current. But the waveform indicated that the noise level of this circuit was very high compared to the rest of circuit. In addition, the efficiency was observed to increase between 200 to 240Vac which was unusual.

6.2.5.2 Possible Cause(s)

As the size of this PCB was the biggest among all the PCB, the spacing between each component was also the widest. This was the same problem as observed in measurement 3. Moreover, no shielding winding and Y1 capacitor were used which could help to filter the mains [5]. The recorded measurements for this circuit might be inaccurate as the circuit is noisy which result in great fluctuations of the readings. This could be the reason on why the efficiency graph showed an increment of efficiency between 200 to 240Vac.

6.2.5.3 Proposed Solution

Re-design the PCB by using a green masked PCB instead. This would allow the components to be placed closer to each other without the fear of arcing. Arcing usually happened between narrows gaps in the circuit like MOSFET leads which could result in severe failure of the power supply [44].

6.2.5.4 Conclusion

The waveforms derived from measurement 2, 3 and 5 showed that the noise level increased with the decreased of the circuit density. The layout of the circuit might also be another reason for the increase in noise level. Certain track should be kept as short as possible to minimize noise pick up. For example, the connection between the photo transistor of the optocoupler and the ENABLE pin of TNY264 [17]. As mentioned in section 6.2.4.3, the noise problem could not be investigated any further due to the lack of time.

6.3 Standby Power Consumption

This test was conducted with the same setup as with the efficiency test. However, this test was conducted with no load connected and the standby power loss (input power) was measured. The test results of the constructed circuits were recorded and presented in this section.

6.3.1 Measurement 1

The standby power loss for the original 5V circuit was collected at various input voltages and was tabulated below:

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (mA)	Mean (mVV)
102.09	4.41	4.996	0.003	22
135.62	4.45	4.996	0.003	23
200.01	4.71	4.995	0.003	28
241.78	4.99	4.996	0.003	30
264.08	5.31	4.995	0.003	36

Table 6.21 : Standby Power Loss (Measurement 1)

A standby power loss graph had been plotted for this circuit and was shown below:

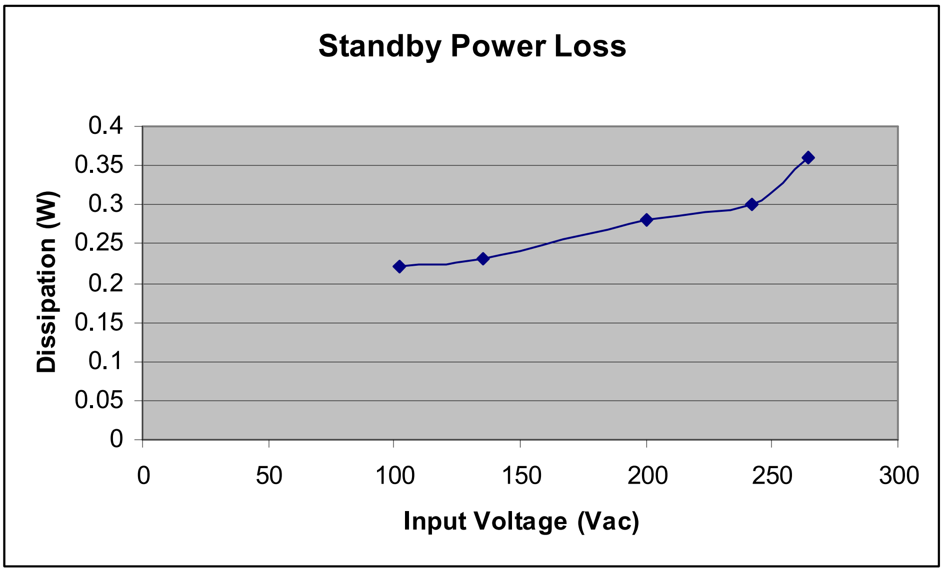

Figure 6.12: Standby Power Loss Graph (Measurement 1)

6.3.1.1 Observation

The graph showed that the standby power consumption increased as the input voltage increased. From the results, it was observed that the standby power loss of this circuit did not exceed 0.36W in all cases.

6.3.2 Measurement 2

The standby power loss for the 5V circuit with its CC circuit disabled was collected at various input voltages and is tabulated below:

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (mA)	Mean (mVV)
101.06	4.89	4.97	0.001	24
135.09	5.19	4.97	0.001	29
199.68	5.53	4.97	0.002	40
241.72	5.85	4.97	0.001	43
265.16	6.11	4.97	0.002	47

Table 6.22 : Standby Power Loss (Measurement 2)

A standby power loss graph had been plotted for this circuit and was shown below:

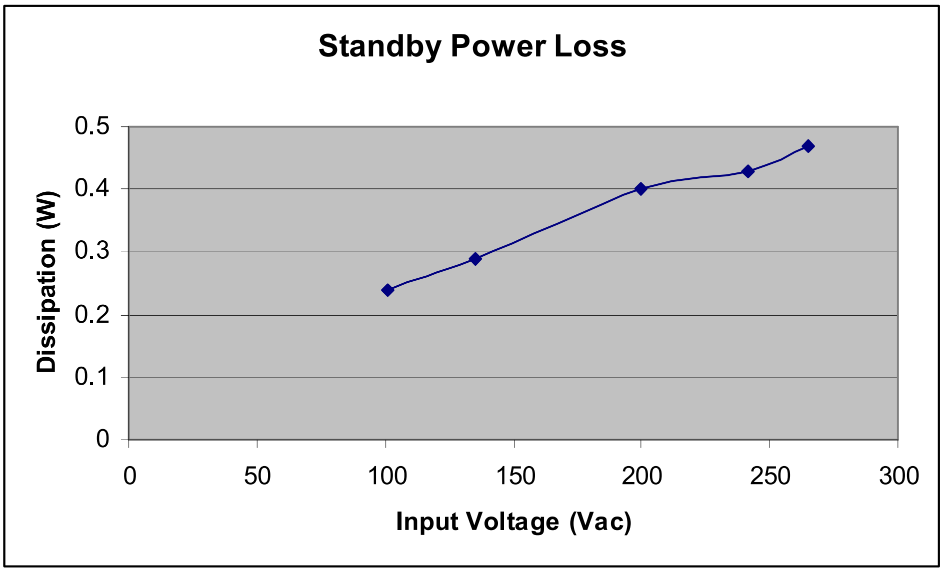

Figure 6.13: Standby Power Loss Graph (Measurement 2)

6.3.2.1 Observation

The graph showed very similar results as with measurement 1, but this circuit dissipated more power. Its highest power loss was observed to be around 0.47W which was slightly higher compared to the first circuit.

6.3.3 Measurement 3

The standby power loss for the 5V circuit with bias winding was collected at various input voltages and was tabulated below:

Input Voltage (Vac)	Input Current (mA)	Output Voltage (V)	Output Current (mA)	Mean (mVV)
101.59	3.68	5.019	0.015	11
135.12	3.58	5.018	0.013	17
201.54	3.78	5.018	0.013	19
240.85	4.06	5.018	0.013	25
264.30	4.25	5.018	0.013	21

Table 6.23 : Standby Power Loss (Measurement 3)

A standby power loss graph had been plotted for this circuit and was shown below:

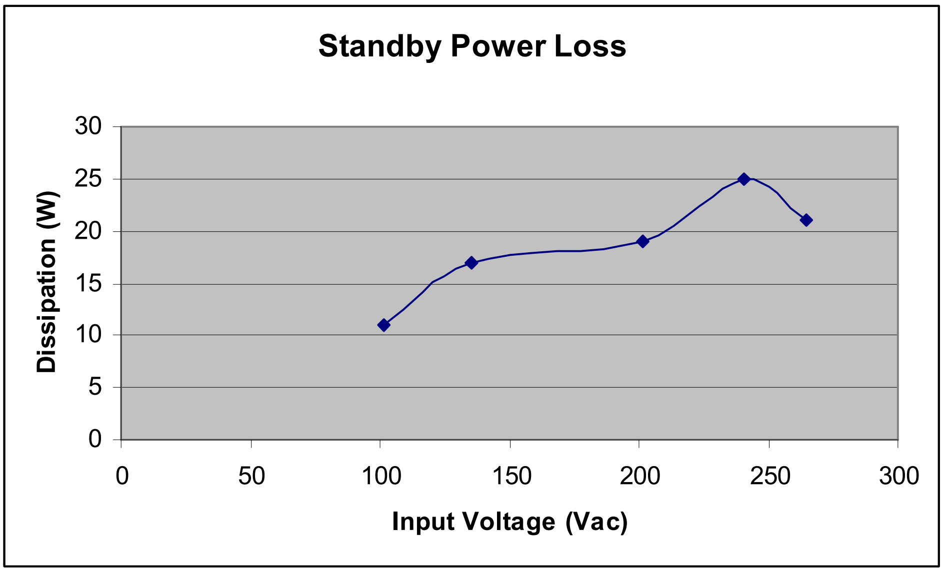

Figure 6.14: Standby Power Loss Graph (Measurement 3)

6.3.4 Observation

From the results, it was shown that the power consumption was the lowest compared to the rest of the circuit. The last point of the graph (at 264.30 Vac) showed that a lower power dissipation level was achieved at its highest input voltage. As mentioned before, this could be an error which is caused by noisy input current waveform. Nonetheless, the highest power loss for this circuit was observed to be not more than 0.25W.

6.3.5 Conclusion

By comparing the results of the three circuits, it was obvious that the third circuit dissipated the least power. This did not come as a surprise as the purpose of the bias winding was to reduce the standby power loss. Although this bias winding did not manage to reduce the no load power consumption to a low 50mW (as expected), it did manage to cap the standby power dissipation to less than 250mW. From this result, it had proved that the bias winding had indeed helped to improve the no load consumption of the design.

To optimize the performance of the bias circuitry, the value of the resistor should be selected in such a way that the current entering the bypass pin (of TNY264) would be around 500mA. The value of the resistor would depend upon the bias output voltage and would be critical in reducing the standby power loss [30].

6.4 Output Ripple Results

The output ripple measurements were taken by using the following setup. The data was collected using a Tektronix (TDS340) digital oscilloscope. All measurements were recorded at 240Vac at three different load conditions (no load, half load and full load). Line 1, 2 and 3 represented full load, half load and no load conditions respectively. In addition, the oscilloscope was set to AC mode to block the DC output of the supply [39].

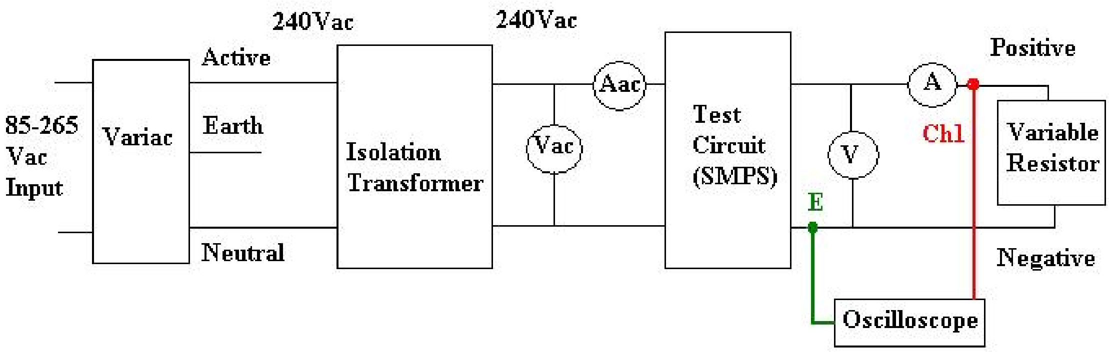

Figure 6.15: Output Ripple Test Layout

6.4.1 Measurement 1

The output ripple waveforms of the 9V circuit had been captured using WaveStar Software for comparison purpose and were present below:

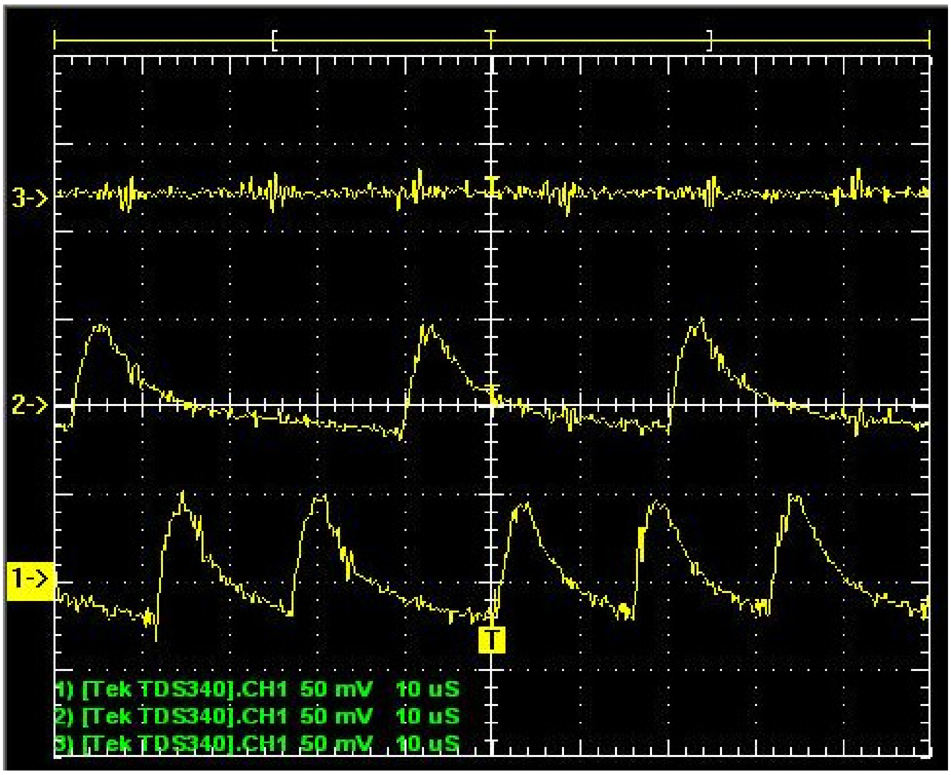

Figure 6.16: Output Ripple Waveforms (Measurement 1)

6.4.1.1 Observation

The waveforms observed are of "sawtooth" shape and the ripple was maintained at not more than 96mVp-p for all the 3 load settings. The output ripple of no load, half load and full load were recorded to be 20mVp-p, 78mVp-p and 96mVp-p accordingly. From the results, they had shown that the output ripple cycles and the amplitude of the lower load was lower than the higher load. This was because TNY264 would operate in all its clock cycles at full load and would skip cycles when the load was lighter.

6.4.2 Measurement 2

The output ripple waveforms of the original 5V circuit had been captured and were shown in this section:

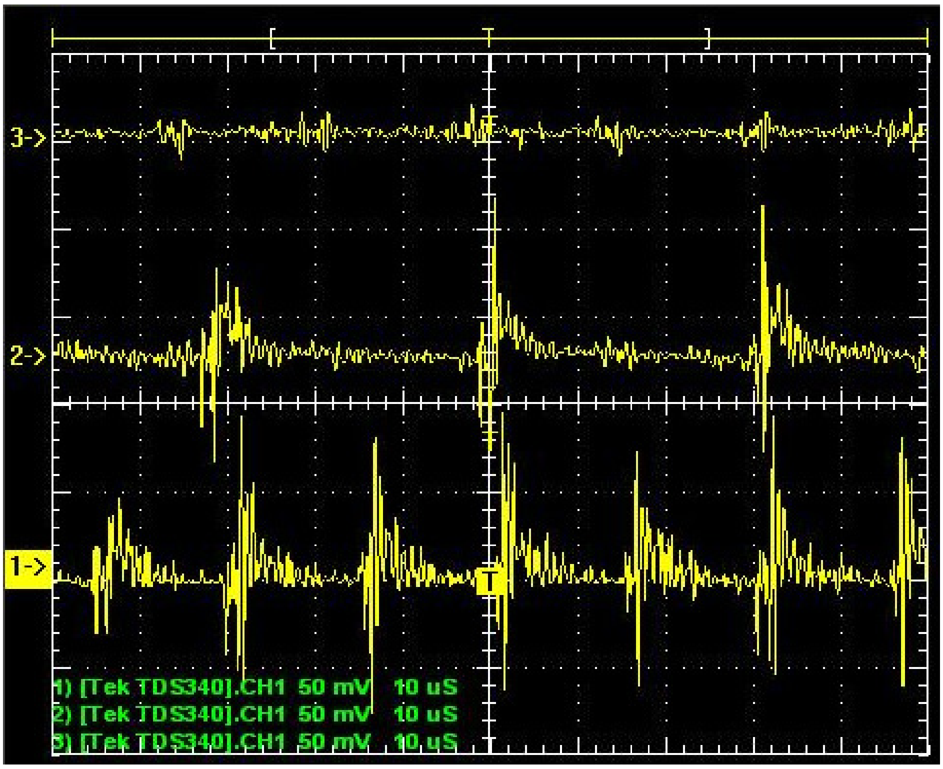

Figure 6.17: Output Ripple Waveforms (Measurement 2)

6.4.2.1 Observation

The results showed that the ripple waveforms were contaminated with noise and produced a higher ripple value compared to the 9V circuit. The output ripple of no load, half load and full load were recorded to be 20mVp-p, 172mVp-p and 190mVp-p accordingly. However, in all cases, the output ripple was kept below 200mVp-p (less than 4% of the output voltage) which was within an acceptable range.

6.4.2.2 Possible Cause(s)

The output filtering did not seem to be operating effectively. This might be due to the higher parasitic capacitance which could exist in the transformer.

6.4.2.3 Proposed Solution

One way to reduce the parasitic capacitances in a high frequency transformer would be to provide shielding. Although the transformer was already shielded, an additional shielding (double shielding) could be introduced to the transformer to further reduce the noise level. A thin copper-foil shielding could also be placed between the primary and secondary winding. This way, the capacitive currents at the primary end could be fed back to the power line with minimal interference. This approach would be ideal for power supplies with low output voltage [5].

6.4.3 Measurement 3

The output ripple waveforms of the 5V circuit with bias winding had been captured and were shown in this section. As the output ripple for this circuit was a lot higher compared to first two circuits, the scope setting was changed from 50mV/div to 200mV/div. Otherwise, “clipping” of the waveform would occur when the waveform was to exceed the reading range.

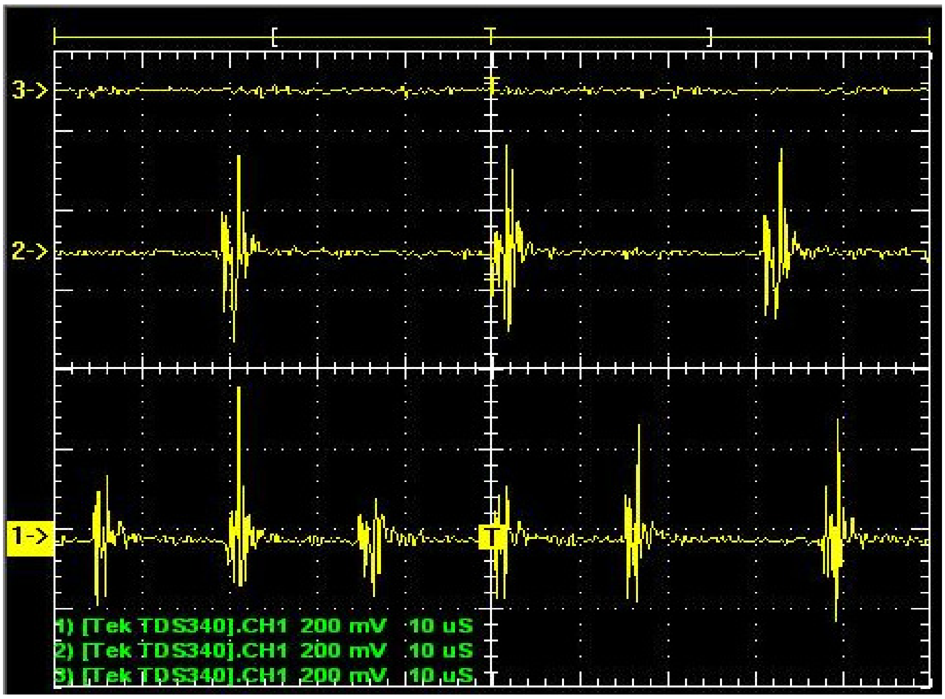

Figure 6.18: Output Ripple Waveforms (Measurement 3)

6.4.3.1 Observation

The results showed that the ripple waveforms were polluted with a lot more noise and produced a much higher ripple value than the previous circuits. The output ripple of no load, half load and full load were recorded to be 20mVp-p, 570mVp-p and 670mVp-p accordingly. The recorded output ripple results were mere estimation as these waveforms fluctuated to a great extent. The maximum output ripple that was measured at full load was 945mVp-p.

6.4.3.2 Possible Cause(s)

As mentioned in 7.4.2.2, one possible reason for this problem was due to the parasitic capacitance in the transformer. Moreover, the absence of a shield winding for this design could be the primary cause for such high output ripple results. As the components on this PCB were spaced further apart compared to the other circuits, the “extra” tracks would contribute more noise to the output.

6.4.3.3 Proposed Solution

The solutions suggested in 6.4.2.3 should be implemented on this circuit since both circuits experience the same problem of noisy output. In addition, by using an output capacitor with a lower ESR will help to reduce the output ripple [39]. Finally, a new PCB should be fabricated for this design to ensure a higher component density. That way, the length of the tracks will be shorter and noise would be minimized.

6.4.3.4 Conclusion

According to the measurements that were recorded, it was highly suspected that the circuit noise issues were closely related to the construction of the transformer and the layout of the PCB. Although the author would like to justify his stand by conducting a further investigation on this matter, time restriction had prevented him from doing so.

With the completion of the various tests, the results showed that the products could performance reasonably well. The diagrams of the two constructed circuits could be found in Appendice 11.10. Since the 2nd circuit was meant for demonstrating its performance with input voltage from the mains, it had a 2 pin mains wire and a fuse installed at its input. As the input capacitor would present a short circuit while it start up (due to the initial charging current requirement), the input current could be very short for a very short period. Normal film type fusible resistor would not be able to withstand this and would blow up after sometime. Therefore, a 250mA anti surge fuse was used in place of the fusible resistor [45].

Chapter 7 - Evaluation

After the construction and testing of the power supplies, they were evaluated against the specifications stated in Chapter 3. From this assessment, the success of this thesis could be gauged.

7.1 Hardware Evaluation

The converters were assessed on their performance in each of the specified criteria.

7.1.1 Wide Input Voltage Range

This specification required the power supplies to take in a wide input voltage range. The power supplies were tested to handle an input voltage range between 100 to 265Vac without any difficulties. Therefore, the power supplies would be suitable to be used in all countries and specification had been fulfilled.

7.1.2 Output Voltage Range

The output voltage of the power supplies were allowed to have a +/- 10% deviation of the nominal DC voltage (either 3 or 5V). For my design, I had chosen to design the circuits to produce 5 V. Both circuits were able to produce output between 4.75 to 5.02V at all load conditions. The maximum variation was calculated to be 5%. Thus, this requirement had been met as well.

7.1.3 Output Voltage Regulation

The products were specified to have a tight regulation on the output voltage and independent of line variations. From the tabulated results in Chapter 7, it was shown that the output voltage stayed constant regardless of the input voltage at different load settings. Consequently, I would say that this objective was accomplished.

7.1.4 Isolation

This condition stated that the mains voltages should be kept well apart from a low voltage load. Since a transformer was used in each design, an isolation barrier was established between the mains and load. In both designs, measures were taken to ensure that no component was place within this barrier to guarantee absolute isolation.

7.1.5 Simplified Design

Simplified design should be achieve by using a small number of components. In the original 5V circuit, only 30 components were used in total. As for the bias winding design, an additional 3 components were used for the bias circuitry (32 components in total since Y1 capacitor was removed). These two circuits were among the simplest designs with the least number of components in the market.

7.1.6 Protection

The circuits were supposed to be designed with some protection features to handle faulty conditions during operation. With the use of TNY264, both circuits had auto-restart features for short circuit and open loop fault protection. In addition, TNY264 offered further protection with its current limit and thermal shutdown circuitry. For these reason, it would be right to say that this term had been satisfied.

7.1.7 Low Cost

It was also stated that the power supplies should be produced at low cost meet the demands for low cost and high performance modules. The total cost* for the 1st and 2nd designs are $26.13 and $50.51. The cost of the 2nd design was relatively high as most of the cost was incurred on construction of the box (with main wire, fuse holder…etc). However, if the box and its associated accessories are excluded, the construction of the 1st and 2nd circuit cost only $18.64 and $19.38 respectively. These prices would be considered as extremely low when compared to the other power supplies in the market. The budget list of the two designs could be found in Appendice 11.11.

(*note: TNY264 and the winding wires were requested as samples and were not included in the budget)

7.1.8 Low Profile

The power units were specified to have a height of not more than 12.5mm so that it could easily be fitted into the required appliance. The first 5V circuit had a height of 13.2mm which is slightly over the specification. This was due to the some of the capacitors which were mounted vertically for the first circuit. If the capacitors were to be mounted horizontally as done in the second circuit, the overall height of the circuit would not exceed the specified value. The maximum height of the 5V circuit with bias winding had a height of not more than 12mm.

7.1.9 Low Power Output

As these converters were supposed to power low energy products, it should be able to produce a low power output. The constructed modules produced an output power of not more than 2.28W.

7.1.10 Energy Efficient

In order to prevent wastage of energy, the no load power consumption of these units should be kept to a minimum. The original 5V circuit and the circuit with the bias winding had a maximum standby power loss of 0.36W and 0.25W respectively.

7.1.11 EMI

Sufficient filtering circuitries should be added to the power supplies to ensure that the EMI was of an acceptable level. In the original 5V design, certain procedures were taken to reduce the EMI level of the circuit. These measures include a π filter, Y1 capacitor and shield winding. As for the bias winding circuit, the measures were almost identical except that the shield winding has been replaced with a bias winding instead.

7.1.12 Fusing

The last condition stated that a fuse should be installed into the power supply to provide additional protection to guard against faulty conditions. In the first 5V circuit, a film type fusible resistor was used in place of a quick blow fuse to cut cost. However, an anti-surge glass fuse was used for the bias winding circuit to handle the inrush current when it was powered from the mains.

7.2 Overall Product Evaluation

By comparing the performance of the power supplies with the specifications, it was evident that the construction of the products was a great success. Although the first 5V power supply had failed to meet the height specification due to some of its huge capacitors, this problem could be easily resolved by mounting the capacitors horizontally (instead of vertically) as done for the second design.

7.3 Personal Evaluation

With the completion of this project, it was important to give an honest review of my performance in the hope of producing better results for future assignments. This could be done by identifying my weaknesses and strengths during my participation of the thesis.

7.3.1 Weaknesses

One of the major mistakes I had committed during the early phase of my thesis was my research approach. My research methods were very limited as I relied solely on web researches and E-journals. These methods proved to be very inefficient as I had failed to obtain important and relevant information to develop my circuits. Consequently, I was penalized heavily for my first assessment. I realized there was something I overlooked. I tried another approach; which was to communicate directly to people of the related field. Things also started to change drastically as I studied more books on this topic.

7.3.2 Strengths

This project would not have been finished in time if I had not gotten technical assistance from engineers and lecturers religiously. The important skill of harnessing the knowledge of experience people was learnt during the process of the thesis. As I encountered countless problems which were foreign to me, I sought consultations with individuals who were experts in the relevant areas almost every day. This approach was discovered to be highly efficient as I was able to obtain solutions faster than searching through books. However, suggestions by them were usually quite brief and I had to reinforce my understanding by reading books whenever possible.

For my thesis, I had attempted to modify a pre-designed circuit with the aim to enhance the performance of the design. Despite the fact that the modification was not really a drastic one, I had successfully changed it to a design which I could call my own. I believe that I had approached the problem in a professional manner by improving the functionality of an existing design through alterations.

7.3.3 Conclusion

Although web research would be a powerful tool which could be employed to obtain useful information, certain cases (eg. troubleshooting and test equipments layout) called for other resources to make up for its inadequacies. Throughout my troubleshooting phase, I was faced with problems which I had difficulty in finding appropriate solutions from books and web researches. As time was not a luxury that I had, it was only through communicating with engineers and lecturers that I managed to resolve those issues in the shortest possible time. I was grateful to their patience and effort spent in those times.
During the course of testing/troubleshooting phase, I realized that many mistakes were committed and corrected. Personally, I felt that this was an important stage as I have growth vastly in knowledge for solving circuit problems. I strongly believed that gaining expertise from the relevant field specialists and strengthening the understanding through reading was an excellent combination which I could utilize in the engineering industry.

Chapter 8 – Future Developments

This chapter described two possible ways which could be implemented to improve the design of the power supplies. Despite that the project was completed, certain approaches that were taken previously could have been changed to best advantage. On the other hand, some procedures could have remained the same. These methods were outlined in the following section.

8.1 Size of Power Supply

The current dimensions for the first and second circuit were 136mm x 52.6mm x 13.2mm and 99.6mm x 44.6mm x 12mm respectively. The size of each circuit was relatively huge when compared to a typical SMPS. I hope that I could make advance improvements to both the circuits by reducing their size considerably. As mentioned before, this could be done by using masked PCB. Presently, the components on the circuit boards were spaced far apart for the fear of arcing. If the circuit boards had protection coatings, their components could be packed closer to each other which would result in a drastic size reduction.

8.2 Multiple Outputs

In several applications, it would be desirable to have a power supply which had more than one output. Therefore, I would propose to design a converter with multiple outputs for future development. Since isolating transformers were used in the initial designs, this modification would be acceptable. More outputs could be attained by introducing more secondary windings to the transformer. The output voltage of each secondary winding could be determined by adjusting the winding turns ratio accordingly [1].

8.3 Task(s) with Different Approach

For this project, I had placed more emphasis on developing a working product based on a pre-designed circuit. Consequently, a lot of calculations were “skipped” during the development of the circuit. As I was afraid that I might not be able to deliver a working product in time, I only managed to work on the calculations of the circuit after the first circuit was developed.

Although most of these calculations were done eventually, I felt that it would have been more systematic to begin my calculation phase before constructing the circuit. I would use the suggested methodology if I were to design another power supply in the future.

8.4 Task(s) with Same Approach

I believe that constructing a pre-designed circuit before developing an improved version of the initial circuit was a correct choice. By doing so, I was able to gain sufficient knowledge and confidence to construct the second circuit. If I had gone straight to developing my proposed design, the outcome of the project might be disastrous. Without realizing the mistakes which I had committed for the first circuit, I would definitely spend more time in troubleshooting the modified circuit.

Chapter 9 – Conclusion

The objective of this thesis was to develop a low profile switched mode power supply which would be able to handle a wide range of input voltage and produce a predetermined output voltage of either 3V or 5V.

Through the product evaluation which was carried out in chapter 7, it was shown that all the requirements for this project had been successfully met. All these were achieved through endless hours of research and development.

The ability to communicate with people and acquire useful information was an art which my supervisor had been encouraging his students to learn. In the course of this project, this was one of the valuable skills which I had picked up along the way.

Throughout the phase of troubleshooting, I had sought for technical support to resolve most of my problems. Despite the fact that the problems were not worked out based on individual effort, I had to admit that the knowledge gained through this process was priceless. As I believed that most of the facts I had acquire were only available through experts with years of hands-on experience, these information would greatly improve my analytic skill in the future.

Since switch mode power supply would be a large market which lacked veteran design engineers, I hoped that the skills that I had learnt during this project would prepare me to face the challenges that await me in the industry.

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Chapter 11 – Appendices

11.1 Voltages in Different Countries

Country	Voltage	Freq./Hz.z
Afghanistan	220	50
Albania	220	50
Algeria	127/220	50
American Samoa	120/220	60
Angola	220	50
Anguilla	240	50
Antigua/Barbuda	230	60
Argentina	220	50
Armenia	220	50
Aruba	115	60
Australia	240	50
Austria	230	50
Azerbaijan	220	50
Azores	220	50
Bahamas	120	60
Bahrain	220	50
Bali	220	50
Bangladesh	220	50
Barbados	115	50
Belarus	220	50
Belgium	230	50
Belize	110	60
Benin	220	50
Bermuda	120	60
Bhutan	220	50
Bolivia	110/220	50
Bosnia-Herzegovina	220	50
Botswana	220	50
Brazil	110/220	60
Bulgaria	220	50
Burkina	220	50
Burma (Myanmar)	230	50
Burundi	220	50
Cambodia	120/220	50
Cameroon	220	50
Canada	120	60
Canary Islands	220	50

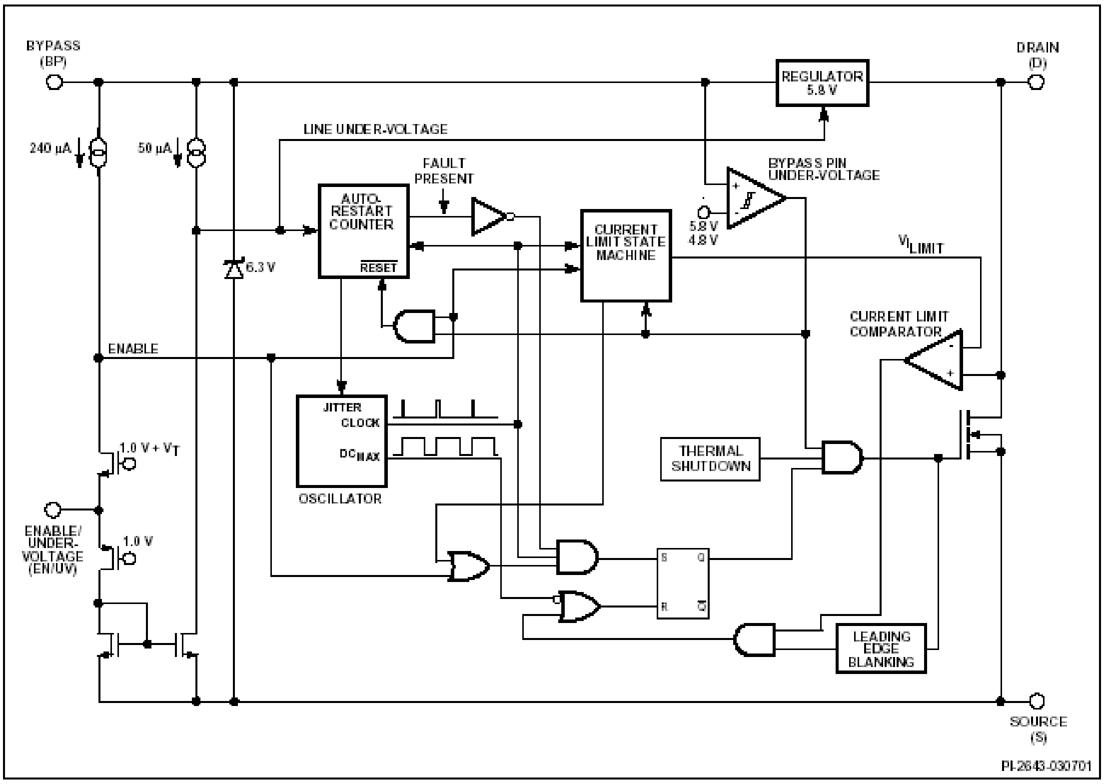
Cape Verde Islands	220	50
Cayman Islands	120	60
Central African Republic	220	50
Chad	220	50
Chile	220	50
China	220	50
Colombia	110	60
Comoros	220	50
Congo	220	50
Costa Rica	120	60
Croatia	220	50
Cuba	120	60
Curacao	110/220	60
Cyprus	240	50
Czech Republic	220	50
Denmark	230	50
Djibouti	220	50
Dominica	230	50
Dominican Republic	110	60
Ecuador	120	60
Egypt	220	50
El Salvador	115	60
England	240	50
Eritrea	220	50
Estonia	220	50
Ethiopia	220	50
Fiji	240	50
Finland	230	50
France	230	50
Gabon	220	50
Gambia	220	50
Georgia	220	50
Germany	230	50
Ghana	220	50
Greece	230	50
Greenland	220	50
Grenada	230	50
Grenadines	230	50
Guadeloupe	220	50
Guam	120	60
Guatemala	120	60

Guinea	220	50
Guyana	110	60
Haiti	110	60
Honduras	110	60
Hong Kong	220	50
Hungary	220	50
Iceland	220	50
India	220	50
Indonesia	220	50
Iran	220	50
Iraq	220	50
Ireland	220	50
Israel	230	50
Italy	230	50
Ivory Coast	220	50
Jamaica	110	50
Japan	100	50/60
Jordan	220	50
Kazakhstan	220	50
Kenya	240	50
Kirghizia	220	50
Korea	110/220	50/60
Kuwait	240	50
Laos	220	50
Latvia	220	50
Lebanon	220	50
Lesotho	240	50
Liberia	120	60
Libya	230	50
Liechtenstein	220	50
Lithuania	220	50
Luxembourg	230	50
Macao	220	50
Macedonia	220	50
Madagascar	220	50
Malawi	230	50
Malaysia	240	50
Mali	220	50
Malta	240	50
Martinique	220	50
Mauritania	220	50
Mauritius	230	50
Mexico	120	60

Moldova	220	50
Monaco	220	50
Mongolia	220	50
Morocco	220	50
Mozambique	220	50
Myanmar (Burma)	230	50
Namibia	220	50
Nepal	220	50
Netherlands	230	50
New Zealand	230	50
Nicaragua	120	60
Niger	220	50
Nigeria	230	50
Norway	230	50
Oman	240	50
Pakistan	230	50
Panama	120	60
Papua New Guinea	240	50
Paraguay	220	50
Peru	110/220	50/60
Philippines	110/220	60
Poland	220	50
Portugal	230	50
Puerto Rico	120	60
Qatar	240	50
Romania	220	50
Russian Federation	220	50
Rwanda	220	50
St. Kitts-Nevis	230	60
St. Lucia	240	50
St. Vincent	230	50
Saudi Arabia	127/220	50/60
Scotland	220	50
Senegal	220	50
Seychelles	240	50
Sierra Leone	230	50
Singapore	230	50
Slovakia	220	50
Slovenia	220	50
Solomon Islands	220	50
Somalia	220	50
South Africa	230	50
Spain	230	50

Sri Lanka	230	50
Sudan	240	50
Surinam	110/220	50/60
Swaziland	230	50
Sweden	230	50
Switzerland	230	50
Syria	220	50
Tahiti	127/220	50/60
Taiwan	110	60
Tajikistan	220	50
Tanzania	230	50
Thailand	220	50
Tonga	110/220	50/60
Trinidad & Tobago	115/230	60
Tunisia	220	50
Turkey	220	50
Turkmenistan	220	50
Uganda	240	50
Ukraine	220	50
United Arab Emirates	220	50
United States	120	60
Uruguay	220	50
Uzbekistan	220	50
Venezuela	120	60
Vietnam	120/220	50
Virgin Islands	120	60
Wales	220	50
Western Samoa	230	50
Yemen	220	50
Yugoslavia	220	50
Zaire	220	50
Zambia	220	50
Zimbabwe	220	50

11.2 Description of TinySwitch II



TinySwitch-II Functional Description

TinySwitch-II combines a high voltage power MOSFET switch with a power supply controller in one device. Unlike conventional PWM (Pulse Width Modulator) controllers, *TinySwitch-II* uses a simple ON/OFF control to regulate the output voltage.

The *TinySwitch-II* controller consists of an Oscillator, Enable Circuit (Sense and Logic), Current Limit State Machine, 5.8 V Regulator, Bypass pin Under-Voltage Circuit, Over Temperature Protection, Current Limit Circuit, Leading Edge Blanking and a 700 V power MOSFET. *TinySwitch-II* incorporates additional circuitry for Line Under-Voltage Sense, Auto-Restart and Frequency Jitter. Figure 2 shows the functional block diagram with the most important features.

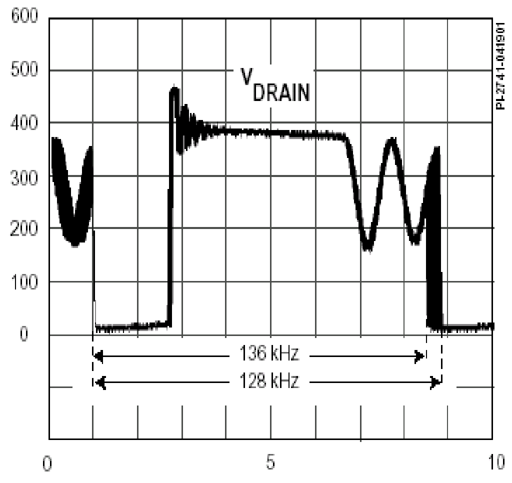
Oscillator

The typical oscillator frequency is internally set to an average of 132 kHz. Two signals are generated from the oscillator: the Maximum Duty Cycle signal (DC_{MAX}) and the Clock signal that indicates the beginning of each cycle.

The *TinySwitch-II* oscillator incorporates circuitry that introduces a small amount of frequency jitter, typically 8 kHz peak-to-peak, to minimize EMI emission. The modulation rate of the frequency jitter is set to 1 kHz to optimize EMI reduction for both average and quasi-peak emissions. The frequency jitter should be measured with the oscilloscope triggered at the falling edge of the DRAIN waveform. The waveform in Figure4 illustrates the frequency jitter of the *TinySwitch-II*.

Enable Input and Current Limit State Machine

The enable input circuit at the EN/UV pin consists of a low impedance source follower output set at 1.0 V. The current through the source follower is limited to 240 µA. When the current out of this pin exceeds 240 µA, a low logic level



(disable) is generated at the output of the enable circuit. This enable circuit output is sampled at the beginning of each cycle on the rising edge of the clock signal. If high, the power MOSFET is turned on for that cycle (enabled). If low, the power MOSFET remains off (disabled). Since the sampling is done only at the beginning of each cycle, subsequent changes in the EN/UV pin voltage or current during the remainder of the cycle are ignored.

The Current Limit State Machine reduces the current limit by discrete amounts at light loads when *TinySwitch-II* is likely to switch in the audible frequency range. The lower current limit raises the effective switching frequency above the audio range and reduces the transformer flux density including the associated audible noise. The state machine monitors the sequence of EN/UV pin voltage levels to determine the load condition and adjusts the current limit level accordingly in discrete amounts.

Under most operating conditions (except when close to no-load), the low impedance of the source follower keeps the voltage on the EN/UV pin from going much below 1.0 V in the disabled state. This improves the response time of the optocoupler that is usually connected to this pin.

5.8 V Regulator and 6.3 V Shunt Voltage Clamp

The 5.8 V regulator charges the bypass capacitor connected to the BYPASS pin to 5.8 V by drawing a current from the voltage on the DRAIN pin, whenever the MOSFET is off. The BYPASS pin is the internal supply voltage node for the *TinySwitch-II*. When the MOSFET is on, the *TinySwitch-II* operates from the energy stored in the bypass capacitor. Extremely low power consumption of the internal circuitry allows *TinySwitch-II* to operate continuously from current it takes from the DRAIN pin. A bypass capacitor value of 0.1 µF is sufficient for both high frequency decoupling and energy storage.

In addition, there is a 6.3 V shunt regulator clamping the BYPASS pin at 6.3 V when current is provided to the BYPASS pin through an external resistor. This facilitates powering of *TinySwitch-II* externally through a bias winding to decrease the no load consumption to about 50 mW.

BYPASS Pin Under-Voltage

The BYPASS pin under-voltage circuitry disables the power MOSFET when the BYPASS pin voltage drops below 4.8 V. Once the BYPASS pin voltage drops below 4.8 V, it must rise back to 5.8 V to enable (turn-on) the power MOSFET.

Over Temperature Protection

The thermal shutdown circuitry senses the die temperature. The threshold is typically set at 135 °C with 70 °C hysteresis. When the die temperature rises above this threshold the power MOSFET is disabled and remains disabled until the die temperature falls by 70 °C, at which point it is re-enabled. A large hysteresis of 70 °C (typical) is provided to prevent overheating of the PC board due to a continuous fault condition.

Current Limit

The current limit circuit senses the current in the power MOSFET. When this current exceeds the internal threshold (I_{LIMIT}), the power MOSFET is turned off for the remainder of that cycle. The current limit state machine reduces the current limit threshold by discrete amounts under medium and light loads.

The leading edge blanking circuit inhibits the current limit comparator for a short time (t_{LEB}) after the power MOSFET is turned on. This leading edge blanking time has been set so that current spikes caused by capacitance and secondary-side rectifier reverse recovery time will not cause premature termination of the switching pulse.

Auto-Restart

In the event of a fault condition such as output overload, output short circuit, or an open loop condition, *TinySwitch-II* enters into auto-restart operation. An internal counter clocked by the oscillator gets reset every time the EN/UV pin is pulled low. If the EN/UV pin is not pulled low for 50 ms, the power MOSFET switching is normally disabled for 850 ms (except in the case of line under-voltage condition in which case it is disabled until the condition is removed). The auto-restart alternately enables and disables the switching of the power MOSFET until the fault condition is removed. Figure 5 illustrates auto-restart circuit operation in the presence of an output short circuit.

In the event of a line under-voltage condition, the switching of the power MOSFET is disabled beyond its normal 850 ms time until the line under-voltage condition ends.

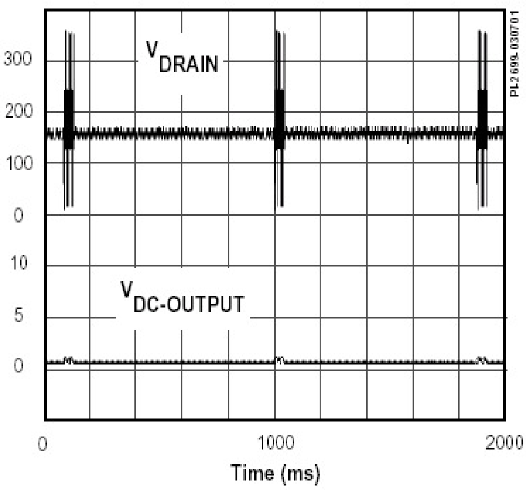


Figure 5. TinySwitch-II Auto-Restart Operation.

Line Under-Voltage Sense Circuit

The DC line voltage can be monitored by connecting an external resistor from the DC line to the EN/UV pin. During power-up or when the switching of the power MOSFET is disabled in auto-restart, the current into the EN/UV pin must exceed 50 µA to initiate switching of the power MOSFET. During power-up, this is implemented by holding the BYPASS pin to 4.8 V while the line under-voltage condition exists. The BYPASS pin then rises from 4.8 V to 5.8V when the line under-voltage condition goes away. When the switching of the power MOSFET is disabled in auto-restart mode and a line under-voltage condition exists, the auto-restart counter is stopped. This stretches the disable time beyond its normal 850ms until the line under-voltage condition ends.

The line under-voltage circuit also detects when there is no external resistor connected to the EN/UV pin (less than ~ 2 µA into pin). In this case the line under-voltage function is disabled.

TinySwitch-II Operation

TinySwitch-II devices operate in the current limit mode. When enabled, the oscillator turns the power MOSFET on at the beginning of each cycle. The MOSFET is turned off when the current ramps up to the current limit or when the DC_{MAX} limit is reached. As the highest current limit level and frequency of a *TinySwitch-II* design are constant, the power delivered to the load is proportional to the primary inductance of the transformer and peak primary current squared. Hence, designing the supply involves calculating the primary inductance of the transformer for the maximum output power required. If the *TinySwitch-II* is appropriately chosen for the power level, the current in the calculated inductance will ramp up to current limit before the DC_{MAX} limit is reached.

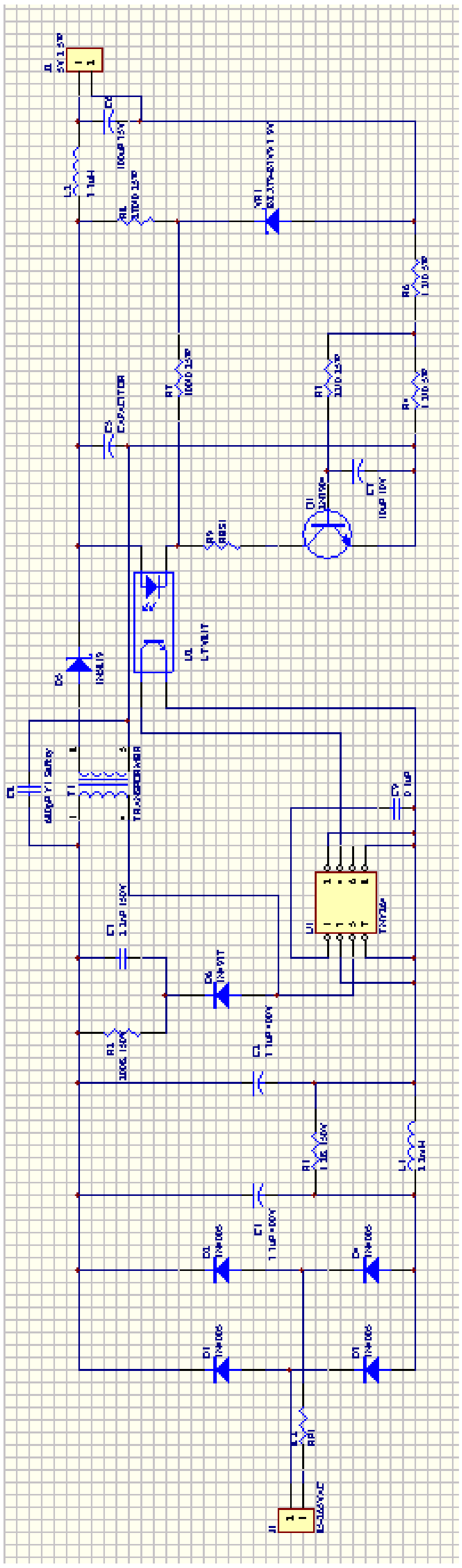
Enable Function

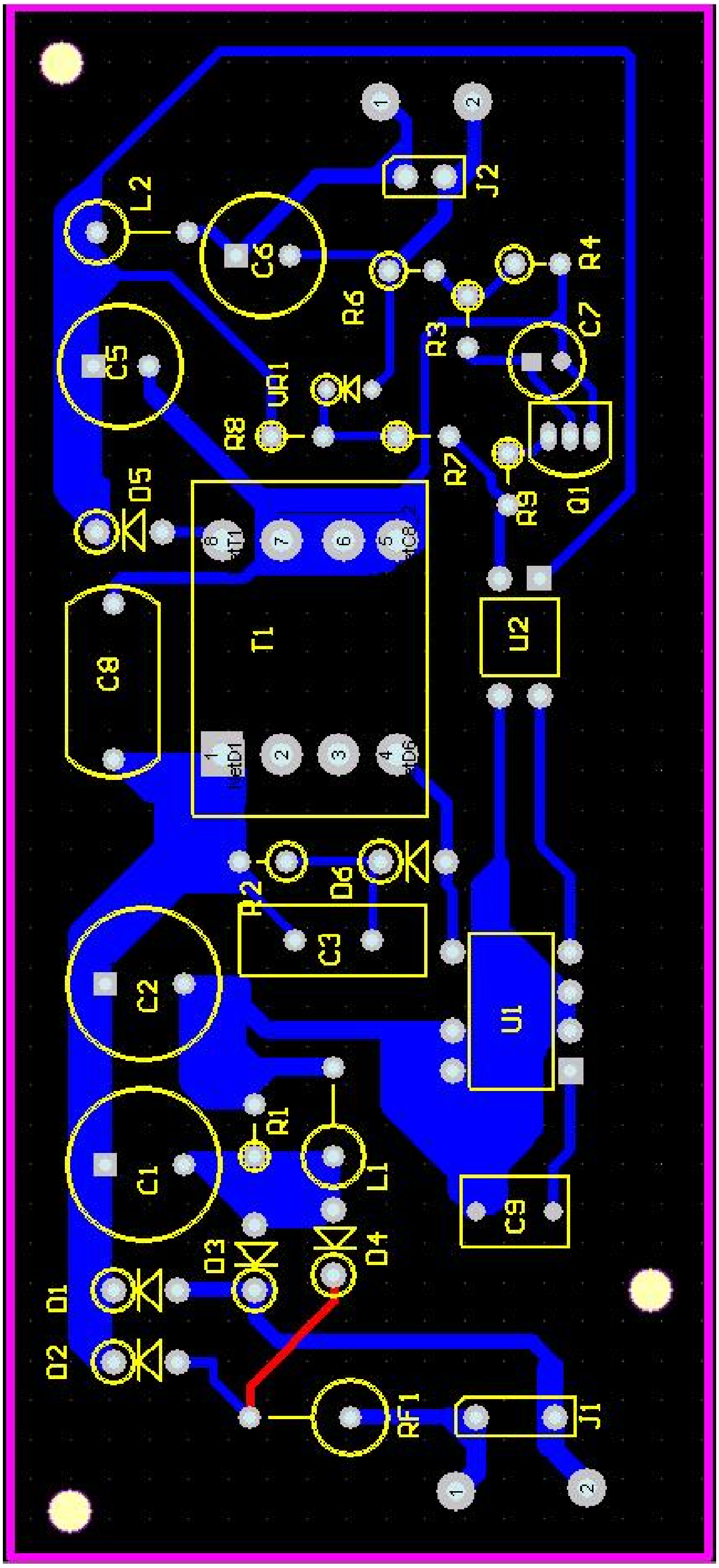
TinySwitch-II senses the EN/UV pin to determine whether or not to proceed with the next switch cycle as described earlier. The sequence of cycles is used to determine the current limit. Once a cycle is started, it always completes the cycle (even when the EN/UV pin changes state half way through the cycle). This operation results in a power supply in which the output voltage ripple is determined by the output capacitor, amount of energy per switch cycle and the delay of the feedback.

The EN/UV pin signal is generated on the secondary by comparing the power supply output voltage with a reference voltage. The EN/UV pin signal is high when the power supply output voltage is less than the reference voltage.

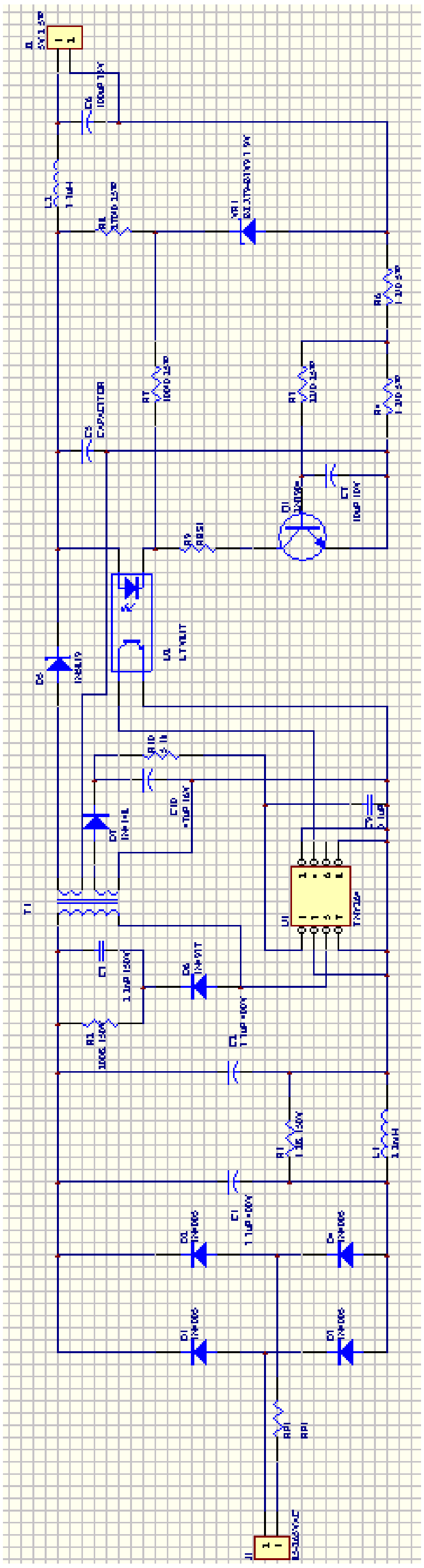
In a typical implementation, the EN/UV pin is driven by an optocoupler. The collector of the optocoupler transistor isconnected to the EN/UV pin and the emitter is connected to

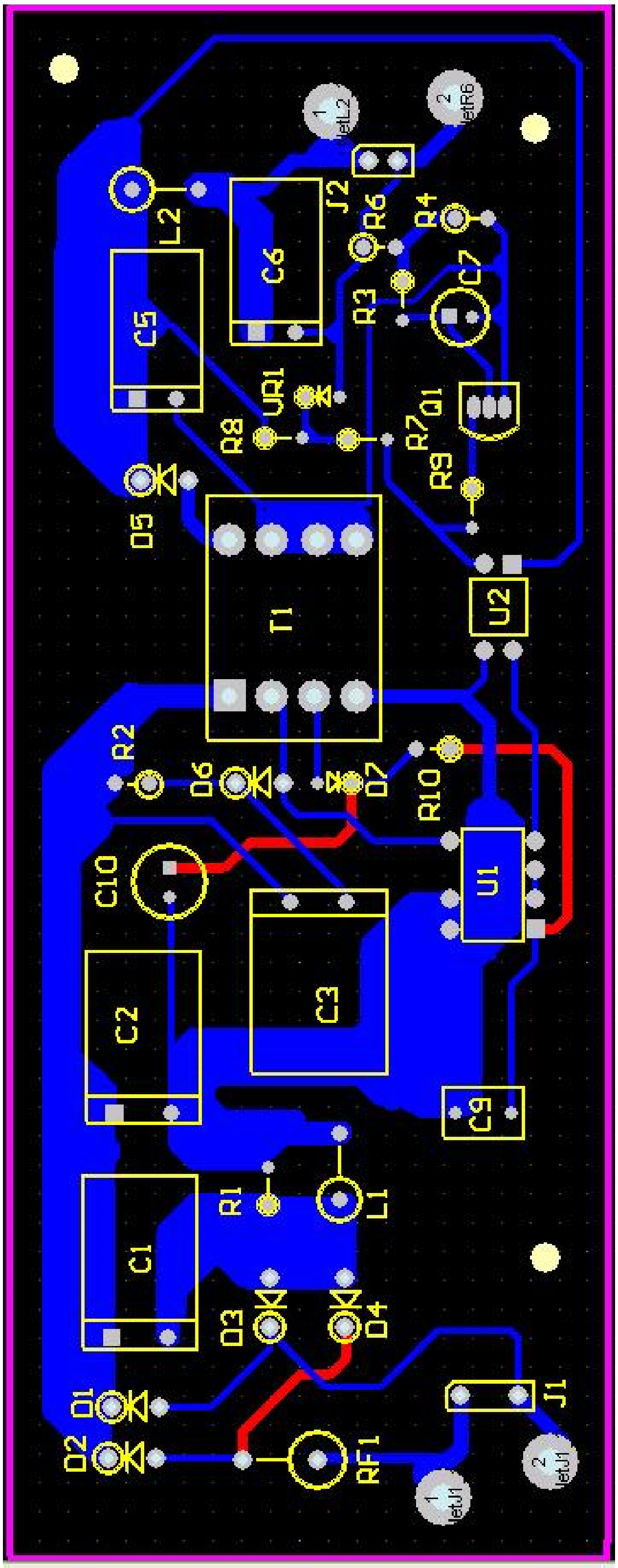
11.3 Schematic and PCB of 5V/2.5W Circuit




L2
C6
J2
R4
R6
R3
C7
C5
UR1
R8
R7
R9
Q1
D5
T1
C8
U2
R2
D6
C3
C2
U1
C1
R1
L1
D3
D4
C9
D1
D2
RF1
J1

11.4 Schematic and PCB of 5V/2.5W Circuit with Bias Winding




L2
C5
C6
J2
R6
R4
C7
R3
VR1
R8
R7
Q1
R9
D5
T1
U2
R2
D6
D7
R10
U1
C10
C3
C2
C9
R1
L1
C1
D3
D4
J1
D1
D2
RF1

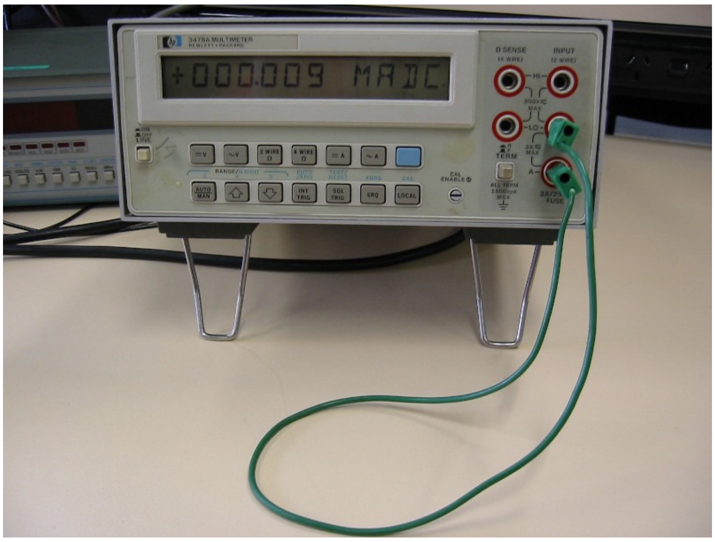
11.5 Results From “PI Expert”

Parameter	Unit of Measure	Primary Value	Output 1	Comment
Transformer Construction Parameters				
Core/Bobbin		EFD15-neosid-fig3former		Core and Bobbin Type
Core Manuf.		Generic		Core Manufacturing
Bobbin Manuf		Generic		Bobbin Manufacturing
LPmin	uHenries	1336		Minimum Primary Inductance
NP		98		Primary Winding Number of Turns
AWG	AWG	35		Primary Wire Gauge (Rounded to next smaller standard AWG value)
CMA	Cmils/A	312		Primary Winding Current Capacity
VOR	Volts	135.00		Reflected Output Voltage
BW	mm	9.15		Bobbin Physical Winding Width
M	mm	0.0		Safety Margin Width
L		2.0		Number of Primary Layers
AE	cm^2	0.15		Core Effective Cross Section Area
ALG	nH/T^2	139		Gapped Core Effective Inductance
BM	Gauss	2530		Maximum Operating Flux Density
BAC	Gauss	1265		AC Flux Density for Core Curves
LG	mm	0.11		Gap Length
LL	uHenries	26.7		Estimated Transformer Primary Leakage Inductance
LSEC	nHenries	20		Estimated Secondary Trace Inductance
Secondary Parameters				
NSx			4.00	Secondary Number of Turns
Rounded Down NSx				Rounded to Integer Secondary Number of Turns
Rounded Down Vox	Volts			Auxiliary Output Voltage for Rounded to Integer NSx
Rounded Up NSx				Rounded to Next Integer Secondary Number of Turns
Rounded Up Vox	Volts			Auxiliary Output Voltage for Rounded to Next Integer NSx
AWGSx Range	AWG		21 - 25	Secondary Wire Gauge Range Comment: Primary wire gauge is less than recommended minimum (26 AWG) and may overheat

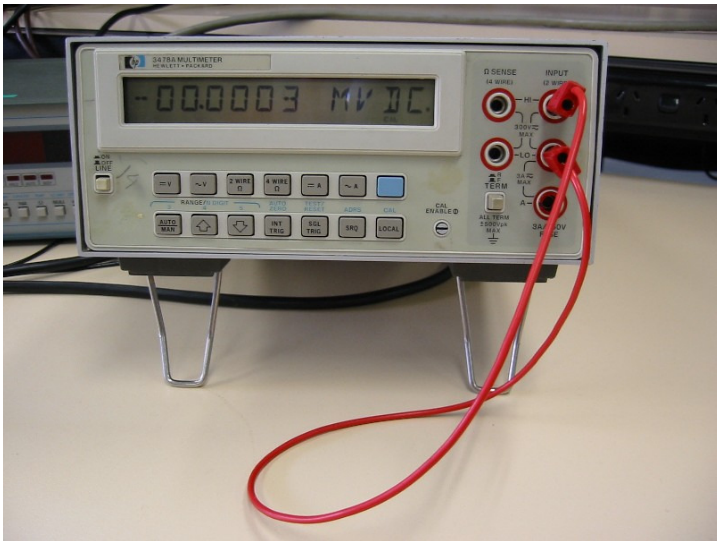
11.6 Other Transformer Parameters

SYMBOL	DESCRIPTION	UNIT
A_e	effective cross-sectional area of a core	mm^2
A_{min}	minimum cross-sectional area of a core	mm^2
A_L	inductance factor	nH
B	magnetic flux density	T
B_r	remanence	T
B_s	saturation flux density	T
$\hat{B}$	peak flux density	T
C	capacitance	F
D_F	disaccomodation factor	–
f	frequency	Hz
G	gap length	μm
H	magnetic field strength	A/m
H_c	coercivity	A/m
$\hat{H}$	peak magnetic field strength	A/m
I	current	A
l_e	effective magnetic path length	mm
L	inductance	H
N	number of turns	–
P_v	specific power loss of core material	kW/m^3
Q	quality factor	–
T_c	Curie temperature	°C
THD/μ_a	Total Harmonic Distortion factor	dB
V_e	effective volume of core	mm^3
α_F	temperature factor of permeability	K^{-1}
$\tan\delta/\mu_i$	loss factor	–
η_B	hysteresis material constant	T^{-1}
μ	absolute permeability	–
μ_o	magnetic constant ($4\pi \times 10^{-7}$)	Hm^{-1}
μ_s'	real component of complex series permeability	–
μ_s''	imaginary component of complex series permeability	–
μ_a	amplitude permeability	–
μ_e	effective permeability	–
μ_i	initial permeability	–
μ_r	relative permeability	–
μ_Δ	incremental permeability	–
ρ	resistivity	Ωm
$\Sigma(l/A)$	core factor (C1)	mm^{-1}

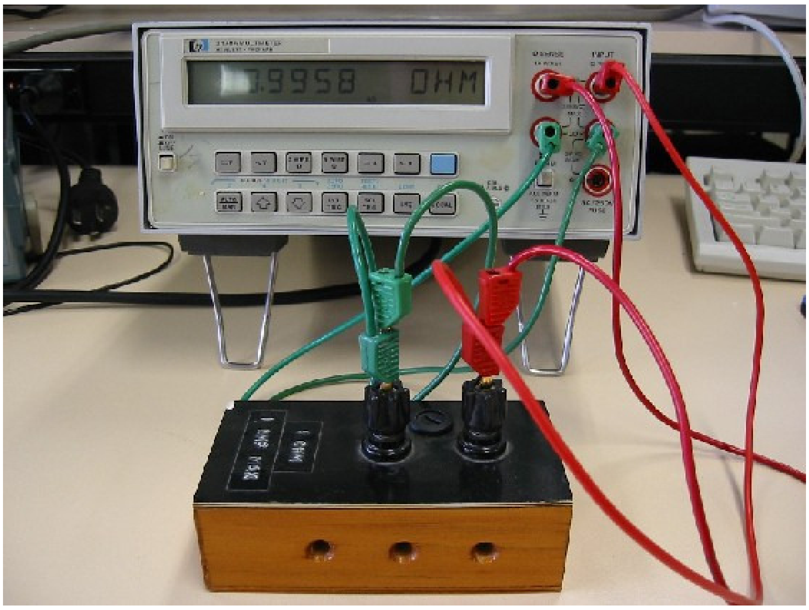
11.7 Accuracy Test for Ampere Meter



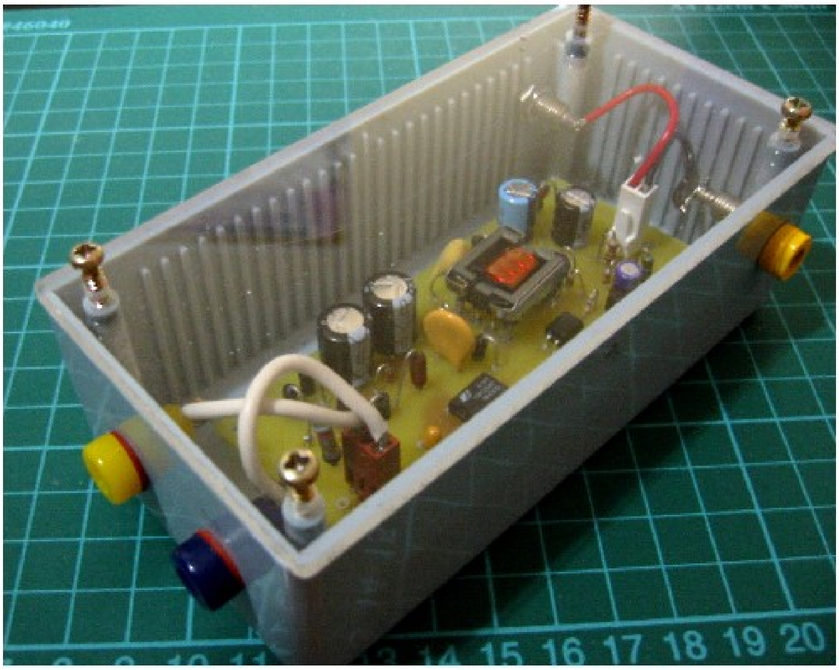
11.8 Accuracy Test for Voltage Meter



11.9 Accuracy Test for 1 ohm Resistor



11.10 Diagram of the Constructed Circuits



11.11 Budget List for Circuit

Budget List for 5V/2.5W Circuit (First Circuit)			
Quantity	**Description**	**Cost Each**	**Cost**
4	Diode 1A 600V (1N4005)	$0.28	$1.12
1	Diode 1A 600V (1N4937)	$0.67	$0.67
1	Diode Schottky 1A (1N5819)	$0.89	$0.89
1	Transistor NPN to 92 (2N3904)	$0.26	$0.26
1	Diode Zener 500mW 3.9V (BZX79-C3V9)	$0.11	$0.11
2	0.5W 1R2 Resistor	$0.15	$0.30
1	0.25W 200K Resistor	$0.07	$0.07
1	0.125W 1K2 Resistor	$0.15	$0.15
1	0.125W 270R Resistor	$0.15	$0.15
1	0.125W 22R Resistor	$0.15	$0.15
1	0.125W 47R Resistor	$0.15	$0.15
1	0.125W 100R Resistor	$0.15	$0.15
1	1W 8R2 Fusible Resistor	$0.26	$0.26
1	35V 100uF Capacitor	$0.27	$0.27
1	16V 330uF Capacitor	$0.47	$0.47
1	10V 10uF Capacitor	$1.42	$1.42
1	50V 0.1uF Capacitor	$3.31	$3.31
1	250Vac 680F Capacitor	$0.61	$0.61
1	1000V 2200pF Capacitor	$0.71	$0.71
1	Axial, BC Suppression Choke (3.3uH)	$0.60	$0.60
1	Axial, BC Suppression Choke (2200uH)	$0.69	$0.69
1	Opto-Isolator (PC 817)	$2.29	$2.29
1	400V 3.3uF Capacitor	$0.58	$0.58
2	32-721-47 EFD15 Gapped F47	$0.75	$1.50
1	EFD15 8 Pin Coil Former	$1.10	$1.10
2	EFD15 Clip	$0.20	$0.40
1	PCB Slot Box 125x60x40mm	$7.49	$7.49
	Total Including GST		**$26.13**

Budget List for 5V/2.5W Circuit With Bias Winding (Second Circuit)			
Quantity	**Description**	**Cost Each**	**Cost**
4	Diode 1A 600V (1N4005)	$0.28	$1.12
1	Diode 1A 600V (1N4937)	$0.67	$0.67
1	Diode Schottky 1A (1N5819)	$0.89	$0.89
1	Transistor NPN to 92 (2N3904)	$0.26	$0.26
1	Diode Zener 500mW 3.9V (BZX79-C3V9)	$0.11	$0.11
2	0.5W 1R2 Resistor	$0.15	$0.30
1	0.25W 200K Resistor	$0.07	$0.07
1	0.125W 1K2 Resistor	$0.15	$0.15
1	0.125W 270R Resistor	$0.15	$0.15
1	0.125W 22R Resistor	$0.15	$0.15
1	0.125W 47R Resistor	$0.15	$0.15
1	0.125W 100R Resistor	$0.15	$0.15
1	1W 8R2 Fusible Resistor	$0.26	$0.26
1	35V 100uF Capacitor	$0.27	$0.27
1	16V 330uF Capacitor	$0.47	$0.47
1	10V 10uF Capacitor	$1.42	$1.42
1	50V 0.1uF Capacitor	$3.31	$3.31
1	1000V 2200pF Capacitor	$0.71	$0.71
1	Axial, BC Suppression Choke (3.3uH)	$0.60	$0.60
1	Axial, BC Suppression Choke (2200uH)	$0.69	$0.69
1	Opto-Isolator (PC 817)	$2.29	$2.29
1	400V 3.3uF Capacitor	$0.58	$0.58
2	32-721-47 EFD15 Gapped F47	$0.75	$1.50
1	EFD15 8 Pin Coil Former	$1.10	$1.10
2	EFD15 Clip	$0.20	$0.40
1	Diode DO-35 (1N4148)	$0.03	$0.03
1	16V 47uF Capacitor	$0.57	$0.57
1	0.5W 5K1 Resistor	$0.14	$0.14
1	Black Box 95x160x61mm	$9.92	$9.92
1	Nlyon Cable Gland	$2.63	$2.63
1	2 Pin Mains Wire	$11.99	$11.99
1	250mA Anti Surge Glass Fuse	$0.59	$0.59
1	Fuse Holder	$3.00	$3.00
	Total Including GST		**$50.51**