# DEVELOPMENT OF THE PUSH PULL SELF DRIVE SYNCHRONOUS RECTIFICATION CONVERTER

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**UNIVERSITI SAINS MALAYSIA**
**2009**

# DEVELOPMENT OF THE PUSH PULL SELF DRIVE SYNCHRONOUS RECTIFICATION CONVERTER

**by**

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**Thesis submitted in fulfillment of the requirements**
**for the degree of**
**Masters of Science**

**March 2009**

## ACKNOWLEDGEMENTS

**In the name of Allah, the Beneficent, the Merciful.**

First and foremost I offer my sincerest gratitude to my supervisor, A.P. Dr. Soib Taib and my co-supervisor, Dr. Mohd. Fadzil Ain for their support throughout my research with patience and knowledge whilst allowing me the freedom to work in my own way. One simply could not wish for better and friendlier supervisors.

I would like to thank to Mr. Shaukhi and Mr. Jamaludin for their kindness during the laboratory works. Huge thanks to Mr. Nazir and Dr. Syed Sahal for their advice and support. And to all whom have helped me in any ways. Thank you very much.

I could not have made it without the love and support from my wife, Nurul Shuhada Aseri. Thank you very much for being there for me. Finally, I present this work as a tribute to my parents, Mamat Abdullah and Dayang Sulong. Million thanks for your love, perseverance and determination in educating me.

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# LIST OF SYMBOLS

| | | |
|---|---|---|
| $I_{pk}$ | Maximum inductor peak current | 21 |
| $P_{out}$ | Typical topology power rating | 21 |
| $R_{ds(on)}$ | MOSFET on-resistance | 23 |
| k | Coupling coefficient | 54 |
| a | Transformer turns ratio | 55 |
| N1 | Primary winding turns | 55 |
| N2 | Secondary winding turns | 55 |
| L1 | Primary inductance | 55 |
| L2 | Secondary inductance | 55 |
| $R_T$ | Timing resistor | 60 |
| $C_T$ | Timing capacitor | 60 |
| $R_D$ | Deadtime resistor | 60 |
| $R_{vd}$ | Potentiometer value | 61 |
| $R_{up}$ | Up divider resistor | 63 |
| $R_{down}$ | Down divider resistor | 63 |
| $V_a$ | The PWM drive signal for push leg | 64 |
| $V_b$ | The PWM drive signal for pull leg | 64 |
| $P_o$ | Output power | 67 |
| $I_o$ | Output current | 67 |
| $\eta$ | Efficiency | 67 |
| $D_{max}$ | Maximum duty cycle | 67 |
| $t_{ON(max)}$ | Maximum ON time conduction | 67 |
| T | Full switching cycle in seconds | 68 |

## LIST OF ABBREVIATION

# ABSTRAK

Tesis ini mengemukakan satu rekabentuk baru bagi penukar DC-DC untuk kegunaan aplikasi voltan rendah. Rekabentuk cadangan berdasarkan bekalan kuasa mod tersuis dengan topologi tolak tarik. Penerus segerak pacu sendiri telah digunakan di dalam peringkat penerusan bagi penambahbaikan dalam proses tersebut. MOSFET daripada jenis N dan P telah digunakan untuk meringkaskan litar kawalan penerus segerak. Kedua-dua jenis MOSFET itu mempunyai rintangan semasa bekerja yang sangat rendah dan boleh digunakan bagi meningkatkan kecekapan penukar berbanding kaedah konvensional. Penukar ini bekerja di bawah frekuensi pensuisan tinggi bagi meningkatkan nisbah kuasa ke isipadu. Tambahan lagi, masa mati telah ditentukan pada tahap minimum untuk memastikan penukar ini menukar tenaga pada kecekapan tinggi. Penapis aliran rendah pasif telah juga digunakan bagi menghasilkan keluaran voltan yang bebas riak. Topologi muktamad iaitu penukar tolak tarik dengan rektifikasi segerak pacu sendiri telah dibina menggunakan litar kawalan yang mudah tetapi mengekalkan kecekapan yang baik. Simulasi menunjukkan rekabentuk ini beroperasi secara cekap dengan penerus segerak pacu sendiri. Frekuensi pensuisan ditetapkan pada 30 kHz bagi meminimumkan tekanan pensuisan dan kehilangan konduksi. Perlaksanaan praktikal menunjukkan rekabentuk ini berupaya beroperasi pada kecekapan maksimum 84.1%. Di samping itu, rekabentuk ini cuma menghasilkan riak voltan keluaran sebanyak 50m$V_{p\text{-}p}$ sahaja dan dianggap baik bagi keluaran DC teratur.

# ABSTRACT

This thesis presents a new DC-DC converter design for low voltage application. The proposed design is based on isolated push pull topology switched mode power supply. Self-driven synchronous rectification is introduced in the rectification stage in order to create an improved way of rectifying process. N-Channel and P-Channel MOSFETs are used to simplify the synchronous rectification control circuit. Both MOSFETs offer ultra low On-resistance which can be used to achieve higher efficiency than the conventional converter. This converter operates at high speed switching frequency to gain high power-to-volume ratio. In addition, minimum deadtime is set in the design to ensure high efficiency in input-output power transfer. Passive low pass filter is implemented to produce ripple free output voltage in the design. The finalize topology which is push pull with self-driven synchronous rectification is constructed using simple control circuit but maintains good efficiency in its operation. Simulation results show that the proposed converter reacts very well with the self-driven synchronous rectification method. Switching frequency is set to 30 kHz to minimize the switching stress and conduction losses. Practical implementation of the converter shows that the converter operates at a maximum efficiency of 84.1%. Besides, the design only produces 50m$V_{p-p}$ ripple output voltage and considered good for a regulated DC output.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

For the past few decades, a lot of improvements have arisen for the need of better and greener power supply. By better and greener, it means that the power supply must have the best aspects in its category such as efficiency, sizing, component counts, complexity and of course the most important part that the world is moving to which is power generation from renewable and natural energy such as solar, wind and ocean. The common issues that are discussed in the field of power electronics related to the overall losses which lead to the efficiency, selection of component or material, design cost and the reliability of the design. There are many techniques and topologies that have already been used or still under research to fulfill the demand mentioned earlier.

It is all started back in 1660, when Otto von Guericke constructed the first electrical machine that consisted of a large sulphur globe which, when rubbed and turned, attracted feathers and small pieces of paper. Guericke was able to prove that the sparks generated were truly electrical. The first suggested use of static electricity was the so-called "electric pistol". Invented by Alessandro Volta (1745-1827), an electrical wire was placed in a jar filled with methane gas. By sending an electrical spark through the wire, the jar would explode [1]. Later in 1947, John Bardeen, Walter Brattain & William Shockley all co-invented the transistor at Bell Labs. This tiny and powerful device changed the future of electronics tremendously. Comprise of semiconductor material that amplifies a signal or opens or closes a circuit, transistors have become the major component in all electric and electronic circuits. With small size and uses less power, there is little heat to dissipate and consistently does not fail quickly. Nevertheless, circuits became smaller and smaller resulting in practical, space and cost effective design. It is then utilized by the power supply circuit to replace vacuum tube in its design which had many disadvantages such as bigger size, used more energy and created more heat. Aptly, transistor has given a new revolutionized trend in power supply circuits by making design smaller and last longer. From that time, majority of power supplies circuits used transistor enabling lots of power conversion methods in order to increase efficiency and reliability. Some of the conversion techniques invented are linear power supply, switched mode power supply and resonant power supply.

In 1970’s, the most popular technique for controlling DC power used linear power supply or linear regulator. Linear regulators were used predominantly in ground-based equipments where the generation of heat and low efficiency were not of major concern and also where low cost and a short design period were desired. They were very popular as board level regulators in distributed power systems where the distributed voltage was less than 40VDC. For off-line (plug into the wall) products, the power supply must be provided with transformer isolation to produce dielectric isolation from the ac power line before the linear regulator circuit. Linear regulators could only produce output voltages lower than their input voltages and each linear regulator could produce only one output voltage. Each linear regulator had an average efficiency of between 35 and 50 percent [2]. The losses were dissipated as heat.

In the era of 1980’s onwards, the terms pulsewidth modulated (PWM) and resonant/quasi-resonant switching power supplies dominated the market and these topologies have been the key for the flexible power supplies until now. They are also known as switch mode power supply (SMPS) where power is transferred with turn on and off mechanism producing higher efficiency by minimizing the losses during conversion and energy transfer between source and load. PWM switching power supplies are much more efficient and flexible compared to the linear regulators. Typically, these power supplies use switching frequency below 100 kHz and commonly used within portable products, aircrafts and automotive products, small instruments, off-line applications, and generally for applications where high efficiency and multiple output voltages are required. Their weight is much lesser than that of linear regulators since they require less heatsinking for the same output ratings but the cost is more expensive compared with linear regulator. Resonant or quasi-resonant is a variation of the basic PWM switching power supply but uses higher switching frequency typically above 100 kHz and is invented for lighter weight and smaller size design, and most importantly, where a reduced amount of input-output radiated noise (interference) is desired. Although resonant or quasi-resonant power supply produces the highest efficiency compared to linear regulator and PWM power supply but this power supply technology requires the greatest amount of engineering design time and usually costs more than the other two technologies. This type of supply is normally used in aircraft avionics, spacecraft electronics, and lightweight portable equipment and modules. Table 1.1 shows the comparison of the three main topologies.

Table 1.1 Comparison of the three power supplies technologies.

| | Linear Regulator | PWM Switching Regulator | Resonant Transition Switching Regulator | Quasi-Resonant Switching Regulator |
|---|---|---|---|---|
| Cost | Low | High | High | Highest |
| Mass | High | Low-medium | Low-medium | Low-medium |
| RF Noise | None | High | Medium | Low-medium |
| Multiple Outputs | No | Yes | Yes | Yes |
| Efficiency | 35-50% | 70-85% | 78-92% | 78-92% [2] |

DC voltage is widely used in electronic sectors from such a miniature device in nanotechnology to the huge application such as underground and overground trains. Compared to AC voltage, DC voltage has a lot of benefit in terms of energy management flexibility and low cost protection circuit scheme. Table 1.2 summarized the rating of DC voltage usage in known applications.

Table 1.2 The rating of DC voltage in known applications.

| Rating | Application |
|---|---|
| 3.3V | CMOS IC controller |
| 5V | CMOS and TTL IC |
| 12V | TTL IC and commercial IC controller |
| 20V | Portable device |
| ±48V | Standard telecommunication voltage |
| 110V- 415V | Industrial DC motor |
| kV | HVDC transmission |

Semiconductor and electronic technologies are moving rapidly and everything needs to be compact, easy and portable. It is the idea to study the DC conversion in this voltage rating which is 20V to produce the best in the portability world and keep pace with the technology movement. Some of the applications associated with this voltage rating are small brushless motor, stepper motor, normal power regulator, notebook automotive adapter, portable measurement apparatus, high end engine control unit (ECU), vehicle discharge lamp lighting and etc. On the other hand, this voltage rating seems to work very well with the renewable and natural resource energy such as solar power which varying from 12V to 22V at the most.

For lower voltage rating DC-DC converter typically below 24V, the major issue discussed is the power dissipation by the diodes in the rectifying stage. With lower and lower voltage output rating of the converter, the effect of the loss is significantly affecting the overall performance and efficiency of the converter. Even with the lowest power dissipation diode which is schottky diode, the problem still has big impact on the converter. The method that eliminates the usage of the diodes in the rectifying stage is called synchronous rectification (SR) or sometimes known as switching rectifier is the best method to overcome the problem. Metal Oxide Silicone Field Effect Transistor (MOSFET) is used to swap diode in the rectifying stage and current researches show that the SR method can improve efficiency and reliability of a converter.

## 1.2 Scope of Work

World demands the best in engineering and for power supply technology everything must be compact enough for space and cost saving. SMPS offers the best in this category by producing the highest efficiency in DC-DC conversion using high frequency PWM technique, low volume to power density ratio, high durability and reliability and meets the standard for electromagnetic interference (EMI) and electromagnetic compliance (EMC) product. To produce SMPS that comply with the criteria above, study must be made in the following areas;

- DC power conversion using efficient and powerful switching converter topology with input-output isolation through chopper transformer.
- Practical PWM gate drive control using commercial IC for SMPS.
- Output rectification using MOSFET which known as synchronous rectification (SR) or switching rectifier instead of traditional diode.
- Simple and efficient self-driven control scheme for SR circuit

## 1.3 Objectives of Work

In this research, the main objective is to develope a high efficiency DC-DC converter using high frequency switching technique. For SMPS, the overall efficiency may be gained from power circuit, driver circuit, chopper transformer, synchronous rectification circuit and output filtering. Therefore, to fulfill the objectives, follow are steps taken.

- To select the best switching topology for 12V input and 20V, 3A isolated DC-DC converter.
- To construct drive control circuit operating at 30 kHz using PWM technique from commercial SG3525A.
- To use power MOSFET to rectify the output AC waveform hence generating a new way of rectifying AC waveform in the rectification process.
- To filter using low pass filter to achieve low ripple DC output voltage.

## 1.4 Thesis Outline

Chapters in this thesis are arranged in a way to show the chronology of the development and design of the DC-DC converter itself. The thesis consists of five chapters.

Chapter one is the introduction which covers the history and overview of the power supplies, scope and objectives of the work. In this chapter, the development of the power supplies is explained briefly. Scope and objectives are discussed to fulfill the design and implementation of the proposed converter.

Chapter two explains in details about everything related with SMPS technology including basic switching elements in the DC-DC converter and the fundamental principle of the topologies. After that, basic non-isolated and isolated topologies will be briefly explained. At the end, the related researches using SR techniques are described and reviewed and the techniques show that the efficiency improvement of a low voltage DC-DC converter can be achieved.

Chapter three explains the development of the proposed DC-DC converter. It covers all necessary steps taken for the design which include simulation, power circuit and driver design, chopper transformer construction, rectifying using SR circuit, SR control circuit and output filtering.

Chapter four shows all the experimental results from the proposed converter. Discussion will relate to all the data and to verify the agreeable between the simulation and the constructed converter design.

Chapter five concludes the development of the proposed design. Future work will extend this project to a new level of research sooner.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

DC-DC conversion is a process to convert a DC input voltage to another level of DC output voltage usually at a different level than the input. With different conversion technique, output voltage can be customized from as small as few volts to as high as kilovolts. Basically, DC-DC conversion is not as simple as the idea of converting a level of DC input voltage to another DC output voltage level. The conversion process needs good integration between input stage, input-output isolation stage and the output stage. Input stage consists of input power circuit and drive control usually implemented by high frequency technique. Input-output isolation is made of high frequency transformer and the output stage consists of rectifying and filtering circuit. If any of these parts cannot match, the conversion process will not operate as desired.

Another factor that influences the performance and cost of a DC-DC converter is the component selection. Semiconductor industry offers a lot of discrete devices to be used in DC power supply design. Depending on the desired design characteristic, usage of higher rating and well protective component such as transistor brings extra cost to the production. For isolated topologies which have included the use of magnetic elements, the selection of core material and type will also determine the performance of the DC-DC conversion process. Nowadays, with the advanced in semiconductor industry, there is practical method to provide an efficient, controllable, and fast operation DC power supply due to the present of high switching operation, great noise isolation and well regulated bus voltage output.

In this chapter, basic elements in SMPS will be briefly explained. Some basic non-isolated and isolated topologies and recent topologies using synchronous rectification will be presented.

### 2.2 Switching Elements in Switched Mode Power Supply

The two elements in SMPS that need to be discussed are power diode and MOSFET which contribute major losses in SMPS design. Proper understanding of the behaviour and operation of these devices can result in an efficient SMPS.

#### 2.2.1 The Power Diode

With only two terminals, power diode is the simplest among all devices in static switching devices. With one terminal known as anode and another terminal known as cathode, diode only allows current to conduct in unidirectional path. Figure 2.1 shows the symbol of a diode and the practical characteristic of a power diode [3].

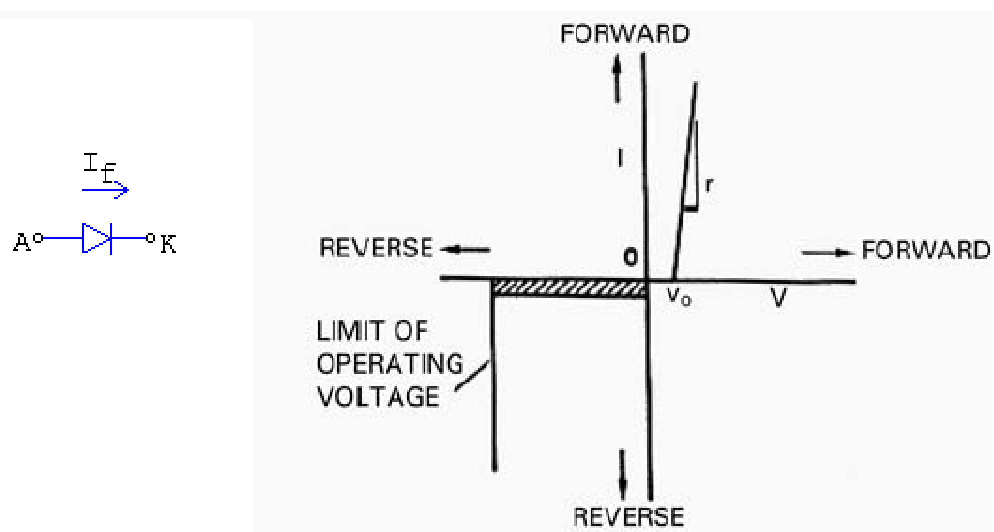


Figure 2.1 Diode: Symbol and characteristics.

When anode terminal, A has higher potential than cathode terminal, K, diode is said to be in forward biased condition and forward current, $I_f$ will flow from terminal A to K. During conduction, diode will experience a forward voltage drop, $V_f$ and it is the source for loss in power diode. When terminal K has higher potential than terminal A, the device is in reverse biased condition and only small leakage current flows from K to A and usually can be ignored. From Figure 2.1, in reverse quadrant, when a strong reverse current or reverse voltage appears, the device is said in avalanche breakdown and the diode will become shorted and often damaged.

In practical, the important parameter for the power diode is the reverse recovery time, $t_{rr}$. Reverse recovery time is the amount of time taken for a diode to turn off when the voltage across it alternates from forward bias to reverse bias polarity. Ideally, the value is zero but practically Figure 2.2 shows the reverse recovery time for typical diode under soft and abrupt condition. As a rule of thumb, the lower $t_{rr}$, the faster the diode can be switched.

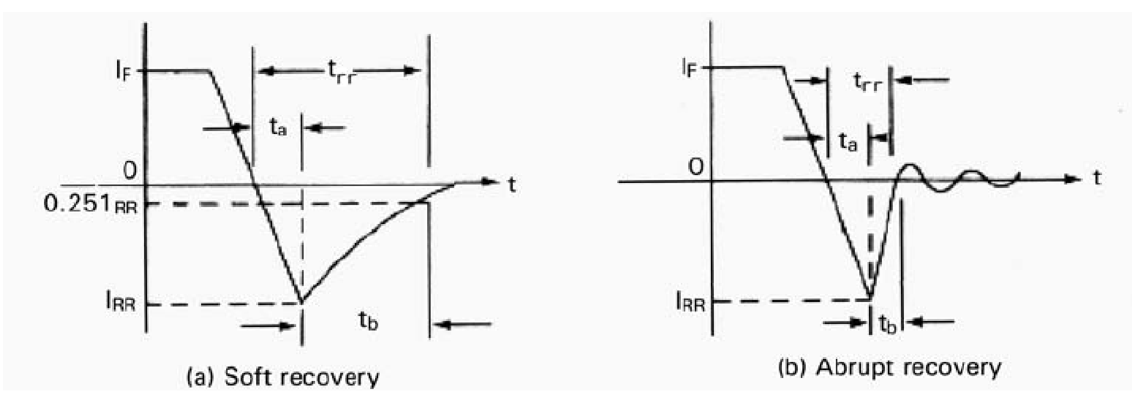


Figure 2.2 Reverse recovery time for a typical diode [3].

Reverse recovery time is given by,

$$t_{rr} = t_a + t_b \quad (2.1)$$

If $t_b$ is negligible compared to $t_a$ (which is commonly occurred) then,

$$t_{rr} = \sqrt{\frac{2Q_{rr}}{di/dt}} \qquad (2.2)$$

From equation 2.2, maximum reverse current, $I_{RR}$ is given by,

$$I_{RR} = \frac{2Q_{rr}}{t_{rr}} \qquad (2.3)$$

Softness factor, SF is given by,

$$SF = \frac{t_b}{t_a} \qquad (2.4)$$

Where;

$Q_{rr}$ is the storage charged from forward conduction to reverse blocking condition.

$t_a$ is time between zero crossing and the maximum reverse current and it is due to the charge stored in the depletion region of the junction.

$t_b$ is time between maximum reverse current $I_{RR}$ and 25% of the of the maximum reverse current $I_{RR}$ and is due to charge stored in the bulk semiconductor material.

$I_f$ is the forward biased current.

$I_{RR}$ is the maximum reverse current.

Depending on the purpose of the diode to be used in SMPS, different diodes bring different effects to SMPS behaviour. Therefore, it is important to know the characteristic of each diode before using them in the design. Table 2.1 summarizes the types and characteristics for diodes used in SMPS.

Table 2.1 Types and characteristics of diodes

| Type | Characteristics |
|---|---|
| General purpose diode | -Relatively high reverse recovery time (25µs).<br>-Used in low frequency/speed application (<1 kHz).<br>-High current rating (1A-10 kA).<br>-High voltage rating (50V-5 kV).<br>-Typical voltage drop between (0.7V-2.5V).<br>-Generally manufactured using diffusion process. |
| High voltage rectifier diode | -Lower reverse recovery time (100ns).<br>-The lowest maximum current rating (500mA).<br>-The highest forward voltage drop (10V).<br>-High voltage rating (up to 30 kV). |
| Fast recovery diode | -Have low recovery time (<5µs).<br>-High current rating (1A-3 kA).<br>-High voltage rating (50V-2 kV).<br>-For voltage above 400V, diode is made using diffusion process with reverse recovery time decreased by gold or platinum diffusion to increase conductivity.<br>-For voltage below 400V, diode is made using epitaxial substrate provides faster switching with reverse recovery times at 50ns. |
| Power Zener diode | -Designed to operate in breakdown region.<br>-Zener voltage levels over a wide range (<300V).<br>-Continuous power rating over moderate range (250mW-75W)<br>-Used in transient suppression as a clamp and absorb up to 50kW for limited times. |
| Schottky diode | -Relatively low forward voltage drop (0.2V-0.9V).<br>-Higher leakage current (>100mA).<br>-Low current rating (1A-300A).<br>-Low voltage rating (<100V).<br>-Recovery time only influenced by capacitance of silicon-metal interface. |

### 2.2.2 The Power MOSFETs

Evolved in the era of 1970's, metal oxide silicone field effect transistor (MOSFET) or also known as insulated gate field effect transistor (IG-FET) has developed new way in power supplies design. Invented to improve the switching characteristics and storage time of typical bipolar transistor, this device plays important role in the operation of high frequency SMPS. Figure 2.3 shows the typical comparison of MOSFET and other types of transistors. Compared to other transistors, MOSFET can be switched at higher switching frequency but to a limited few kilowatts power rating. Nowadays, many higher rating MOSFETs are available in the market and capable of handling voltage up to 600V and current as high as 40A with switching frequency up to megahertz range. Figure 2.3 shows the typical comparison as a benchmarking.

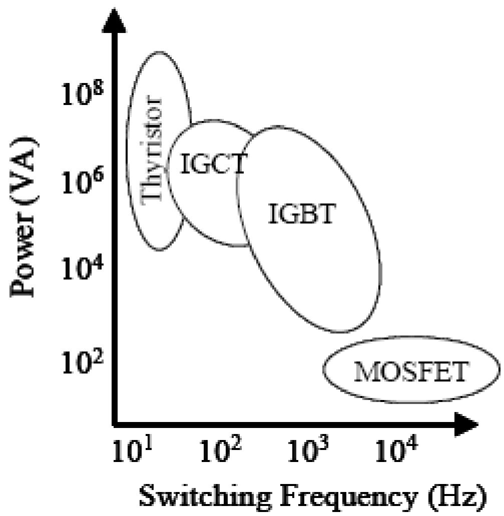


Figure 2.3 MOSFET in typical switching environment and output power rating [3].

There are two types of MOSFETs which are enhancement and depletion types. For each type, there are also two types namely N-Channel and P-Channel. Between enhancement and depletion type, similarities exist in its structure and drain current to drain-to-source voltage characteristics (output characteristics), $i_d$-$v_{ds}$ except the ability to conduct at zero gate bias [4]. Depletion MOSFET enables channel conduction at zero gate bias but not for enhancement type. Figure 2.4 shows the symbols for all types of MOSFETs. In Figure 2.4, depletion symbol differs from enhancement type in one respect: the vertical line representing the channel is solid, signifying that a physical channel exists.

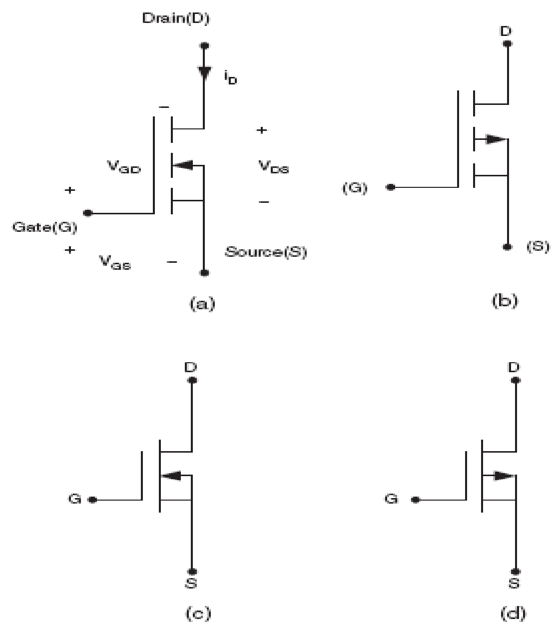


Figure 2.4 MOSFET types. (a) N-Channel enhancement type
(b) P-Channel enhancement type (c) N-Channel depletion type
(d) P-Channel depletion type

Most MOSFETs used in power electronic applications are N-Channel, enhancement type. For the enhancement MOSFET to carry drain current, a channel between the drain and the source must be created. This occurs when the gate-to-source voltage, $V_{gs}$ exceeds the device threshold voltage, $V_{th}$. For $V_{gs}>V_{th}$, the device can be either in the triode region, which is also called "constant resistance" region or in the saturation region depending on the value of drain-to-source voltage, $V_{ds}$. When $V_{gs}<V_{th}$, the device operates in the cut-off region (off-state) resulting in no induced channel. When MOSFET is used as a switching device, only saturation and cut-off region are allowed for full on-off operation. The typical value for $V_{th}$ is ±4.4V and maximum $V_{gs}$ is ±20V. Figure 2.5 shows the turn on-off sequence and switching trajectory of a practical power MOSFET[3].

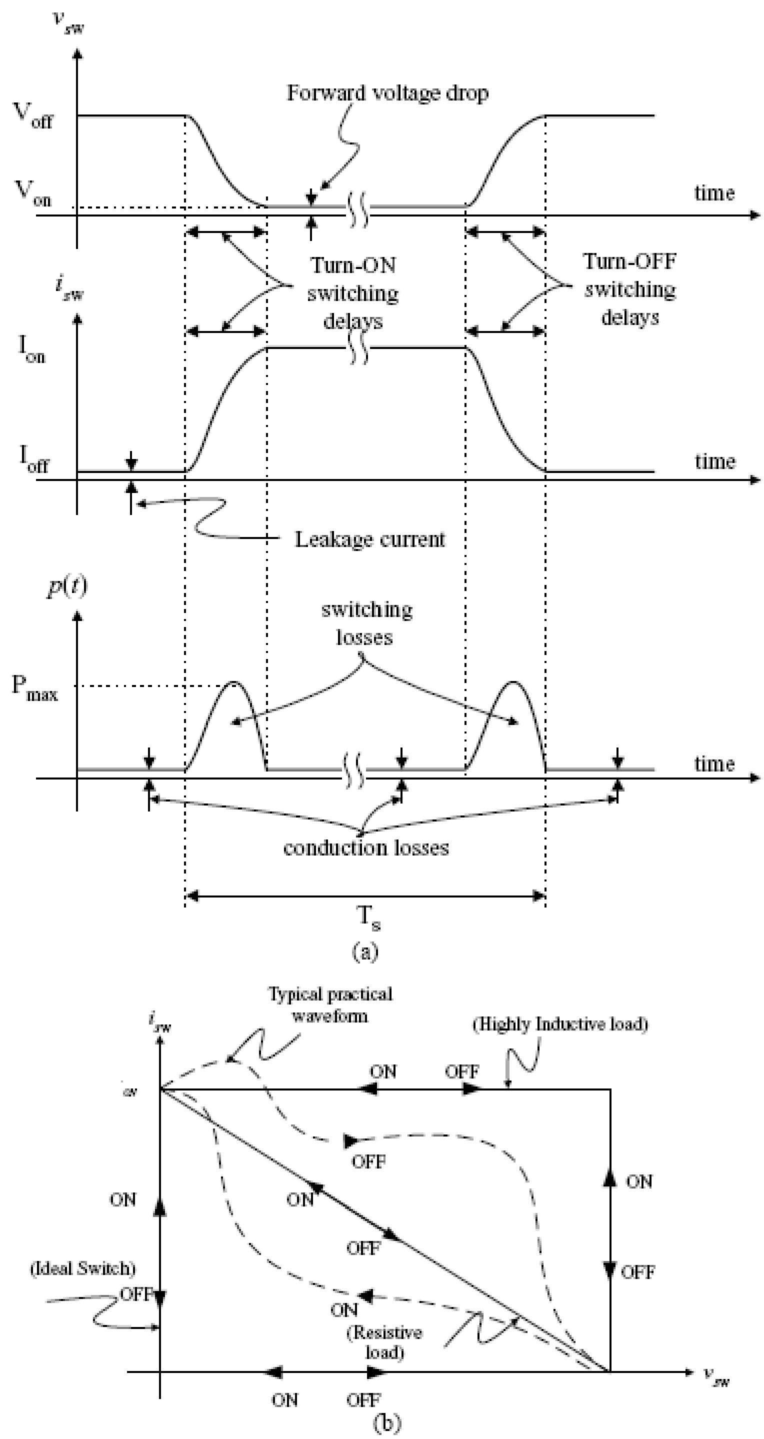


Figure 2.5 Practical MOSFET on-off sequence.
(a) switching current, voltage and power waveforms
(b) switching trajectory

The average switching power and conduction power losses can be evaluated from these waveforms. With different devices, the exact practical switching waveforms vary from each other, but Figure 2.5(a) gives a reasonably good representation. Moreover, other issues such as temperature dependence, power gain, surge capacity, and over-voltage capacity must be considered when addressing specific devices for specific applications. Figure 2.5(b) illustrates how switching takes place from on to off and vice versa and called as switching trajectory, which is simply a plot of $i_{sw}$ versus $v_{sw}$ .

Switching losses, $P_s$ is given by,

$$P_s = \frac{1}{2} \times V_{sw} \times I_{sw} \times f_{sw} \times \left(t_{on} + t_{off}\right) \tag{2.4}$$

Where $V_{sw}$ is the MOSFET drain-to-source voltage
$I_{sw}$ is the MOSFET drain current
$f_{sw}$ is the switching frequency
$t_{on}$ is the turn on delay
$t_{off}$ is the turn off delay

## 2.3 Basic Topologies in SMPS

In SMPS, basically there are two types of topologies which are non-isolated and isolated topologies. Basic topologies in the non-isolated topology are buck, boost, buck-boost and cuk converter while for isolated family, there are flyback, half-bridge, full-bridge and push-pull converter. Each topology has its own plus and minus criteria and different topology comes with different characteristic. For instance, one topology has low parts count and cost but only capable of handling limited amount of power while another has relatively higher parts count and cost but capable of handling much higher output power. But at the end, the most important parameter needs to be determined is the efficiency. Therefore, identity of each topology does not resemble the weakness of the design but it can encourage researchers to improve and redesign new converter based on the basic topology. Figure 2.6 summarized the power supply family tree.

For the time being, most commercial SMPS operate in the frequency range from 10kHz to 50kHz but trend to develop commercial converters using frequency above 100kHz is growing rapidly. Utilizing new topologies, trade off especially between cost and size is highly anticipated for a practical and efficient power supply. Figure 2.7 to 2.10 show the graphic illustration of known non-isolated and isolated SMPS [2].

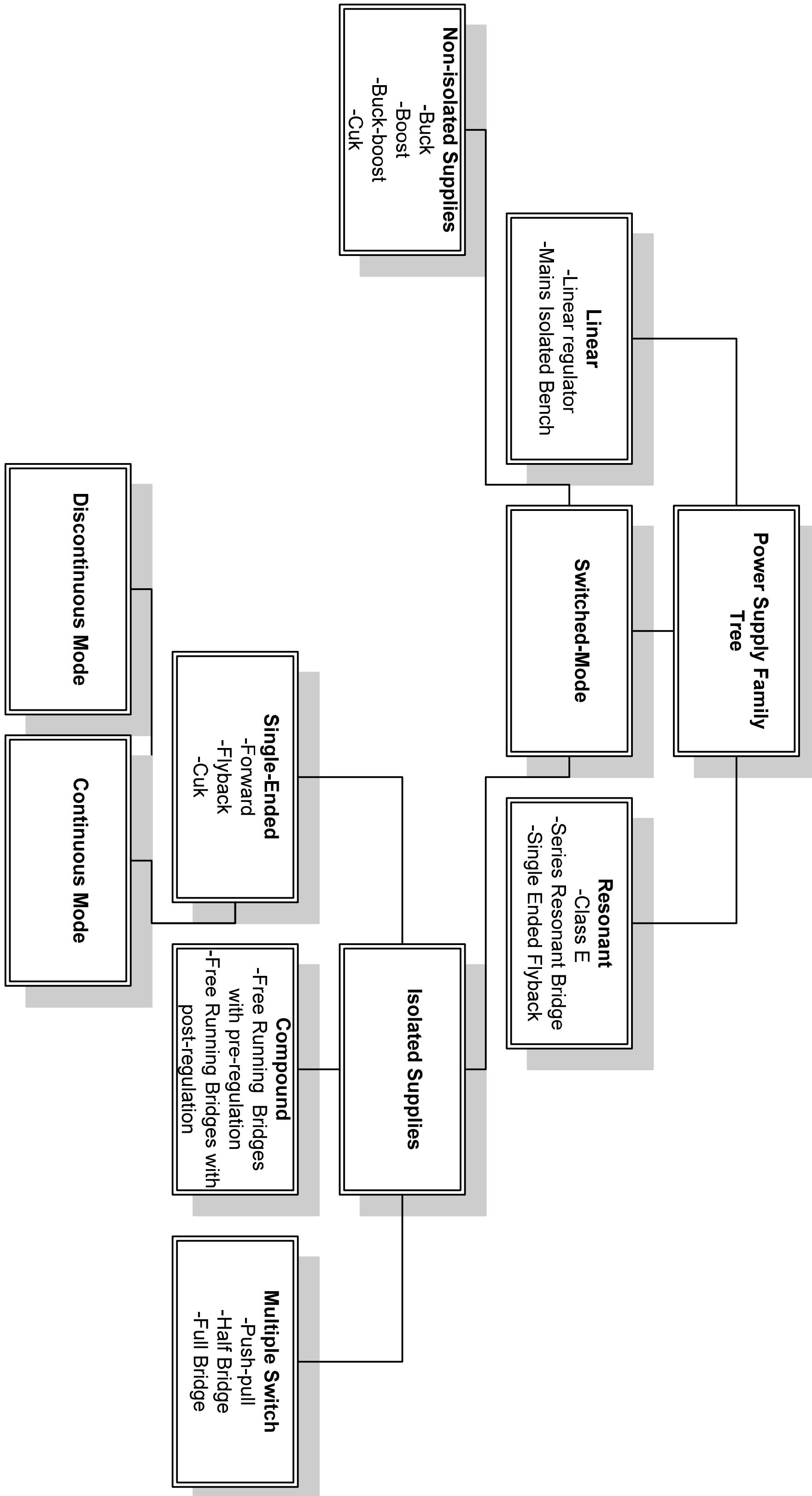


Figure 2.6 Power supply family tree.

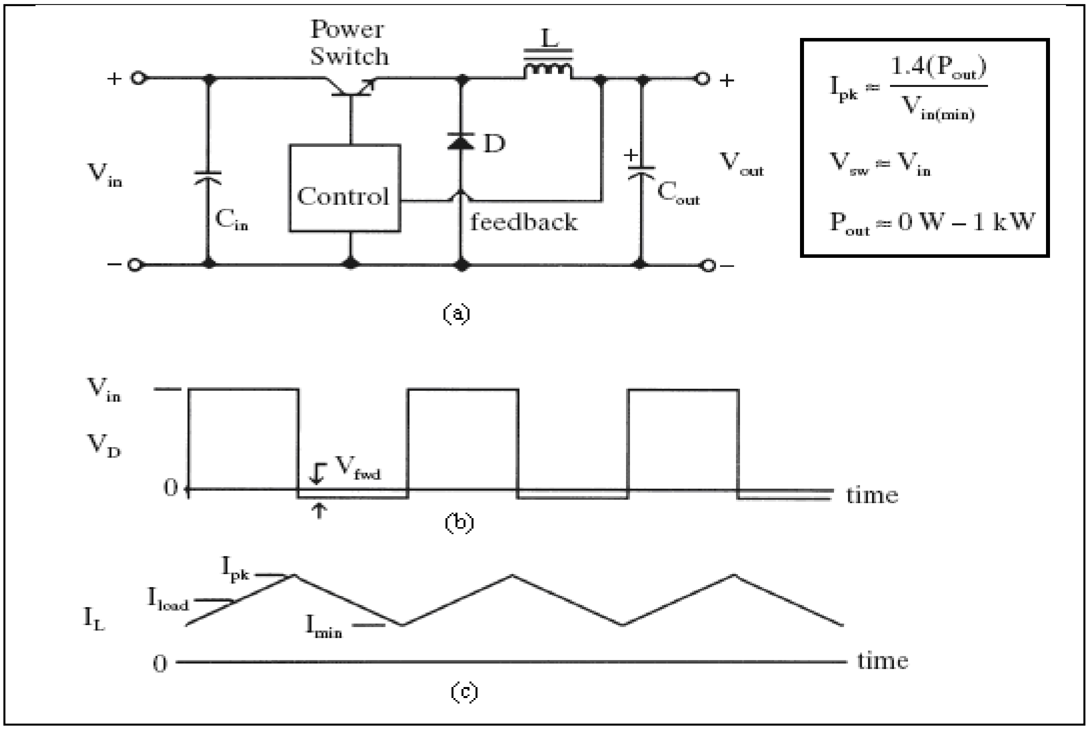


Figure 2.7 The buck (step-down) converter. (a) topology circuit (b) switched voltage waveform (c) inductor current waveform.

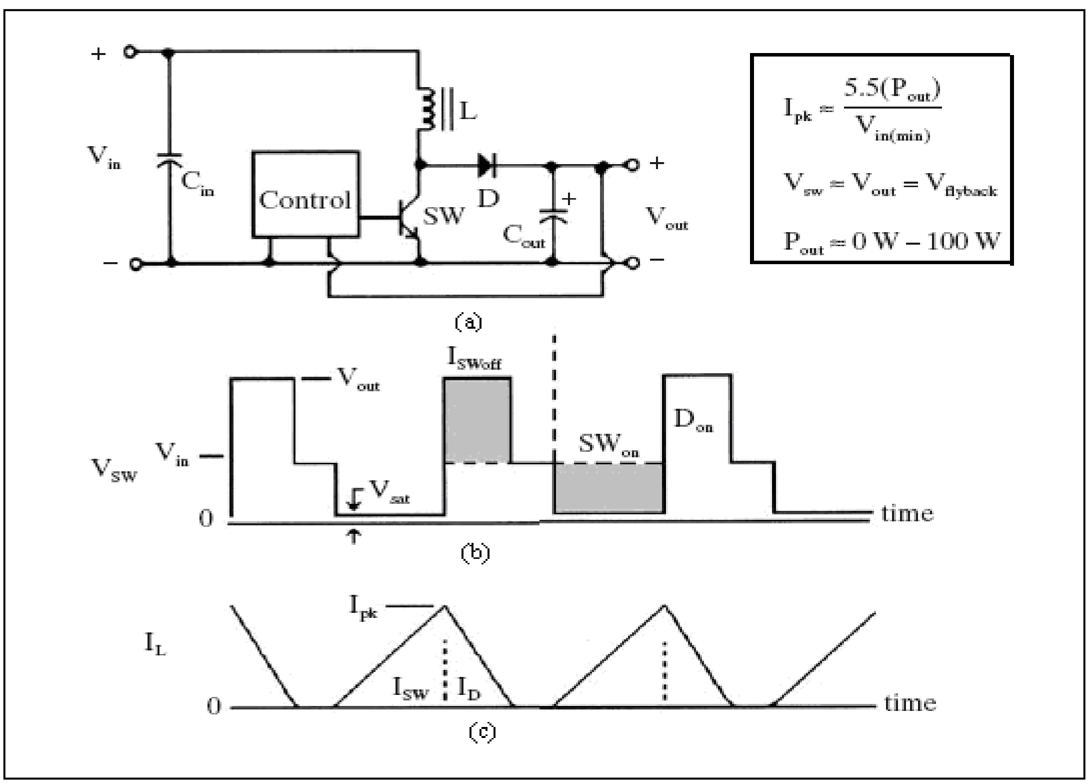


Figure 2.8 The boost (step-up) converter. (a) topology circuit (b) switched voltage waveform (c) inductor current waveform

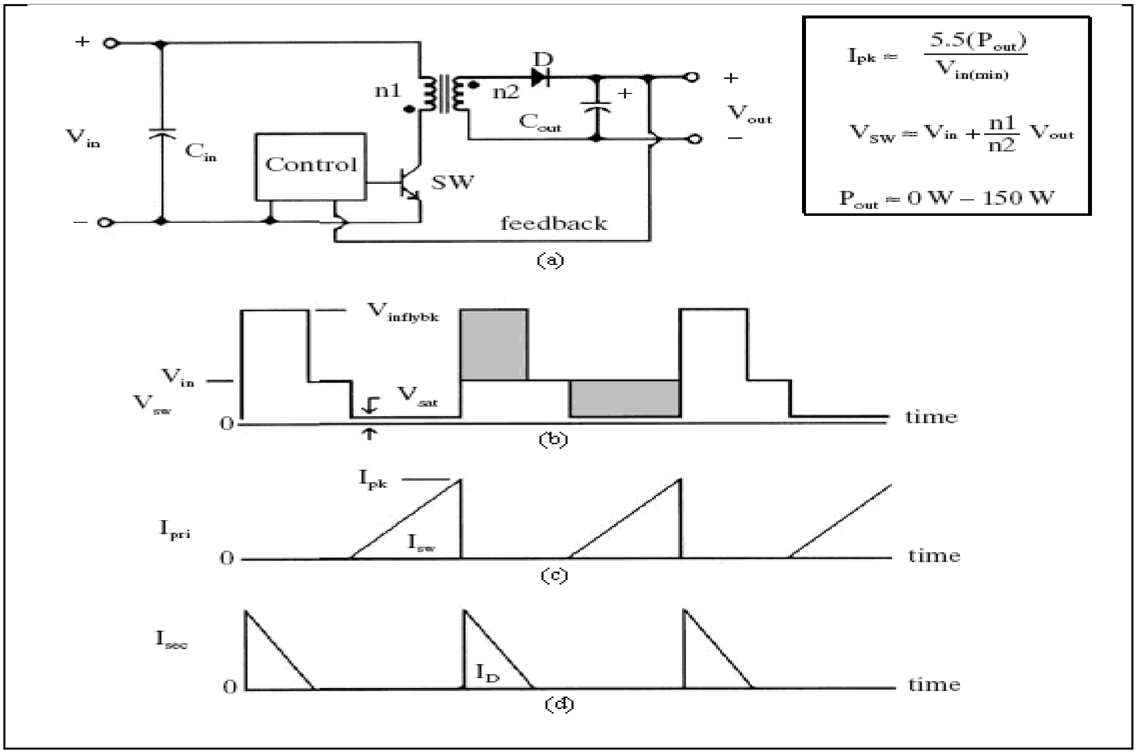


Figure 2.9 The flyback converter. (a) topology circuit (b) switched voltage waveform (c) input primary current (d) secondary output current waveform.

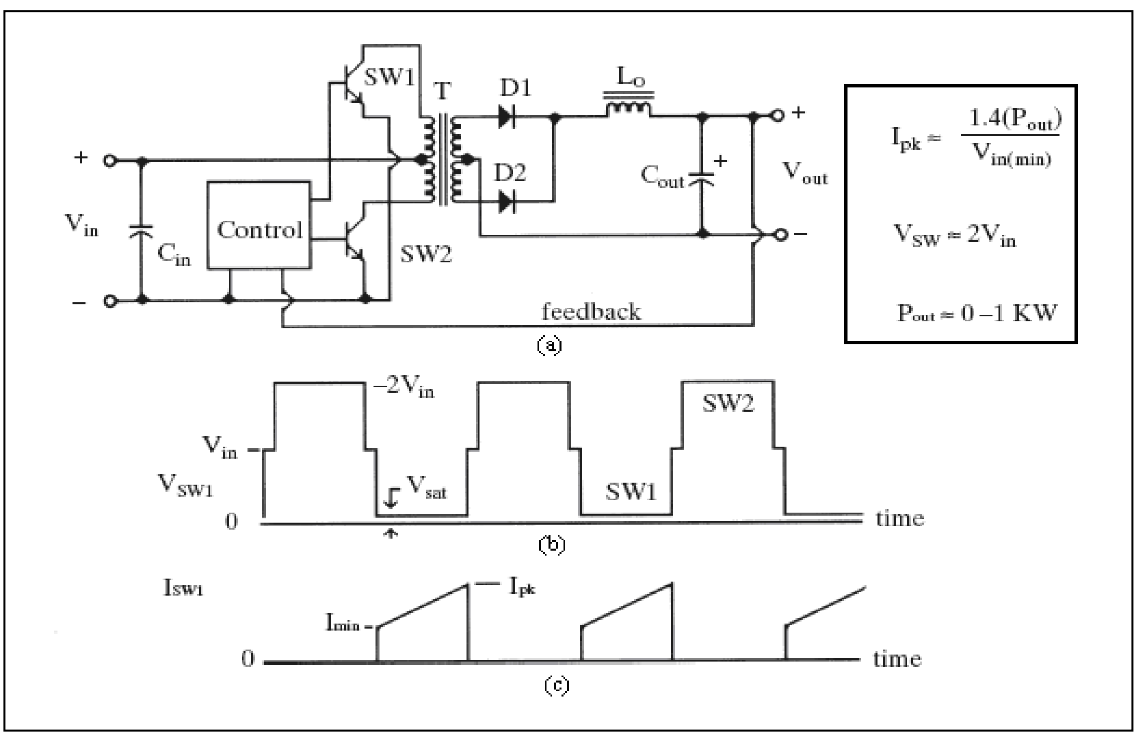


Figure 2.10 The push-pull converter. (a) topology circuit (b) switched voltage waveform (c) switched input current waveform.

Where $V_{in}$ is DC input voltage

$V_{out}$ is DC output voltage

$I_{pk}$ is maximum inductor peak current

$V_{sw}$ is MOSFET drain-to-source voltage

$P_{out}$ is typical topology power rating

## 2.4 Transformer

In DC-DC converter, transformer is the mother or heart of it. Basically, transformer is formed with several windings wound together in a core medium. It works by allowing power transfer from input to output using flux linkage. At the same time, it provides isolation between them. Negative effects such as saturation, flux imbalance and losses are the issues related to transformer design and construction. Many references [5-9] discussed a lot about designing and constructing chopper transformer. Even with the details, it is a big challenge in order to design an efficient and reliable transformer due to unseen factors such as symmetry effects, core effects and winding effects. Table 2.2 shows the comparison of core types normally used in the transformer construction. Transformer is highly recommended for topology with higher power output typically more than 1kW. But with great advantage in providing isolation safety between input-output, more and more topologies with lower power output occupy transformer in its design.

Table 2.2 Core used in chopper transformer.

| Type | Inductance values | Materials | Advantages or Disadvantages |
|---|---|---|---|
| Toroid | High | -Powdered iron<br>-Ferrite iron | -Frequency range from 5 kHz to 50 kHz.<br>-Core may be magnetic or nonmagnetic material.<br>-No physical air gap is required. |
| Pot | Adjustable to approximately ± 10% | Ferrites | -Frequency range from 50 kHz to 500kHz.<br>-Ferrite cores extend the frequency up to 20 Mhz.<br>-Minimizes magnetic coupling to adjacent components.<br>-Air gap can be provided within the body of the core to reduce losses, saturation problem and more efficient at high frequencies. |
| Fabricated | Fulfill large-inductance and high-current requirements | Soft iron stampings or molded solid of iron or ferrites | -Used at low frequencies when either large inductance values or high current requirements are involved.<br>-Shapes of both the solid and laminated-type resemble alphabetical forms such as E,I,U,F and are designated as such.<br>-Allow various air gaps throughout the core, which permit control of permeability and flux saturation [7]. |

## 2.5 Synchronous Rectification and Control Strategy

In conventional DC-DC converter, rectification process is carried out by diodes. Diode has forward drop voltage, $V_f$ typically from 0.3V to 10V. Schottky diode has the lowest drop ranging from 0.3V to 0.7V while high voltage rectifier diode has the highest drop ranging up to 10V. The problem with $V_f$ is that it generates loss. Diode loss can be computed by amount of current flows through it multiplied by the drop voltage. Therefore, the more current flows through the diode, the greater the loss is. Similarly, the higher the value of $V_f$, the higher the loss suffered by the diode. Ideally, to eliminate the loss, $V_f$ should be zero. This can be done by using MOSFET because theoretically, when MOSFET conducts at fully ON state, it will not have any forward drop voltage.

Nowadays, new design of MOSFET has very low on-resistance, $R_{ds(on)}$ value which is in the order of few milliohms. So, at fully ON state, MOSFET has only few millivolts forward drop, $V_f$. With this characteristic, MOSFET significantly reduces the rectification loss commonly suffered by the diode. In addition, MOSFET can be configured to allow bidirectional current path while diode only allows current to flow in unidirection. Added together, MOSFET offers an effective and efficient way to increase efficiency in the rectifying process. The rectifying process using MOSFETs is called synchronous rectification (SR) or switching rectification. Synchronous rectification has two main control techniques namely self-driven and external driven or control-driven technique. Figure 2.11 and Figure 2.12 show self-driven and external driven respectively.

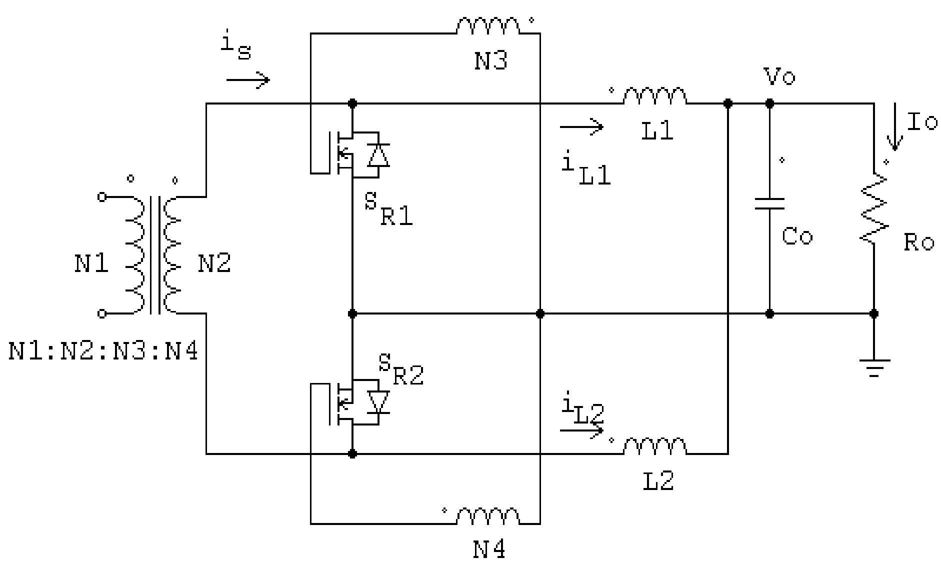


Figure 2.11 Self-driven synchronous rectification circuit [10].

In a self-driven SR, chopper transformer consists of four windings (N1, N2, N3 and N4). N1 is primary winding, N2 is secondary winding and N3, N4 are the auxiliary windings. The two auxiliary N3 and N4 windings will provide the automatic drive of the gate since no driver circuit is used to control the gate drive of the MOSFETs. N3 and N4 operate in phase shift and only let one MOSFET conduct at a time. The main problem of this technique is synchronization of the MOSFET's body diode during the on-off switching transition. During on-off transition, deadtime is needed to avoid any short circuit in both SR MOSFETs. However, the deadtime period must be adjusted to the shortest time to limit internal body diode conduction. Upon conduction, body diode generates loss and it will decrease circuit efficiency. Besides, inductance value in auxiliary winding N3 and N4 must be determined precisely to avoid insufficient gate drive voltage.

External driven SR is best used for frequency operation above 100 kHz. Using this technique, external switching IC is used to drive the SR's MOSFET. Figure 2.12 shows the external driven SR circuit. In the figure, external signals drive MOSFETs directly without any intervention with the secondary circuit. This control technique has very high gate drive accuracy. However, this technique depends on the propagation delay of the discrete IC [10]. Naturally, external gate drive has its own propagation delay which later will triggered brief overlapping of the MOSFETs gate drive and would short the secondary side. Therefore, another delay time circuit needs to be introduced within the external drive circuit to avoid the short circuit. It is very costly and complex compared to the self-driven technique.