A STUDY ON ELECTRONIC BALLAST FOR ILLUMINATION EQUIPMENT

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PREFACE

This is the thesis on the research development of the Neutral Point type converter and its application to one-stage electronic ballast for illumination equipment and can be summaries of all 6 chapters which are stated as below.

Chapter 1 addresses the total harmonic distortion (THD) issues and development around THD correction method. Harmonic distortion limit regulation, IEC 61000-3-2 and filtering methods are also presented. Problems related to electronic ballast is laid and research objectives are stated.

Chapter 2 explains the electronic ballast block structure, the main operation in common electronic ballast are rectifying (AC-DC) and inverting (DC-HF). THD filtering method and circuit is also presented. In order to satisfy Harmonic distortion strict limit, the active filtering circuit is used in the AC-DC part of the electronic ballast. Each filtering circuit is compared to get the best filtering method, the Neutral Point type converter that can be applied to the one-stage electronic ballast.

In chapter 3, the Neutral Point type boost converter, the mainstream in the Neutral point type converter is presented. This converter can be applied to the one-stage electronic ballast, making more compact compared to the two-stage electronic ballast by eliminating one switching element and a control circuit.

This chapter also presents 2 more improved version of the Neutral Point type boost converter, the improvised boost converter and the PFC inverter. Improvised boost converter enables current flow even during low voltage intake by adding two capacitors with low capacitance operating as charge-pump. PFC inverter is a miniaturized version of the Neutral Point type boost converter electronic ballast. In this circuit, the common mode filter is connected to the inverter part of this circuit, reducing circuit element by sharing the common mode capacitor with the inverter circuit's capacitor.

In chapter 4, the Neutral Point type buck-boost converter is presented to solve the inrush current from the previous Neutral Point type boost converter. The circuit disables a closed loop connection between input voltage source and the electrolytic capacitor thus reducing inrush current. The buck-boost circuit operation only allows current only from inductor flow through the electrolytic capacitor thus making the Neutral Point type converter less complicated.

In chapter 5, the application of both Neutral point type boost converter and Neutral point type buck-boost converter in form of voltage free electronic ballast is presented. It can tolerate both 200V and 100V input voltages, by switching from boost operation to buck-boost operation according to input voltage with mechanical switch. The circuit is design based on most buildings input mains fixture in Japan with 100V and 200V lines. The circuit is simple and uses less circuit elements and control unit compared to conventional voltage free equipments.

Finally in chapter 6, the conclusions of this thesis are presented. Unsolved problems and future research are also suggested.

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LIST OF ABBREVIATIONS AND TECHNICAL SYMBOLS

Symbols	Symbols definitions
λ	Power factor
η	Efficiency
W_{in}, V_{in}, I_{in}	Input power , Input voltage , Input current
W_{out}, V_{out}, I_{out}	Output power , Output voltage , Output current
V_L, V_{C2}, V_{I2}	Voltage between two points of the circuit element represented by subscript
I_{L2}, I_D, I_R,	Current flowing through circuit element represented by subscript
Va , Ia	High frequency voltage , High frequency current
V_{DC}, V_{dc}, V_{dd}	Direct current voltage , Drive voltage
E, E_{CS}	Direct current voltage source
S, Q, S_1, S_2, Q_1, Q_2	Switching elements
T_{ON}	Time period when switching element is turned ON
T_{OFF}	Time period when switching element is turned OFF
t_{on}	Time period of current flowing through inductor during switching element is turned ON
t_{off}	Time period of current flowing through inductor during switching element is turned OFF
R, R_1, R_2	Resistor or resistance
L, L_1,L_2	Inductor or inductance
C, C_1, C_2	Capacitor or capacitance

LIST OF TECHNICAL SYMBOL

Symbol	Symbol definition
C_s	Smoothing condenser, electrolytic capacitor or capacitance
C_r	Resonating capacitor or capacitance
C_c	Coupling capacitor or capacitance
D, D_1, D_2	Diode
T, T_1, T_2	Transformer
ω	Angular frequency
fs	Switching frequency
LAMP	Fluorescent lamp
PFC	Power Factor Correction
CMF	Common Mode Filter
NMF	Normal Mode Filter

CHAPTER 1 Introduction

1.1 Total Harmonic Distortion

In the coming of the solid-state electronic revolution today, we have an environment rich in nonlinear loads, such as UPS equipment, computers, variable-speed drives, and electronic fluorescent lighting ballasts. Operation of these devices represents a double-edged sword. Although they provide greater efficiency, they can also cause serious consequences to power distribution systems in the form of harmonic distortion. So far, electronics equipment designer's focus is about the size of the power devices consumption but "consumption power waveform condition" is usually neglected [1]. In recent years, the waveform distortions in power electronics have been found to be the significant factors leading to equipment failure and accidents [1][2]. The inconsistent quality of power supplied from the power system, which could cause failure to a variety of equipment when power system quality doesn't match the electric power equipment quality demand. In contrary, to maintain the quality from the power supply side could also interfere with load operations from the demand side through the interface devices. For example, supply current waveform distortion causes overheating to building's sub-station equipment which also causes electronic equipment to fail [3][4].

Total Harmonic Distortion (THD) is also known as waveform distortion. A distorted waveform is made up of the main sinusoidal wave (called the fundamental) and one or more harmonic wave. A harmonic wave has a frequency that is an integer multiple of the fundamental. For example, a distorted 60Hz current wave might contain harmonic at 120Hz (called a second-order harmonic), 180Hz (third-order harmonic) and other multiple of 60Hz. Clean sinusoidal waveforms contain no harmonic distortion [5][6].

1.1.1 Sources

Normal Japanese household power (commercial power line) is in the 100V alternate current voltage and in a sinusoidal waveform. If a linear load equipment, for example, heating wire is connected to the power source, the electric current which flows through is a sinusoidal waveform. But actually when electronic equipments which contain semiconductor devices are connected, the electric current which flows through are often a non-sinusoidal current waveform. A simple example is shown in Figure 1.1. If the power source is connected to a capacitor input type rectifier circuit, the current wave-form resembles a pulse current flowing near the voltage peak, containing high THD content [3] [6].

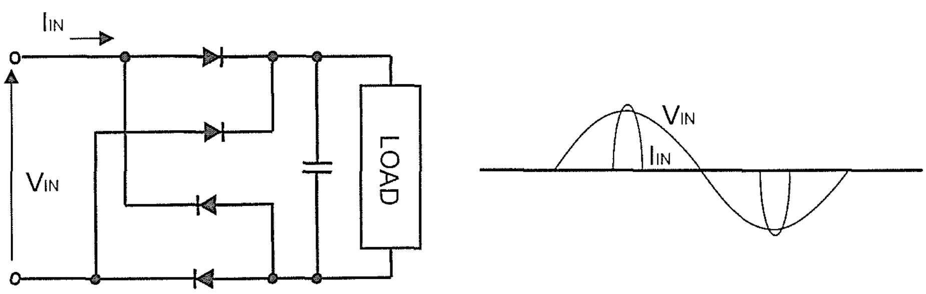

Figure 1.1: Condenser input rectification circuit

Circuit in Figure 1.2 is an example of input current waveform with high THD content. This circuit uses thyristors used in dimmer control circuit and electronic ballast for fluorescent lamps. The thyristor control's current flow through period, current flows during thyristor is turned ON, but no current flows during turn OFF. The high frequency switching of ON and OFF generates harmonics distortion [3] [6].

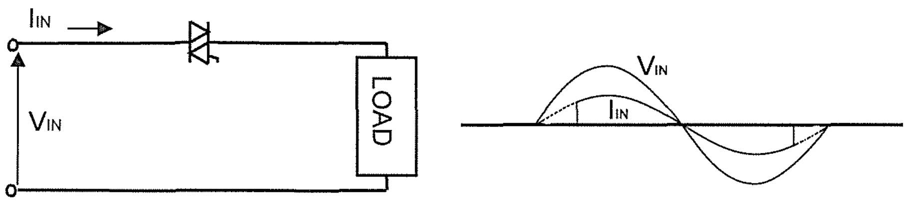

Figure 1.2: Thylistor phase control circuit

1.1.2 Effects

The total harmonic distortion doesn't cause problems if it's generated by a single device. However, if more devices were to generate total harmonic distortion, serious problems occur during power transmission. Both current and voltage should be sinusoidal. Any distortion of the current wave shape distorts the voltage in the electrical distributing system thus reducing power factor. Distorted current could also interfere with operation of electronic equipment (both nearby and remote), causes improper operation of grid protective devices (fuses, circuit breakers and relays), interfere with nearby communication circuit and overheat motors, transformers, capacitors and neutral conductors [4].

1.1.3 Containment Regulations

The IEC-61000-3-2 is a regulation standard to prevent damage caused by total harmonic distortion set by the International Electrotechnical Commission (IEC). This regulation applies to all electrical equipment that has an input current up to 16A per phase, suitable for connection to the low-voltage AC public mains distribution network. A public mains low-voltage distribution network exists if more than one independent consumer can draw power from it. The flow chart in Figure 1.3 is intended as a guideline for the application of IEC-61000-3-2. Based on the application specific conditions it will determine if the standard is applicable or not. Our research on lighting equipments fall into class C category. In this category, each harmonic order has the percentage limit based on the fundamental waveform as shown in Table 1.1 [3].

Table 1.1: Harmonics limit for each Class

Harmonic order (odd)	Class A limit (A)	Class B limit (A)	Class C percentage limit (from fundamental) (%)	Class D percentage limit (mA/W)	Class D limit (A)
1	-	-	-	-	-
3	2.30	3.45	30×power factor	3.4	2.30
5	1.14	1.71	10	1.9	1.14
7	0.77	1.155	7	1.0	0.77
9	0.40	0.60	5	0.50	0.40
11	0.33	0.495	3	0.35	0.33
13	0.21	0.315	3	0.30	0.21
$13 < n < 39$	2.25/n	3.375/n	3	3.85/n	2.25/n

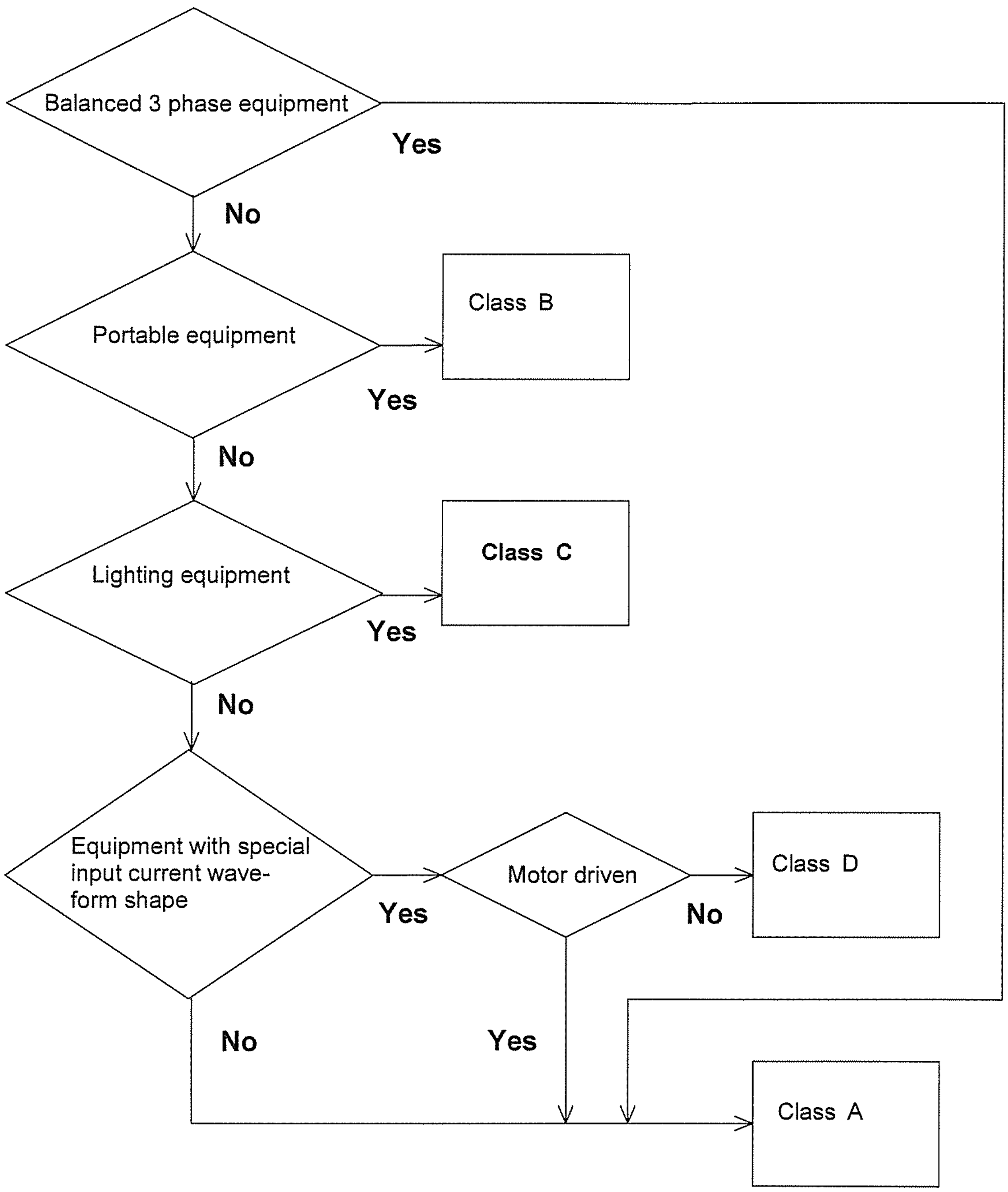

Figure 1.3: Guideline flowchart harmonics limit for each of electronic equipments.

1.2 Total Harmonic Distortion reduction method

In general, most power source for electrical equipment (load) that requires high frequency voltage input is shown in Figure 1.4 [7]. The noise filter circuit prevents noise leakage emitted by AC-DC rectification circuit or DC-HF inverter circuit into power source mains. The AC-DC rectification circuit can be in many kind of circuit form, from the condenser input rectification to a much simpler full bridge rectification circuit. DC-HF conversion circuit converts the AC-DC converter's circuit output, (in direct current) into high frequency for the load. Resonant circuit coordinates the DC-HF circuit operating conditions with the voltage or current condition required by the load. Normally, the AC-DC converter is design to filter out harmonic distortion. Filtering harmonic includes;

(1) Filtering THD in the circuit system

(2) Not emitting harmonic distortion.

In the AC-DC converter design, a choke coil is used to filter out harmonics. As shown in Figure 1.5 condenser input rectification circuit, the choke coil suppresses current peak. Power lost is at minimum and it is simple circuit configuration, but makes the circuit heavier and reducing input voltage range [7].

Another important aspect in harmonic filtering is that the circuit does not emit harmonic distortion. Figure 1.6 shows the boost chopper active rectification circuit. The circuit controls the input current of the load so that the current waveform is proportional to the mains voltage waveform (a sine wave). But the disadvantages of this circuit are circuit configuration complexity and cost related problems [8].

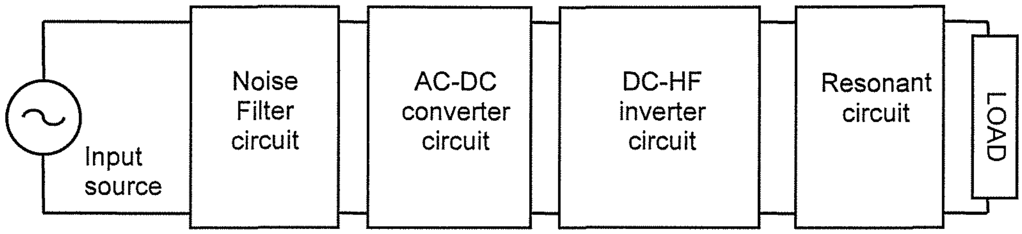

Figure 1.4: Block diagram of typical electronic equipment

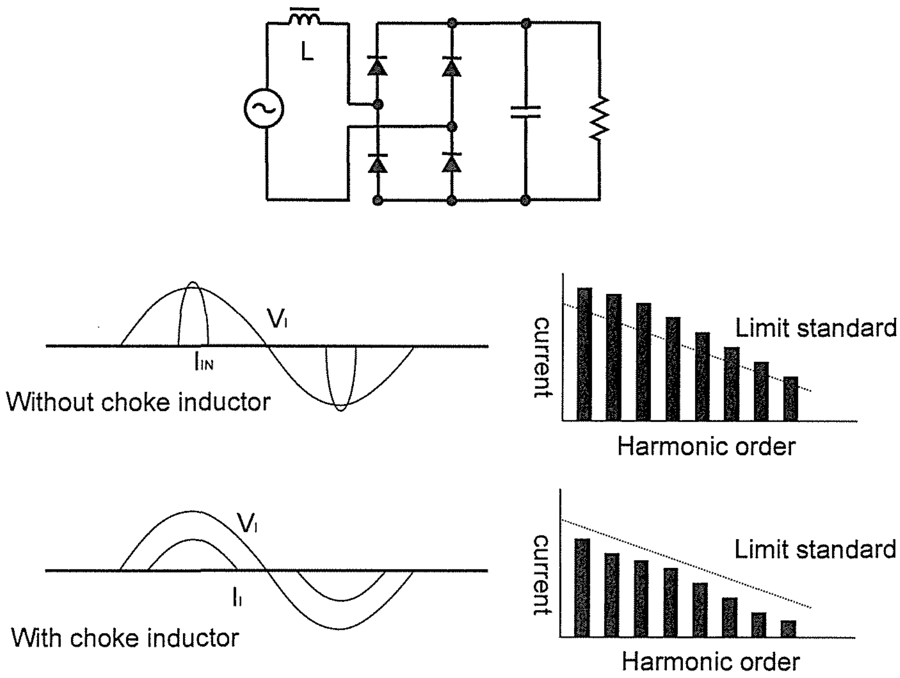

Figure 1.5: Choke inductor in condenser input rectification circuit

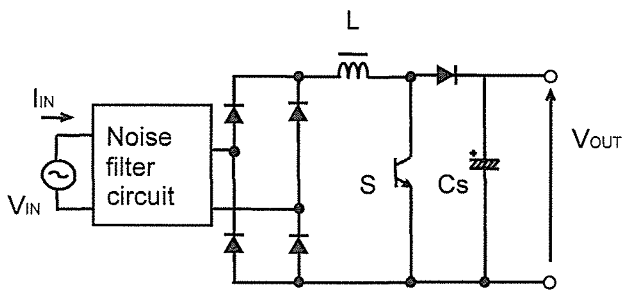

Figure 1.6: Boost chopper active rectification circuit

1.2.1 Two-converter to one-converter circuit method.

The active filtering smoothing circuit filters out harmonic distortion from input current mains and preventing from harmonic distortion back into voltage mains line. IEC also sets very strict guideline for illumination equipment under class C to prevent damage caused by THD. Illumination equipment which utilizes the active filtering method introduced previously is developed. Active filtering is inserted in parallel to the inverter on a inverter type electronic ballast thus the name two converter circuit method electronic ballast [9]. Figure 1.7 shows an example of a two-converter electronic ballast, the boost chopper circuit is connected to the inverter circuit in cascade. Switching element S1 operates in high frequency and current flowing through inductor L1 in a serrate pattern. Noise filter connected to input mains filters out high frequency component of inductor L1 current thus, input current has low THD and attains sinusoidal waveform. The input current satisfies IEC 61000-3-2 class C regulations for illumination equipment for THD limit.

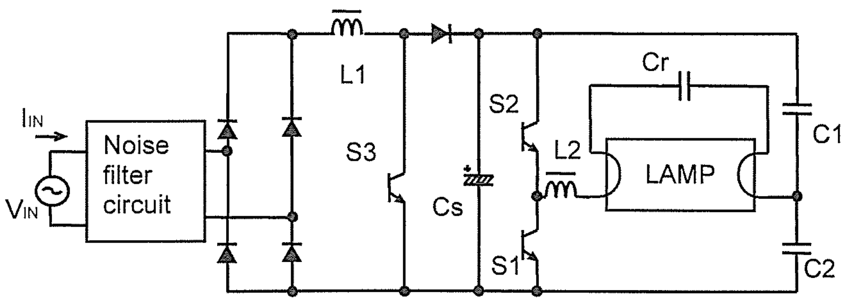

Figure 1.7: Boost chopper active filtering electronic ballast (two-converter circuit method)

The two-converter circuit method has problems related to efficiency, has many circuit component and high cost [10]. Recent electronic ballast uses the same switching element for AC-DC rectification circuit and DC-HF inverter and known as the one-converter electronic ballast [11]. Figure 1.8 shows the boost chopper circuit and inverter circuit shares one switching element, the one-converter circuit method electronic ballast. In comparison to circuit in Figure 1.7, one switching element with its control unit circuit has been reduced. There are many kinds of AC-DC rectification method, which opens more possibility and development for the one-converter method which many had proposed. The circuit method can reduce the cost of electronic ballast but doesn't improve circuit efficiency.

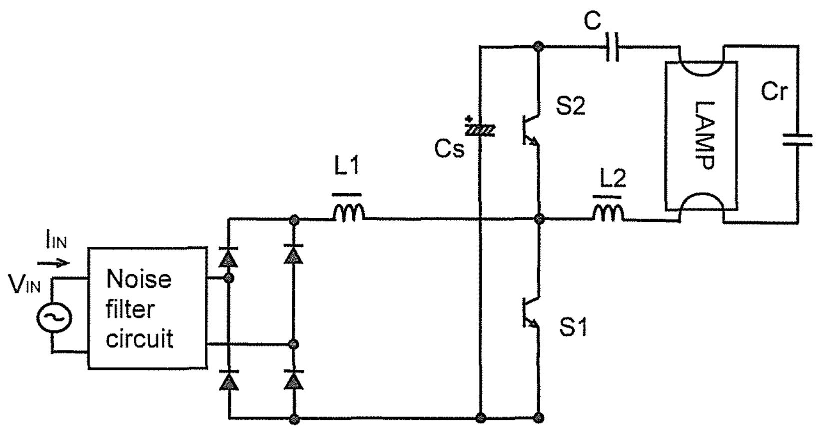

Figure 1.8: Boost chopper active filtering electronic ballast (one-converter circuit method)

1.3 Research Objective

Artificial lighting represents a major component of energy consumption, accounting for a significant part of all energy consumed worldwide. Proper lighting can enhance task performance or aesthetics, while there can be energy wastage and adverse health effects of poorly designed lighting. Resent development in illumination engineering, highly focusing on development in LED lighting due to low energy consumption and high power factor. But until now, luminance per cost for LED is still high [12]. Fluorescent lamp is still the mainstream as lighting equipment and can have high efficiency if driven by good ballast. This research is about electronic ballast for illumination equipment and the focused objective is stated as below

(1) Produce and improve high efficiency rectifier circuits

Electronic ballast usually has higher power factor than magnetic ballast as well as eliminate flickering due to high frequency operation. Power factor more than 90% and above is considered as high power factor [1][13]. Electronic ballast can be divided into 2 main blocks that is the inverter circuit and the converter circuit. Inverter circuit operates in high frequency and because of that, it is might distort the input current of the electronic ballast. It is crucial for the converter (or rectifier) part of the circuit to filter out harmonics distortion.

(2) Produce a electronic ballast that uses less electronic component by applying the one-converter type electronic ballast

Previously developed two-stage electronic ballast has two differential task circuit which is the active filter circuit; converts AC to DC in high frequency and the inverter circuit which converts the DC back to AC for fluorescent lamp. Two sets of switching elements with control circuit are used to drive both circuits separately. The one-stage electronic ballast converter uses only one set of switching elements with control circuit by using the same switching elements for both AC to DC and DC to AC circuit operation [7][14][15].

(3) Eliminate inrush current

Inrush current can affect electrical component such as tripping circuit breakers and fuses. During start-up, momentary contact bouncing in switches may cause the contact to be pitted due to arching between contact points. The surge can also cause serious damage, such as welding switch contact together [2]. Electronic ballast proposed in chapter 4 in this thesis achieved to reduce inrush current.

(4) Produce 200V and 100V voltage tolerable one-stage electronic ballast based on the Neutral Point type converters

The voltage free electronic ballast that can tolerate input voltages from 100V to 242V adapts the two-stage electronic ballast method with separate sets of control circuit for switching elements both for the converter and inverter circuits. In chapter 5, the Neutral Point type Voltage free converter that can tolerate both 100V and 200V as in most buildings in Japan accommodates 100V and 200V mains are proposed and discussed [16]. The circuit has a simple system and uses less circuit elements and control unit circuits. It can convert from boost operation to buck-boost by only switching ON and OFF with the mechanical switch.

CHAPTER 2 Total Harmonic Distortion (THD) filtering technique for Electronic Ballast

Active filtering method protects input mains and also maintains the input current in sinusoidal waveform by filtering out noise caused by high frequency switching operations. IEC 61000-3-2 class C regulation for input current harmonic content is a very strict regulation for illumination equipments [1][3][4]. In order to satisfy the strict regulation, electronic ballast that applies the active filtering method is developed. In the chapter, various types of Total Harmonic Distortion (THD) filtering is discussed and comparison is made among each filtering method to accomplish the best method in terms of cost, circuit complexity, circuit control, power factor and other aspects. The Neutral Point type converter system is also briefly introduced and this circuit system is the backbone of other circuit system that would be introduced in other chapters in this thesis.

2.1 Electronic Ballast for Fluorescent Lamp

Electronic ballast is a device with definition stated below;

1) Start's and run the lamp
2) Intended to limit the amount of current to an appropriate level for the lamp

Starting from 1978, electronic ballast was commonly used for illumination device in Japan [1]. From the same year, electronic ballast also is used for household purpose but in terms of cost, it was more expensive compared to magnetic ballast. The electronic ballast has several advantages;

1) Lamp using electronic ballast doesn't flick and has high luminance
2) Easy light modulation/dimming
3) Compact and light-weighted

With resent advancement in semiconductor and inverter technology, it is now possible to increase ballast efficiency and to reduce production cost. Figure 2.1 shows the block structure of the electronic ballast. Common electronic ballast consist of filters to filter out component caused by high frequency switching, rectifier circuit to convert alternate current from mains input to direct current, high frequency conversion circuit to increase frequency, and lamp circuit to run and control the lamp. Electronic ballast Maker Company produces electronic ballast with various power factors' efficiency, depending on circuit configuration [17]. For example, Figure 2.2 shows the household use electronic ballast for a 30W fluorescent lamp and Figure 2.3 shows the high efficiency electronic ballast.

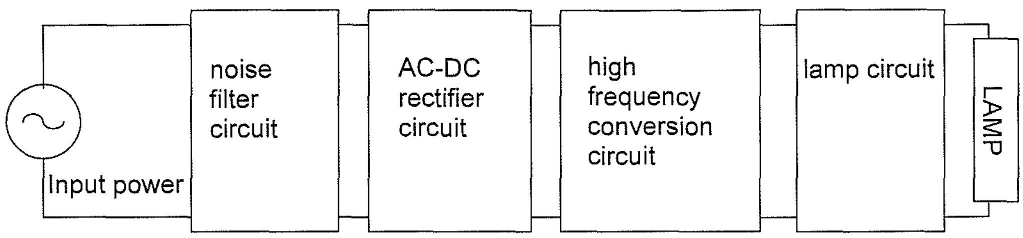

Figure 2.1: Block structure of the Electronic ballast

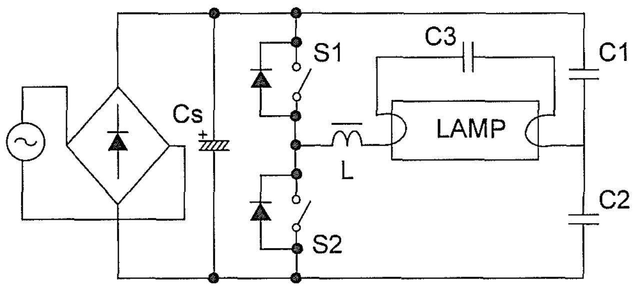

Figure 2.2: Household low efficiency electronic ballast

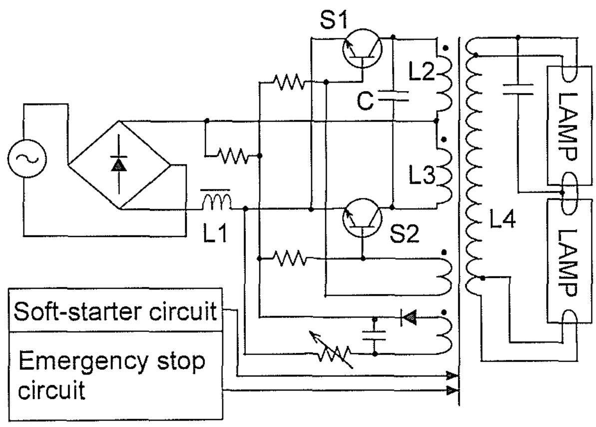

Figure 2.3: High efficiency electronic ballast

2.1.1 Rectification Method

To achieve high efficiency electronic ballast, it is important to increase the rectifier circuit efficiency, feeding low ripple direct current voltage to the inverter. Figure 2.4 shows the rectification method with each input voltage and input current waveform. The rectification methods are condenser input rectification, active rectification and partial smoothing rectification. The common household electronic ballast implies the condenser input rectification method shown in Figure 2.4(a) in its rectifier circuit part of the electronic ballast. In this rectification method, current only flows during input voltage is higher than the reservoir condenser's voltage creating a pulse current waveform, with 60% or lower power factor [18]. Electronic ballast used in offices or buildings implies the active rectification method shown in Figure 2.4(b) in its rectifier circuit part of the electronic ballast. The circuit operates in high frequency, and so filter is needed in the input voltage line but the inductance and capacitance value are small thus circuit miniaturization can be achieve. This rectification method has the highest power factor and THD reduction method, but has circuit complication and cost disadvantages [17][19][20]. As to maintain a relatively high power factor with reduced circuit cost, the partial smoothing rectification method shown in Figure 2.4(c) is proposed [19][21]. This method has the same problematic aspect as the condenser input rectification where, input current only flows through the circuit when input voltage is higher than V_{dc}, but V_{dc} voltage can be set lower so that more current can flow through the circuit. Normally, V_{dc} voltage is set to half of the input voltage and up to 85% or more power factor can be achieved [17][19][20].

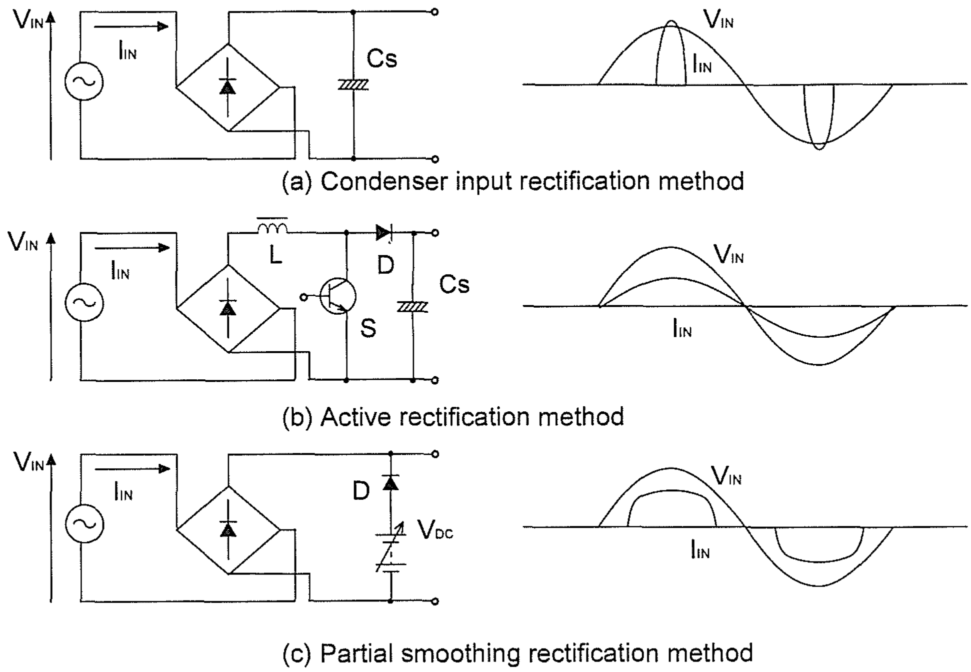

Figure 2.4: Rectification methods for Electronic ballast

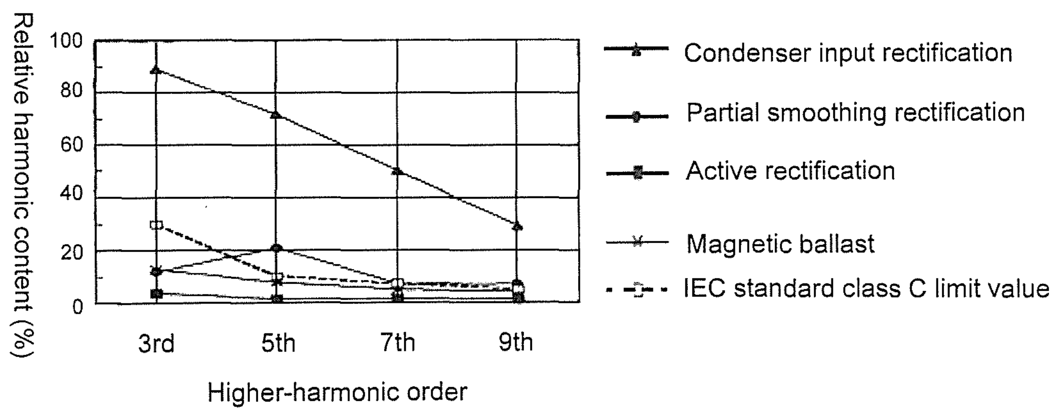

Figure 2.5: Relationship of each rectification method with Harmonic Distortion of input current

2.1.2 Inverting Method

Figure 2.6 shows the lamp or oscillator circuits which run and control the lamp also known as an inverter circuit. Figure 2.6(a) is the single switch inverter first introduced in America on 1978 [2]. Figure 2.6(b) shows the current fed push-pull inverter circuit. Figure 2.6(c) and figure 2.6(d) shows the current ideal form of inverter circuit and used in most electronic ballast. Throughout the years, the inverter method is increasingly used in illumination equipments.

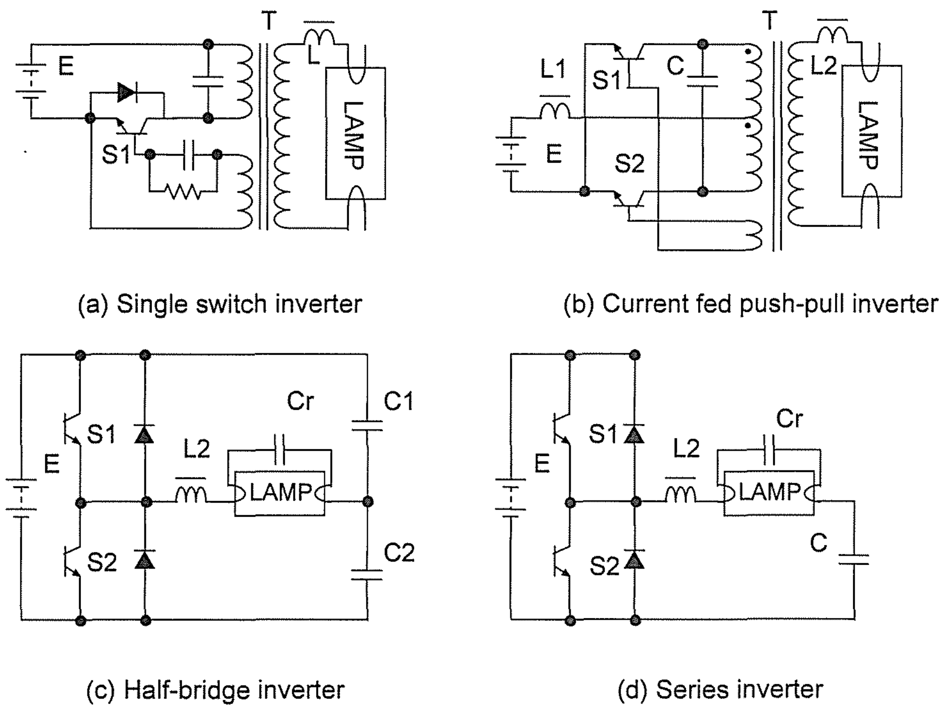

Figure 2.6: Inverting methods

2.1.3 Fluorescent Lamp

Fluorescent lamps are a type of gas discharge tube. Pair of electrodes at each end is sealed along with a drop of mercury and some inert gas at very low pressure inside a glass tube. The inside of the tube is coated with a phosphor which produces visible light when excited with ultra-violet radiation. The electrodes are in form of filaments which for preheat and rapid or warm start fixtures are heated during the starting process to decrease the voltage requirements and remain hot during normal operation as a result of the gas discharge (bombardment by positive ions). When the lamp is off, the mercury/gas mixture is non-conductive. When power is first applied, a high voltage is needed to initiate the discharge. However, once this takes place, a much lower voltage is needed to maintain it. The current passing through the low pressure gasses emits UV. The gas discharges radiation is almost entirely mercury radiation, although gas mixture is mostly inert gas (nearly 1% of mercury). The internal phosphor coating very efficiently converts most of the UV to visible light. The mix of phosphor(s) is used to tailor the light spectrum to the intended application. Thus, there are cool white, warm white, colored, and black light fluorescent lamp (long wave UV) lamps. Fluorescent lamps are about 2 to 4 times as efficient as incandescent lamps at producing light at the wavelengths that are useful to humans. Thus they run cooler for the same effective light output. The bulb themselves also last longer, 10000 to 20000 hours compared to 1000 hours for a typical incandescent bulb. However, for certain types of ballast, this is only possible if the fluorescent lamp is left on for long periods of time without frequent ON-OFF cycles. Figure 2.7 shows the fluorescent lamp used in this research, the FLR36T6W by NIPPO

ELECTRIC CO. The lamps luminance is 1500(lm) (when lamps current is 200mA) and the intended price by the manufacture is 1700 yen (from 2006 catalog). Electrical characteristic of the lamp based on manufacturers recommended ballast circuit is shown in Table 2.1.

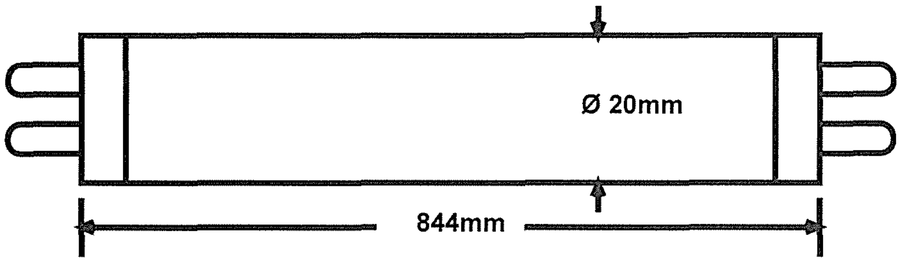

Figure 2.7: Diagram of FLR 36T6W manufactured by NIPPO ELECTRIC CO

Table 2.1: Electrical characteristics of the FLR36T6W fluorescent lamp

	Electronic ballast (LAH2-11ESC-T)	Magnetic ballast (AB-115 and AB-116)
Input Current (A)	0.26	0.25
Input Power (W)	25	23
Lamp Power (W)	19	15

2.2 Total Harmonic Distortion Filtering Methods and Circuits

The main concept structure of the electronic ballast as shown in Figure 2.1, but in circuit function perspective, the electronic ballast can be divided into 2 parts, that is the [DC voltage source] and the [inverter circuit]. Flow chart in Figure 2.7 shows the classification of THD reduction circuit methods. It can be divided into 3 categories, passive filtering, active filtering (semiconductor switching elements is used) partial smoothing [8]. From the topic of active filtering, it is further divided into 3 categories, the chopper circuit where energy is stored and released through the inductor in high frequency switching operation, charge-pump circuit where energy is stored and released through low capacitance capacitor in high frequency switching operation and charge-pump chopper hybrid circuit where both inductors and capacitors are used to store and release energy in high frequency switching operation [22][23]. The chopper circuit method is divided in two that is the standalone method where separate switching elements are used for the converter and inverter circuit and the combined chopper circuit where a switching element is shared by both converter and inverter circuit [24][25]. Energy from input mains current is stored in inductor and released as counter-electromotive force, charging the smoothing capacitor into load. This circuit operation is repeated by turning ON and OFF switching elements to control current path.

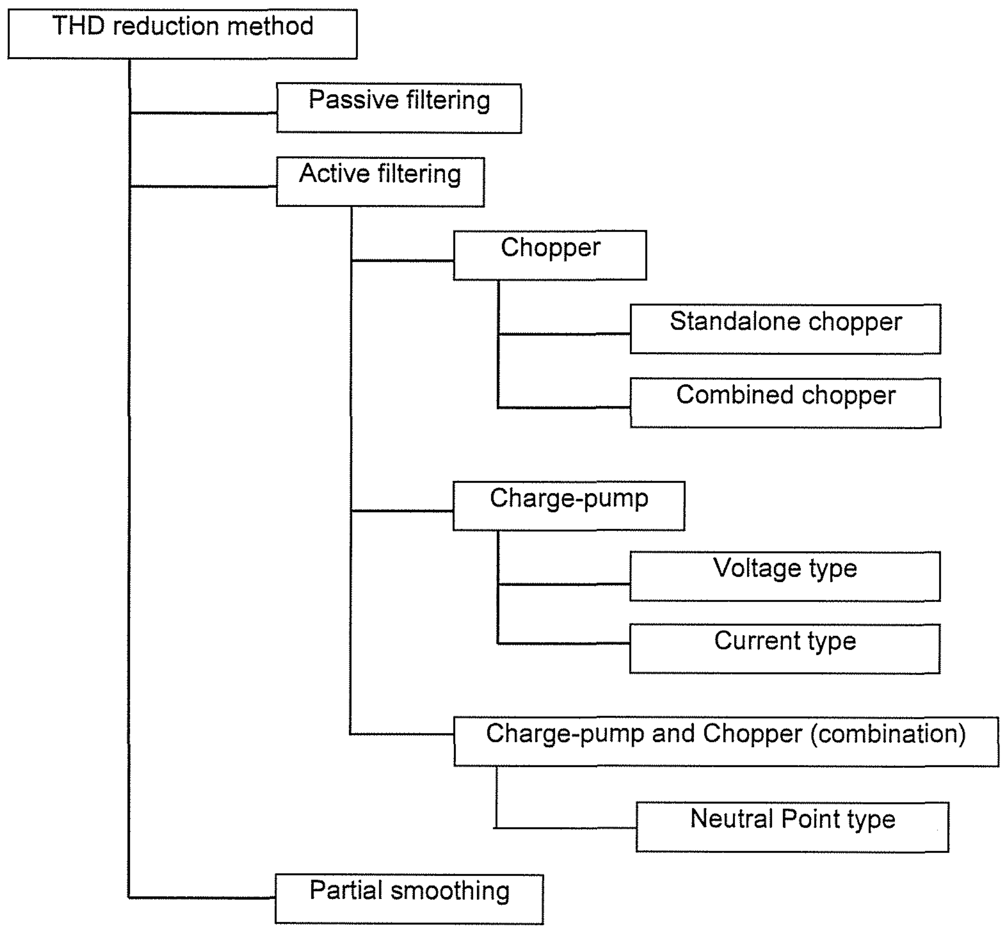

Figure 2.8: THD reduction circuit method classification flow chart

2.2.1 Passive Filtering

As shown in Figure 2.8, electric current from mains passes through the LC passive filter before rectification circuit. Before entering the rectification circuit, THD is filtered out by LC passive filter and to satisfy the THD regulation standard, the choke coil must be in high inductance. For example, a 40W x 2 electronic ballast requires around 30VA value inductance. This eliminates the merit of electronic ballast as being lightweight and in terms of cost, it's more expensive compared to other methods.

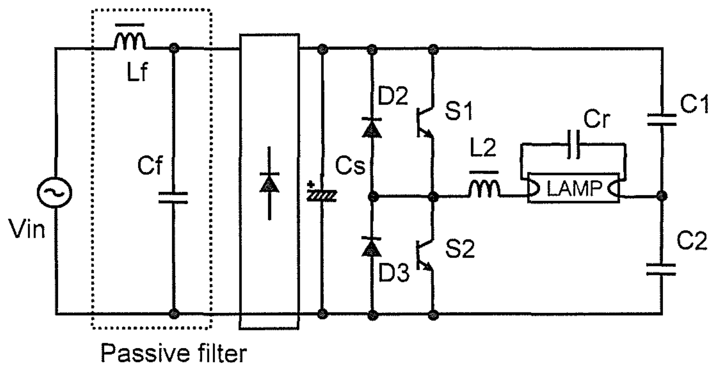

Figure 2.9: LC passive filter circuit

2.2.2 Partial Smoothing or filtering

As discussed previously, the partial smoothing electronic ballast doesn't satisfy the class C regulation [19][21]. To satisfy the class C regulation, improvements have been made for the circuit as shown in Figure 2.9. In this circuit, the charge pump method is inserted at the DC input part of the circuit. The charge pump method enables current flow during low voltage period, thus reducing THD. It is also called the high frequency waveform correction charge-pump circuit method as the circuit connects directly to the inverter circuit.

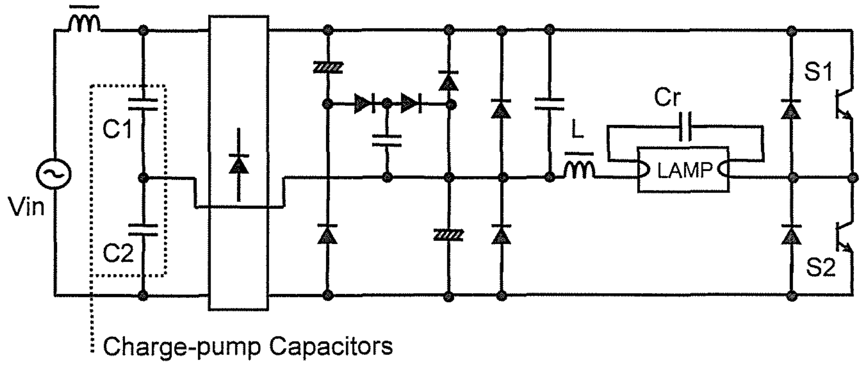

Figure 2.10: Partial smoothing

2.2.3 Active filtering

The active filter concept uses power electronics (transistors, IC) to produce harmonic component which cancel the harmonic component from nonlinear loads. As electric source equipment, this method improves the input current waveform thus increasing the efficiency of the circuit. In illumination equipment, the circuit is connected to the inverter circuit and many type of active filtering method is proposed.

(1) Standalone Chopper circuit

The standalone chopper circuit has two control unit circuits for switching elements each for the converter part and the inverter part of the circuit. Constant voltage output of the converter part can be achieved by controlling the duty-cycle of the switching elements.

The circuit requires more circuit elements which lead to high cost and the cascade connection of the converter output with inverter output increases circuit inefficiency [26][27].

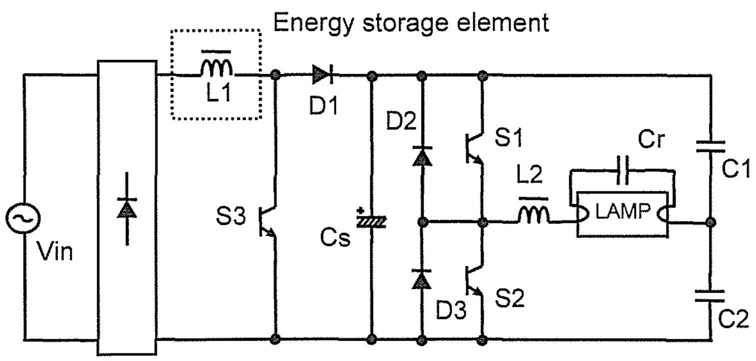

Figure 2.11: Standalone chopper circuit

(2) Combined Chopper Circuit

The combined chopper circuit uses one switching element for converter and inverter part of the circuit thus reducing circuit elements, the main advantage for this circuit, but increases difficulties to regulate the converter's output voltage and at the same time controlling the inverter part of the circuit [28]. Figure 2.11 shows the boost type combined chopper with the inverter circuit. The full bridge diode, inductor Lo, smoothing capacitor Cs and switching element Q2 operates in a discontinuous conduction mode. Switching element Q1 and Q2 operates as inverter for load. In this circuit Q2 is used both as switching elements for the converter part and the inverter part.

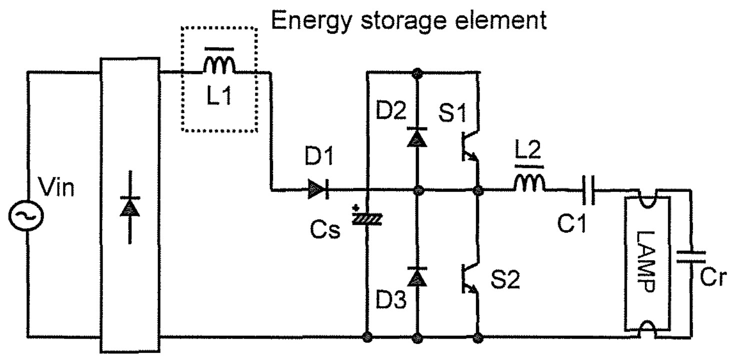

Figure 2.12: Combined chopper circuit

(3) Charge-pump

A charge-pump method uses capacitors as energy storage elements unlike the chopper method where the energy is stored in the inductor. The capacitor C, pulls current from voltage main and release current in repetition, acting as a pump, thus the name charge-pump [29][30]. The basic operation of the electronic ballast is energy which is transferred from input voltage mains through capacitor Cs to inverter circuit which resonates in high frequency voltage and current for the load. This method uses small capacitance capacitor (C1) operates in high frequency drawing current input mains to the inverter part of the circuit. Figure 2.12(a) shows the circuit diagram schematics and (b) shows the circuit concept. The inverter part of the circuit is represented by high frequency voltage source (Va). When V_a is lower than input voltage mains (Vin), current will charge capacitor C1 and contrary when V_{in} is lower than V_a, power accumulated by Capacitor C1 will flow into and charge electrolytic capacitor Cs. The high frequency pumping operation enables current to flow into the circuit even in low voltage (input mains).

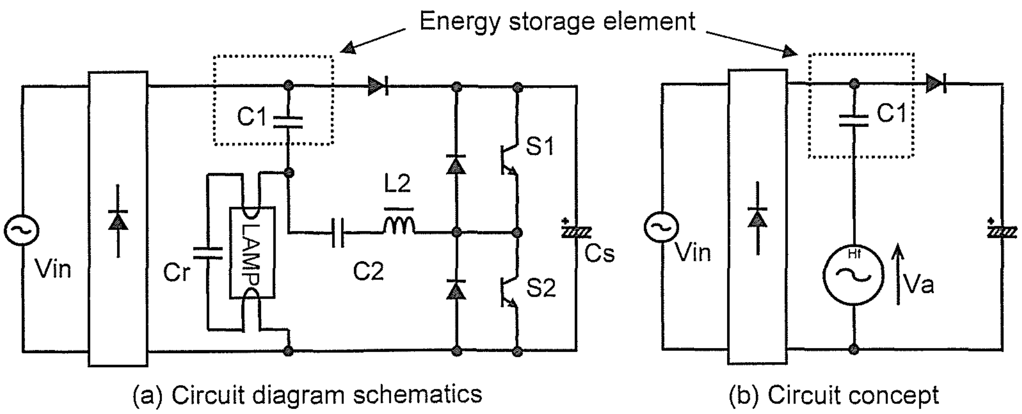

Figure 2.13: Charge-pump circuit

(4) Charge-pump and Chopper (combination)

Figure 2.13 shows the charge-pump and chopper combination circuit and also called the hybrid circuit [23]. In this circuit, the primary winding of transformer T operates as the inductors choke in a chopper circuit. The low capacitance capacitor C operates a charge-pump enables current flow during low voltage period. Smoothing capacitor C_{out} is connected parallel to capacitor C1 and primary inductor of transformer T, creating a resonant circuit. This circuit has low inrush current because the large capacitance smoothing capacitor is connected with the switching element in a closed loop.

Figure 2.15 shows the neutral point type circuit and its based on a combination of two half-wave rectifier circuits. The circuit operation depends mainly on the ON and OFF states of the switching elements (S1 and S2). When switching elements are turned ON; input current will flow through and charge inductor (L), and when switching elements are turned OFF, current due to counter-electromotive force accumulated by the inductor from past circuit operation will flow to and charge the electrolytic capacitor Cs. Lamp current will resonate between inductor L2 and capacitor Cr in sinusoidal waveform.

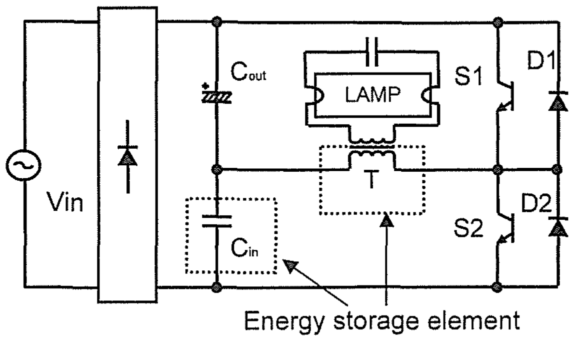

Figure 2.14: Charge-pump and chopper (combination) circuit

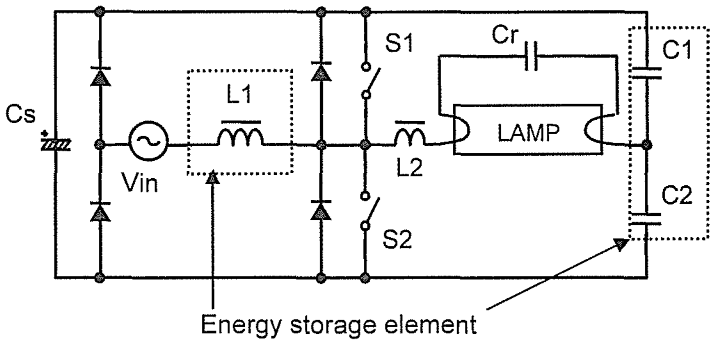

Figure 2.15: Neutral point type boost inverter electronic ballast circuit

(5) Comparison among each active filtering method

Table 2.1 summaries each active filtering method discussed in 2.3.3. From the table, it can be concluded that the charge-pump method has circuit complexity but low smoothing voltage, in comparison to neutral point type method which produce high smoothing voltage with less circuit complexity. The standalone chopper and combined chopper circuit uses more circuit elements and thus higher cost. The charge-pump method has difficulties in circuit control. For the other methods, energy from input voltage mains charges the inductor and energy is released and transferred to electrolytic condenser. In the other hand, the charge-pump method stores energy in small capacitance capacitor before releasing and transferred to electrolytic capacitor. The unbalanced load condition sends feedback and changes the transient operation of the inverter. This changing process is done in high frequency oscillating due to energy from low capacitance voltage is difficult to control in theory. The neutral point type method has high smoothing voltage problems but can be resolve by using either buck converter or buck-boost converter type circuit. This circuit has merit of using less circuit element thus reducing cost compared to standalone chopper and combined chopper circuit even when changing to the buck converter or buck-boost converter type circuit. From the reasons discussed above, it is concluded that the best active filtering method is the neutral point type method [11][31][32].

Table 2.2: Comparison among each active filtering method

	Standalone chopper	Combined chopper	Charge-pump	Neutral point type
Circuit elements	the most	fewer than left	few	few
Smoothing voltage	high *	high *	low *	high *
Control level	easy	difficult	difficult	easy
Cost	high *	lower than left *	low *	low *

* depending on load

2.3 Neutral Point type Electronic Ballast

The most effective method to reduce total harmonic distortion is the neutral point type circuit and below is the circuit operation explanation. Switching elements S1 and S2 has higher frequency than input voltage and because of that the circuit operation is explained including 4 assumptions stated below.

1. Input voltage can be expressed in a form of a direct current input source.
2. The output voltage of the capacitor (Vc) will be ideal. (The voltage will remain constant across the capacitor's terminal).
3. The output load can be expressed as resistor (R)
4. Each circuit element is an ideal circuit element. (There is no dissipation of energy due to resistance in each circuit elements)

Following four assumptions stated above, the circuit operation is explained according to the ON and OFF states of the switching elements S1 and S2 as shown in Figure 2.14. The circuit operations can be divided to eight state operations where depending on the polarity on the input voltage source, four state operations are during positive half cycle and the other four during negative half cycle. Each state operation relationship with input voltage and ON and OFF state of the switching elements is shown in Table 2.2.

Table 2.3: Switch operation in each state

State	1	2	3	4	5	6	7	8
Input Voltage	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(-)
Switch S1	ON	OFF	OFF	OFF	OFF	OFF	ON	OFF
Switch S2	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF

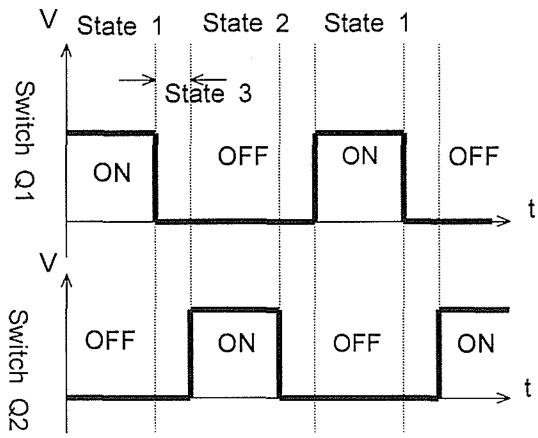

Figure 2.16: ON-OFF conditions of the switching elements in each state operation

(1) State a1 (S1: ON, S2: OFF)

Current form input voltage mains flows through switching element S1 and charges inductor L1. Condenser Cs and capacitor C1 releases energy stored during past circuit operation, flows through into load.

(2) State a2 (S1: ON, S2: OFF)

Energy released from capacitor C1 stops (takes short period of time due to low capacitance). Meanwhile inductor L1 is still being charge and energy from condenser Cs is still being release and flowing into load.

(3) State b (S1: OFF, S2: OFF)

Counter-electromotive force accumulated from past circuit operation of inductor L together with voltage input mains current flow into load. The current also flow through and charges condenser Cs. Current flowing into load is in the opposite direction with state a1 and 2. This state is called dead time where both switches turn off in the same time but only occur in short period time.

(4) State c1 (S1: OFF, S2: ON)

After state b, inductor L still releases energy until it dries up. Since S2 is turned ON, capacitor C2 releases energy into load in a closed loop. Time taken for inductor L to released energy depends on the main input voltage, higher voltage charges the inductor with more energy thus making energy dissipation longer.

(5) State c2 (S1: OFF, S2: ON)

Inductor L1's voltage drop to 0V, energy from condenser Cs feeds the load and also during this period, current flows through and charges capacitor C1.

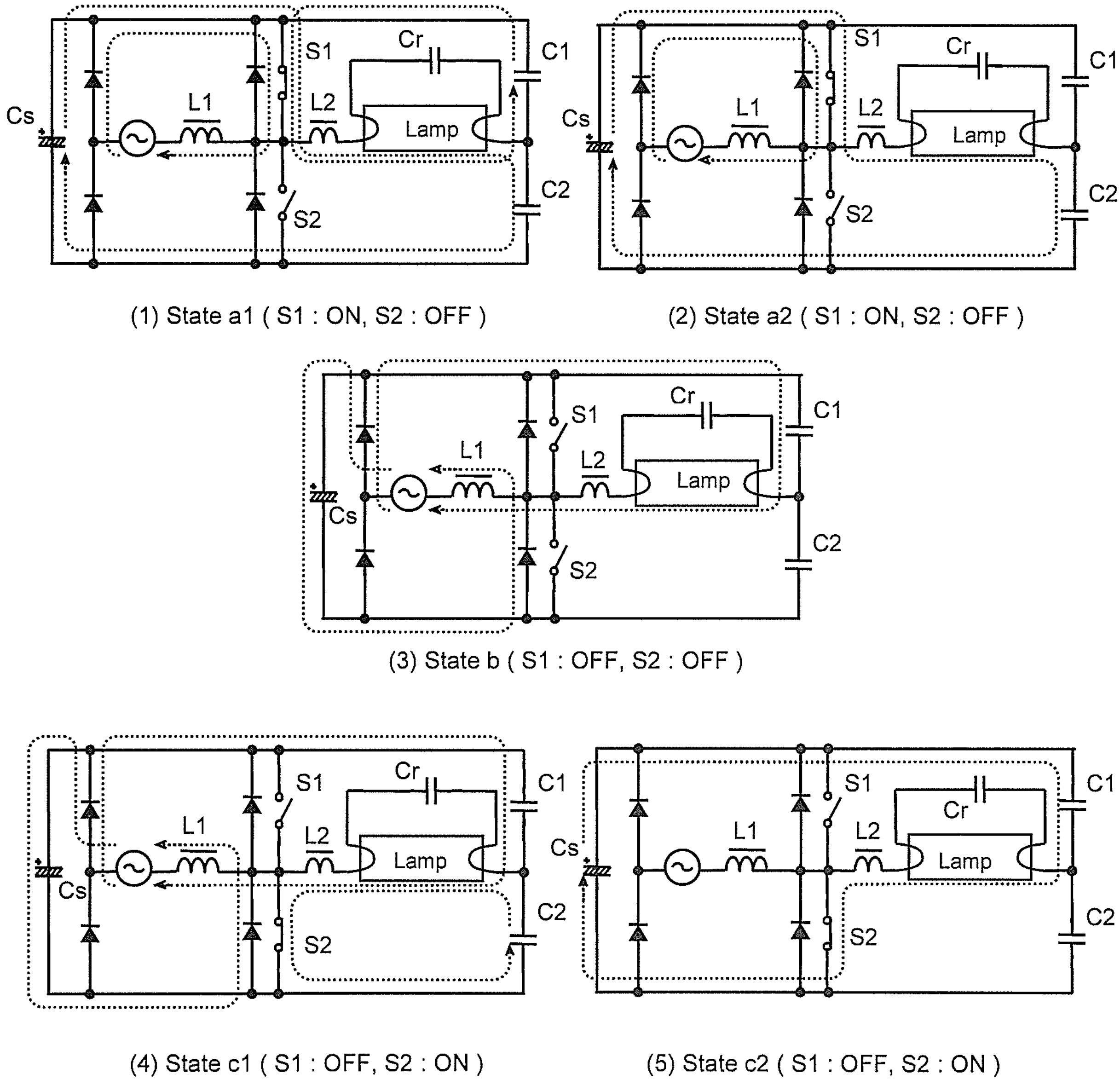

Figure 2.17: Neutral point type electronic ballast circuit operations

From the circuit operation description, in circuit state operations, all current flows into load. The lamp current oscillates with capacitor Cr connected in parallel with load and the current waveform is sinusoidal form. Filtering circuit is connected in the input mains, filters out noise caused by high frequency switching thus input current waveform is a sinusoidal waveform. The circuit satisfies the IEC standard regulation, compact, light-weighted and has high power factor. But the neutral point type electronic ballast has some problematic factors such as;

1) Boost operation applies voltage stress to circuit elements [33][34][35]
2) Inrush current occurs during initial star-up (closed loop connecting input mains with condenser) [34][35]
3) Ripple content in output /load voltage [34][35]

2.4 Summary

The IEC 61000-3-2 regulation standard is quite a difficult regulation to follow. Because of that, most electronic ballast adapts the active rectification method for the rectification part of the electronic ballast. The active rectification method was developed long before the IEC 61000-3-2 regulations. Recent electronic ballast circuit adapts the one converter concept where the active rectification circuit is combined with high frequency converter circuit. It is considered that the neutral point type, branch of the active filtering method for it merits on reduced cost, circuit complexity and increased efficiency, is the most effective method to reduce Harmonic Distortion [9][26]. Although some problems arises due to boost operation of the circuit, new circuit configuration base on the neutral point type converter circuit concept is proposed and will be discussed in the next chapter.

CHAPTER 3 Neutral point type boost converter filtering method

High-frequency electronic ballast which has various advantages such as low current loss and high output efficiency, and being compact and lightweight, in modern practice, they are fast becoming the main ballast equipment associated with fluorescent lamps. To satisfy the International Standard on input mains current harmonic emission IEC 61000-3-2, recent electronic ballast adopts the two-converter electronic ballast method consisting a converter circuit and an inverter circuit. However, it has drawbacks such as large circuit size, many circuit elements and its high cost [27]. To counter these problems, it is important to reduce circuit elements. The one-converter type electronic ballast method makes it possible to reduce the usage of switching elements by sharing the same switching elements with both the converter circuit and the inverter circuit, thus eliminating one switching element and one control unit circuit [11]. In this chapter, the Neutral point type boost converter is analyzed and problematic points are discussed and improvements are made for this system. Two types of circuit under the neutral point type boost converter system is also introduced and discussed.

3.1 Neutral Point type boost converter circuit topology

Figure 3.1(a) shows the circuit diagram schematics of the neutral point type boost converter. The circuit was modeled based on the active filter circuit shown in Figure 3.1(b). The neutral point type boost converter consists of four diodes (D1, D2, D3, and D4), inductor L, two switching elements (S1, S2), and electrolytic capacitor Cs. The circuit can have the same output results as the active filter circuit according to input source and switching elements duty cycle. In comparison to the active filter circuit, the neutral point type boost converter has 1 additional switching element but by using FET as switching element, diode D3 and D4 can be replaced by the fly-wheel diode built in the FET.

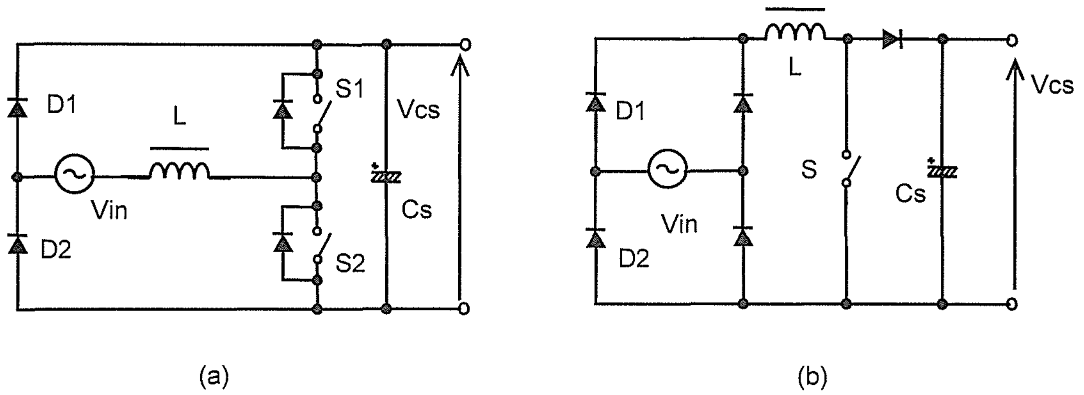

Figure 3.1: Circuit diagram schematics of (a) Neutral point type boost converter circuit and (b) Active filtering (standalone chopper) circuit

3.1.1 Circuit Operations

(1) State 1(a) (S1: ON, S2: OFF $V_{in}<V_{Cs}$)

Figure 3.2(a) shows the current flow during state 1(a). Input current from input source flows through D1 and switching element S1 into inductor L.

(2) State 1(b) (S1:ON, S2:OFF $V_{in}>V_{Cs}$)

Figure 3.2(b) shows the current flow during state 1(b). Input current from input source flows closed circuit of (D1-S1-L-V_{in}) and (D1-Cs-S2's fly-wheel diode-L –V_{in}).

In both state 1(a) and 1(b), the maximum current flowing through inductor L is shown in equation 3.1. Switch S1 is turned ON and the corresponding time is shown as T_{ON} in the equation.

$$I_{1p} = \frac{1}{L}\int V_{in} dt = \frac{V_{in}}{L} T_{ON} \qquad \dots (3.1)$$

Power accumulated by inductor L is shown in equation 3.2.

$$P_{ON} = \frac{L}{2} I_{1p}^2 = \frac{V_{in}^2}{2L} T_{ON}^2 \qquad \dots (3.2)$$

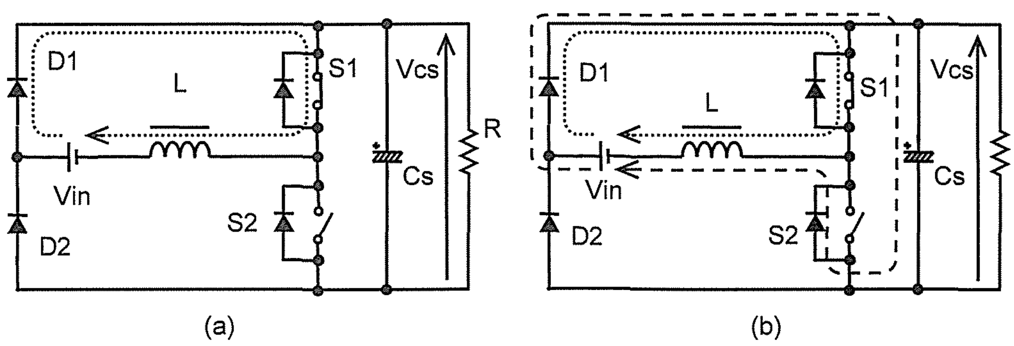

Figure 3.2: Current flow during (a) state 1(a) (S1: ON, S2: OFF $V_{in}<V_{Cs}$) and (b) state 1(b) (S1:ON, S2:OFF $V_{in}>V_{Cs}$)

(3) State 2 (S1: OFF, S2: OFF)

Figure 3.3 shows the current flow during state 2 and 4. After state 1 and 3, dead time occurs (both switching elements turn OFF) but this happens for only a moment. Counter-electromotive force current (Ic) from inductor L accumulated during state 1 and input current from input source passes through diode D1, electrolytic capacitor Cs and fly-wheel diode S2. The current charges the electrolytic capacitor Cs

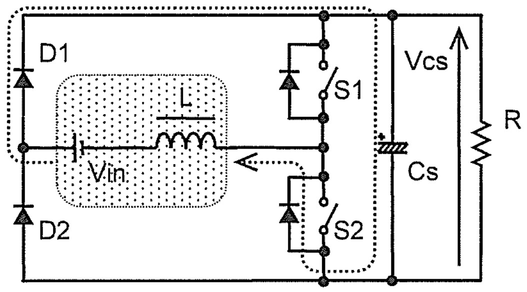

Figure 3.3: Current flow during state 2 and 4 (S1: OFF, S2: OFF)

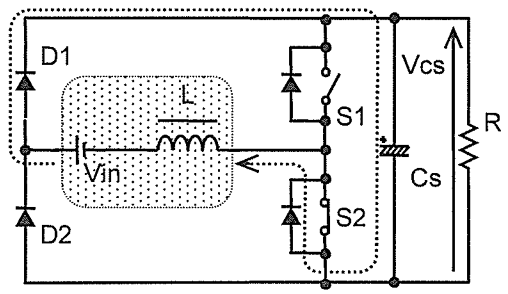

Figure 3.4: Current flow during state 3 (S1: OFF, S2: ON)

(4) State 3 (S1: OFF, S2: ON)

In state 3, switching element S2 turns ON and the circuit's current flow is a continuation of state 2. Figure 3.4 shows the current flow during state 3. During state 2, state 3 and state 4, the counter electromotive force current flowing through inductor L is shown in Equation 3.3

$$I_2 = \frac{V_{in}}{L} T_{ON} - \left(\frac{V_{Cs} - V_{in}}{L} \cdot T_{OFF} \right)$$

... (3.3)

The time T_{OFF} needed to discharge the energy until current due to counter-electromotive force drops to zero(Ic=0), is shown in Equation 3.4

$$T_{OFF} = \frac{V_{in}}{V_{Cs} - V_{in}}$$

... (3.4)

The duty-cycle of the switches is 50%, thus the output voltage twice the input current as shown in Equation 3.5.

$$V_{Cs} = 2V_{in}$$

... (3.5)

State 4 (S1: OFF S2: OFF)

After state 3, dead time again occurs and both switches turn OFF. The circuit operation the continuation of state 3 and the current will flow until all the energy stored in inductor L is used.

3.1.2 Circuit Experiment and results

To verify the functions of the boost converter, some experiments have been performed under the following conditions. The power source is 100V A.C and frequency 60Hz. A low pass filter (L.P.F) is installed on the input side of the power source. The oscillating circuit is a separate excitation type using power MOSFET driven by a gate-driver-IC IR2155. The duty cycle is 50%. Characteristics of each circuit have been measured with changing the value of the load resistance.

Figure 3.5 shows the comparison of characteristics between the boost converter (PBC) and standalone chopper active filter (AF). The transverse axis indicates output power (W_{out}). Vertical axes indicate input power (W_{in}), output voltage (V_{dc}), power factor and efficiency (η). Both circuits have similar characteristics, and experimental results rightly show the relationship between the variable deduced in the above section.

Figure 3.6 shows an example of input current waveform of the boost converter. From the observed waveform, it is seen that no current flows into the circuit during the period of low input voltage (marked with two circles). Therefore, it is necessary to improve the circuit so that the current may flow into the circuit even in the period of low voltage.

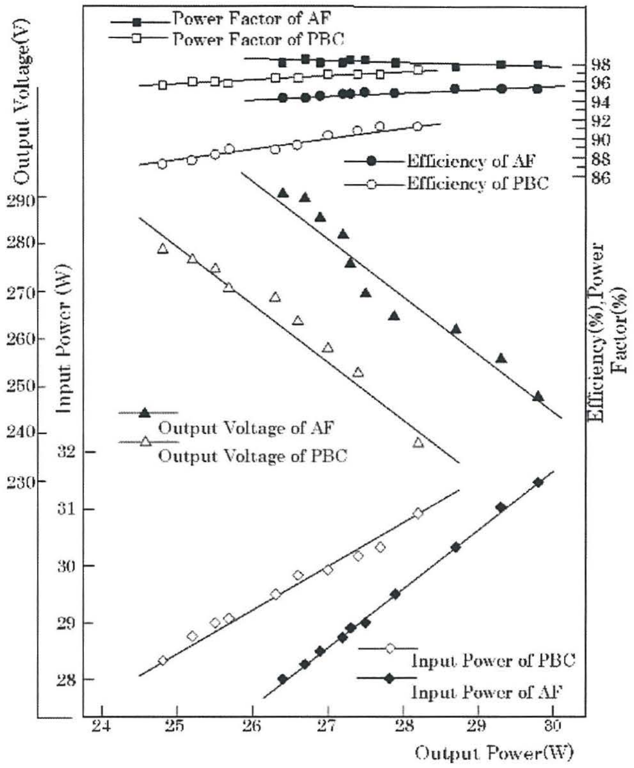

Figure 3.5: Characteristics of the neutral point type boost converter (PBC) and the active filter (AF).

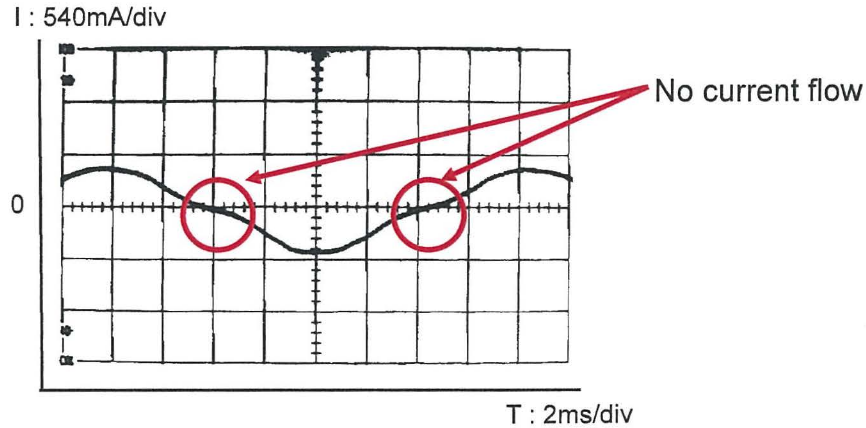

Figure 3.6: Current input waveform of circuit in Figure (3.1(a)). The circle marks indicate that no current flow during low input voltage.

3.2 Improvised Neutral Point type boost converter

In order to solve the defect of the boost converter circuit mentioned above, an improved circuit is proposed. The improvement can be achieved by adding the charge pump function to the original circuit (which was discussed under chapter 2.2.2). The charge pump function is realized by adding two small capacitors C1 and C2 together with two diodes D5 and D6, as illustrated in Figure 3.7. The capacitor C1 (or C2) is discharged during the period in which switch S1 (or S2) is ON, and it is charged during the period in the switch is OFF. In other words, each capacitor works as a charge pump that repeats charge and discharge in high frequency [33]. The two diodes work effectively when the charge cannot be perfectly discharge from each capacitor during the period in which the switch is ON. By the work of the charge pump, it becomes possible to draw the input current to the circuit during the period in which source voltage is comparatively low.

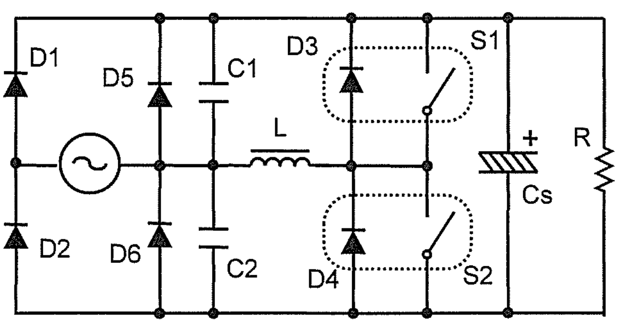

Figure 3.7: Modified Neutral point type boost converter circuit diagram schematic

3.2.1 Circuit operations

(1) State 1(a) (S1: ON, S2:OFF Vin<Vcs)

Current from electrolytic capacitor Cs and capacitor C1 will flow into inductor L, and also flow into Capacitor C2 as shown in Figure 3.8(a)'s circuit flow for a short period of time until voltage drops under the input sources voltage.

(2) State 1(b) (S1:ON, S2:OFF , Vcs<Vin)

Input current from input source will then flow through diode D1, switching element S1 and inductor L, and another loop through capacitor C1 as shown in Figure 3.8(b)'s current flow. The current charges both inductor L and capacitor C1.

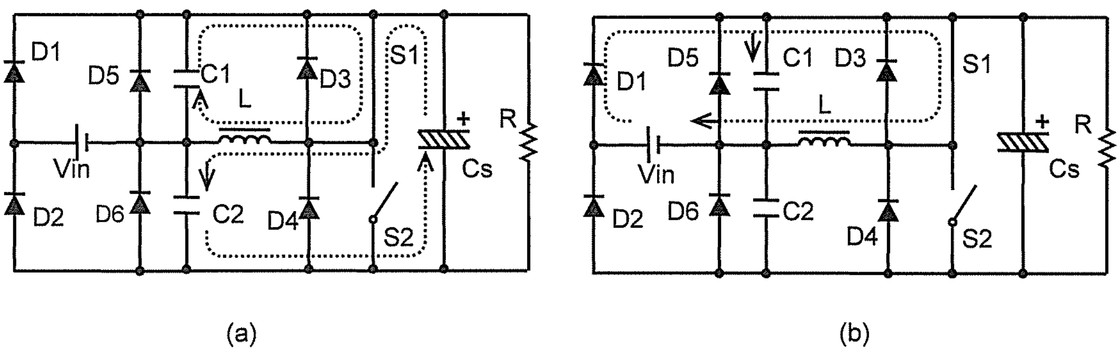

Figure 3.8: State 1 (Switch S1: ON S2: OFF) during (a) Vin<Vcs and (b) Vcs<Vin

(3) State 2 (S1: OFF, S2: OFF)

Dead time occurs (both switching elements turn OFF) for a short period of time. Counter electromotive force from inductor accumulated during state 1 together with current form input source charges electrolytic capacitor Cs. Capacitor C2 is also charged.

(4) State 3 (S1: OFF S2: ON)

The circuit operation in state 2 continues until all energy in inductor L is used. In time period when input voltage is high, energy accumulated by the inductor L is also high. The discharge operation of inductor L continues until state 3. When discharge operations end, the current flow is shown in Figure 3.9(b).

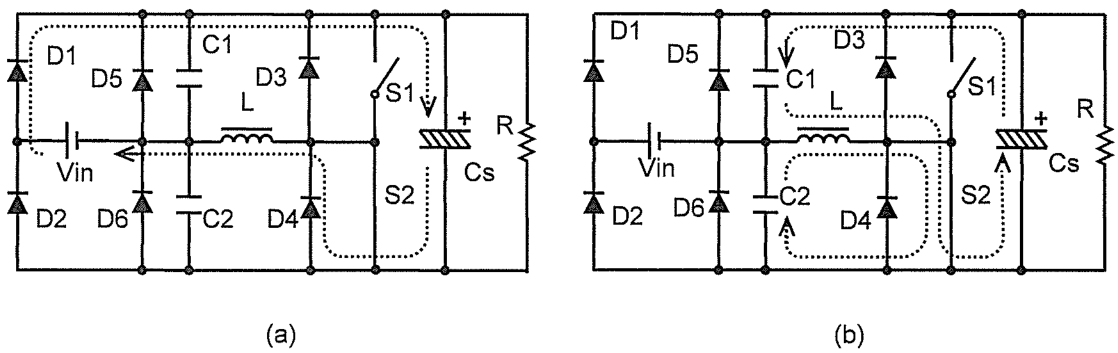

Figure 3.9: (a) Current flow during state 2 and 3 (b) Current flow during state 3 (Vin<Vcs)

(5) State 4 (S1: OFF S2:OFF)

Again, dead time occurs. The amount of counter-electromotive force and energy stored in Capacitor C2 is relatively low, and current cannot flow into electrolytic capacitor Cs.

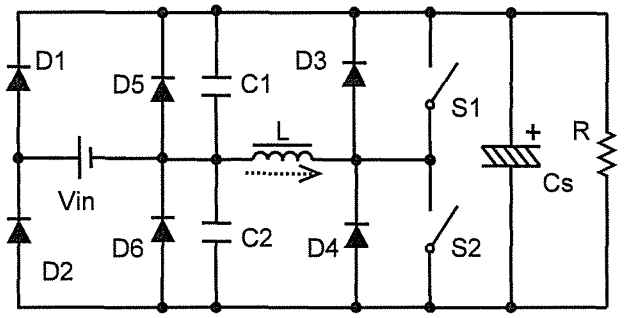

Figure 3.10: Current flow during State 4 (Switch S1: OFF, S2: OFF)

3.2.2 Circuit Experiment and results

Experiment has been carried out under the condition equal to the experiment of the Neutral Point type boost converter described in the previous section (chapter 3.1.2). Figure 3.11 shows the input current waveform of the improvised boost converter. From the observed waveform, it can be confirmed that current flows into the circuit during the period of low input voltage (marked with two circles). In continues circuit operation, capacitor C1 and C2 draws current from input voltage source and discharging it into inductor L in high frequency or in other word, operates as a charge pump. By adding these capacitors, current can be drawn into the circuit even during low input voltage period.

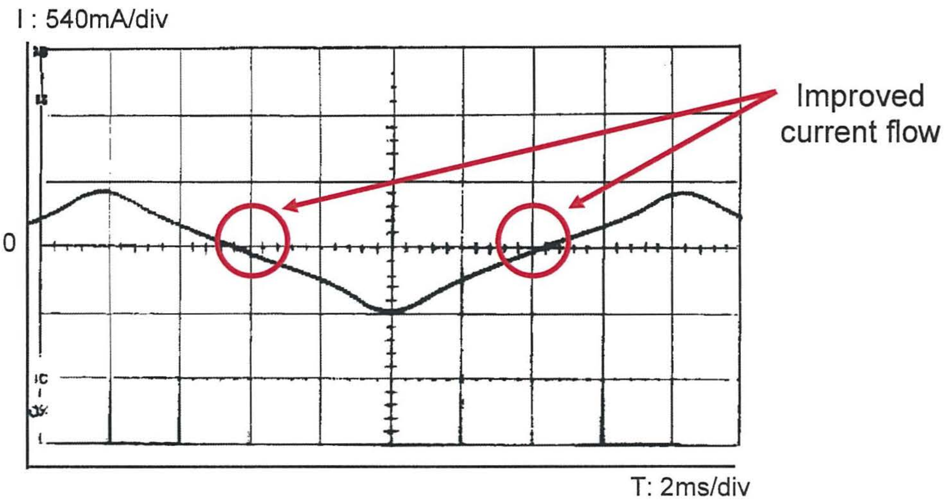

Figure 3.11: Current input waveform of improvised circuit in Figure (3.9). The red circle marks indicate that current flow during low input voltage due to charge pump operations.

3.2.3 Electronic Ballast application experiment and results

As a one-converter type circuit method, the advantages of the Improvised Neutral Point type converter can be shown by applying to the electronic ballast. Two configuration of electronic ballast is experimented, which is the typical half-bridge type inverter and the series inverter as shown in Figure 3.12(a) and (b). The one-converter type circuit electronic ballast can contribute to improvement of the efficiency and reduction of circuit components. In both circuits, two switching devices are used to both of the inverter circuit and converter circuit. Each electronic ballast input current and voltage waveforms are shown in Figure 3.13(a) and (b). In the experiments, power is supplied from 100V A.C. power line through Low Pass Filter. As switching device, MOSFET driven by gate-driver IC with 50% duty cycle is used. The fluorescent lamp is slim light FLR42T6W. The resonance frequency is approximately 60 kHz. As a result, substantially sinusoidal waveform of input current has been obtained without control of duty ratio, and the power has accomplished over 99%. Figure 3.14(a) and (b) depicts the harmonic distortion characteristics of the input current shown in Figure 3.13(a) and (b). It has been proven that both circuits sufficiently satisfied the maximum limits of the harmonic current in IEC 1000-3-2 Class C.

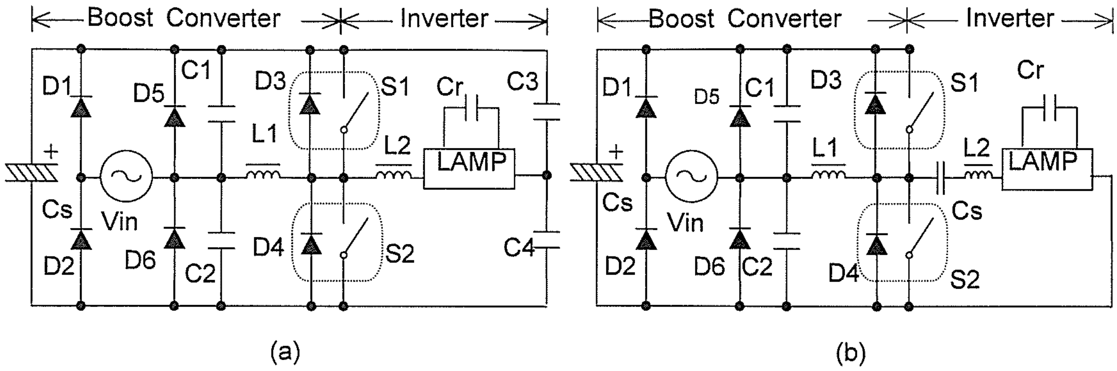

Figure 3.12: Electronic ballast application of Figure (3.9) with (a) half bridge inverter and (b) series inverter

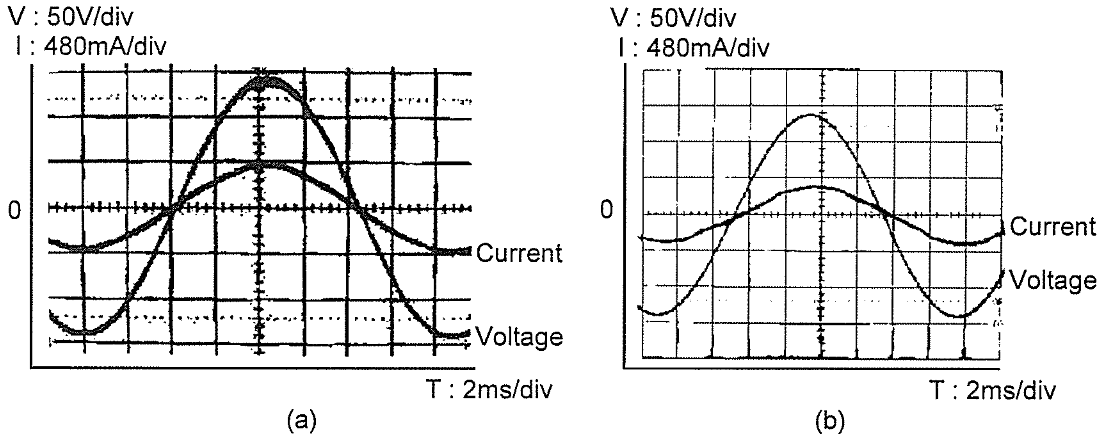

Figure 3.13: Input voltage and current waveform of, (a) circuit figure (3.14(a)) and (b) circuit figure (3.14(b))

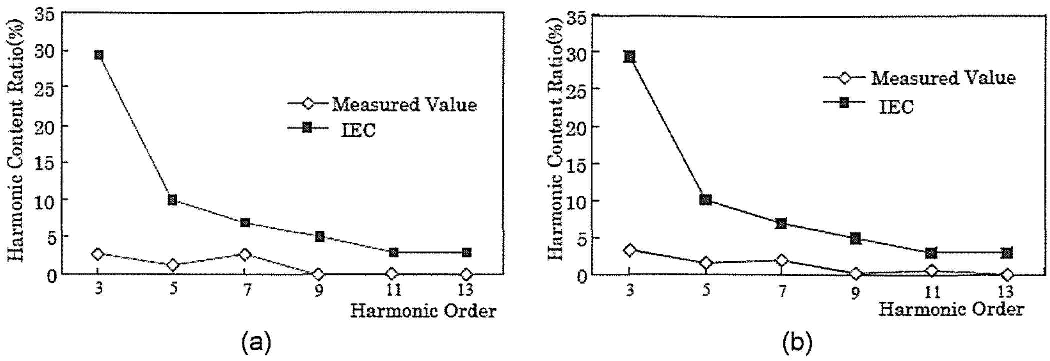

Figure 3.14: Content rate of harmonics of the input current of (a) circuit in Figure (3.14(a)) and (b) circuit in Figure (3.14(b)) with IEC harmonics standard for class C

3.3 PFC (Power Factor correction) inverter circuit

Circuit based on the Neutral point type boost converter is further miniaturized by reducing or sharing more circuit elements while still achieve high power factor and keeping harmonic distortion in low rate. The PFC inverter circuit is built in with the common mode filter and normal mode filter and maintaining the one-converter type method. The common mode filters is insert in the input side of the Neutral point type boost converter electronic ballast allowing it to share its condenser with the half bridge inverter part of the electronic ballast[4][36].

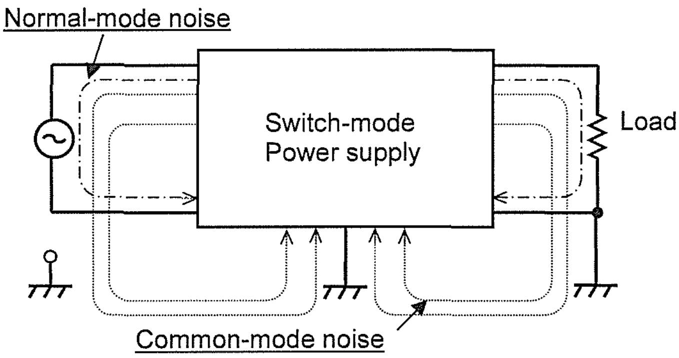

Figure 3.15: Normal-mode and Common-mode noises

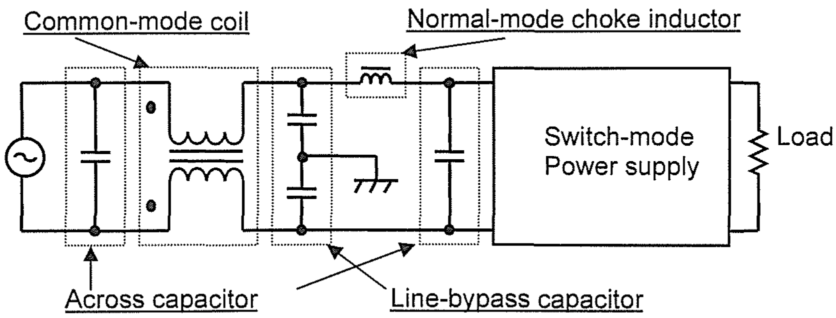

Figure 3.16: Normal-mode and Common-mode noise filtering methods

Noise source can be divided into three main categories, that is the EMI, the RFI and Ground Loops. EMI (electromagnetic interference) is a signal that can cause undesirable performance in devises or system. It consists of devices from which radio frequency are emitted such as cellular telephone and computers. RFI (radio frequency interference) is caused via conduction over signal line AC power distribution systems. Ground loop is caused when equipment is grounded primary to ensure safety from fire and hazard but ground current can be very unpredictable. It can be caused by voltage differences induction from other cables or devices, wiring error, ground faults or normal equipment leakage. Ground loops are one cause of common-mode noise. In the case of SMPS (switch-mode power supply), there are two types of noises that is the common-mode noise and the normal-mode noise. Normal-mode noise is the noise signal which appears between a set of phase conductors. Meanwhile common-mode filter is the noise signals from the neutral and the ground conductor [37]. Both noises flow are illustrated in Figure 3.15. To filter-out normal-mode noise, capacitor connected in parallel (across capacitor) and choke inductor is inserted between input source and the SMPS. Both capacitor and choke will be referred to as normal-mode filter. Common-mode noise is filtered out using the common-mode coil and line-bypass capacitors and both will be referred to as common-mode filter. Both filters are illustrated in Figure 3.16.

The PFC inverter derivate from the neutral point type boost converter can correct the power factor and harmonics of the supply to improve the performance of the florescent lamp.

In the Neutral Point type boost converter Electronic ballast, the common-mode filter and normal-mode filter is connected parallel to the AC power source line as shown in Figure 3.15(a). Figure 3.15(b) shows the PFC inverter circuit. The capacitors of the common-mode filter are shared with the inverters capacitors thus reducing the circuit elements as a whole.

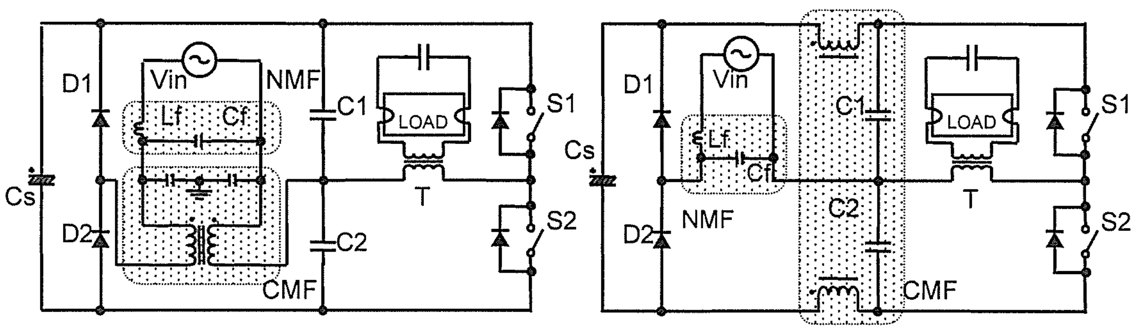

Figure 3.17: (a) Neutral point type boost converter Electronic ballast (b) PFC converter

3.3.1 Circuit operation

(1) State 1 (S1: ON, S2: OFF, during (a) Vin<V_{Cs} and (b) V_{Cs}<Vin)

In state 1(a) both electrolytic condenser Cs and capacitor C1 discharges and current flows into primary winding of transformer T and to load. During this state, capacitor C2 is also charged. In both state 1(a) and 1(b), input current from mains charges the primary winding of inductor T. In addition during state 1(b) input current from mains also charges electrolytic capacitor Cs and capacitor C1. The current flow of each state 1(a) and 1(b) are shown in Figure 3.16.

(2) State 2 (S1: ON, S2: OFF)

Dead time occurs; both switching elements turn OFF simultaneously but for only a short period of time.

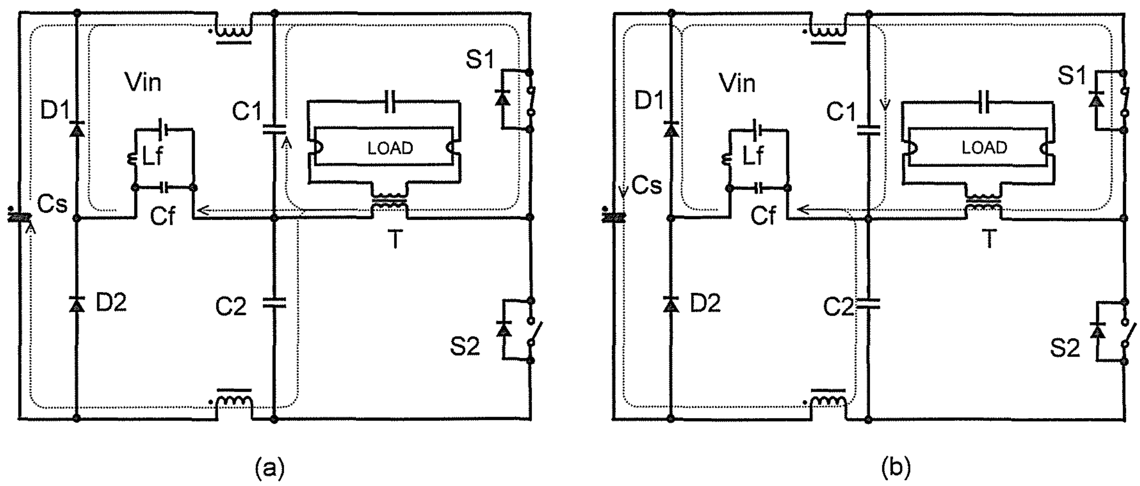

Figure 3.18: Current flow during State 1 (S1: ON, S2: OFF, during (a) (Vin<V_{Cs}) and (b) (V_{Cs}<Vin))

(3) State 3 (S1: OFF, S2: ON, during (a) Vin<V_{Cs} and (b) V_{Cs}<Vin)

In state 1(a) both electrolytic condenser Cs and capacitor C2 discharges and current flows into primary winding of transformer T and to load. During this state, capacitor C1 is also charged. During state 1(b) input current from mains charges electrolytic capacitor Cs and capacitor C2. The current flow of each state 3(a) and 3(b) are shown in Figure 3.17.

(4) State 4 (S1: ON, S2: OFF)

Dead time occurs again. The cycle repeats with the same circuit operation for negative input voltage mains.

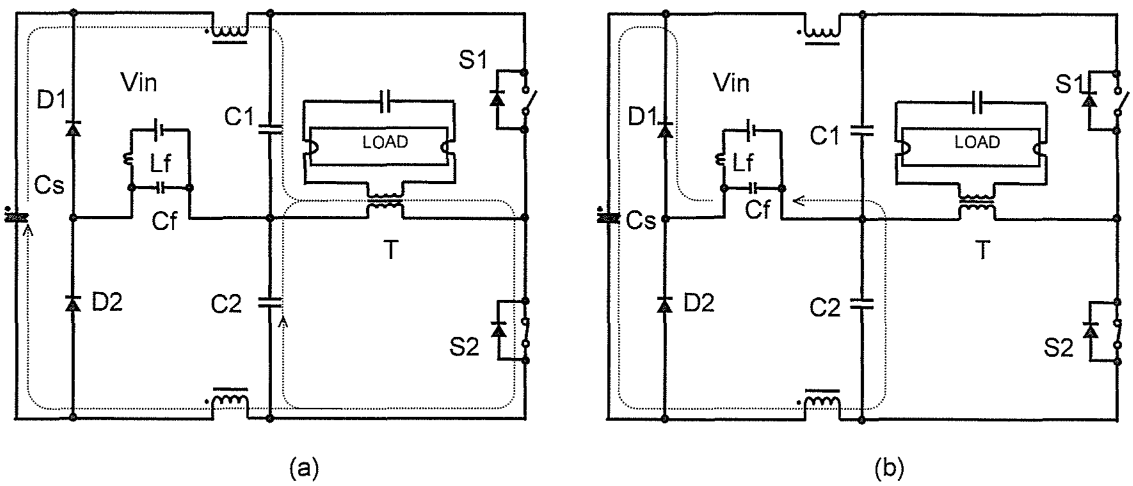

Figure 3.19: Current flow during State 3 (S1: OFF, S2: ON, during (a) (Vin<V_{Cs}) and (b) (V_{Cs}<Vin))

3.3.2 Circuit experiment and results

The PFC inverter circuit was constructed and tested with a fluorescent lamp. IR2153 is used as control circuit signal for switches S1 and S2 and the duty cycle of MOSFET is 50%. Waveforms of input voltage and input current of proposed circuit are shown in Figure 3.18 and the waveform of input current is almost sinusoidal wave. Figure 3.19 shows the output voltage waveform. The relative harmonic content of input current is shown in Figure 3.20 and confirms that the relative harmonic distortion content is lower than the IEC limit standard.

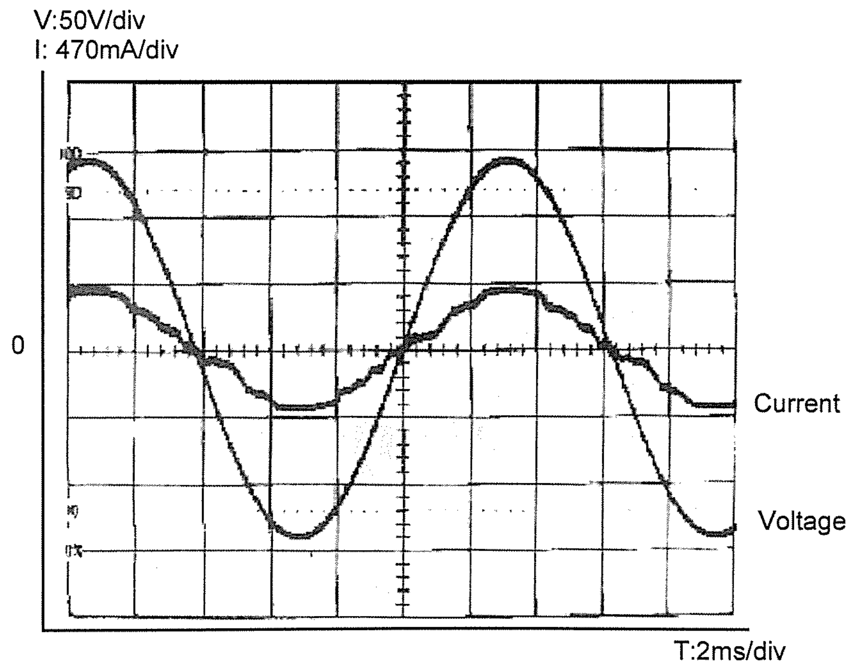

Figure 3.20: Input voltage and current waveform

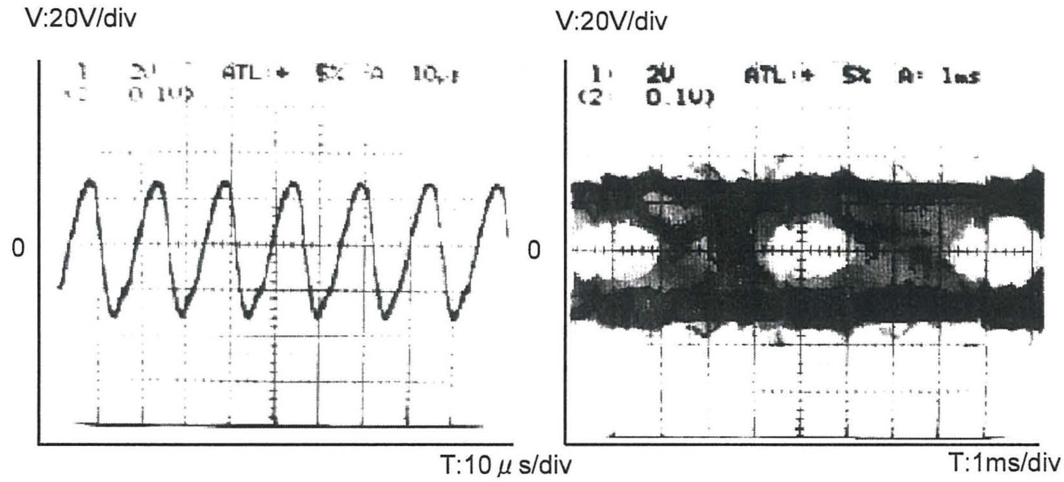

Figure 3.21: Output voltage waveform

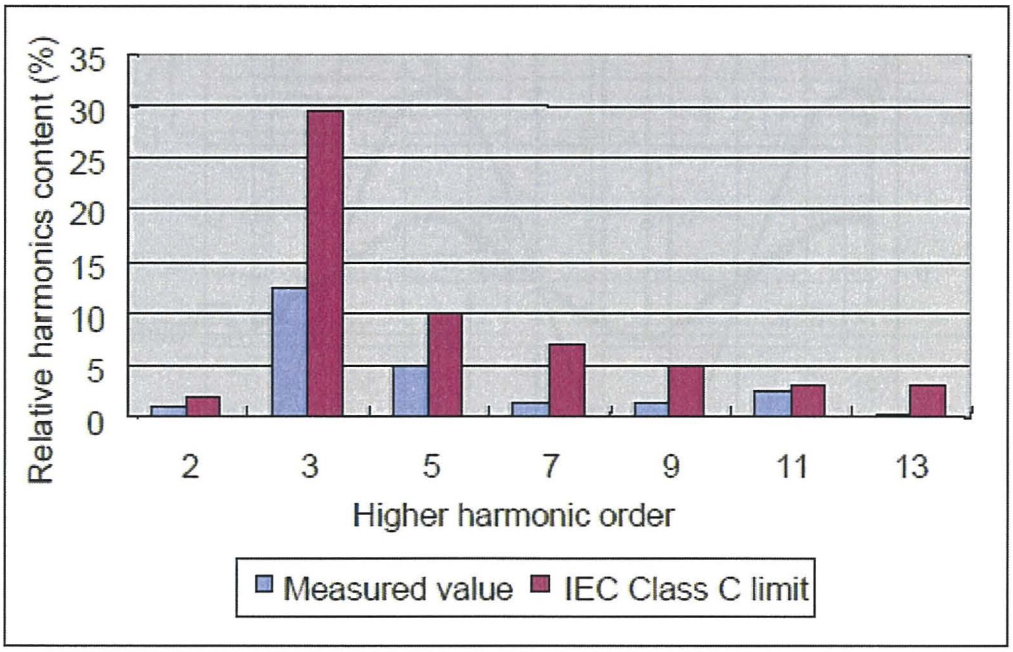

Figure 3.22: Content rates of harmonics of input current of proposed system with IEC harmonics limit standard for Class C

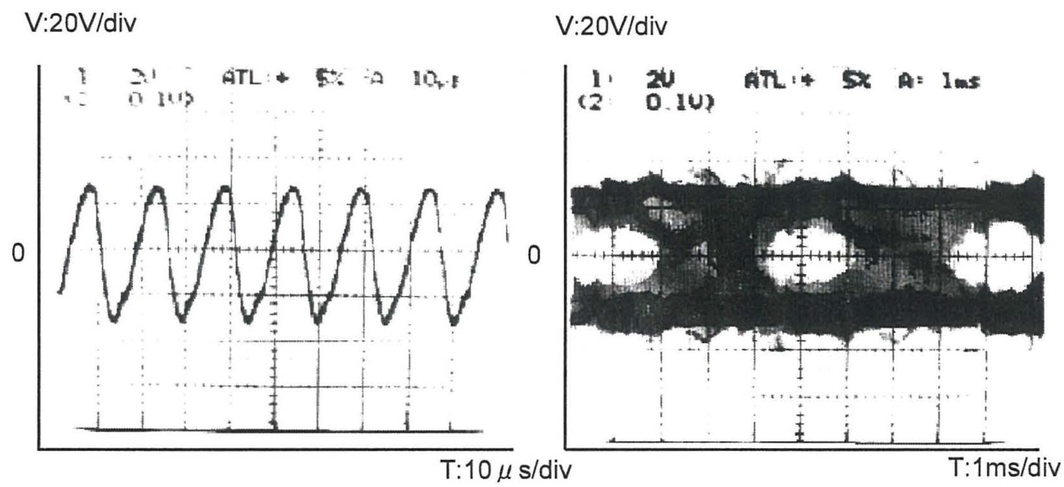

Figure 3.21: Output voltage waveform

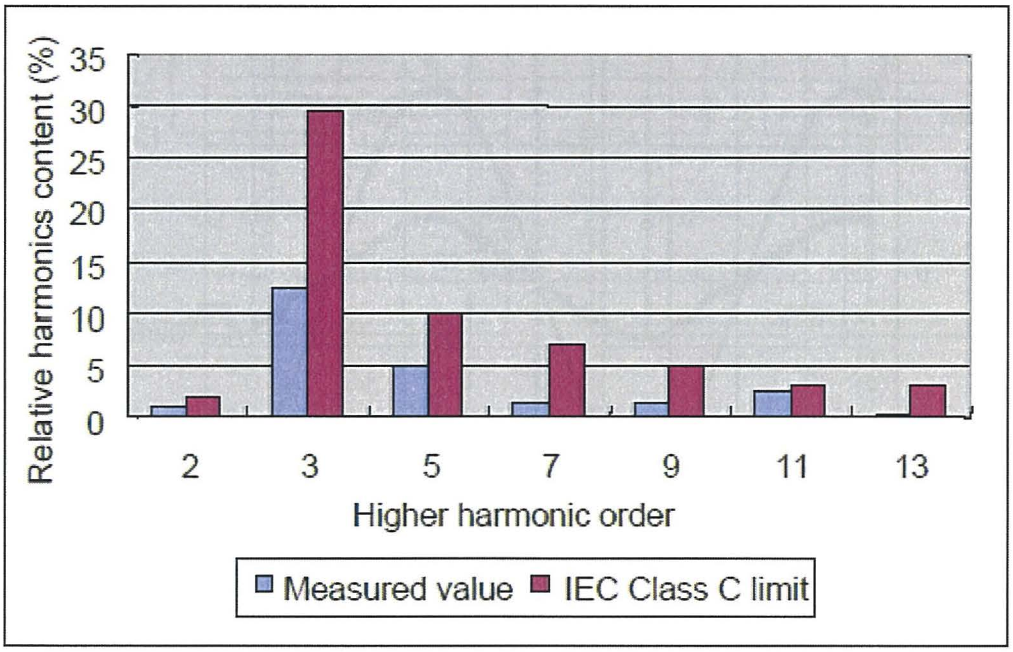

Figure 3.22: Content rates of harmonics of input current of proposed system with IEC harmonics limit standard for Class C

3.4 Summary

In this chapter, the neutral point type boost converter is analyzed and compared to other active filtering method, mainly the standalone chopper circuit (used in two-converter type electronic ballast). Variability in switching element's duty-cycle is needed to achieve low harmonic distortion although in the Neutral point type boost converter (used in one-converter type electronic ballast) the duty-cycle is set to 50%.

Improvised neutral point type boost converter solved this problem by adding two additional capacitors operating as charge-pumps in the circuit. Input current form mains can be drawn into the circuit even during low voltage point due to charge-pumping operations. This circuit is applied to one-converter type electronic ballast by sharing switching elements by both converter and inverter circuit. The circuit was experimented and results shows that it runs safely while achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

The PFC inverter circuit further miniaturizes the electronic ballast. Common-mode and normal-mode filters are usually connected to the input voltage source of the electronic ballast to suppress noise. PFC inverter reduces circuit element by sharing capacitor of the inverter part of the circuit with the common-mode filter, by attaching the common-mode filter in the inverter part of the circuit. The circuit was experimented results shows that it runs safely, achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

The neutral point type boost converter has high inrush current during initial start-up due to its circuit configuration. This problem is discussed in the next chapter.

CHAPTER 4 Neutral point type buck-boost converter filtering method

The previously discussed neutral point type boost converter system which can be applied to one-converter type electronic ballast had proven to have high power factor and satisfies the IEC 61000-2-3 class C harmonic distortion limit standard. As a one-converter electronic ballast, less circuit element and control circuit is needed compared to the two-converter electronic ballast. However, this circuit system has several problems due to boost operation such as stress on circuit element and occurrence of inrush current during initial start-up [27]. Inrush current can affect electrical component such as tripping circuit breakers and fuses. During start-up, momentary contact bouncing in switches may cause the contact to be pitted due to arching between contact points. The surge can also cause serious damage, such as welding switch contact together.

In this chapter, the boost operation of the neutral point type converter is replaced with the buck-boost operation. This disables a closed loop connection between input voltage source and electrolytic capacitor [15]. This circuit also can be applied to one-stage electronic ballast thus still maintains the advantages.

4.1 Circuit Topology

The neutral point type buck-boost converter is design based on the half-wave rectifier circuit. The circuit operation mainly depends on the ON and OFF condition of the switching elements (switching element S1 during positive half cycle and switching element S2 during negative half cycle). When switching element turns ON, current from input voltage charges inductor L and when switching element turns OFF, counter-electromotive force current of inductor L flows through and charges electrolytic capacitor (C). The electrolytic capacitor is parallel to the output voltage as in direct current. The circuit topology is shown in Figure 4.1. Unlike the neutral point type boost converter circuit, additional four diodes (D3, D4, D5, and D6) are used to allow only current from inductor L to flow to the capacitor during discharge. There is also no closed loop connection between the input voltage and the electrolytic capacitor. As a result, this circuit reduces the chance of an inrush current to occur.

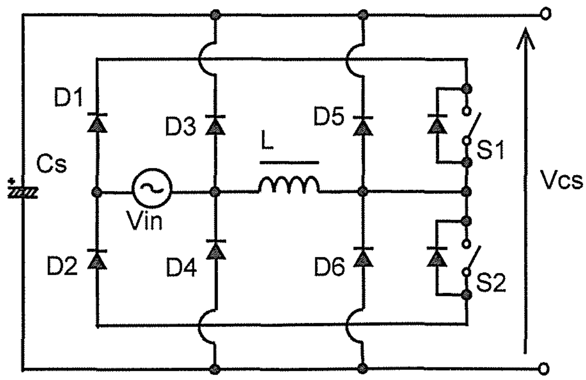

Figure 4.1: Neutral point type buck-boost converter circuit diagram schematics

4.1.1 Circuit Operation

The circuit operation of Neutral point type buck-boost. Switching operational conditions follow the same state operation of the neutral point type electronic ballast mentioned in Chapter 2. Each circuit operation of the positive half cycle is described.

State 1 (a) (S1: ON, S2: OFF, $V_{in}<V_{Cs}$)

Figure 4.2(a) shows the current flow during circuit operation state 1(a). Input current (I1) from input source flows through diode D1 passes through switching element S1 and inductor L. Current I_{load} flow from capacitor C into load R.

State 1 (b) (S1: ON, S2: OFF, $V_{in}>V_{Cs}$)

Figure 4.2(b) shows the current flow during circuit operation state 1(b). As same as in state 1(a), input current (I_1) from input source flows through diode D1 passes through switching element S1 and inductor L. Furthermore current from input voltage flows through closed loop of (Vin-D1-S1-D5-Cs-D4) charging the electrolytic capacitor Cs. In both state 1 (a) and state 1 (b) the maximum current (I_{1p}) flowing through inductor L is shown in Equation 4.1.

$$I_{1p} = \frac{1}{L}\int V_{in}dt = \frac{V_{in}}{L}T_{ON} \qquad \text{... (4.1)}$$

Power accumulated by inductor L is shown in Equation 4.2

$$P_{ON} = \frac{L}{2}{I_{1p}}^2 = \frac{{V_{in}}^2}{2L}{T_{ON}}^2 \qquad \text{... (4.2)}$$

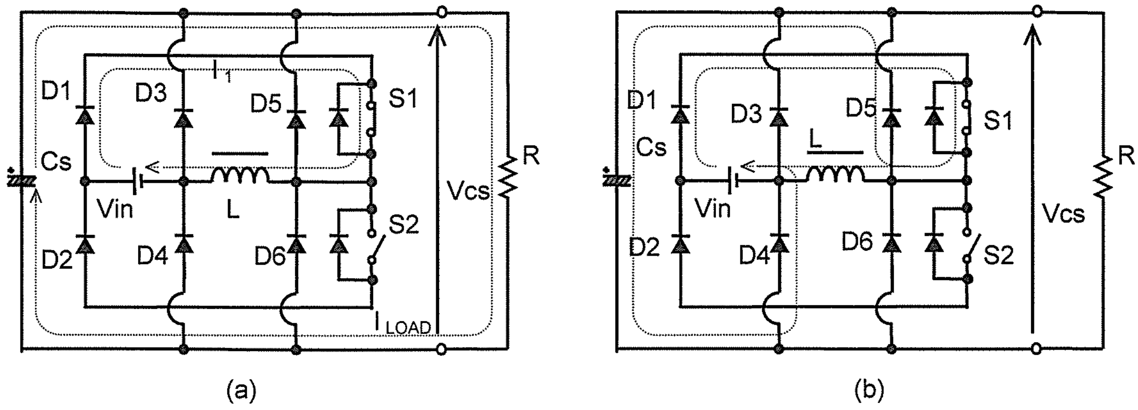

Figure 4.2: Current flow during (a) state 1(a), S1: ON S2: OFF Vin<Vcs and

(b) state 1(b), S1: ONS2: OFF Vcs<Vin

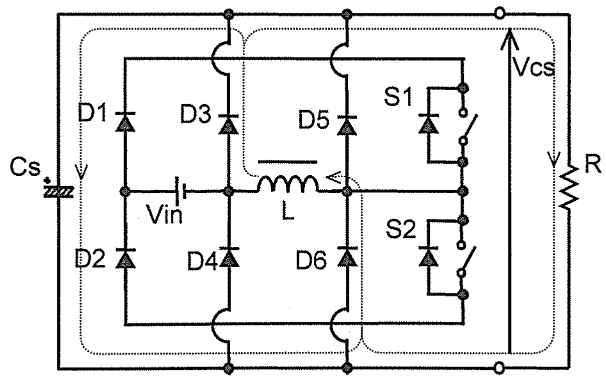

Figure 4.3: Current flow during state 2, S1:OFF S2:OFF

State 2 (S1: OFF S2: OFF)

Figure 4.3 shows the current flow during state 2. After state 1 both switching elements turns OFF (dead time) and counter electromotive-force current from inductor L accumulated during state 1 passes through diode D3, electrolytic capacitor Cs, diode D6. The circuit operation continues until all the energy stored in inductor (**L**) is used. The counter-electromotive force current flowing through inductor (**L**) is shown in Equation 4.3.

$$I_{Cs} = \frac{V_{in}}{L} T_{ON} - \frac{V_{Cs}}{L} \cdot T_{OFF}$$

... (4.3)

The time (T_{OFF}) needed to discharge the energy until the current due to the counter-electromotive force drops to zero ($I_{Cs} = 0$), is shown in Equation 4.4.

$$T_{OFF} = \frac{V_{in}}{V_{Cs}} T_{ON}$$

... (4.4)

The duty-cycle of the switches is 50%, thus the output voltage is equal to the input voltage as shown in Equation 4.5.

$$V_{Cs} = V_{in}$$

... (4.5)

The proposed neutral point type converter operates as a buck-boost converter circuit. Equation (4.3) ~ (4.5) are for calculating the designated current of inductor L.

From the circuit diagram schematics, each terminal point of inductor L, electrolytic capacitor Cs and resistor R are connected in parallel. Therefore the relationship between inductor's voltage (V_L) electrolytic capacitor's voltage (V_{Cs}) and load voltage (V_R) is shown in Equation 4.6

$$V_L = V_{Cs} = V_R$$

... (4.6)

From the current flow, the designated current of inductor L is equivalent to the designated current of electrolytic capacitor and the designated current of load, as shown in Equation 4.7

$$I_L = I_{Cs} + I_R$$

... (4.7)

Based on Equation 4.6 and 4.7, the inductor's terminal voltage is shown in Equation 4.8.

$$V_L = A\exp\left\{\frac{1}{2}\left(-\frac{1}{RCs}+\sqrt{\frac{1}{R^2Cs^2}+\frac{4}{LCs}}\right)t\right\} + B\exp\left\{\frac{1}{2}\left(-\frac{1}{RCs}-\sqrt{\frac{1}{R^2Cs^2}+\frac{4}{LCs}}\right)t\right\}$$

... (4.8)

The designated current of inductor during state 2 is shown in Equation 4.9.

$$I_L = A\left\{\frac{1}{R}+Cs(\alpha+\beta)\right\}\exp\{(\alpha+\beta)(t-t_1)\} + B\left\{\frac{1}{R}+Cs(\alpha-\beta)\right\}\exp\{(\alpha-\beta)(t-t_1)\}$$

... (4.9)

A and B are constant value and t_1 represents the time duration during the change of state 1 to state 2. The constant value A and B are expressed in Equation 4.10.

$$A = \frac{V_{in} t_1 R}{L\{1 + RCs(\alpha + \beta)\}[1 - \exp\{2\beta(t_2 - t_1)\}]}$$

$$B = \frac{V_{in} t_1 R}{L\{1 + RCs(\alpha - \beta)\}[1 - \exp\{-2\beta(t_2 - t_1)\}]}$$

... (4.10)

The time duration for the inductor to discharge the energy in state 2 is represented by t_2. α and β are represented as in Equation 4.11.

$$\alpha = -\frac{1}{2RCs}$$

$$\beta = \frac{1}{2}\sqrt{\frac{1}{R^2 Cs^2} + \frac{4}{LCs}}$$

... (4.11)

State 3 (S1: OFF S2: ON)

Figure 4.4(a) show the current flow during state 3. After state 2, switching element S2 turns ON, and continues the same current flow from state 2. Inductor's L energy discharges into electrolytic capacitor C and load R until all the energy is drained.

State 4 (S1: OFF S2: OFF)

Figure 4.4(b) shows the current flow during state 4. After state 3, switching element S2 turns OFF, and continues the same current flow from state 2 and 3. Inductor's L energy discharges into electrolytic capacitor C and load R until all energy is drained. State 2 and 4 can be considered as a dead time and happens only for 1.2 μ s.

For the neutral point type buck-boost converter, the direction of current flow during the positive half cycle of input voltage is directed by switching element S1 and during negative half cycle, the direction of current flow is directed by switching element S2.

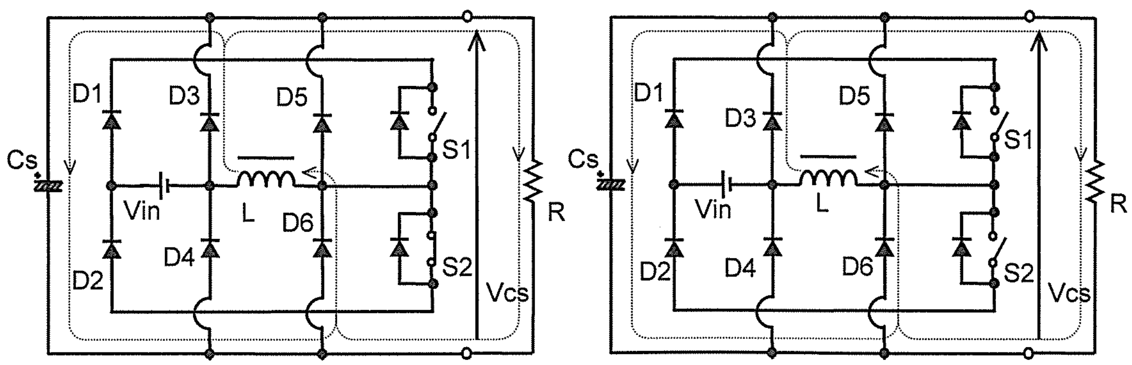

Figure 4.4: Current flow during (a) state 3 (S1: OFF S2: ON) and (b) state 4 (S1: OFF S2: OFF)

4.1.2 Circuit Experiment

The Neutral point type buck-boost converter circuit (Figure 4.1) was built and used with incandescent lamps. A low pass filter (cut-off frequency is 15 kHz) was connected to the input voltage. The output load was adjusted to have similar energy consumption to a fluorescent lamp (NIPPO FLR36T6W). To facilitate comparison, we set the output voltage of the proposed circuit to be the same as the previously developed neutral point type boost converter circuit output voltage, which is approximately 200V. Figure (4.5(a)) shows the input voltage and current of the converter and Figure (4.5(b)) shows the output voltage of the converter. The Neutral Point type buck-boost converter's circuit operation is a result of various combinations of the switching frequency of FET switching elements, the value of inductor L and the size of load. While considering the input current as a smooth sinusoidal waveform, which follows from equation (4.3), we adjusted the switching frequency of the FET switches and the inductor (L) value by trial and error.

The final combination of value satisfies the hypothesis stated in equation (4.3). Figure (4.6(a)) shows the calculated version of designated current of inductor from equation (4.9) and Figure (4.6(b)) shows a part of the measured designated current of inductor L in the proposed circuit. Figure (4.7) shows the value of the converter's output voltage as the inductor L value changes, when the FET switching frequency is 50 kHz.

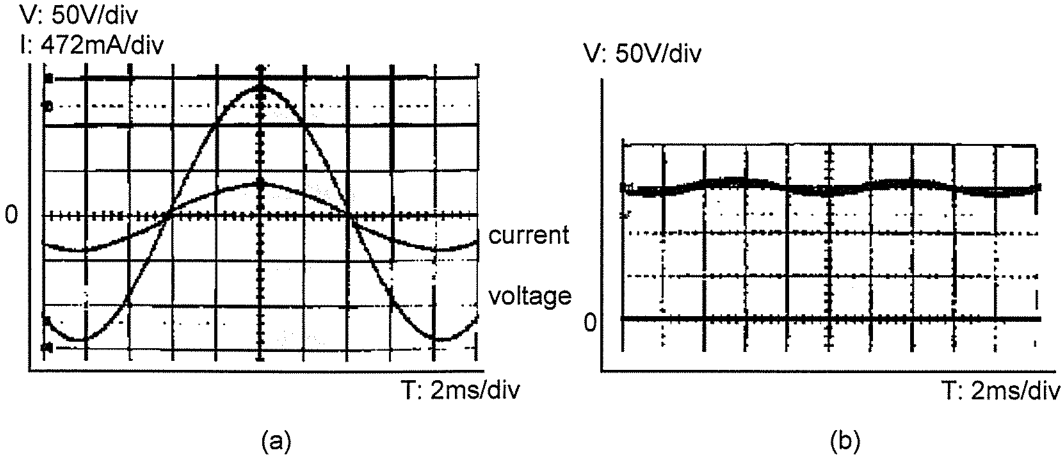

Figure 4.5: Waveform of (a) Input voltage and current and (b) output voltage of circuit diagram schematics in (Figure 4.1)

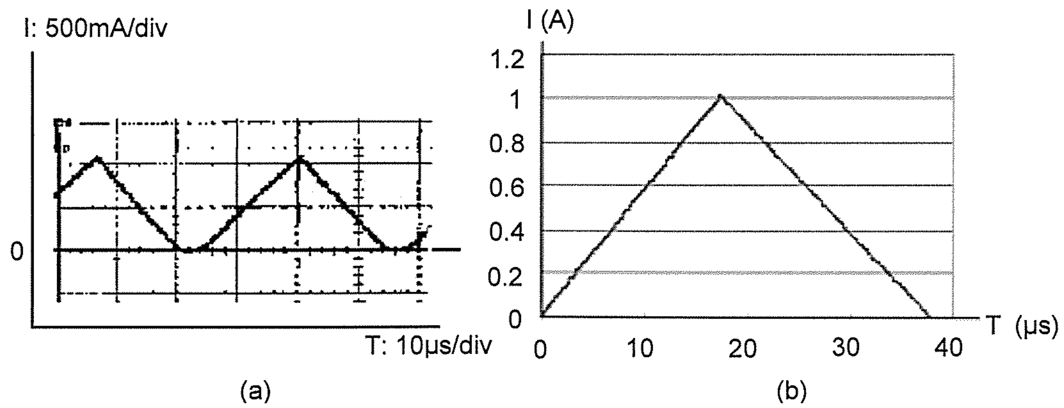

Figure 4.6: (a) Calculated inductor current waveform from Equation 4.9 and (b) Measured inductor current waveform

As the value of inductor L increases, it will plateau to a value around 100V of output voltage. The output of the converter would be the input voltage for the electronic ballast. Because the mains voltage in Japan is 100V, the authors decided to set the input voltage to 100V. According to Equations 4.5 and 4.6, the output voltage of the converter would be 100V. The converter output of 100V is not sufficient to power the half bridge inverter part of the electronic ballast and based on the neutral point type boost converter previously by the authors, the output voltage of the converter was 200V. In order to achieve a higher output voltage for the converter, we used a lower inductance value of inductor L in the circuit. In consideration of the neutral point type buck-boost converter output voltage value (Figure 4.7), the authors decided that the inductor L value should be approximately 1mH. The result of experiments with the neutral point type buck-boost converter using the decided value, as shown in Equation 4, confirm that the neutral point type converter is a current intermittence type converter.

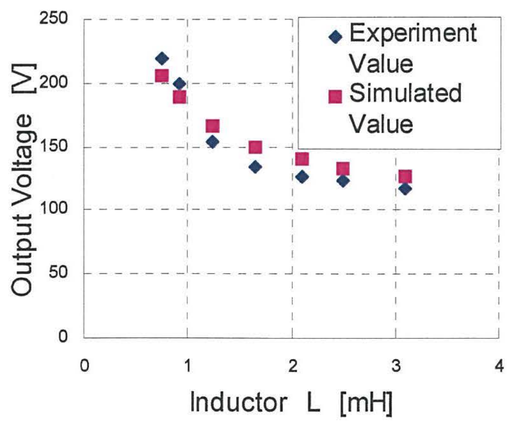

Figure 4.7: Neutral point type buck-boost converter output voltage against inductors value graph when input voltage is set to 100V.

4.2 Electronic ballast application

Figure 4.8 shows the Neutral point type buck-boost converter application to electronic ballast. In this circuit diagram schematics, direct current from neutral point type converter flows through diodes D7 and D8 and the switching elements S1 and S2. The switching elements are both shared within the converter and inverter circuit, thus a one-stage converter method electronic ballast is achieved. Half bridge inverter is used for the inverter part of the electronic ballast. Figure 4.8(b) shows the equivalent circuit of the electronic ballast. The direct current voltage source Vcs is the direct current output obtained in the neutral point type buck-boost converter. The equivalent circuit operation is controlled by the ON-OFF conditions of the switching elements and the relationship of state operation with switching element S1 and S2 are shown in chapter 2.

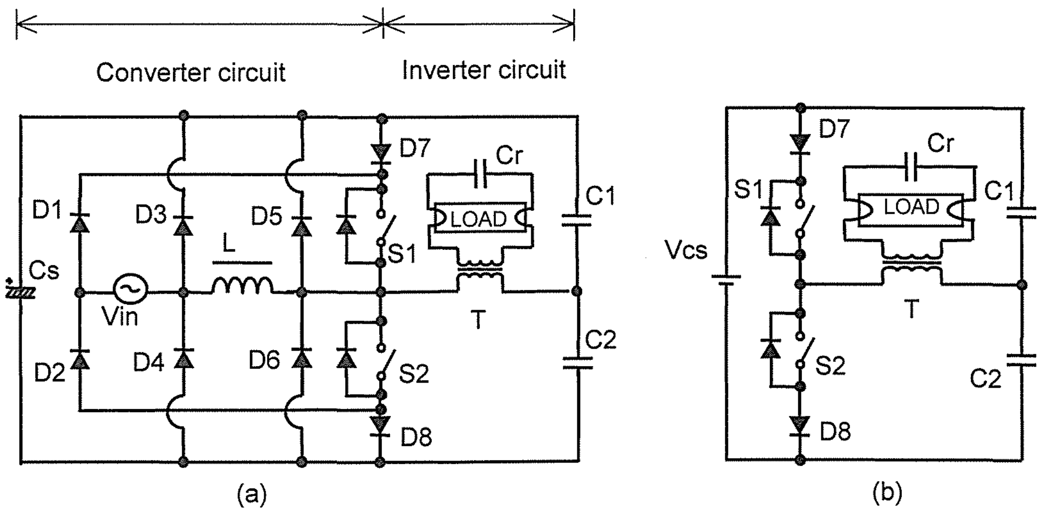

Figure 4.8: (a) Neutral point type buck-boost converter electronic ballast, (b) Direct current voltage (VCs) source is the output of the neutral point type buck-boost converter circuit.

4.2.1 Circuit Operation

State 1 (S1: ON S2: OFF)

As shown in Figure 4.9, electric current I_1 from direct current voltage Vcs flows through diode D7, switching element S1 and on to the primary winding of transformer T and capacitor C2. Energy stored during past circuit operation in capacitor C1 passes through diode D7 into primary winding of transformer T as current I'_1. The designated current flowing through the primary winding of the transformer is shown in equation 5.1

$$I_T = I_1 + I_1^{'}$$

… (5.1)

As a result both current I_1 and I_2 flowing in the primary transformer winding are equal and the voltage terminal point of C1 (V_{C1}) and C2 (V_{C2}) are shown in equation 5.2

$$V_{Cs} = V_{C1} + V_{C2}$$

… (5.2)

In state 1 , capacitor C1 is charging at the same time as capacitor C2 discharging. This implies that both capacitance C1 and C2 are the same at steady state as shown in equation 5.3

$$V_{C1} = V_{C2} = \frac{Vc}{2}$$

… (5.3)

At this point,

$$V_{C1} = \frac{q_1}{C_1}\ ,\ V_{C2} = \frac{q_2}{C_2}$$

$$\frac{dq_1}{dt} = I_1^{'}\ ,\ \frac{dq_2}{dt} = I_1$$

... (5.4)

Therefore

$$I_1 = I_1^{'}$$

... (5.5)

As a result, the current flowing through the primary winding of transformer T becomes 2I1.

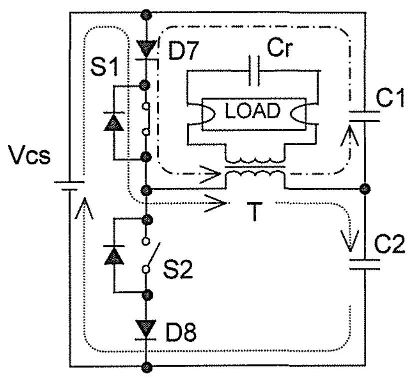

Figure 4.9: Current flow during state 1 (S1: ON S2: OFF)

State 2 and State 4 (S1: OFF S2: OFF)

The circuit operation of state 2 and state 4 Figure 4.10(a) occurs after state 1 and state 3. During this state, there is no current flow but happens only for 1.2μs.

State 3 (S1:OFF S2:ON)

The circuit operation during state 2 is shown in Figure 4.10(b). Electric current I_2 from direct current voltage source flows into capacitor C1 and primary winding of transformer T through switching element S2 and diode D8. The circuit operation in state 2 is similar to that in state 1, with the exception that the current flowing through the primary winding is of opposite polarity.

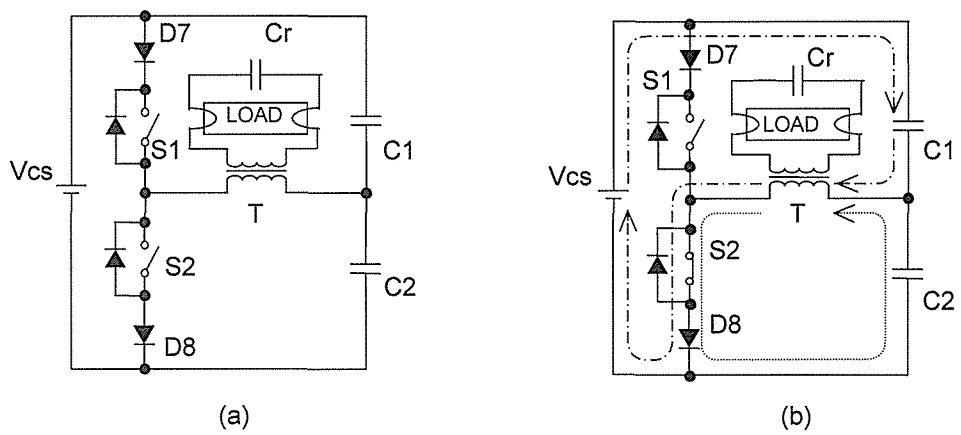

Figure 4.10: (a) No current flow during state 2 and 4 (S1: OFF S2: OFF) (b) Current flow during state 3 (S1: OFF S2: ON)

4.2.2 Experiment Results

The neutral point type buck-boost converter electronic ballast was built and experimented with fluorescent lamp as load. A low-pass filter (cut-off frequency 15 kHz) was connected in parallel to the input voltage. The low-pass filter facilitated measurements while changing the value of circuit elements and switching frequency during the experiment. Table 4.1 shows the circuit electrical parameters used during the experiment. Table 4.2 shows the electronic parts used in the experiment.

Table 4.1: Experiment results

Input voltage	100.0V	Lamp voltage	133.5V
Input current	0.239A	Lamp current	0.340A
Input power	24.0W	Lamp power	18.2W
Power factor	99.6%	Oscillation frequency	49.5kHz

Table 4.2: Experiment parts parameter of circuit in (Figure 4.8).

Part	Specification
FET S1,S2	IRF840L
Diode D1-D8	5GLZ47
Electrolytic capacitor Cs	500V 22μF
Capacitor Cr	1.6kV 8.2nF
Capacitor C1, C2	630V 100nF
Inductor L	0.905mH
Transformer T	Primary:0.946mH Secondary:3.64mH
Half bridge driver	IR2153
Fluorescent lamp	FLR36T6W

The neutral point type buck-boost electronic ballast input current waveform is smooth and sinusoidal (Figure 4.11). The lamp voltage and the lamp current are smooth sinusoidal waveforms (Figures 18 and 19, respectively). In addition the output voltage and output current have low ripple count. The electronic ballast has low harmonics content and satisfies the IEC harmonics limits standard for Class C (Figure 4.14). The circuit system has no input surge current due to capacitor bank energization compared to the Neutral Point type boost converter system as the system has a closed circuit between the power source and the smoothing capacitor Cs. The inrush current peak value in the circuit system (Figure 4.8) only occurs due to the low-pass filter and only when the switching elements are turned ON.

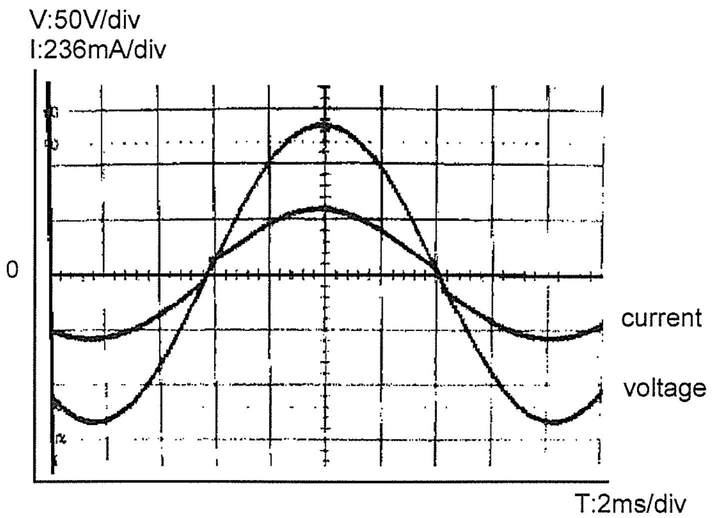

Figure 4.11: Input voltage and current waveform

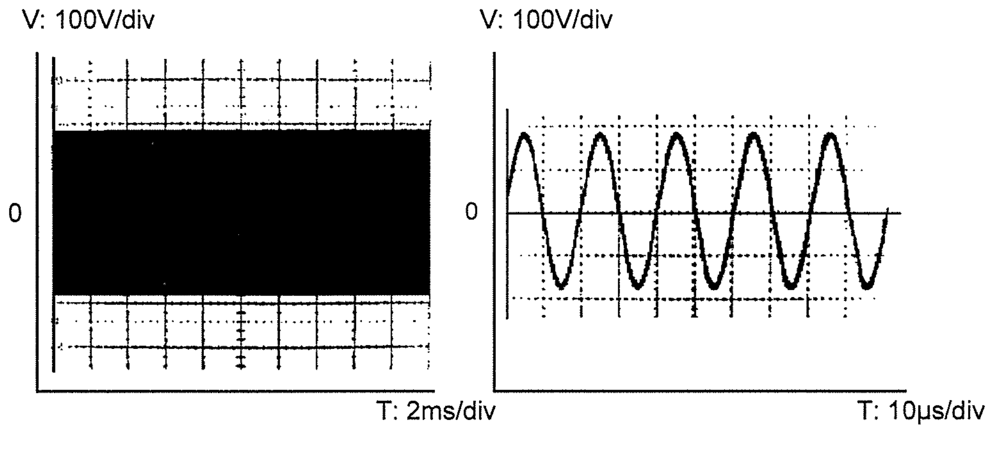

Figure 4.12: Output voltage waveform

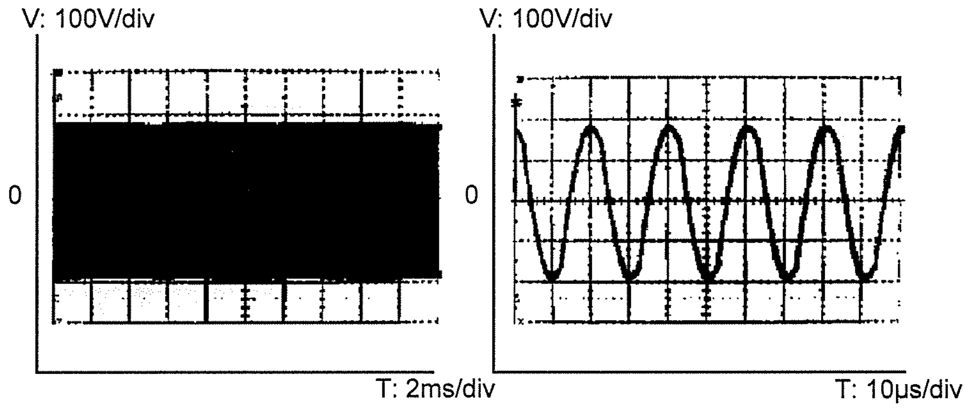

Figure 4.13: Output current waveform

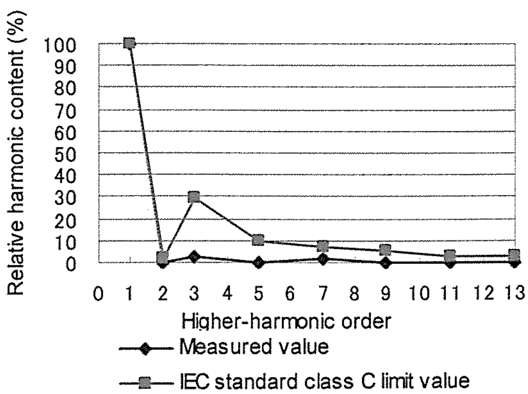

Figure 4.14: Content rates of harmonic distortion of input current with IEC harmonic limit standard for class C

Figure 4.15(a) shows the inrush current at time of power supply injection from power source when switching elements are not operational. Figure 4.15(b) shows the inrush current when low pass filter is inserted. This confirms that inrush current only occurs due to low pass filter and only when the switching elements are turned ON compared to the Neutral point type boost converter system shown in Figure 4.16.

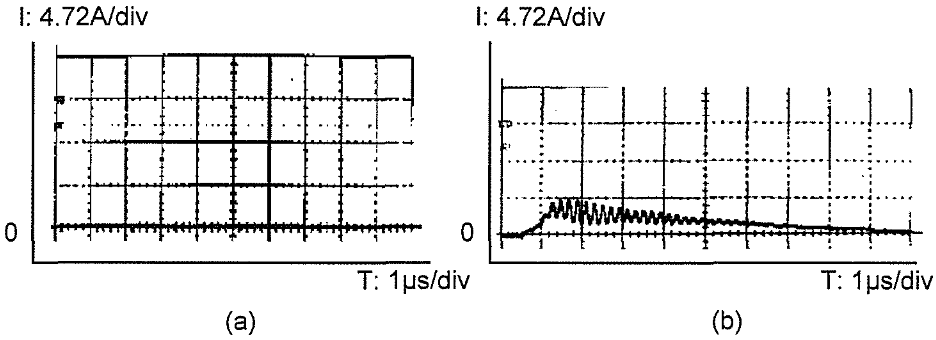

Figure 4.15: Inrush current of the Neutral Point type buck-boost converter electronic ballast, (a) without low-pass filter and (b) with low-pass filter.

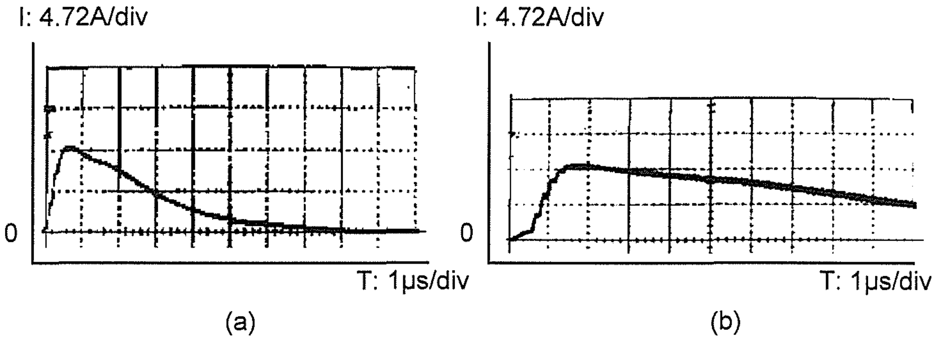

Figure 4.16: Inrush current of the Neutral Point type boost converter electronic ballast, (a) without low-pass filter and (b) with low-pass filter.

4.3 Circuit Comparisons

Circuit comparison (Electronic ballast) was made between;

(a) Commercially available two-stage electronic ballast developed by Toshiba (Figure 4.17 (a))

(b) Commercially available two-stage electronic ballast developed by National (Figure 4.17(b)).

(c) The one-stage electronic ballast based on the Neutral Point type Boost converter designed by our laboratory and commercialized by NIPPO (Figure 4.17(c)).

(d) The one-stage electronic ballast based on the Neutral Point type Buck-boost converter (circuit schematic in Figure 4.8).

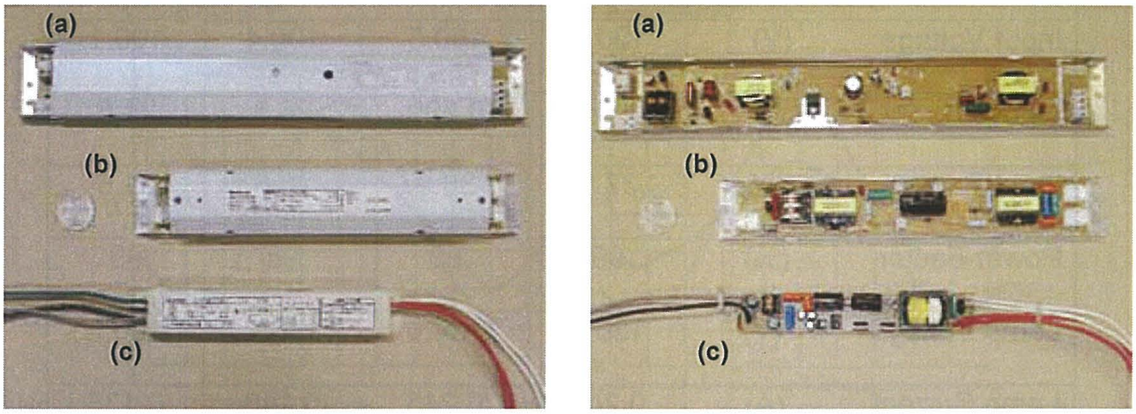

Figure 4.17: Experimented electronic ballast

From Figure 4.17, we found that the one-stage converter electronic ballast requires only one transformer instead of two is more compacted and miniaturized compared to the two-stage converter electronic ballast. Nevertheless, this is not a perfect comparison because electronic ballast makers designed the circuit for suited fluorescent lamp with different sizes and length. Due to our equipment and laboratories limitation, the load we used in this experiment is the NIPPO FLR36T6W which is the appropriate load to the NIPPO electronic ballast (Figure 4.17(c)). However, the load is in the same class of a typical 40W type fluorescent lamp for all the electronic ballast in this comparison. Table 4.3 shows the circuit electrical parameter used during the experiment. All four electronic ballast has very high power factor. The Neutral Point type electronic ballast has slight higher circuit efficiency compared to the other electronic ballast.

Table 4.3: Electrical parameter of each electronic ballast

	(a)	(b)	(c)	(d)
Input Voltage (V)	100.8	100.5	100.4	100.1
Input Current (A)	0.377	0.390	28.6	21.6
Input Power (W)	37.6	38.9	28.6	21.6
Power Factor (%)	99	99	98	99
Lamp Voltage (V)	136.0	134.0	170.2	136.2
Lamp Current (A)	0.249	0.245	0.146	0.136
Lamp Power (W)	38.86	32.83	24.9	18.5
Circuit Efficiency (%)	82	84	87	85

Figure 4.18 shows the input voltage and current waveform and input currents harmonic distortion level with comparison to IEC limit standard is shown Figure 4.19 for all four electronic ballast.

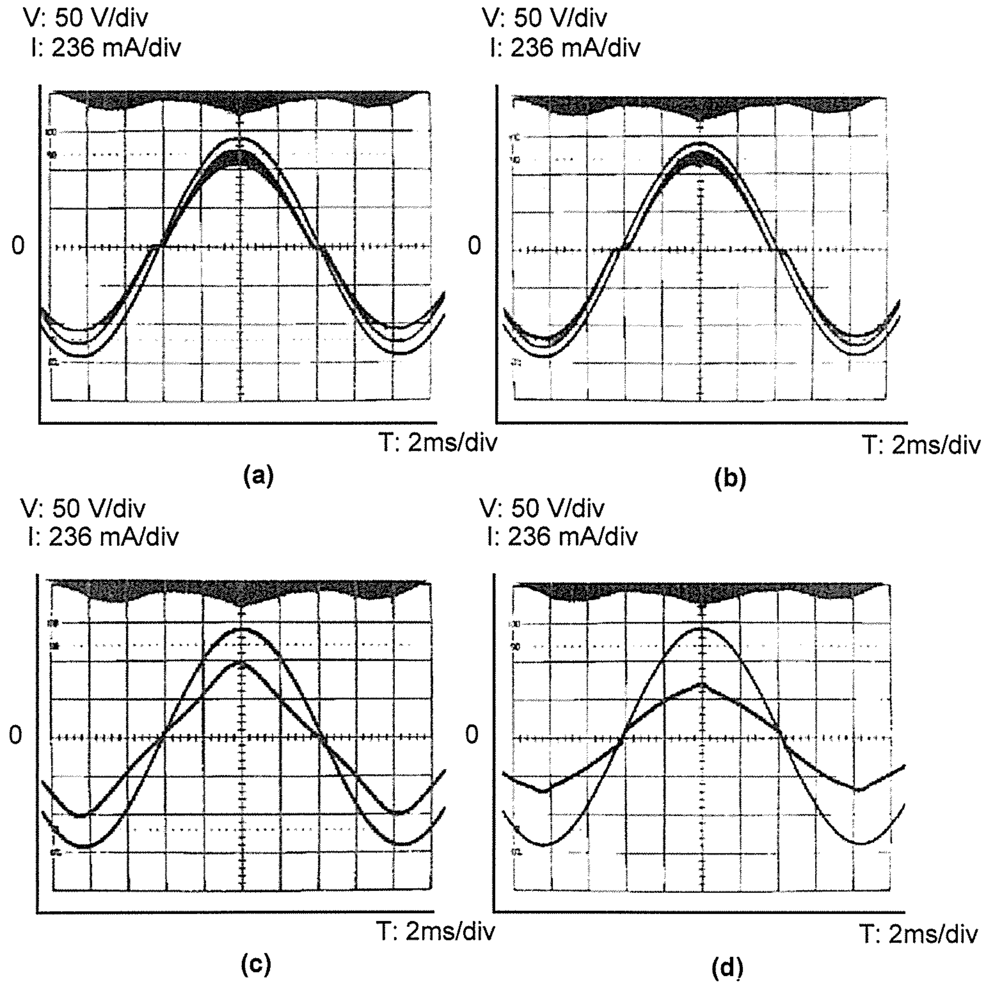

Figure 4.18: Input voltage and current waveform

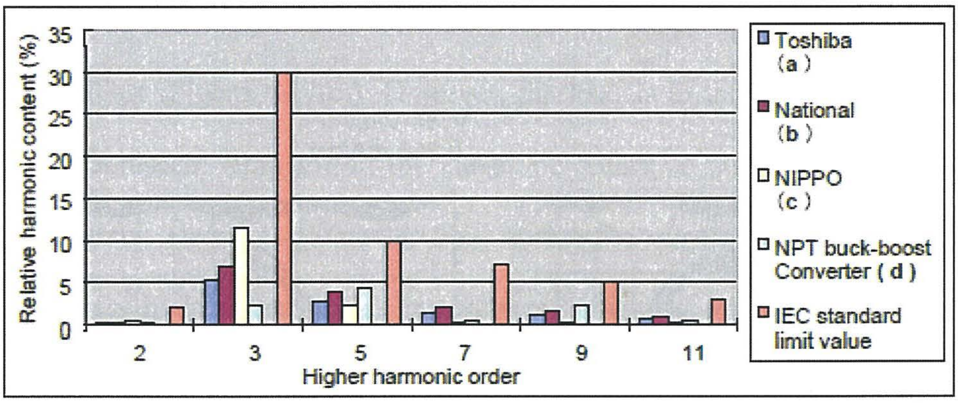

Figure 4.19: Content rates of harmonic distortion of input current with IEC harmonic limit standard for class C

All four circuits satisfy the IEC harmonic distortion limitation standard. Next, Figure 4.20 shows the output voltage and current of the circuits. Figure 4.21 shows the enlarged caption of the output voltage and current waveform.

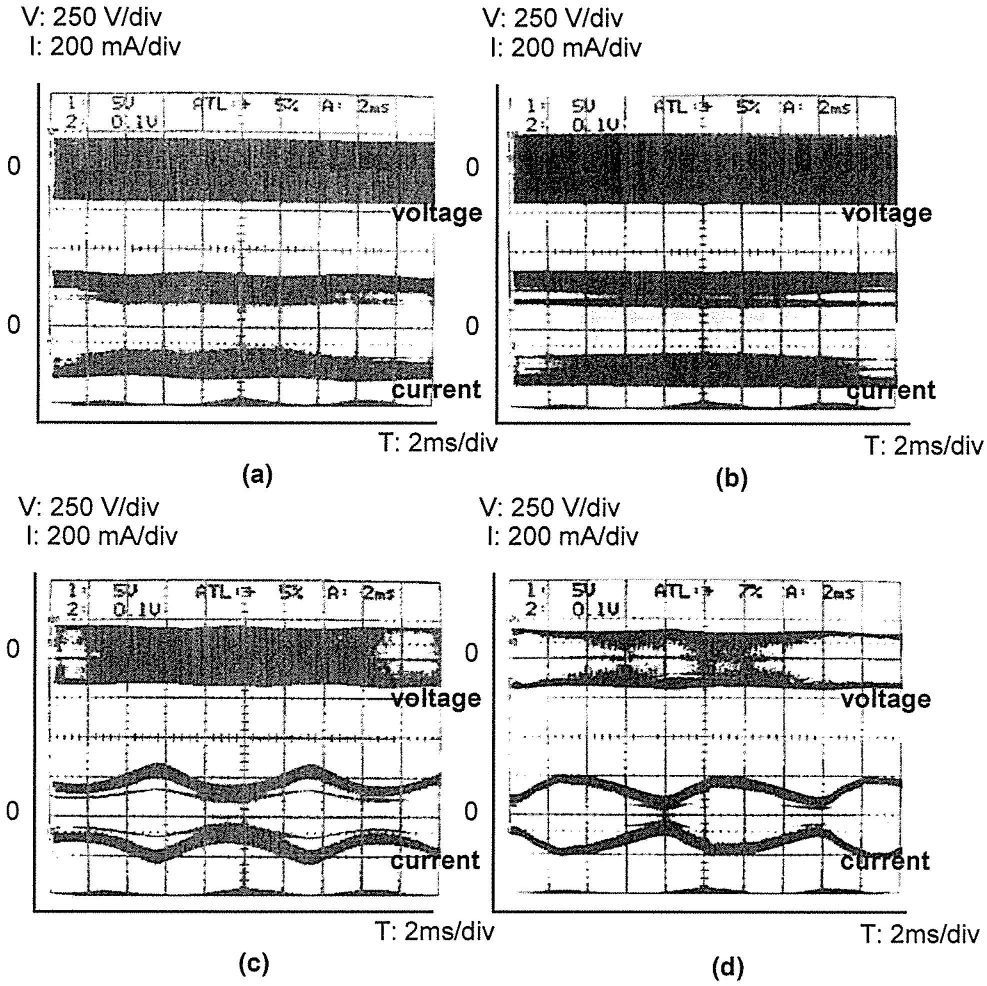

Figure 4.20: Output voltage and current

Both of the two-stage converter circuit electronic ballasts (Figure 4.20 (a) and (b)) output voltage and current waveform has no ripple. Meanwhile for the one-stage converter electronic ballast (Figure 4.20 (c) and (d)), the output voltage has shown slight ripple but becomes very clear for the output current.

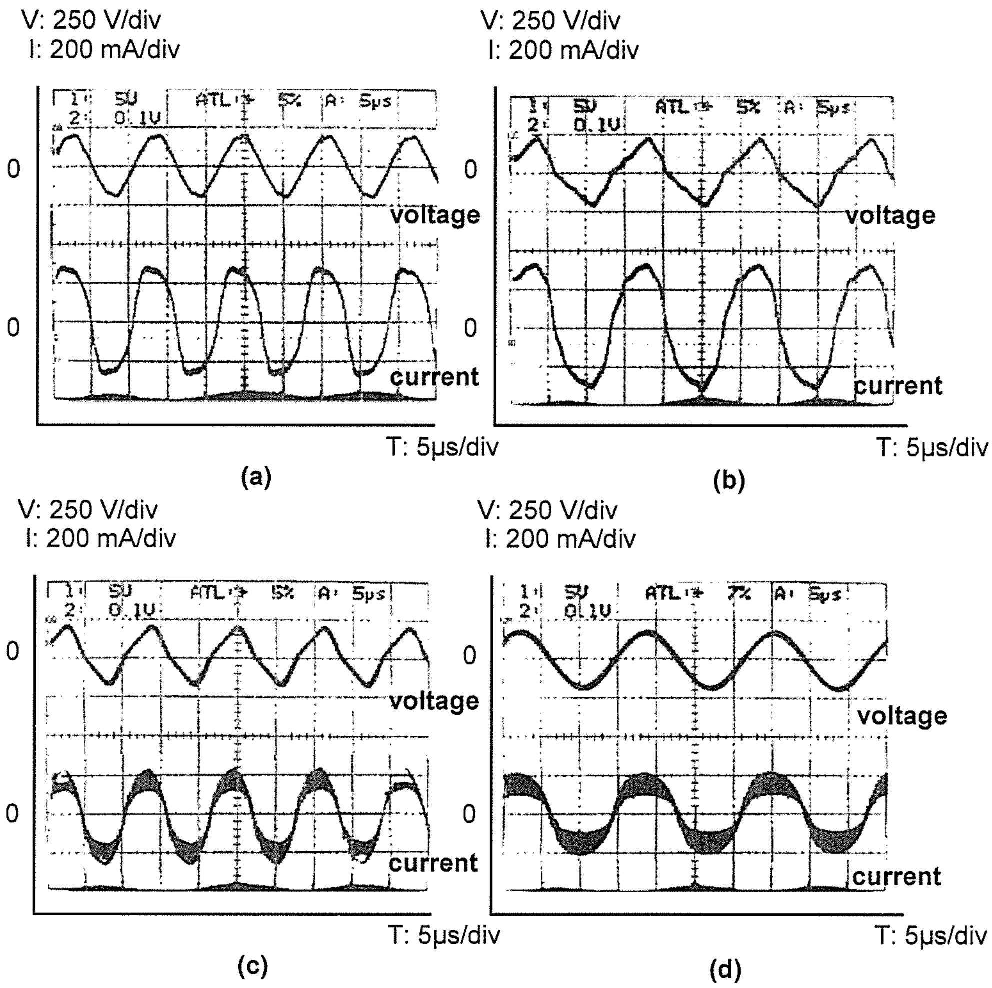

Figure 4.21: Enlarged caption of the output voltage and current.

Luminous efficiency can be determined by the lamp voltage and current waveform. Sinusoidal waveform means higher efficiency. From Figure 4.21, neutral point type buck-boost converter electronic ballast has better efficiency. Meanwhile the other 3 commercialized electronic ballast output voltage became close to a triangular waveform. This is due to effects of various protection circuit built into the electronic ballast

4.4 Summary

In this chapter, the neutral point type buck-boost converter is introduced to reduce the inrush current, the problematic neutral point type boost converter system. The neutral point type buck-boost converter's circuit configuration is design so that no closed loop between input source voltage and the electrolytic capacitor existed thus reduces inrush current. Current only from inductors flows through electrolytic capacitor into load thus making it less complicated. The circuit was experimented results shows that it runs safely, achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards. The circuit was also compared with other commercialized electronic ballast and the results shows that the electrical characteristic, power factor and circuit efficiency is the same or higher. Next chapter will discuss the application of this circuit together with the neutral point type boost converter.

CHAPTER 5 Application of Neutral Point type Converter

5.1 Neutral Point type Voltage Free converter

The voltage free electronic ballast enables a wider range of input voltage to light-up the fluorescent lamp. The voltage free electronic ballast in Figure 5.1 is a two-stage electronic ballast. The circuit has two separate set of control unit circuit for both the converter and inverter parts of the circuit. The voltage output of the converter part in the circuit is constantly inspected and the feedback circuit adjusts the frequency and duty ratio of switching element. The circuit system is complicated, needs many circuit elements and large circuit size which increases cost [16]. Therefore we consider applying the one-stage converter circuit as voltage free electronic ballast. Most building's input voltage source main's fixtures in Japan are the 200V line and the 100V line. By only switching ON and OFF of a mechanical switch, the electronic ballast can allow input voltage of 200V and 100V. This can be realized with the neutral point type converter circuit developed by our laboratory. The circuit a simple system, uses less circuit elements and control unit circuit [7][14][15]. The neutral point type voltage free converter can convert from boost operation to buck-boost by only switching ON and OFF the mechanical switch.

5.1.1 Circuit Topology

Figure 5.2 shows the neutral point type voltage free converter circuit diagram schematics. The circuit can accommodate input voltage of 100V and 200V. Switches S1 and S2 are turned ON and OFF both on the same time, therefore switch S1 and S2 can be represented as switch S. Switches S1 and S2 are combined to form one mechanical jump switch such as SCR's or voltage controlled switch. When switch S is turned ON and input mains voltage is set to 100V, the circuit operation resembles the neutral point type boost converter circuit. Both current from input mains and counter-electromotive force of the inductor flows into electrolytic capacitor during discharge (boost operation), and the output voltage is twice the amount of input voltage [14][33]. When switch S is turned OFF and input mains voltage is set to 200V, the circuit operation resembles the neutral point type buck-boost converter circuit. Current only from counter-electromotive force of the inductor flows into electrolytic capacitor during discharge (buck-boost operation), and the output voltage is the same amount as the input voltage [27][34].

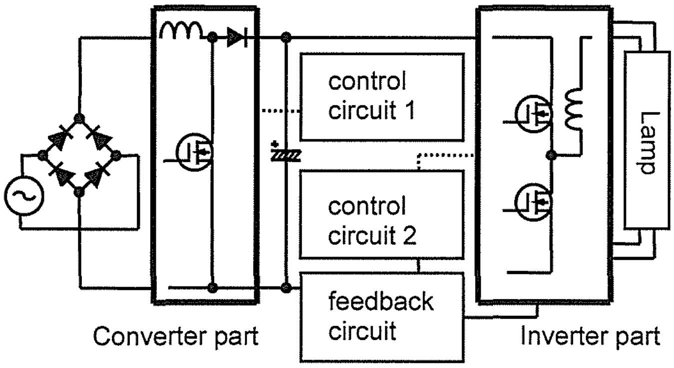

Figure 5.1: Circuit schematic diagram of two-converter method voltage free electronic ballast with 100V-242V input mains tolerance.

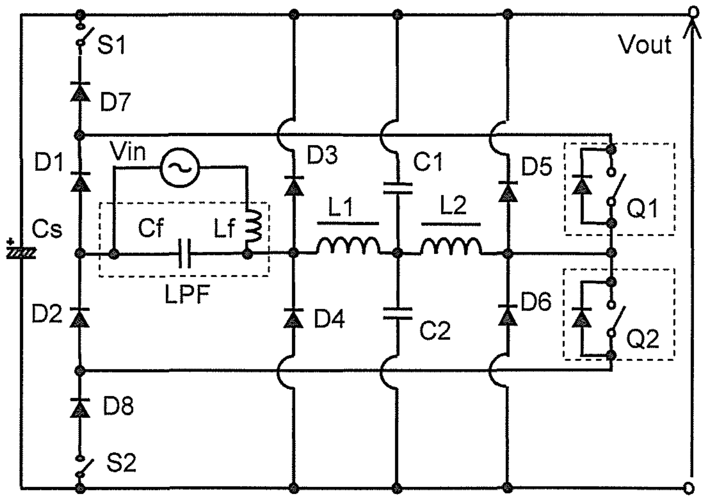

Figure 5.2: Neutral point type voltage free converter circuit schematic diagram

5.1.2 Experiment of the converter circuit

The circuit (Figure 5.2) was built and used with incandescent lamps as load. The output load was adjusted to have similar energy consumption to a fluorescent lamp (NIPPO FLR36T6W). First, the input source voltage is set to 200V and mechanical switch S (S1 and S2) is turned OFF. The converter circuit's output voltage is shown in Figure 5.3(a). Next, the input source voltage is changed to 100V and mechanical switch S (S1 and S2) is turned ON. The converter circuit's output voltage is shown in Figure 5.3(b). The experiment result shows that when the input voltage is either 100V or 200V, the converter circuit's output voltage is around 280V is achievable and output voltage is almost the same. Similar output voltage or constant power source is needed to minimize the output power difference between input voltage of 100V and 200V. The switching element's (Q1 and Q2) duty-cycle is set to 50% and this value cannot be adjusted. This is because the switching elements are also used as switches for the inverter part of the electronic ballast; therefore it cannot tolerate input voltages other than 100V and 200V.

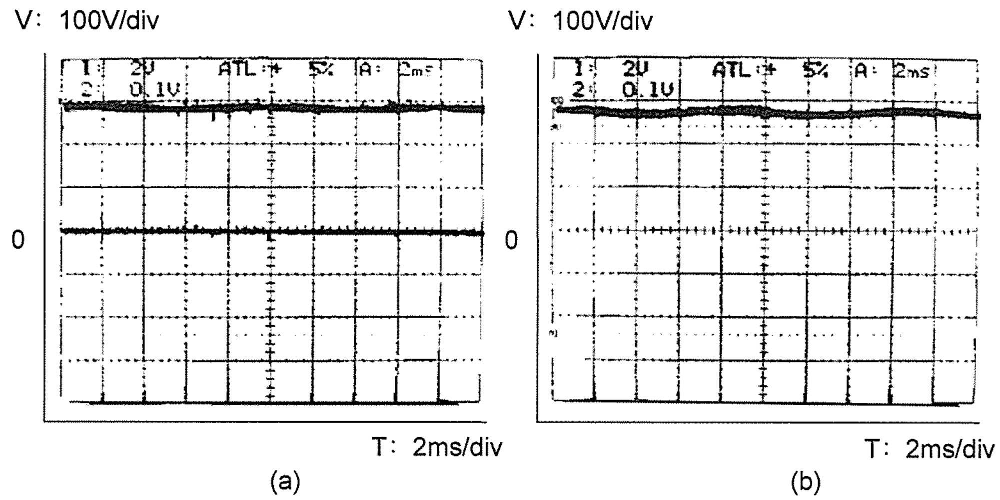

Figure 5.3: Output voltage waveform of the converter circuit during, (a) Switch S is to be turned OFF and input voltage set to 200V and (b) Switch S is to be turned ON and input voltage is set to 100V. Output voltage around 280-300V is achievable for input voltage of 100V and 200V

5.2 Electronic ballast application experiment and results

The circuit schematic diagram of the electronic ballast is shown in Figure 5.4. In this circuit, direct current from neutral point type voltage free converter circuit flows through diode D9 and D10 and the switching elements (Q1 and Q2). Both switching elements (Q1 and Q2) operate as switches for the converter and the inverter parts of the electronic ballast, thus reducing circuit element. Upon ignition the capacitor Cr warms the filament of the lamp and during steady state, power oscillates back and forth between the capacitor Cr and the secondary winding of transformer T.

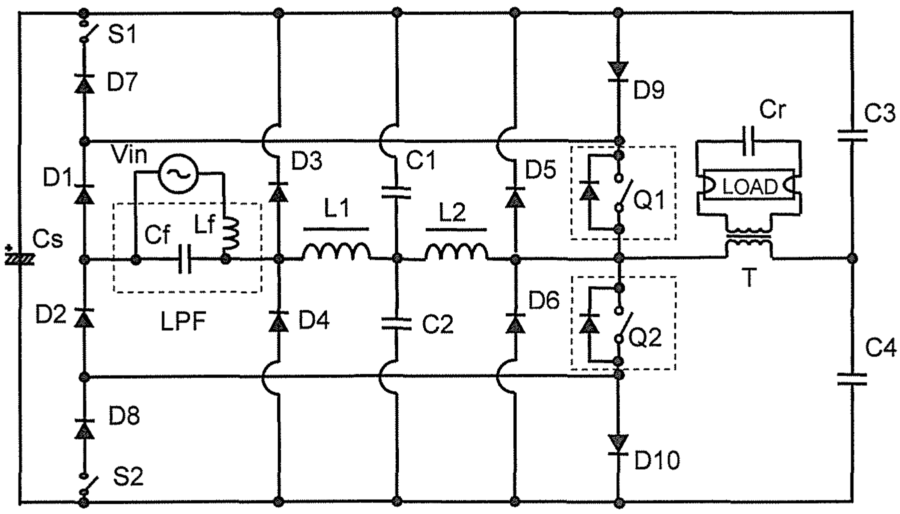

Figure 5.4: Neutral point type voltage free converter electronic ballast circuit diagram schematic

The circuit (Figure5.4) was built and experimented with fluorescent lamp as load. Table 5.1 and 5.2 show the circuit electrical parameters used during the experiment. Table 5.3 shows the electronic parts used in the experiment. A low pass filter was connected in parallel to the input voltage to facilitate measurements while the value of circuit elements and switching frequency is varied during the experiment.

Table 5.1: Experiment results (Switch S turns ON)

Input voltage	100V	Lamp voltage	107V
Input current	0.309A	Lamp current	0.24A
Input power	30.6W	Lamp power	25.68W
Power factor	98%	Oscillation frequency	95kHz

Table 5.2: Experiment results (Switch S turns OFF)

Input voltage	200V	Lamp voltage	110V
Input current	0.172A	Lamp current	0.235A
Input power	31W	Lamp power	25.85W
Power factor	90%	Oscillation frequency	95kHz

Table 5.3: Electronic parts parameter of Figure 5.4 experimented circuit

Part	Specification
FET Q1, Q2	IRF840L
Diode D1-D10	5GLZ47
Electrolytic capacitor Cs	500V 22μF
Capacitor Cr	2.17nF
Capacitor C1,C2	2.2nF
Capacitor C3,C4	5.57nF
Inductor L1	0.656mH
Inductor L2	0.645mH
Transformer T	Primary :1.6mH Secondary :1.6mH
Half bridge driver	IR2153
Fluorescent lamp	FLR36T6W

The waveform input voltage and current are nearly a perfect sinusoidal waveform (Figure 5.5) and the relative harmonic content of the input current was measured during both 200V and 100V input voltage.

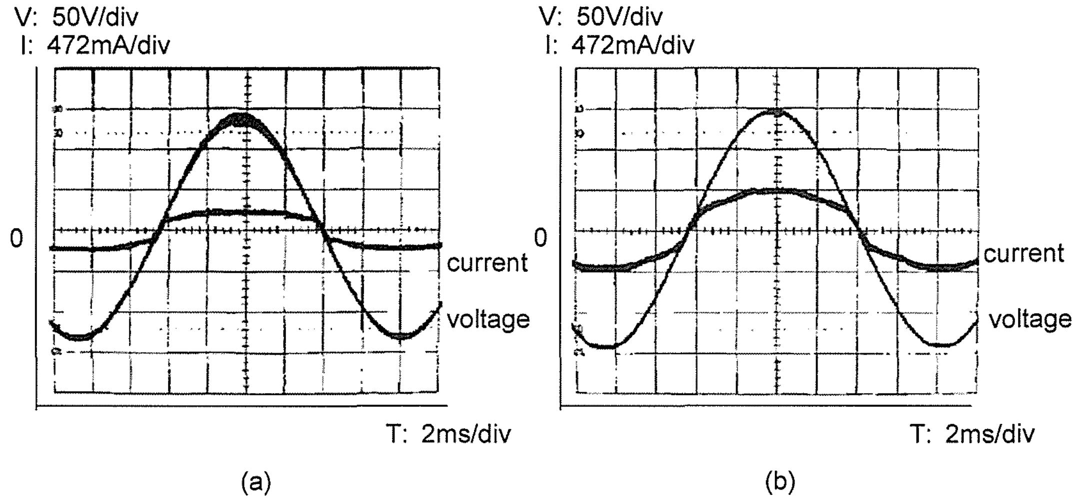

Figure 5.5: Input voltage and current waveform of the voltage free electronic ballast during, (a) Switch S is turned OFF and input voltage set to 200V and (b) Switch S is turned ON and input voltage is set to 100V

Figure 5.6 shows the harmonic content compared to IEC harmonic standard 61000-3-2 class C. The relative harmonic distortion content limit for both 200V and 100 V was satisfied.

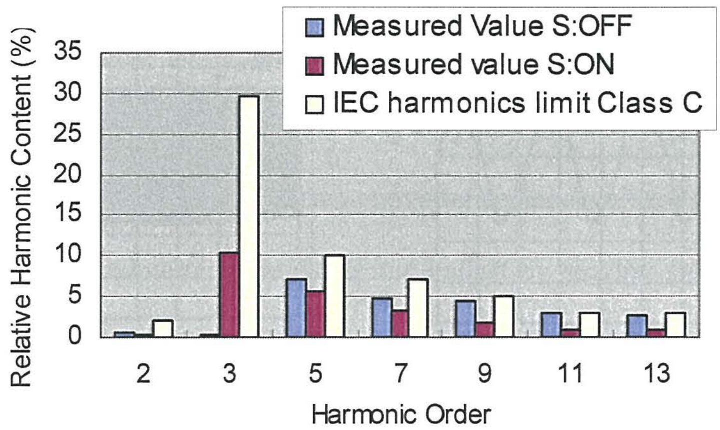

Figure 5.6: Content rates of harmonics of the input current of proposed system with IEC harmonics limit standard for Class C

The output voltage is almost flat with low ripple (Figure 5.7), and with the enlarged scale, the output voltage is nearly a perfect sinusoidal waveform during both 200V and 100V input voltage.

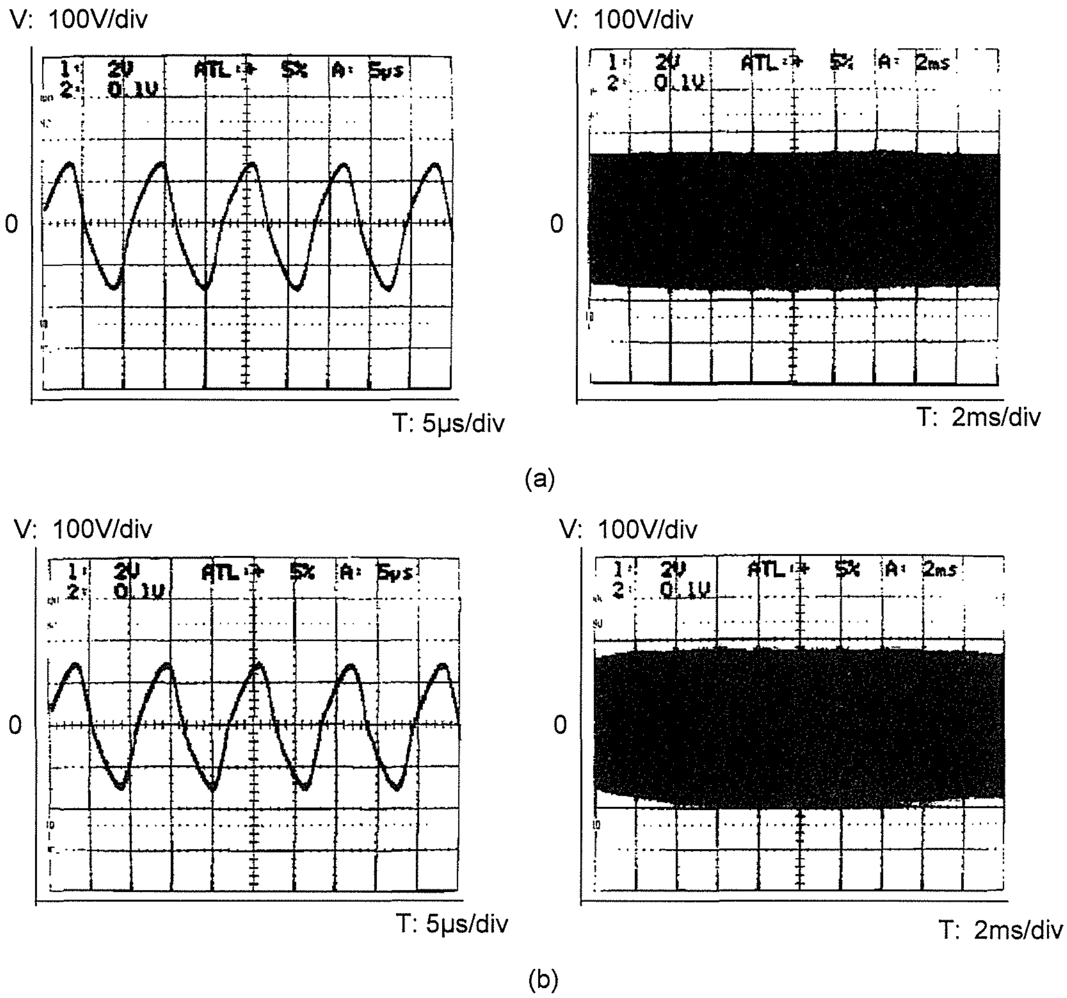

Figure 5.7: Output voltage waveform of the voltage free electronic ballast during, (a) Switch S is turned OFF and input voltage is set to 200V and (b) Switch S is turned ON and input voltage is set to 100V

5.3 Summary

In this chapter, the voltage free converter, an application of the Neutral Point type boost converter and Neutral Point type buck-boost converter in one circuit. This circuit can receive 100V and 200V input voltage mains as in most building in Japan. By only turning mechanical switch ON and OFF, the electronic ballast can suite both voltages. Mechanical switch can also be replaced with automatic switches such as SCR'S or voltage controlled switches. The circuit is a simple system and uses less circuit elements and control unit circuit compared to the two-converter method voltage free system. This circuit is applied to one-converter type electronic ballast by sharing switching elements by both converter and inverter circuit. Electronic ballast circuit was experimented and results shows that it runs safely achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

CHAPTER 6 Conclusions

Nearly 20% of electricity consumption is used for illumination in Japan. Advancement in power electronics with the introduction of solid state electronic equipments gives way to improve efficiency and more importantly reduce energy consumption of the illumination equipment. Solid state electronic equipments operate is high frequency and is the major cause of harmonic distortion that causes surge and lower the power quality. This effects other electronic equipments that are connected to the grid or system. To eliminate damages caused by harmonic distortion, IEC standard or other strict guideline has been set for electronic equipment including illumination equipments. In order to satisfy these guidelines, many type of electronic ballast has been proposed notably the two-stage electronic ballast. This thesis is about the research development of the Neutral Point type converter and its application to one-stage electronic ballast

Total Harmonic Distortion emitted by the electronic ballast, types of filtering method and filtering circuits were discussed. The one-stage electronic ballast for illumination equipment was proven to have more advantages compared to the two-stage electronic ballast in terms of cost and without sacrificing power factor and efficiency.

The Neutral point type boost converter method system was analyzed and this circuit can be applied to a one-stage electronic ballast by sharing two switching elements with both converter and inverter part of the electronic ballast. The improvised Neutral Point type boost converter allows input current form mains to be drawn into the circuit even during low voltage point by adding two additional capacitors operating as charge-pumps in the circuit. The PFC converter further miniaturizes the electronic ballast by reducing circuit elements. Capacitor of the inverter part of the circuit is shared with the common-mode filter, by placing the common-mode filter in the inverter part of the circuit. All three circuits were experimented and results shows that it runs safely while achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

The drawback of the Neutral Point type boost converter, which is the inrush current, occurs during initial start-up of the electronic ballast is addressed. The Neutral Point type buck-boost converter's circuit configuration is designed so that no closed loop between input source voltage and the electrolytic capacitor existed thus reduces inrush current. Current only from inductors flows through electrolytic capacitor into load, making it less complicated. The circuit was experimented and the results show that it runs safely while achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

The application of both Neutral Point type boost converter and Neutral Point type buck-boost converter to the voltage free converter is presented. This circuit can receive 100V and 200V input voltage mains as in most buildings in Japan. By only turning ON and OFF of the mechanical switch, the electronic ballast can suite both voltages. The circuit is a simple system and uses less circuit elements and control unit circuit This circuit is applied to the one-converter type electronic ballast by sharing switching elements by both converter and inverter circuit. Electronic ballast circuit was experimented and results show that it runs safely while achieved high power factor and satisfies the IEC 61000-3-2 harmonic distortion limit standards.

This thesis gives us useful knowledge on electronic ballast for illumination equipment. Most of the electronic ballasts proposed in this thesis are developed based on the Neutral Point type electronic ballast circuit. Future research would be on developing the Neutral Point type buck converter for application to electronic ballast. Using only buck-boost operation or other method beside boost and buck-boost operation in creating a one converter voltage free circuit based on the Neutral Point type converter would be the next task for research, also in the future, applying this circuit method to other type of load that requires high frequency, low noise or distortion level beside illumination can be considered. .One major limitation that still remains is that noise due to high frequency switching operation. This can be solved by applying soft switching technique in the future research.

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RESEARCH ACHIEVMENTS

1. Scientific Journal Publication

Author , Paper title, Journal , Date		Chapter
1	Nabil M HIDAYAT, Masaaki NAKAMURA, Yoshito KATO, Nobuo TAKAHASHI, Ichiro YOKOZEKI and Yoshio ITOH " Development of a Neutral Point Type Converter and Application as an Electronic Ballast, " Journal of Light & Visual Environment, The Illuminating Engineering Institute of Japan, 2010 Vol.34 No.1, pp 47-54, April 2010.	4
2	Nabil M HIDAYAT, Yoshito KATO, Yoshio ITOH, " One-stage Converter Method Neutral Point Type Voltage Free Converter and Application to an Electronic Ballast " Journal of Light & Visual Environment, The Illuminating Engineering of Japan, 2010 Vol.34, No.3, pp 138-145, December 2010.	5
3	Nabil M HIDAYAT, Masaaki NAKAMURA, Yoshito KATO, Yoshio ITOH, "Electronic Ballast Using Neutral Point Type Buck Converter", Journal of Light & Visual Environment, The Illuminating Engineering of Japan, 2011 Vol.35, No.2 (to be publish), August 2011.	

2. Conferences Proceedings

	Author , Title , Conference , Date	Chapter
1	Nabil M. HIDAYAT, Masaaki NAKAMURA, Yoshito Kato, Nobuo TAKAHASHI, Yoshio ITOH, "One converter Type Voltage Free Neutral Point Type Converter and Application to Electronic Ballast", IEEE International Conference on Industrial Technology (ICIT2008), Chengdu China 21-24 April 2008, IEEE Catalog No. CFP08CIT-CDR, WA2B5	5
2	Nabil M. Hidayat, Yoshito Kato, Yoshio Itoh, Nobuo Takahashi, Ichiro Yokozeki, " Neutral Point type Boost Chopper Circuit and Application to electronic ballast ", The 2nd International Power Engineering and Optimization Conference (PEOCO2008) Malaysia, 4-5 June 2008, ISBN 978-983-9414-83-7 CDR, Session R1-5	3
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4	Yoshito Kato, Masaaki Nakamura, Nabil M. Hidayat, Nobuo Takahashi, "Improvement of an input waveform of a Neutral Point Type Step-down Converter", PEDES 2006, New Delhi, India, 12-15 December 2006, IEEE Catalog No. 06TH8899C, 3A-14	3
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