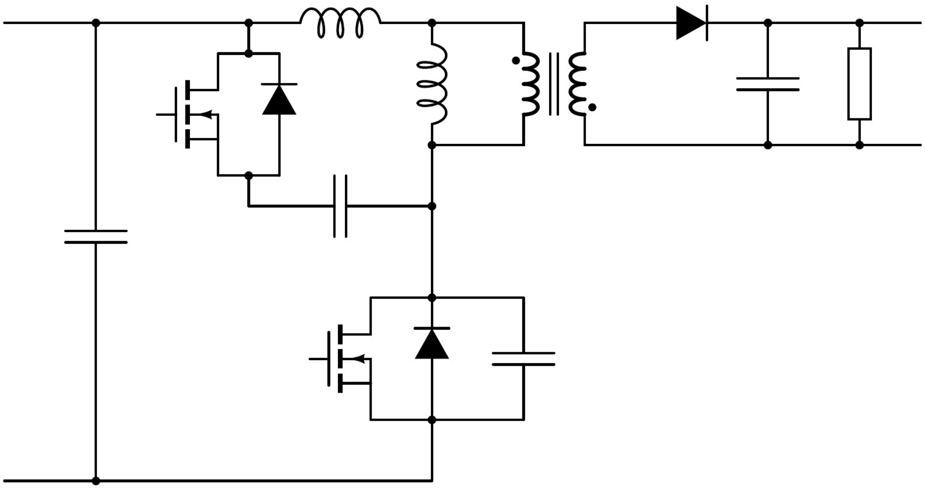

Implementation of highly efficient converter for DC residential supplies

Implementation & life cycle cost analysis of a highly efficient DC/DC- converter in a DC powered residence

Bachelor's thesis in Electrical Engineering

HABIBULLAH NASERI
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DEPARTMENT OF ELECTRICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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Cover: Topology of an active clamp flyback converter with resistive load.

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Abstract

Historically, the AC systems has been dominating the energy, generation, transmission, and distribution sector. But research has shown that at a residential level, the AC to DC conversation can be eliminated by supplying the household loads with a DC source. This leads to cutting the AC/DC conversion losses and focusing on making the DC/DC conversation more efficient. This study aims to measure and compare the end-to-end efficiency of an active clamp flyback converter with a planar transformer and a conventional transformer and determine the potential implementation of these converters in household appliances. Load profiles for different household appliances were determined to see at what power levels they operated on. A literature review was done to reach these goals, and measurement methods were developed and tested. Lastly, a life cycle cost analysis was performed.

The results from the measurements on the flyback converter showed that the converter with the conventional transformer was 4% more efficient than the one with the planar transformer for all loads.

The measurements of the household appliances show the power consumed during various operating stages. And the total power consumption during one week corresponds to the real-life power consumption of an average household.

Theoretical improvements were made to the flyback converter to decrease power losses. These losses are significant on a large but perhaps not for all devices from an economic standpoint.

Keywords: DC/DC converter, Active clamp flyback converter, Efficiency, Household appliances.

Acknowledgements

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Habibullah Naseri and Hazim Novljanin, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
CCM	Contionuse Conducting Mode
DCM	Discontionuse Conducting Mode
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineers
LCR	Inductance, Capacitance, and Resistance
LLC	Life Cycle Cost
LCD	Liquid-Crystal Display
LED	Light-Emitting Diode
OS	Operation Stage
RMS	Root-Mean-Squared
SD	Secure Digital
SDHC	Secure Digital High Capacity
SMPS	Switch Mode Power Supply
SDGs	Sustainable Development Goals

Nomenclature

Below is the nomenclature of symbols that have been used throughout this thesis.

Symbols

I_r	Rising time
t_f	Falling time
C_c	Clamp capacitor
I_p	Primary side current
I_s	Secondary side current
I_0	Output current
i_D	Diode current
i_{SW}, I_{sw}	Switch current
i_m	Magnetizing current
S_w	Primary switch
S_a	Clamp switch
D_r	Secondary side diode
V_{in}	Input voltage
V_d	Input voltage
V_0	Output voltage
V_{out}	Output voltage
C_{oss}	Snubber capacitor
L_k	Leakage inductance
L_m	Magnetizing inductance
V_{ds_sw}	Primary switch voltage
I_{Lm}, I_m	Magnetizing current
V_c	Clamp voltage
V_{gs}	Gate source voltage

V_{DS}	Drain source voltage
P_{in}	Input power
P_{out}	Output power
η	Efficiency
P	Power
Ω	Resistance
L	Inductance
C	Capacitance
I_{avg}	Average current
V_{avg}	Average voltage
f_{sw}	Switching frequency
P_{con}	Conduction losses
P_{sw}	Switching losses
t_{on}	Turn on time
I_c	Clamp capacitor current
U	Voltage
I	Current
I_{rms}	RMS current
$R_{DS(on)}$	Drain source, turn on resistance
I_{ripple}	Ripple current
P	Power
$P_{con.par}$	Conduction losses whit paralleled switches

Contents

1

Introduction

1.1 Background

From the discovery of electricity until today, the electricity demand has been rising significantly around the globe[1]. Supplying the industries, streets, and houses with electricity has helped mankind step into a brighter future. As the world moves towards a more sustainable and electrified future using renewable energy sources such as hydro, wind, and solar energy, a redesign of the existing power system at different levels could prove to be a significant solution to decrease energy losses and increase efficiency in energy consumption.

Historically, the Alternating Current (AC) system has been dominating the generation, transmission, and distribution of electricity due to lower transmission losses and low generation cost[2]. These led to the Direct Current (DC) system being kept in the shadows. The widely spread of the AC system have also reached buildings. Many household appliances such as television and personal computers were powered with DC. Thus there is a need to convert the AC to DC and further DC to DC for a suitable current level. Such conversation causes significant losses, which has been a vital topic for some researchers during the past years[3]. The focus has been on minimizing the losses and increasing efficiency. According to research, a possible solution for potential energy saving could be removing the AC to DC conversion by feeding the building with DC with the help of a DC network connected[4]. This will result in cutting the AC to DC conversation loss, thus focusing only on minimizing the losses and increasing the efficiency of the DC to DC conversation.

1.2 Aim

This project aims to compare the end-to-end efficiencies of an active clamp flyback converter with a planar transformer and one with a conventional transformer. In addition, household appliances will be measured, and the potential of using an active clamp flyback converter to supply electrical loads in a residential building will be determined. Lastly, a life cycle cost analysis is to be made to determine what economic benefits there are with the better performing transformer than the other and if any improvements can be made. The last part is to be done through a theoretical study.

1.3 Problem

Reducing power losses will be an essential building block in the sustainable future insight, and by eliminating the AC to DC conversion stage, significant power losses can be reduced. Thus, focusing only on DC to DC converters and implementing a highly efficient converter in DC residential supplies will result in more efficient and sustainable energy consumption.

To determine the efficiency of the flyback converter, measurements have to be conducted at different power levels. This has to be done because different household appliances operate at different power levels.

Accurate measurements have to be conducted on different household appliances to determine their respective power levels. Therefore a measurement method has to be created and implemented. These load profiles could serve as a guideline for the efficiency mapping of future converters at different power levels.

Since the measurements consist of data points, a Matlab model should be created to simulate the operating ranges and efficiencies of the converters. This model will help in comparing the parameters of the converter and determining the total power losses of the converters at different load levels.

1.4 Scope

This project will only focus on the DC-to-DC conversion at different load levels. Heavy household appliances such as refrigerators, washing machines, dishwashers, and electric ovens/Stove were not considered due to lack of measurement equipment. However, a method for the implementation of the flyback converter in heavy household appliances will be addressed in the discussion section of this report. Since the power consumption of household appliances can vary due to various factors such as the number of people in the household and the season of the year, a decision was made to measure during spring and in a medium/large apartment with a residence of three people. The solutions presented for decreasing power losses of the converter are solely theoretical and will not be physically tested in this project.

The efficiency and conduction losses of the active clamp flyback converter with the conventional transformer were not measured during this project due to damage to the conventional transformer. Thus, this data was taken from previously conducted measurements.

1.5 Previous work

The previous study was conducted on the active clamp flyback converter with a conventional transformer. The study has focused on modeling the losses of a DC to

DC converter and comparing the simulated result with measured results. The study has also measured and calculated the end-to-end efficiency of the converter that has been used in this project.

2

Theory

2.1 Converter Theory

2.1.1 DC/DC Converter

DC-to-DC converters are commonly used in switch-mode power supplies and electric drives for the purpose of obtaining a regulated dc voltage. The incoming voltage to these converters is often unregulated, directly obtained from the rectification of line voltage; therefore, it can fluctuate due to changes in line voltage magnitude. The switch-mode DC/DC converters are used to convert the unregulated fluctuating voltage into a controlled one and to achieve the desired output voltage level[3].

2.1.1.1 Flyback Converter

The flyback converter is derived from the buck-boost converter, which means it can transfer the input voltage level to a lower or higher output voltage level. The advantage of the flyback converter is that it has galvanic isolation between the primary and secondary circuit. The reason for galvanic isolation is to avoid circulating currents and to achieve enhanced safety. The flyback converters are widely used for low power switch mode power supply applications [5]. An ideal flyback converter consists of a source voltage, a transformer, and a MOSFET at the primary side and a diode and a capacitor at the secondary side of the circuit which can be seen in figure 2.1. The MOSFET at the primary side of the circuit acts as a switch. By continuously turning on and off the transistor S_w in figure 2.1, the desired output voltage value can be obtained.

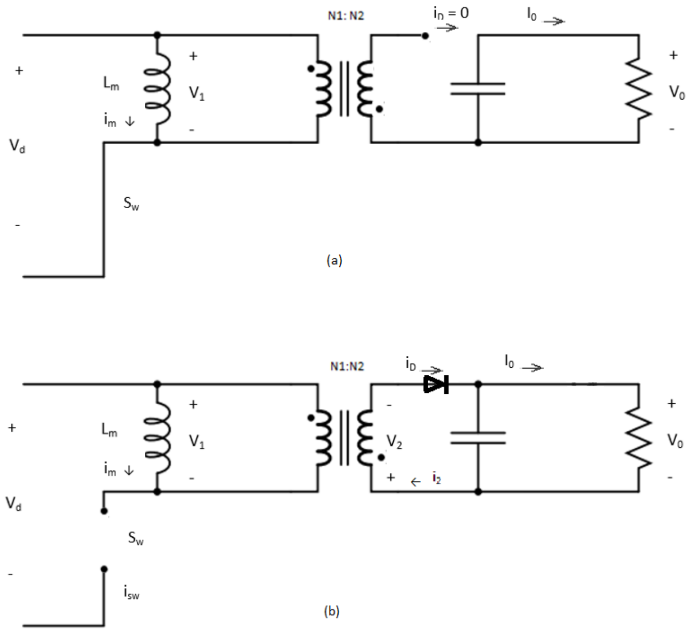


Figure 2.1: Topology of an ordinary flyback converter: (a) switch on (b) switch off.

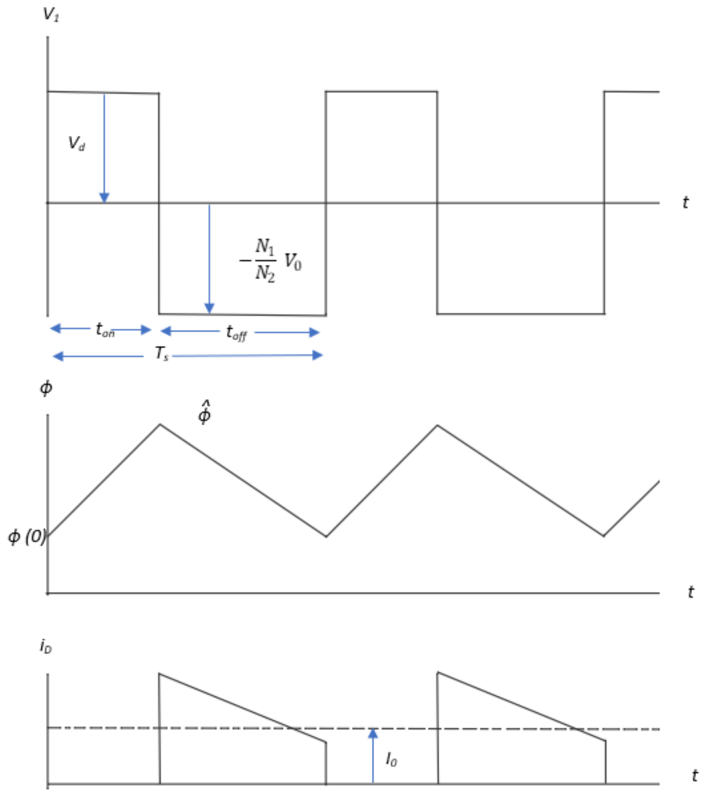


Figure 2.2: Flyback converter waveforms.

Figure 2.1 (a) shows when the switch S_w is on, due to the polarities of winding, the diode D becomes reverse biased. This results in a linear increase in inductor core flux that can be seen in figure 2.2.

The input/output voltage relation of an ideal flyback converter can be derived with the help of figure 2.1 and 2.2. To derive the input/output voltage relation, first, the initial flux inside the transformer core can be described as

$$\phi(t) = \phi(0) + \frac{V_d}{N_1} \cdot t \qquad 0 < t < t_{on} \tag{2.1}$$

where $\phi(0)$ is the initial flux inside the core, V_d is the input voltage N_1 is the turn ratio at the primary side of the circuit and t is the time. Furthermore, the flux peak at the end of the t_{on} interval is

$$\hat{\phi} = \phi(t_{on}) = \phi(0) + \frac{V_d}{N_1} \cdot t_{on} \tag{2.2}$$

Once the t_{on} cycle is finished, the switch turns off, and the energy stored in the core will lead the current to the secondary circuit via diode D, according to figure 2.1(b). The voltage over the secondary winding changes to negative V_0, thus the flux starts to decrease linearly

$$\phi(t) = \hat{\phi} - \frac{V_0}{N_2} \cdot (t - t_{on}) \qquad t_{on} < t < T_s \tag{2.3}$$

and

$$\phi(T_s) = \hat{\phi} - \frac{V_0}{N_2} \cdot (T_s - t_{on}) \tag{2.4}$$

using (2.2) the following expression is obtained

$$= \phi(0) + \frac{V_d}{N_1} - \frac{V_0}{N_2}(T_s - t_{on}) \tag{2.5}$$

Since the sum of change in flux through the core over the period of one cycle should be equal to zero,

$$\phi(T_s) = \phi(0) \tag{2.6}$$

Thus, from (2.5) and (2.6) the transfer function of the flyback converter in continuous conducting mode can be written as

$$\frac{V_0}{V_d} = \frac{N_2}{N_1} \frac{D}{1 - D} \tag{2.7}$$

where D is t_{on}/T_s that is the switching duty ratio. The boundary between continues conducting mode (CCM) and discontinues conducting mode (DCM) can be calculated according to the following expression

$$\frac{\Delta i_m}{2} \leq I_m \tag{2.8}$$

where Δi_m is the peak to peak ripple magnetizing current and I_m is the average magnetizing current. If the average magnetizing current is greater or equal to half of the peak-to-peak ripple magnetizing current the converter operates in the CCM mode else the converter will be working in the DCM mode. Since the flyback converters in this project operate in DCM mode, the waveforms of the active clamp flyback converter can be seen in figure 2.4, and the input and output voltage relationship is described as

$$\frac{V_0}{V_d} = D\sqrt{\frac{R_{load}}{2L_m f_{sw}}} \tag{2.9}$$

where R_{load} is the load resistance, L_m is the magnetizing inductance and f_{sw} is the switching frequency of the flyback converter. The different time periods and steps of operation of an active clamp flyback converter will be described in detail in the next section.

2.1.1.2 Active Clamp Flyback Converter

There are several advantages of the active clamp flyback converter topology, the converter circuit can be seen in figure 2.3. One of the main reasons is the reduction in losses in the converter. As described earlier, there are losses in the leakage inductance of the transformer of the flyback converter. By using a capacitor clamp, it is possible to store the energy from the leakage inductance in the capacitor clamp and deliver it to the output of the converter later in the switching cycle. By controlling the capacitor clamp with a GaN-FET, less energy is required to achieve zero voltage switching. This entails a state of operation where the converter can operate with a higher switching frequency, which can be done with a smaller power supply, energy from the leakage inductance is recycled, and with a reduction in switching losses [6].

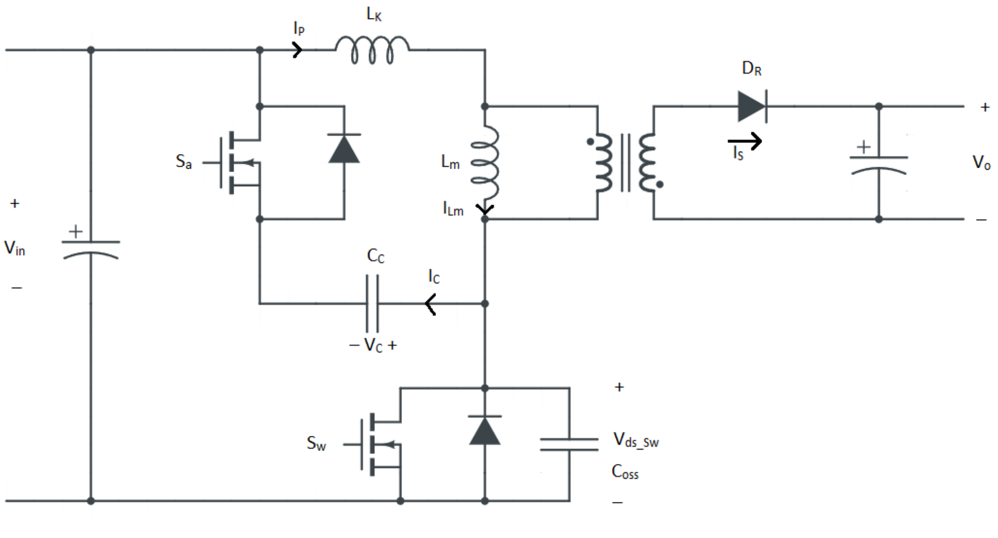


Figure 2.3: Topology of active the clamp flyback converter.

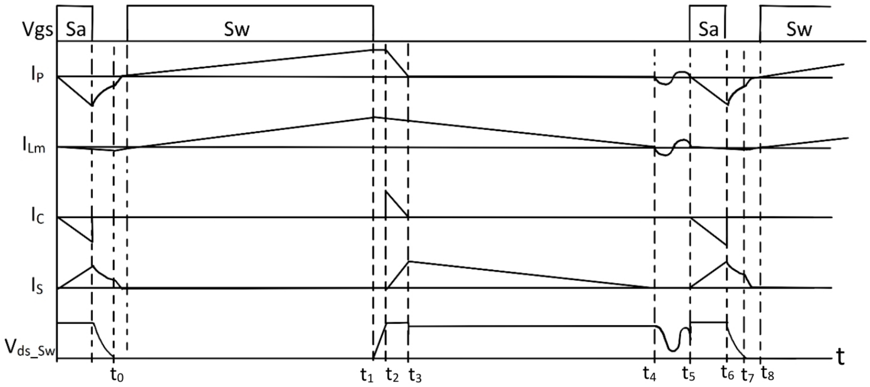


Figure 2.4: Steady state operation waveform of Active clamp flyback converter in DCM mode.

2.1.1.3 Operation stages

The active clamp flyback converter has eight stages of operation during one cycle. These stages are divided into time intervals from t_0 - t_8. The operation stages for each time interval are illustrated in figure 2.4 and figure 2.5 [5].

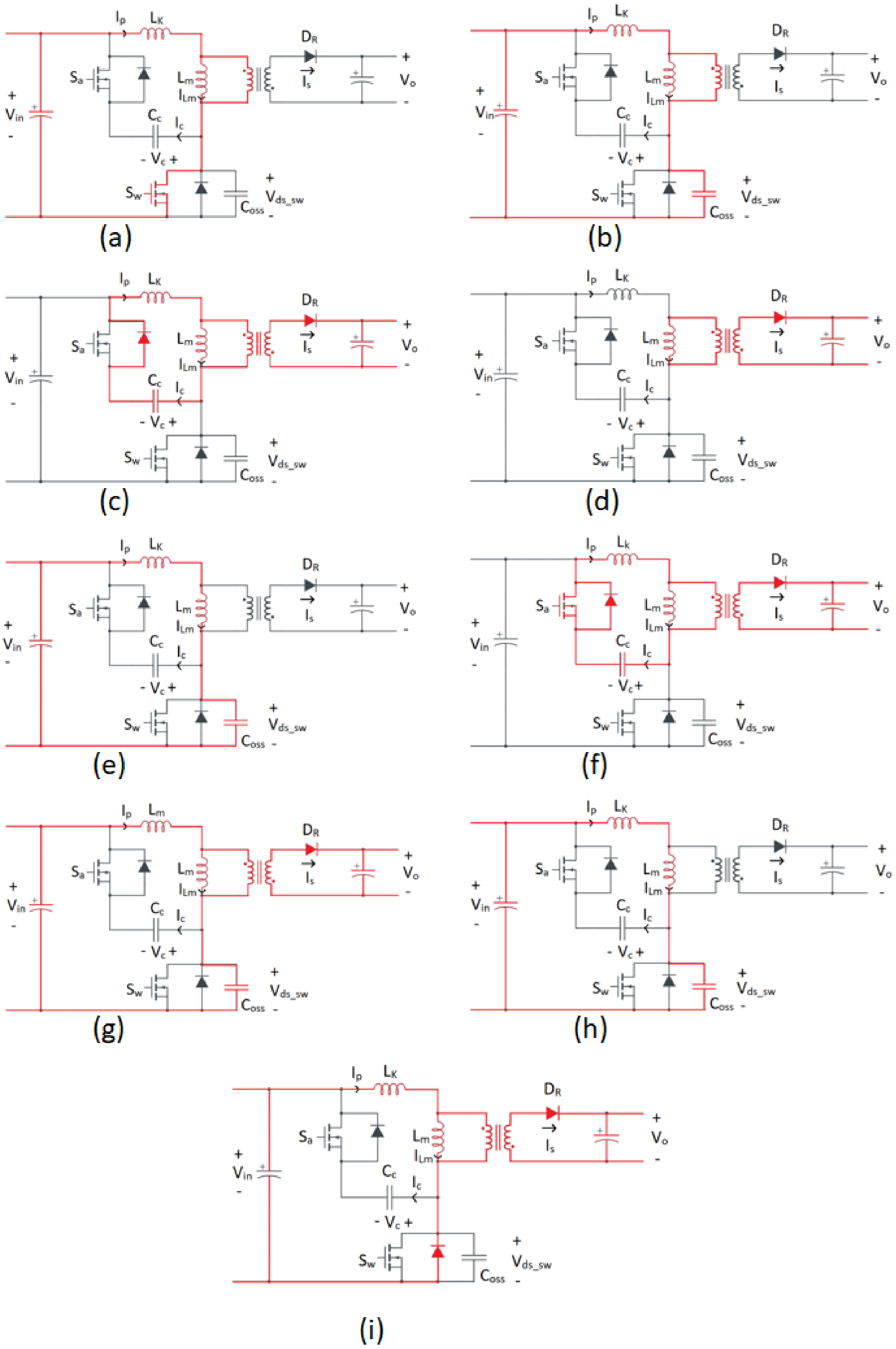


Figure 2.5: Operation stages of the active clamp flyback converter during one duty cycle. (a) OS 1 [t_0 - t_1]. (b) OS 2 [$t_1 - t_2$]. (c) OS 3 [$t_2 - t_3$]. (d) OS 4 [$t_3 - t_4$]. (e) OS 5 [$t_4 - t_5$]. (f) OS 6 [$t_5 - t_6$]. (g) OS 7A [$t_6 - t_7$]. (h) OS 7B [$t_6 - t_7$]. (i) OS 8 [$t_7 - t_8$].

1. Operation stage 1: t_0 - t_1
   During the first stage of operation, the switch S_w is turned ON, and the switch S_a is turned OFF. This leads to the magnetizing and leakage inductance being charged with the energy from the primary side current I_p as the current increases linearly.

2. Operation stage 2: t_1 - t_2
   During the second stage of operation, S_w is turned OFF, and the capacitor C_{oss} is charged by the energy from the magnetizing current. This mode of operation keeps on going until the switch voltage V_{ds_sw} reaches the value of V_{in}+ V_c which is the input voltage and clamp voltage.

3. Operation stage 3: t_2 - t_3
   During the third stage of operation, when the drain-source voltage V_{ds_sw} reaches V_{in}+ V_c, the anti-paralleled diode of S_a and the diode D_R become forward biased. This leads to the energy that is stored in the magnetizing inductor being transferred to the load of the secondary side of the converter. At the same time, the energy from the leakage inductor is stored in the clamp capacitor. When the leakage current reaches zero, and the magnetizing current has been transferred to the secondary side, this stage of the operation is finished.

4. Operation stage 4: t_3 - t_4
   During the fourth stage of operation, the current from the leakage inductance has reached zero value, and the anti-paralleled diode of S_a is turned off. And the remaining energy from the magnetizing inductor is transferred from the primary side of the transformer to the secondary side.

5. Operation stage 5: t_4 - t_5
   During the fifth stage of operation, the magnetizing current that is being transferred to the secondary side has decreased to zero, and as a result of this, the diode D_r stops conducting and turns off. Resonance starts to occur on the primary side of the converter between the magnetizing inductor and the capacitor at S_w as in discontinuous conduction mode (DCM) in a conventional flyback converter.

6. Operation stage 6: t_5 - t_6
   During the sixth stage of operation, the switch S_a is turned on. This leads to that the energy that was previously stored in the clamp capacitor is transferred to the secondary side of the transformer, and the diode D_r becomes forward biased. The current through L_m, and L_k increases negatively.

7. Operation stage 7: t_6 - t_7
   During the seventh stage of operation, the switch S_a is turned OFF. The primary side current discharges the energy from the parasitic capacitor C_{oss}. If the leakage energy is greater than the parasitic capacitor, the diode on the

secondary side is on. When the primary current and the magnetizing current becomes equal the diode in the secondary side turns off and both the leakage inductor and the magnetizing inductor discharges the parasitic capacitance to the source, as shown in figure 2.4 (g) and (h).

8. Operation stage 8: t_7 - t_8
   During the final stage of operation, as C_{oss} reaches zero, the anti-paralleled diode of S_{sw} becomes forward biased. If the primary current is still greater than the magnetizing current, the converter behaves as in figure 2.4 (i), and if they are equal, the converter behaves as in figure 2.4 (h). During this stage, it is possible to achieve zero-voltage switching as V_{ds_sw} is zero. The primary side switch should be turned on before the primary current changes its polarity.

2.1.2 Transformer

One important part of the flyback converter is the transformer. In the converter applications, high-frequency transformers are used, partially for reducing the size and weight of the converter compared to 50 Hz transformers, but also for electrical isolation between the primary and secondary sides of the converter. The electrical isolation is important for avoiding circulating current on the primary side of the converter thus enhancing the safety level of the converter. In this project, two different transformers are studied and tested for implementation in a flyback converter[3]. Conventional transformers are most frequently used in switch-mode power supply (SMPS) typologies. It consists of two conducting coils winded around a ferromagnetic core, representing the primary and respectively secondary side of the transformer.

Another high frequency, low power transformer which is enhanced in weight, size, cost, and performance is the Planar transformer. It is drastically lower in height compared to a conventional transformer. A planar transformer consists of a few flat coils on a printed circuit board (PCB) and two ferrite planar cores. Previously, studies have been done on the conventional transformer. In this project, the data from earlier studies on conventional transformers are used to compare them with the data from planar transformer.

2.1.3 Power & Efficiency Calculations

The end-to-end efficiency of an electrical device is defined as the relation between the useful output power of a system and the total input power of the system. To calculate the electrical input and output power of a device, the input and output voltages and currents have to be determined, and by using the relation

$$P = U \cdot I \tag{2.10}$$

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.11}$$

the power and efficiency of the system can be calculated[7]. Similarly, the voltage over, current through and resistance of a component can be calculated according to

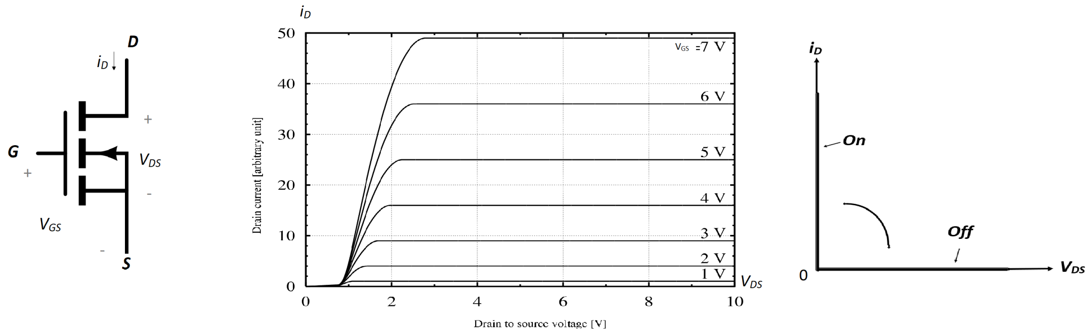
$$U = R \cdot I \tag{2.12}$$

2.1.4 Power Losses of the Active Clamp Flyback Converter

An ideal converter would have the same input and output power, but due to stepping up or down the output voltage level, energy losses occur. Power losses in a converter reduce its overall efficiency. The considerable losses in an active clamp flyback converter are switching and conduction losses on the MOSFET's.

2.1.4.1 MOSFET

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is a voltage-controlled semiconductor power device that can be turned on and off by applying a control signal between gate-source V_{GS}. MOSFETs are most convenient for low-voltage, low-power, and high-frequency switching applications[3]. An ideal N-channel MOSFET symbol, i-v, and ideal switching characteristics can be seen in figure 2.13. Since MOSFETs are voltage controlled, there will be no current flowing between drain and source until the gate-source voltage has reached the threshold voltage. Once the gate-source voltage reaches the threshold voltage, the current starts to flow from drain to source.



(A) (B) (C)

Figure 2.6: N-channel MOSFET, (A) Symbol, (B) i-v characteristic (C) idealized characteristic

An ideal MOSFET can be either on or off. However, real devices such as active clamp flyback converters do not have ideal characteristics thus, there will be power dissipation due to switching and conduction in the MOSFETs. The conduction loss in an active clamp flyback converter can be described by

$$P_{cond} = I_{0,rms}^2 R_{DS(on)} = R_{DS(on)} \frac{V_{out}}{V_{in}} (I_{out}^2 + \frac{I_{ripple}^2}{12}) \tag{2.13}$$

where I is the root-mean-squared (RMS) current that flows from drain to source and $R_{DS(on)}$ is the total resistance between the drain and source during the on the state. In order to achieve high performance and less conduction loss, the on-state resistance should be minimized to as much as possible[8].

Another dominant loss in the practical converters occurs when the transistor is switching on and off, it is called switching loss and is significant in the converters with high frequency. The turn-on and off characteristics of a MOSFET can be seen in figure 2.14 (a) and (b). The switching of the transistor is divided into three phases. In phase 1, when the V_{DS} reaches the threshold voltage, the current starts to flow from drain to source, according to figure 2.14(a). During this process, the current starts to increase whereas the voltage drops, as a result, a turn-on switch loss occurs, which can be seen in brown color in figure 2.14(b). In phase 2, the MOSFET starts to conduct, and thus conduction loss occurs, which can be calculated according to (2.13) and that can be seen in cyan color in figure 2.14(b). In phase 3, the switch is turned off thus, turn-off switch loss occurs, which can be seen in figure 2.14(b). The switching losses can be calculated and described by

$$P_{sw(on)} = \frac{1}{2} V_d I_d (t_{on}) \tag{2.14}$$

$$P_{sw(off)} = \frac{1}{2} V_d I_d (t_{off}) \tag{2.15}$$

$$P_{sw(total)} = (P_{sw(on)} + P_{sw(off)})\ f_{sw} \tag{2.16}$$

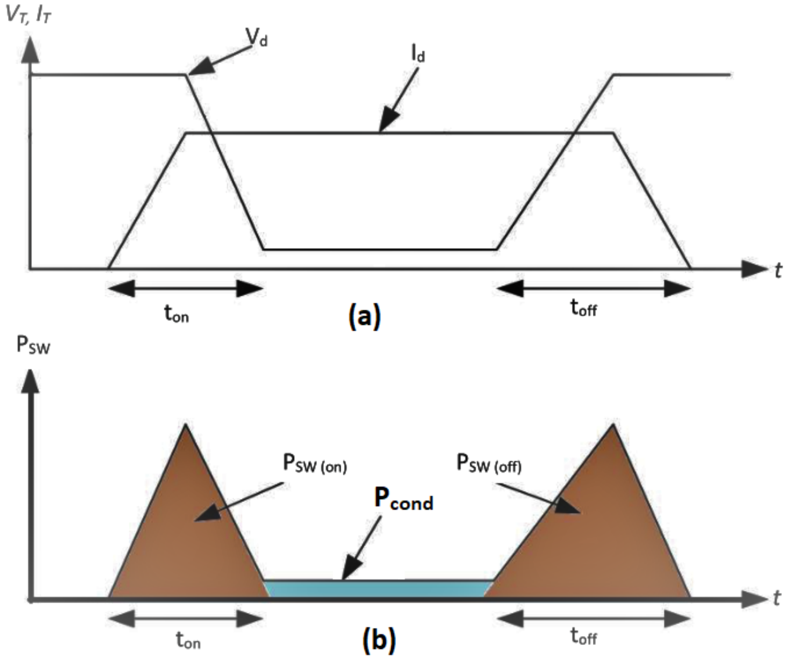


Figure 2.7: Voltage and current behavior while switching on and off a MOSFET

The switching and conduction losses for of the active clamp flyback converter used in this project can be calculated by

$$P_{sw} = \frac{1}{2}V_{sw}I_{sw}(t_f + t_r)f_{sw} + \frac{1}{2}C_{ds}V_{sw}^2 f_{sw} \tag{2.17}$$

$$P_{cond} = I_{Sw,rms}^2 R_{DS(on)} + I_{avg}V_{avg} \tag{2.18}$$

since, the converter operates under zero voltage switching condition[9].

2.2 Apartment

The measurement of household appliances was done in an actual apartment to ensure that the measured data accurately represents the everyday energy consumption of household appliances. The floor plan of the apartment can be seen in figure 2.8. The apartment has an area of 75 square meters, consisting of two bedrooms, a living room, a kitchen, a bathroom, a hallway, and a balcony. The described apartment with three adult residents is defined as a medium/large apartment in Sweden and has an approximate energy consumption of between 4000 - 6000 kilowatt hours per year (kWh/year)[10].

The energy consumption for a household may vary depending on what type of isolation there is in the building, the number of residents, etc. There is, however, an estimation that household appliances and warm water stand for approximately 20% of the total energy consumption respectively, while heating stands for approximately 60%. During this project, measurements will only be conducted on household appliances. That means that the measurement data will have to be corrected to fit the average consumption for an average household in Sweden throughout a year.

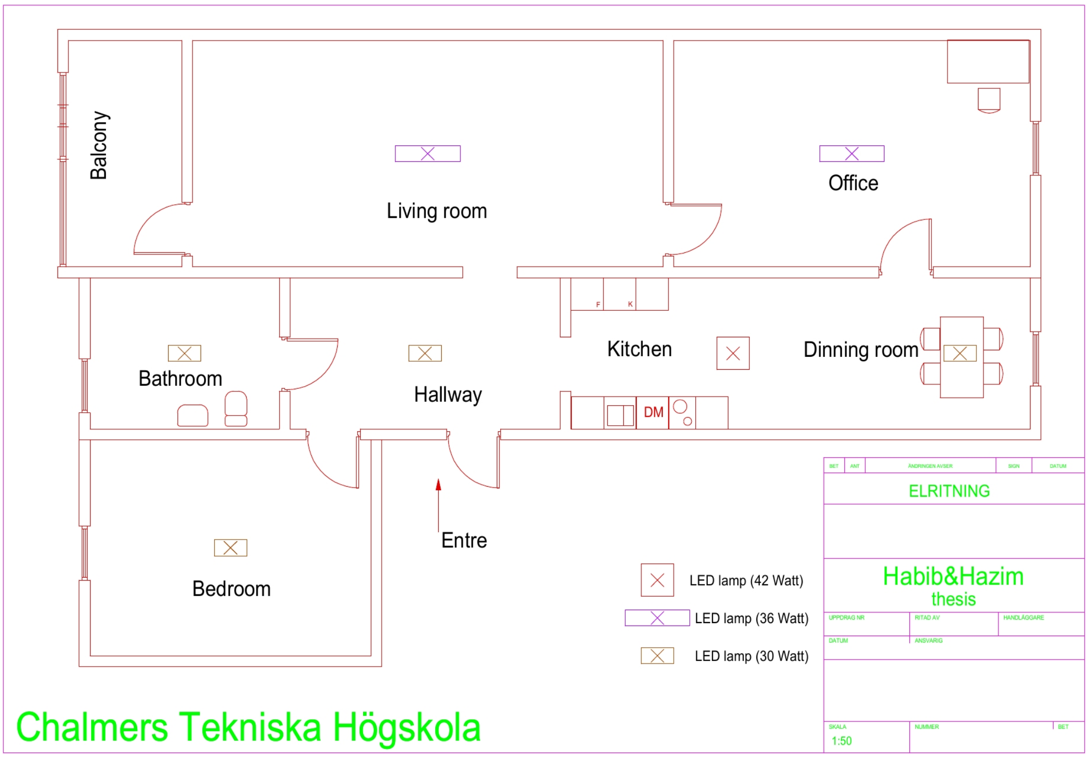


Figure 2.8: Floor plan of the measured apartment.

3

Case Setup

3.1 Pre-study

To calculate the efficiency of the flyback converters accurately, a literature study had to be conducted on previously performed tests and measurements of the active clamp flyback converter. This was done with the purpose of gathering information about the operating ranges of the converter to set up a method to measure the input, output voltages, and currents accurately. A study was also conducted on how to measure and approximate the electrical loads of a household. Various equipment and methods were at our disposal, and the one most suited ones for this frame of work was chosen.

3.2 Equipment

A variety of measurement equipment, power supply sources, and tools were used during this project for different purposes. This section will describe the equipment and its aim to achieve the project's goal.

3.2.1 LCR meter

An LCR meter is an electronic measurement equipment that measures inductance (L), capacitance (C), and Resistance (R) precisely, as can be seen in figure 3.1. The LCR meter in this project was used to confirm the resistivity of the component.
The input and output current is one of the crucial quantities that define the power. It has to be measured precisely because the efficiency is determined by (2.10) and (2.11). A previously conducted measurement proved to be inaccurate. Thus, another measurement method was designed to calculate the input current accurately by using a precision resistor. Therefore, a 10Ω high precision metal film leaded resistor with an accuracy rate of ±0.1% was used in one of the measurement methods, which will be described in section 3.3.1.2, to achieve the most accurate value of input current[11]. A higher accuracy in the input current would improve the measurements.

Table 3.1: Specifications of the high precision resistor

Attribute	Value
Resistance	10 Ω
Power Rating	0.5W
Tolerance	±0.1%
Technology	Metal Film
Series	UPF50
Temperature Coefficient	±5ppm/°C
Maximum Operating Temperature	+125°C
Minimum Operating Temperature	-55°C

The specification of the resistor is listed in table 3.1.

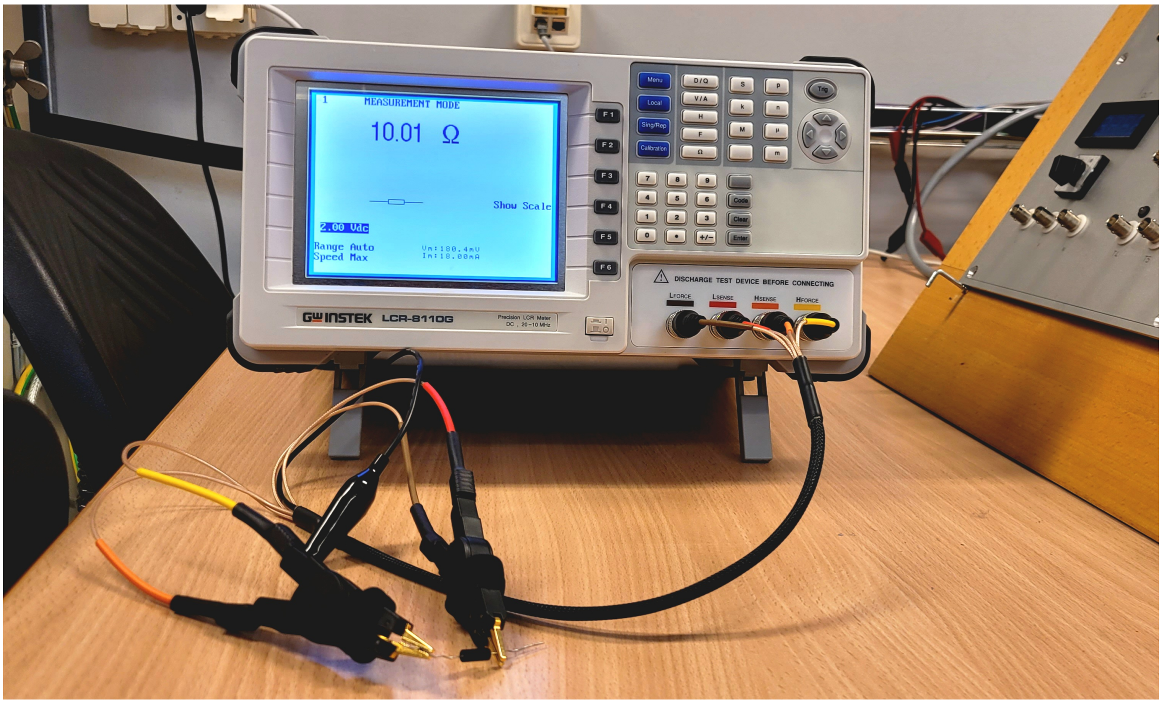


Figure 3.1: LCR meter connected to the precision resistor.

The measurement setup for measuring the precision resistor with the help of an LCR meter is illustrated in figure 3.1.

3.2.2 Fluke digital 175 multimeter

The Fluke digital 175 multimeter is an electric measurement instrument that measures the RMS value of voltage and current with an accuracy of 0.09%[12]. The multimeters were used to measure the input/output voltage and current in this project.

3.2.3 Voltcraft Energy Logger 4000

The Voltcraft energy logger 4000, shown in figure 3.2, is an electrical measurement instrument that measures various electrical parameters, including RMS values of current and voltage, frequency, active power, apparent power, power factor, and cumulated consumption. It has a sampling frequency of one sample per minute. The Voltcraft logger can simultaneously measure and store data from up to 10 devices with different id numbers. Aside from logging various electrical parameters, the energy logger logs the time when the device is switched on and off precisely.

Moreover, it has an LCD screen where all the measurements can be seen live and even the overall consumption history of the last ten days. The energy logger stores data for up to 6 months in an internal storage system[13]. The stored data can be easily transferred with a 32-gigabyte standard SD/SDHC card for further analysis. In addition, the energy logger can even calculate the total electricity cost of a month by knowing the per-unit price of energy. The energy logger was only used to measure different household appliances in this project.

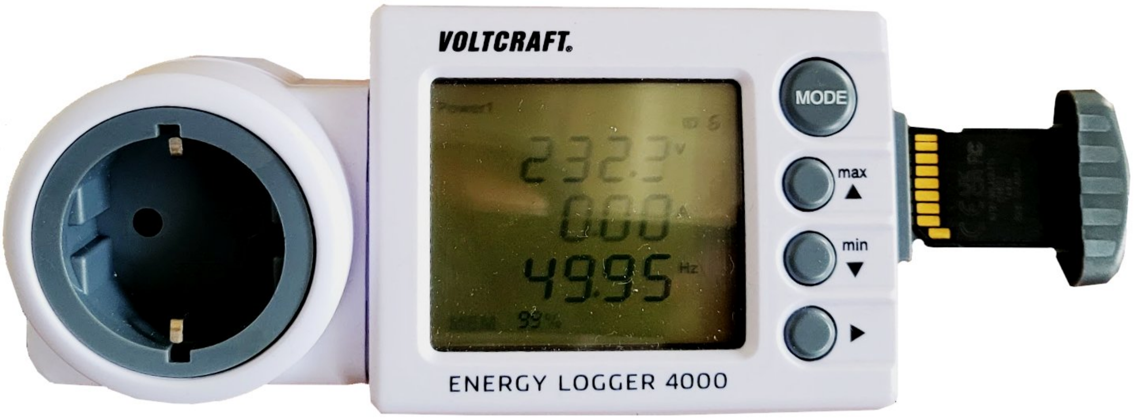


Figure 3.2: Voltcraft energy logger 4000.

3.3 Measurement method

3.3.1 The Active Clamp Flyback Converter

Once a foundation was determined for the operation range of the flyback converter at different loads, it was possible to set up methods to be able to conduct accurate measurements. To calculate the efficiency of the flyback converter, firstly, the input and output power had to be calculated. To do this, the input and output voltages and currents needed to be measured. A total of three different measurement methods were conducted and will be explained in the following sections.

3.3.1.1 Method 1: Measurements With a Rectified AC-Source

The first measurement method was conducted using a three-phase 400V AC supply. The three-phase voltage was connected to a contactor and later on to a three-phase transformer. After that, it was connected to a power-operated rotary transformer which in turn was connected to an AC/DC rectifier. The rectified voltage is used as the input voltage to the flyback converter. Before this connection was made, a Fluke 175 multimeter was connected in series between the rectifier on the lab board and the flyback converter to measure the input current. Another Fluke 175 multimeter was connected in parallel to the DC voltage input of the flyback converter to measure the input voltage.

Lastly, the secondary side of the flyback converter was connected to another Fluke 175 multimeter in series with the resistive load to measure the output current, and the last multimeter was connected in parallel to the output of the converter to measure the output voltage. The connection is illustrated in figure 3.3.

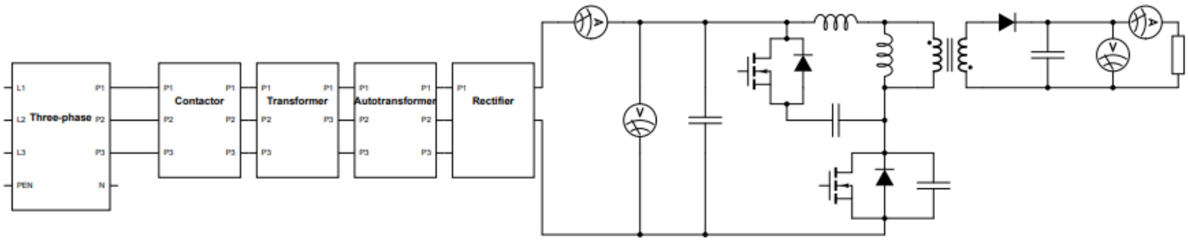


Figure 3.3: Setup diagram for measurement method one.

3.3.1.2 Method 2: Measurements With a Rectified AC-Source and a Precision Resistor

The second connection uses the same setup as previously described in method 1. However, one small change was made at the input of the flyback converter. Instead of connecting a Fluke 175 multimeter in series between the rectifier and input of the flyback converter, a 10 Ω precision resistor was connected instead. This was done with the purpose of measuring the voltage over the precision resistor. Knowing the precise value of the resistor and the voltage over the resistor (2.12) can be used to calculate the input current to the flyback converter.

While performing measurements using this setup, it was necessary to begin each measurement with zero volts as input and carefully increase it to 370 V. The purpose of limiting the input voltage at the beginning of the measurement was to limit the power development in the precision resistor due to the high inrush current and voltage. Not doing this will destroy the resistor.

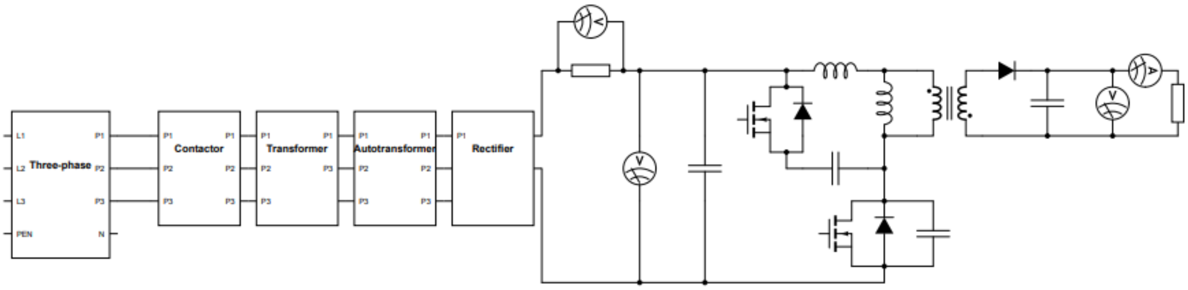


Figure 3.4: Setup diagram for measurement method two.

Figure 3.4 illustrates the setup diagram for measurement method two.

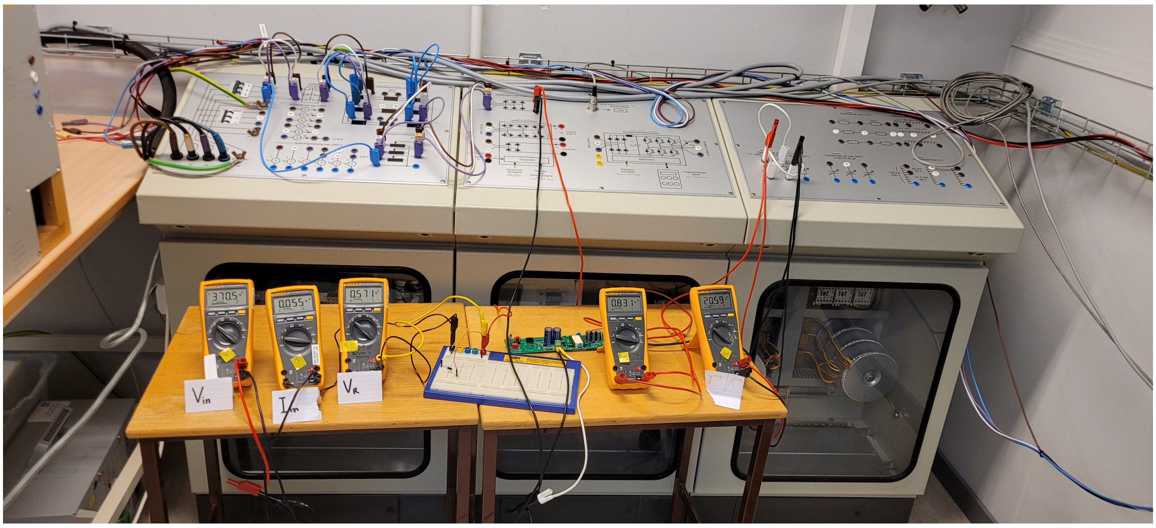


Figure 3.5: Measurement setup of active the clamp flyback converter practically.

Figure 3.5 shows the implementation of measurement method one and two.

3.3.1.3 Method 3: Measurements With a 600V DC Power Supply

A 600V power supply was used as the voltage source in the third measurement setup. However, the flyback converter is designed to have a maximum supply voltage of 390 volts. A decision was made to feed the converter with a constant voltage of 380 volts. The power supply was connected in series with two Fluke 175 multimeters to measure the input current, which was further connected to the input of the flyback converter as shown in figure 3.6 and 3.7. The multimeter had a parallel short circuit wire connected over it to protect the fuse inside the multimeter from the large inrush current.

When the current reaches a lower value during operation, the parallel connection is disconnected. Thus, the current goes through the multimeter. Another Fluke 175 multimeter was connected in parallel to the input of the flyback converter to measure the input voltage, and the secondary side of the flyback converter was connected similarly, as described in the previous two measurement setups.

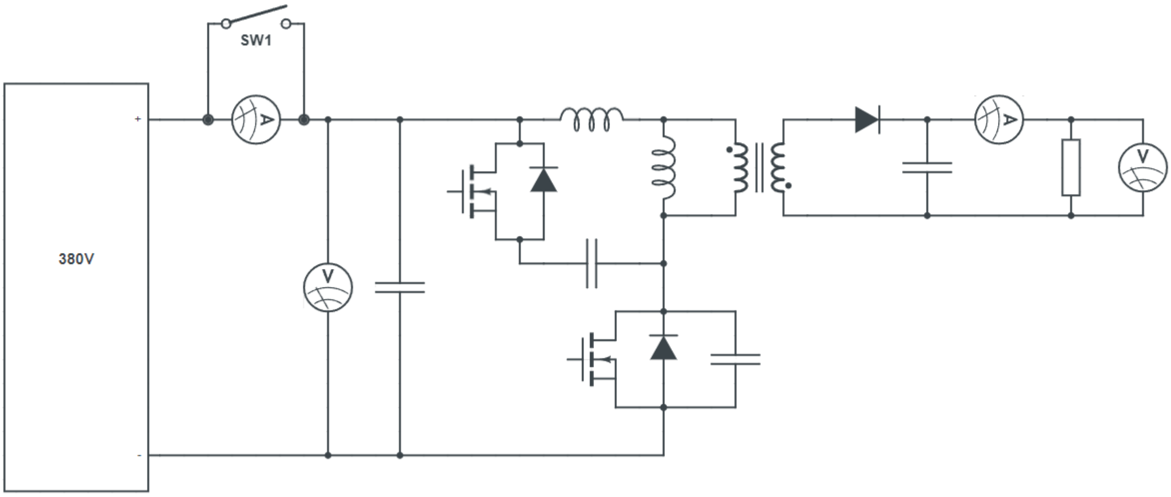


Figure 3.6: Setup diagram for measurement method three.

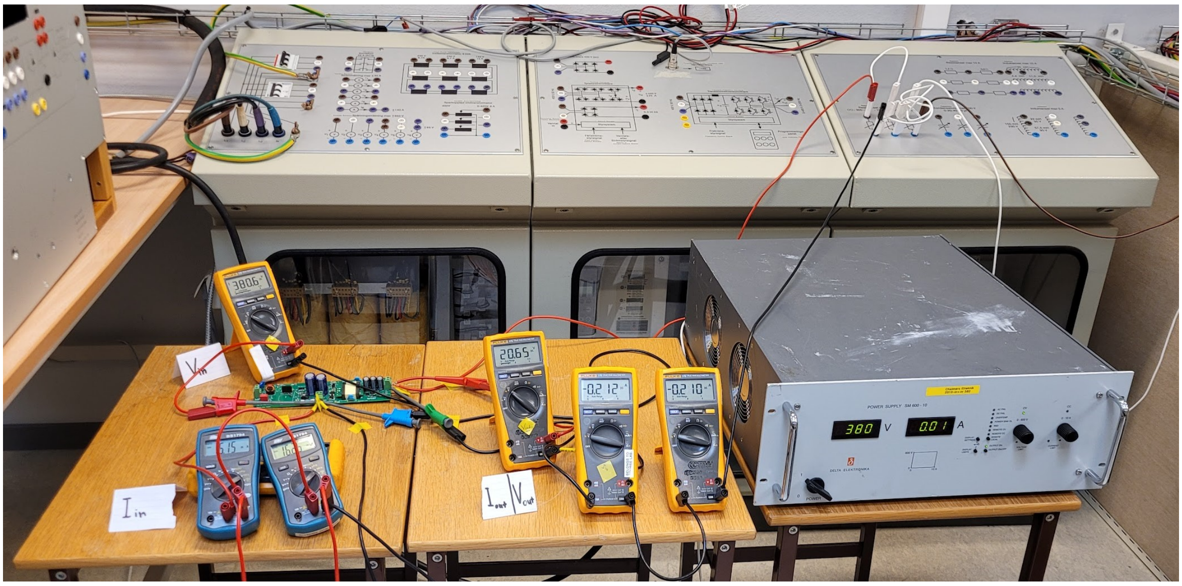


Figure 3.7: Measurement setup of an active the clamp flyback converter practically.

3.3.2 Household Appliances

Ten different household appliances' energy consumption was measured during one week. There were two purposes for measuring the household appliances. Firstly, to measure devices under 60 W to compare the efficiency of the flyback converter with planar and conventional transformer for different household devices. Secondly, to estimate the total energy consumption of a medium/large size apartment.

Two Voltcraft energy logger 4000 were used to measure the energy consumption of household appliances for precisely one week. Later, the data received from the Voltcraft was processed in Matlab for further analysis. Since the measurement data was extensive, the results are shown in graphs in the result section. An illustration of how the household appliances were measured can be seen in figure 3.8 where the coffee maker is connected to the Voltcraft, and the energy consumption is logged each minute.

Figure 3.8: Voltcraft logging the energy consumption of a Coffee Maker.

In this project, the most frequently used household appliances listed in Table 3.1 were measured. Each home appliance was given a unique id number in the Voltcraft during measurement for ease of identification. To ensure that the measurements would be an accurate representation of the load profiles in a household, the residents were encouraged to live a typical life.

The measurement time for each of the devices was ten days. However, data was only imported for a seven-day period. This was to gain a time margin to ensure that no data points were lost during the measurements. During the measurement, the Voltcraft was placed in the power socket all the time, and the devices such as ID 0 and 2 were connected to the Voltcraft only when they were out of charge. These devices were typically used even during the charging. Whereas for the ID 1,3,4,5,6, the devices were connected to Voltcraft during the whole measurement period. Once the measurements were done, the data were analyzed and merged to form a load profile for the total energy consumption of a medium/large size apartment.

Table 3.2: List of household appliances with ID numbers, start and end date of measurements

Device	ID	Start date	End date
Laptop	0	07-03-2022	17-03-2022
Television	1	14-03-2022	24-03-2022
Smart phone	2	17-03-2022	27-03-2022
LED Lamp	3	24-03-2022	03-04-2022
Kettle	4	27-03-2022	06-04-2022
Microwave	5	03-04-2022	13-04-2022
Coffee Maker	6	06-04-2022	16-04-2022
Vacuum Cleaner	7	13-04-2022	23-04-2022
Mixer	8	16-04-2022	26-04-2022
Toaster	9	23-04-2022	03-05-2022

3.4 Data analysis with Matlab

Matlab was used to plot and analyze the data. Since the data from the converter measurements were point-based, Matlab was also used to approximate lines through these data points. The functions generated in Matlab aimed to take any set of active power data (consumed by a device) as an input and output a set of data points representing the end-to-end losses of the active clamp flyback convert.

Lastly, the data points representing the total amount of losses for the planar transformer and the conventional transformer were compared to each other to see which converter had the most losses. This method can be used to compare the efficiency, input/ output current, and power losses of the converter. The Matlab code that was used for this project can be found in appendix B.

4

Results

4.1 Comparison between the planar and conventional transformer

As described earlier, the measurements on the active clamp flyback converter with the planar transformer were done using three different methods. The results from the different measurement setups were slightly deviating depending on whether the values were measured or calculated.

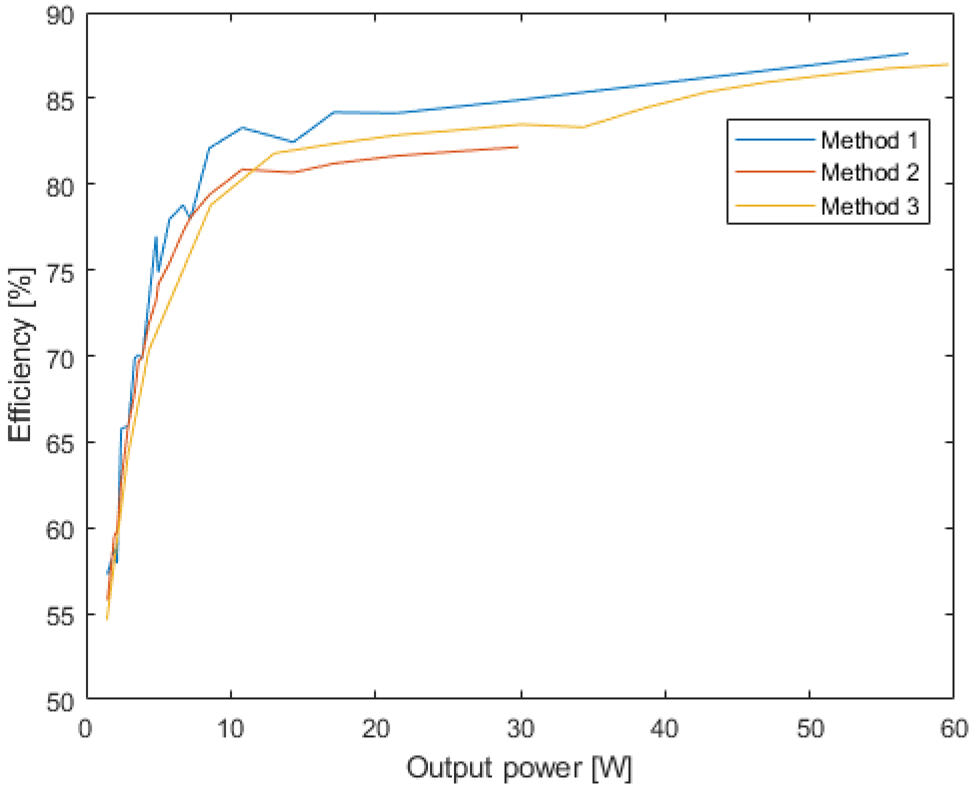


Figure 4.1: Comparison between the efficiency in relation to the output power of the converter using the planar transformer for the three different measurement methods.

A comparison between the results of three different measurement methods results is illustrated in figure 4.1. The results can be found in Appendix A, Table A.1, A.2, and

A.3. The figure shows the relation between the converter's efficiency and the output power to the load. The specific measurement methods are described in section 3.3.2.

Measurements could not be conducted on the converter using the conventional transformer. This was due to technical difficulties with the equipment. The results representing measurement data for the conventional transformer are taken from previously conducted measurements[14].

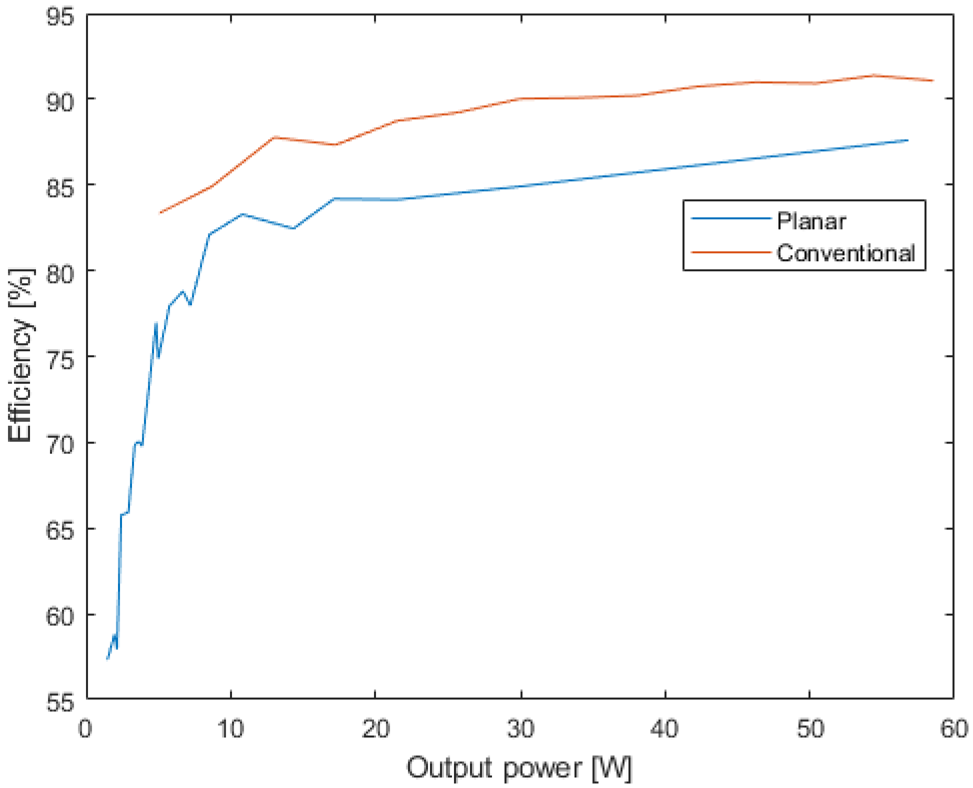


Figure 4.2: Efficiency comparison between power meter and power calculation with rectified AC- source.

Figure 4.2 compares the converter's efficiency using the planar transformer and the conventional transformer. The results representing these two cases were measured using a similar setup. Both measurement methods were done using a rectified AC - source. The difference in this comparison is that the input and output power for the converter using the conventional transformer was measured using a power meter. In contrast, the same values for the planar transformer were calculated according to measurement method one.

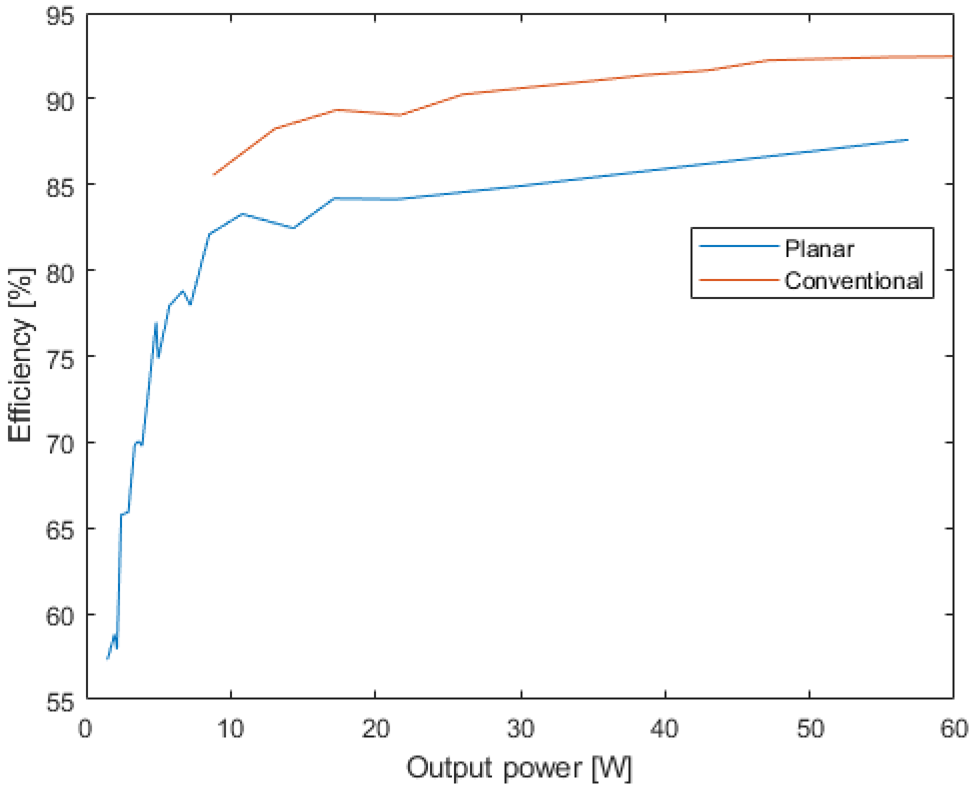


Figure 4.3: Efficiency comparison using measurement method one.

The comparison seen in figure 4.3, uses the same measurement method. In this case, measurement method one.

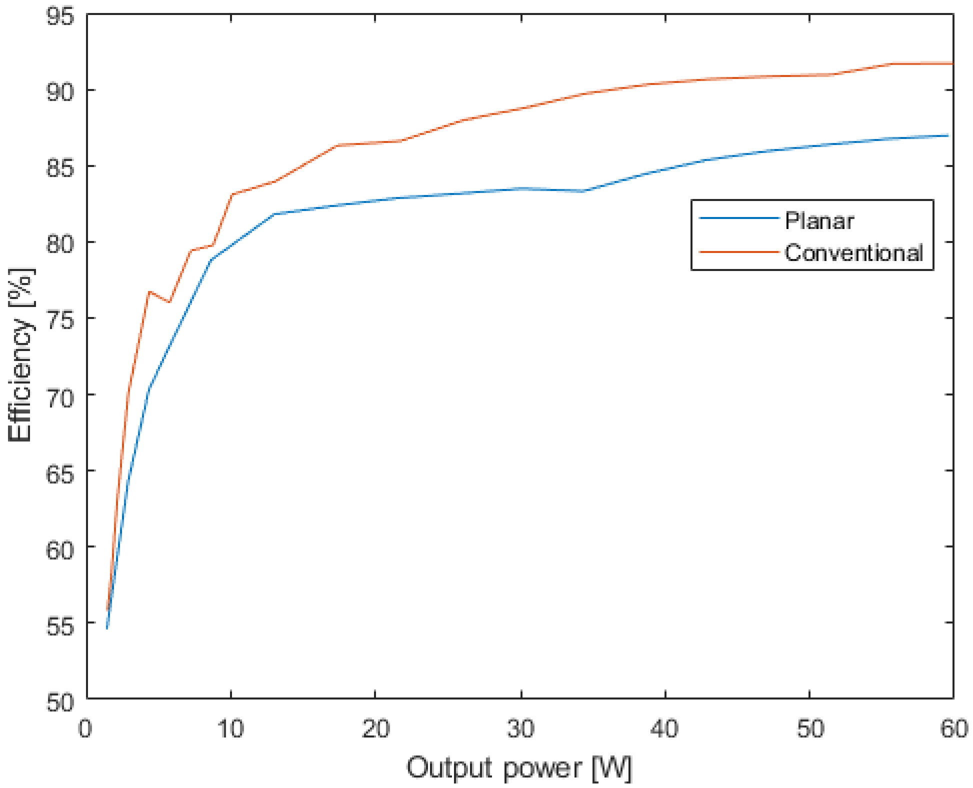


Figure 4.4: Efficiency comparison using measurement method three.

Figure 4.4 illustrates a comparison between the converter's efficiency using measurement method three.

4.2 Power Loss Improvements

Since the conventional transformer proved to be more efficient than the planar transformer, the focus turned toward theoretically improving the efficiency of the active clamp flyback converter by reducing losses. The losses in focus are the conduction losses of the primary MOSFET in the converter. The conduction losses of the MOSFET vary depending on the load that is connected to the converter. Since the MOSFET operates under zero voltage switching condition, (2.17) and (2.18) can be used to calculate the switching and conduction losses of the MOSFET [9]. Since the converter has higher efficiency at higher loads and will most likely operate at these points, these were the ones calculated[14].

Table 4.1: Switching and conduction losses of the primary MOSFET.

P_{out} [W]	$P_{con}[mW]$	$P_{con.par}$ [mW]	P_{sw} [mW]	P_{tot} [mW]	$P_{tot.par}$ [mW]
59.93	217.5	108.75	907.6	1125.1	1016.35
55.74	154.0	77	841.9	995.9	918.9
51.50	163.4	81.7	894.7	1058.1	976.4
47.28	153.8	76.9	911.7	1065.5	988.6
43.05	127.5	63.75	889.0	1016.5	952.75
38.77	93.0	46.5	850.8	943.8	897.3
34.42	72.1	36.05	830.5	902.6	866.55
30.36	96.4	48.2	1040.3	1136.7	1088.5
26.06	90.6	45.3	1024.0	1114.6	1069.3
21.71	92.4	46.2	1028.8	1121.2	1075

Table 4.1 shows the switching, conduction, and total losses of the primary MOSFET while the flyback converter is connected to various loads.

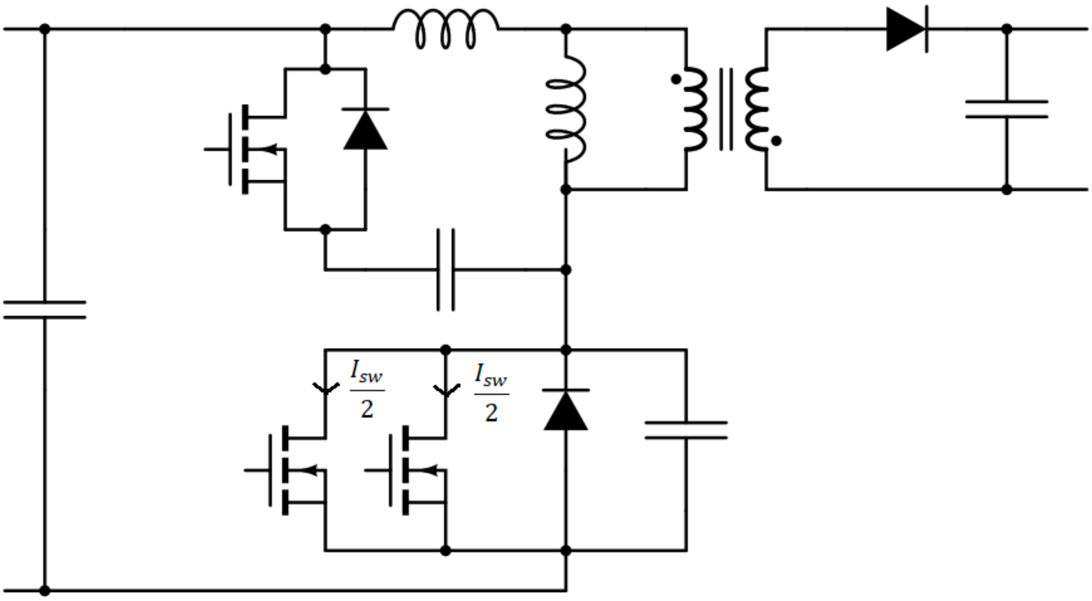


Figure 4.5: Topology of active the clamp flyback converter with two parallel switches.

By connecting a third MOSFET in parallel to the primary MOSFET the current through the MOSFET's will be divided into two equal parts according to Kirchofs current law [7]. The added MOSFET can be seen in figure 4.5. According to (2.18), the conduction losses of the MOSFET is proportional to the square of the RMS value of the switching current. This means that by connecting another MOSFET in parallel to the first one, the current through one of the switches will be half of the original current value, which will lead to a 75 % decrease in conduction losses of the MOSFET. However, since there now are two switches, the total conduction losses will decrease by 50 %. The switching losses, however, will not be affected by connecting two switches in parallel according to (4.1). This is because the switching losses are linearly proportional to the current. The reduction in conduction losses can be seen in Table 4.1. For these power levels, this would lead to an average decrease in power losses by 1.35%.

4.3 Measurements on Household Appliances

Measurement of ten different household appliances was done with the help of a Voltcraft energy logger. The data from Voltcraft were then analyzed and plotted in Matlab. The result of the power consumption of the household appliances and a rough estimation of the total energy consumption of an apartment will be presented in this section.

4.3.1 Laptop

The power consumption of a Laptop was logged for one week. The laptop was charged with an adapter with an output of 15 V DC and 4.3 A and an output power of 65 W. Adapter was plugged into the Voltcraft when the battery was totally out of charge. The laptop was used as usual, even when it was charging. The figure shows the laptop's energy consumption in minutes during one week, including the weekend and the working days.

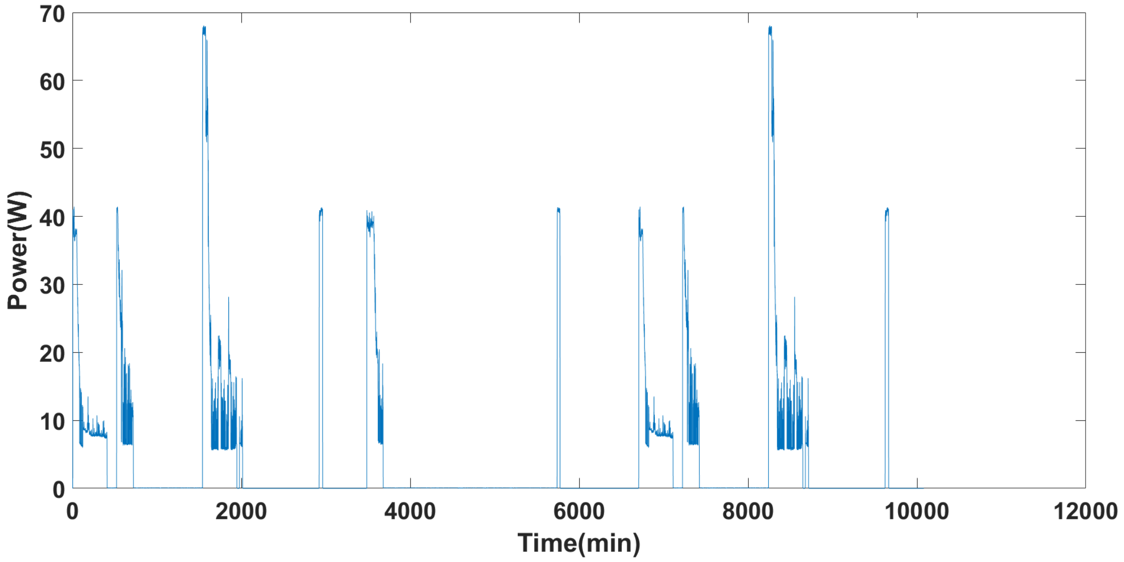


Figure 4.6: Power consumed by a Laptop during one week.

The spikes in figure 4.6 show the charging of the laptop with full power during each day. The first 4000 minutes show the first three working days, and the empty slot between 4000 and 6000 minutes shows the weekend. The data between 6000 and 8000 shows the working days again and is repetitive as the first part of the figure.

A one-day power consumption of the laptop can be seen in figure 4.7. The sudden spike at 1542 minutes shows the start state of charging, where the laptop consumes around 67 W. The laptop was fully charged in 1 hour and 43 minutes. Once the laptop was fully charged, the consumption decreases and stays at 6 Watts. The fluctuation in the measurement during the whole measurement is the result of using the laptop while being charged.

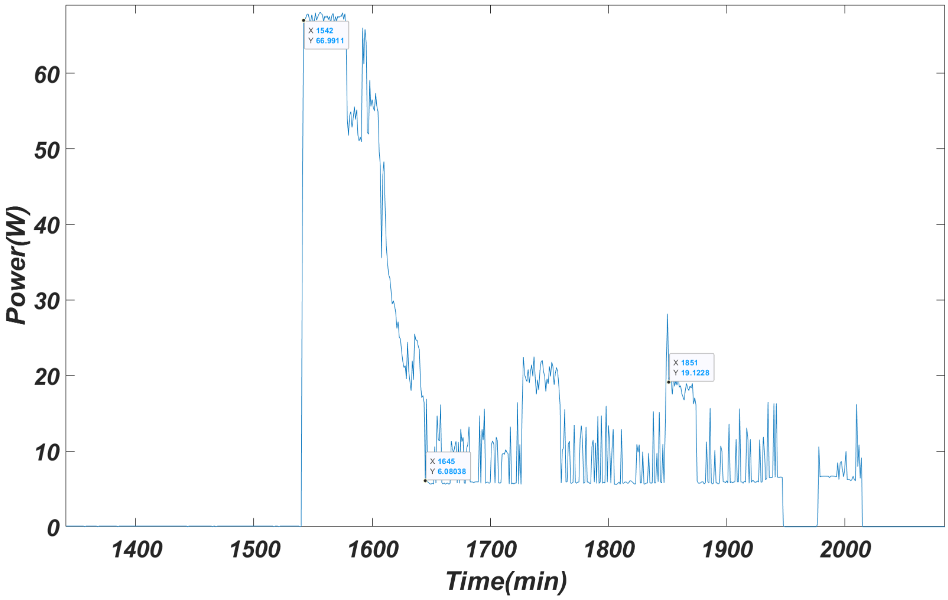


Figure 4.7: Power consumed by a Laptop during one day.

4.3.2 Television

The power consumption of a Television was logged for one week. The TV was connected to the Voltcraft energy logger during the whole measurement period. Figure 4.8 shows how many times and for how many minutes the TV was used during one week and its power consumption. It can be seen that the TV consumes between 60 - 90 Watts when it is on. However, the TV has a constant power consumption of roughly 13 Watts in standby mode.

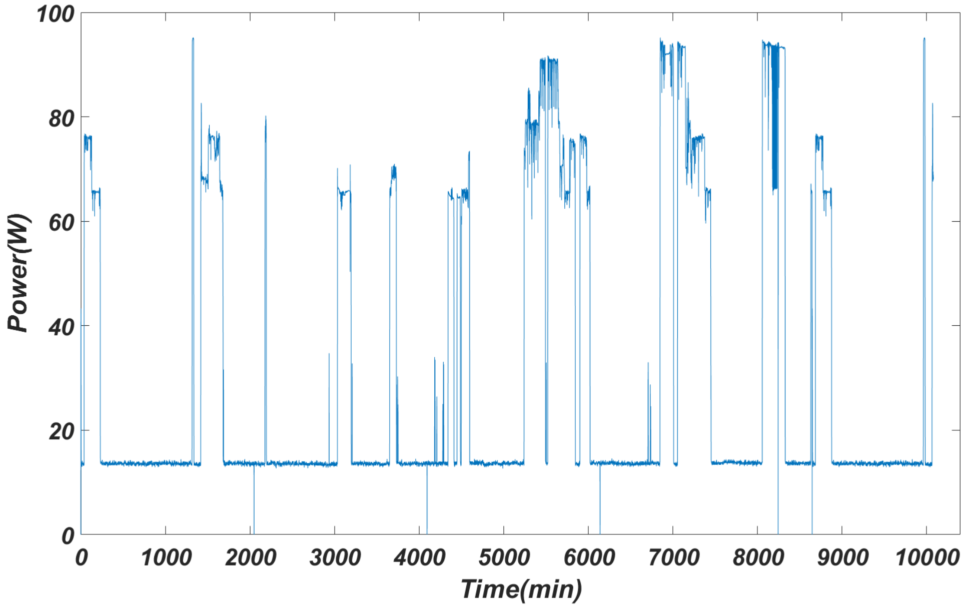


Figure 4.8: Power consumed by a Television during one week.

A one-day power consumption of the TV can be seen in figure 4.9. In one day, the TV seems to be on for 5.5 hours. The maximum power consumed is approximately 94 Watts. The fluctuation during measurement can depend upon the quality and sound level of the TV.

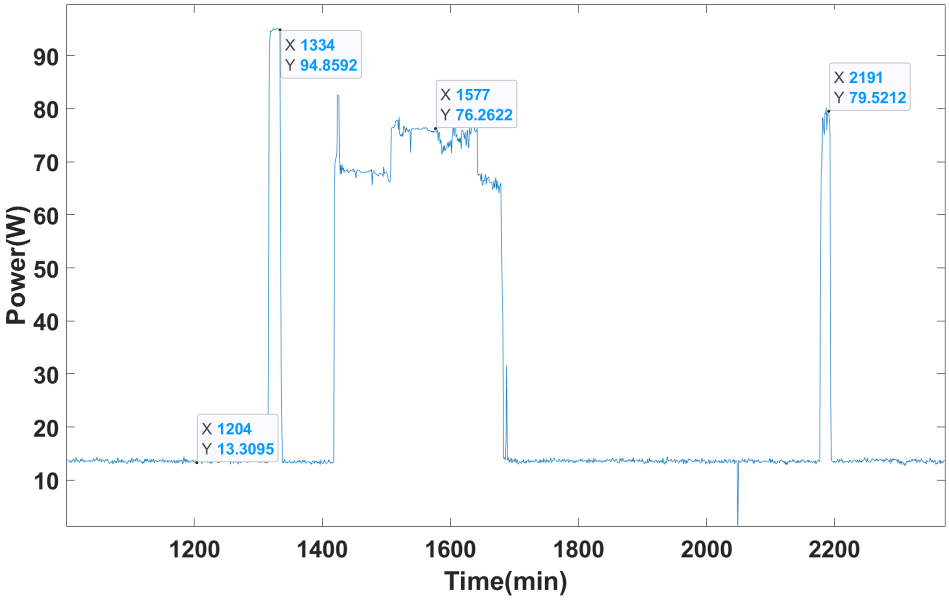


Figure 4.9: Power consumed by a Television during one day.

4.3.3 Smartphone

A Smartphone power consumption was measured and logged with the help of a Voltcraft for one week. It was charged with a 20 Watt output adapter. However, the Smartphone was configured for standard charging and only charging up to 85% of total charging capacity. The maximum power consumed was 16 Watts.

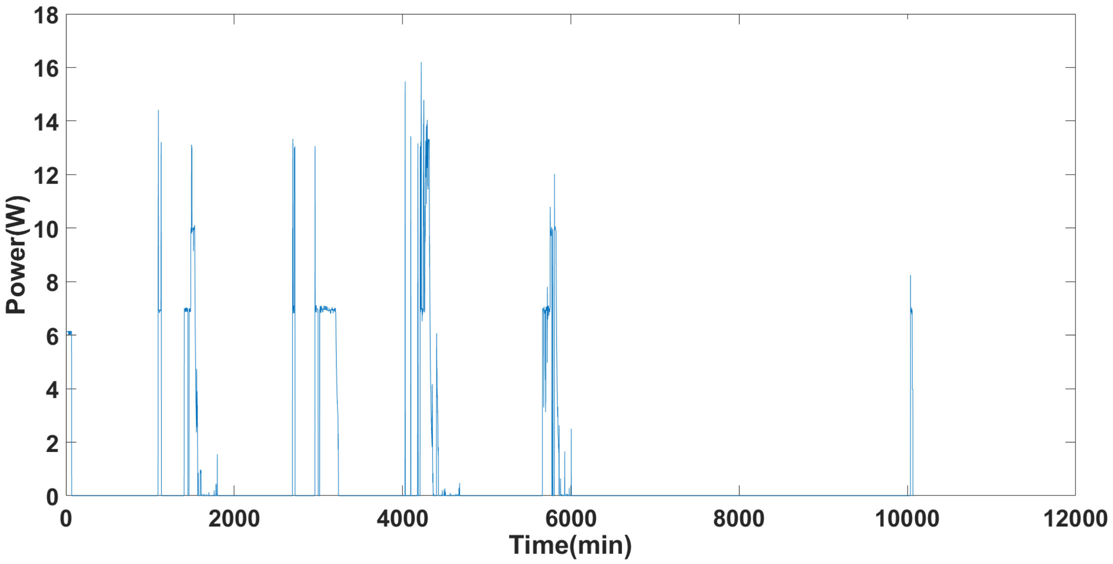


Figure 4.10: Power consumed by a Smartphone during one week.

A one-day power consumption of the Smartphone is illustrated in figure 4.11. It can be seen that the Smartphone was charged mostly between 6 to 10 Watts. The spikes and fluctuation in the figure are the results of using the Smartphone during the charging period.

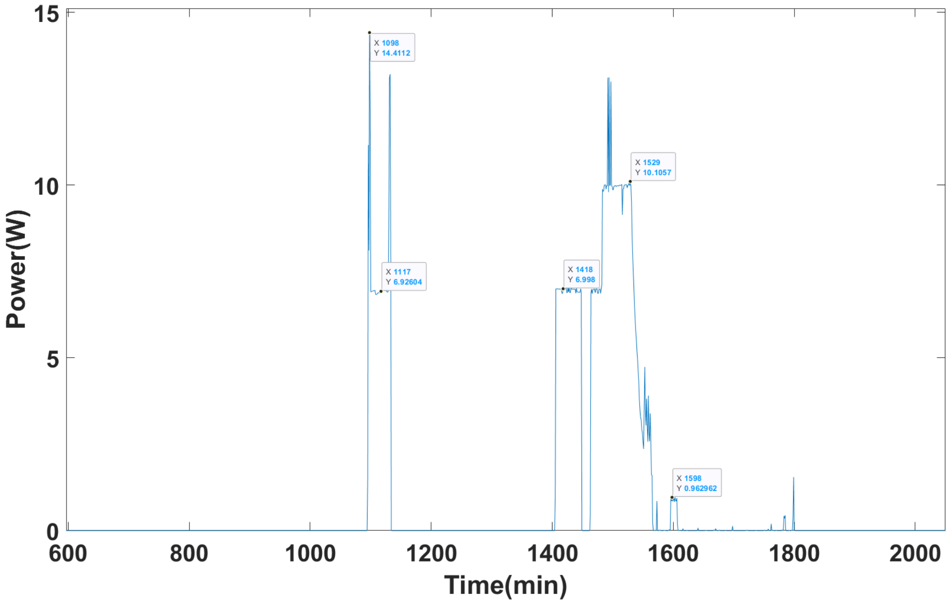


Figure 4.11: Power consumed by a Smartphone during one day.

4.3.4 LED Lamp

The power consumption of a LED Lamp of 6 Watt was measured and logged with the help of a Voltcraft for one week. The lamp was used simultaneously as the roof lamps were turned on. As shown in figure 4.12, the lamp is mostly used during the evening. The lamp was used around six times during one week and operated between 5 to 6 Watts.

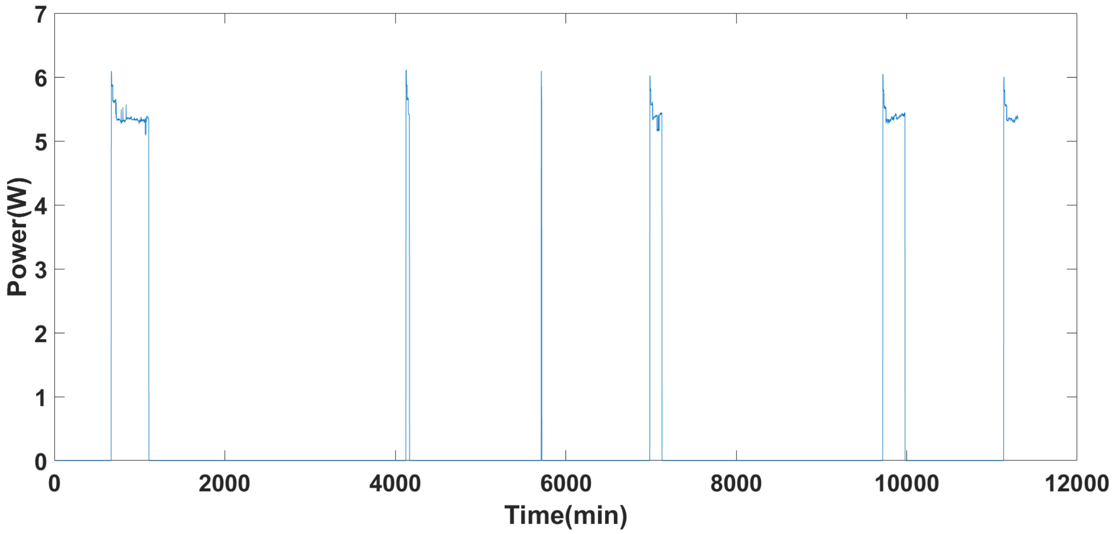


Figure 4.12: Power consumed by a LED Lamp during one week.

A one-day power consumption of a single LED lamp can be seen in figure 4.13. The apartment had lamps with a higher effect than 6 Watt. This measurement was used to form a load profile of lamps in different rooms in the apartment.

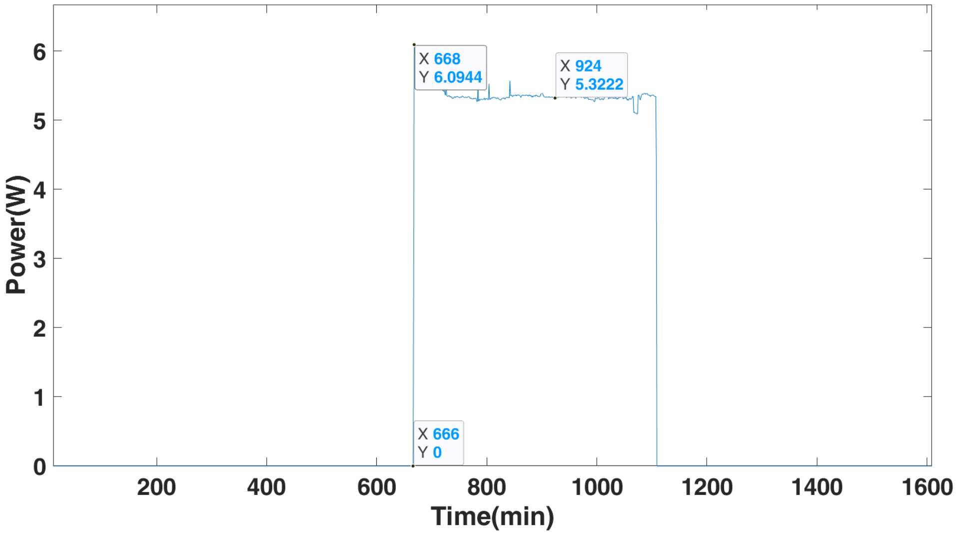


Figure 4.13: Power consumed by a LED Lamp during one day.

4.3.5 Electric Kettle

An electric kettle power consumption was measured and logged with the help of a Voltcraft for one week. As depicted in figure 4.14, the kettle has been in use very often. The kettle operates between 1800 and 2000 Watts.

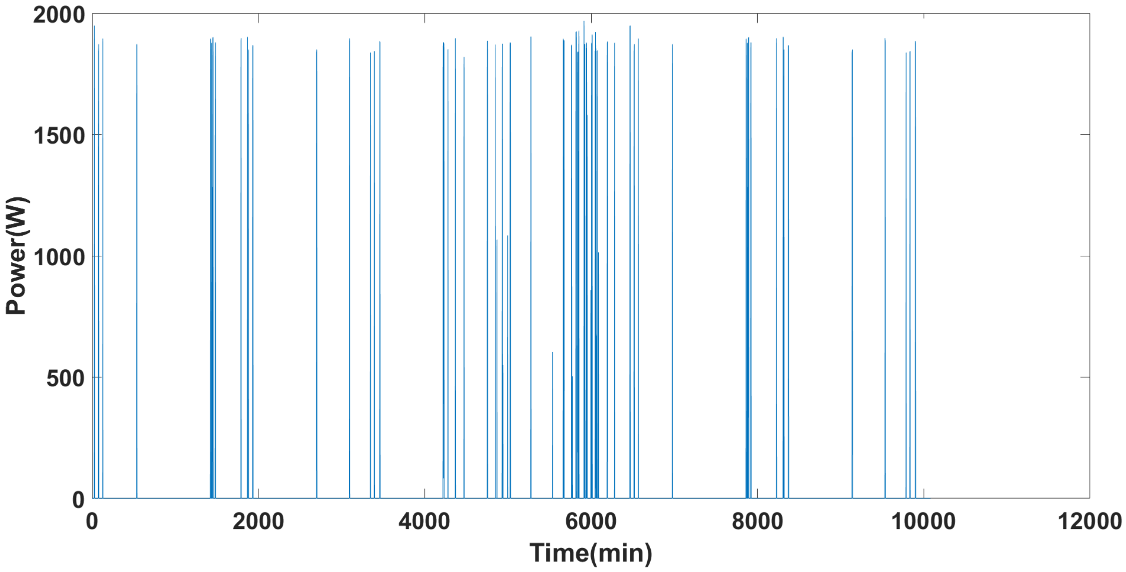


Figure 4.14: Power consumed by an Electric Kettle during one week.

A one-day consumption of an Electric Kettle can be seen in figure 4.15. It can be observed that the kettle is warming up the water for seven minutes almost every time. It was used nine times in one day.

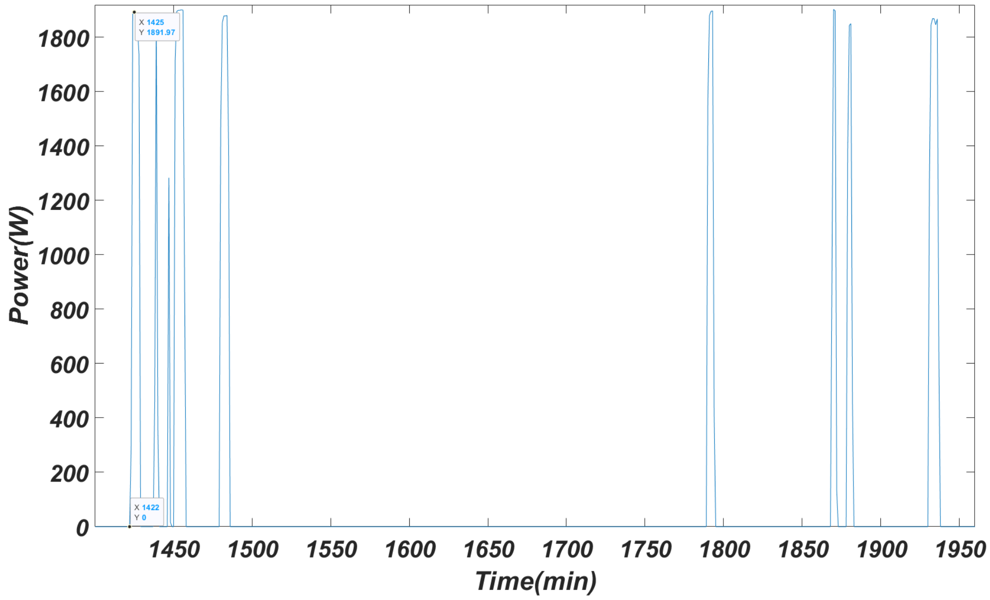


Figure 4.15: Power consumed by an Electric Kettle during one day.

4.3.6 Microwave

The power consumption of a Microwave was measured and logged with the help of a Voltcraft for one week. Figure 4.16 shows that the Microwave was used very often and with different power levels. The gap between 4000 and 6000 shows that the Microwave was not used during the weekend.

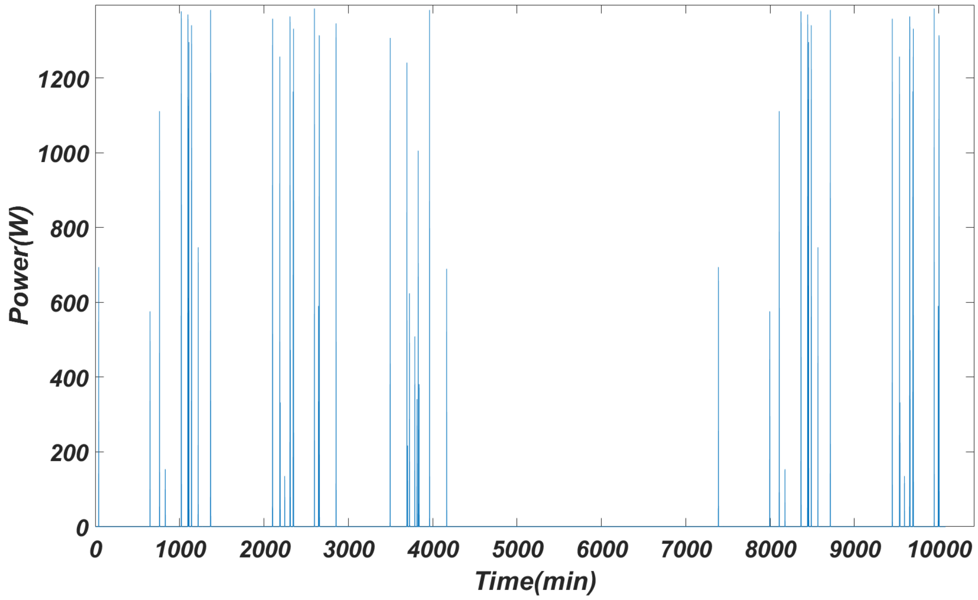


Figure 4.16: Power consumed by a Microwave during one week .

The power consumption of the Microwave for one-day is illustrated in figure 4.17.

An average usage time of the Microwave for each warming is around 4 minutes. The different power consumption levels can depend on the food being heated since the Microwave used in this project was programmable.

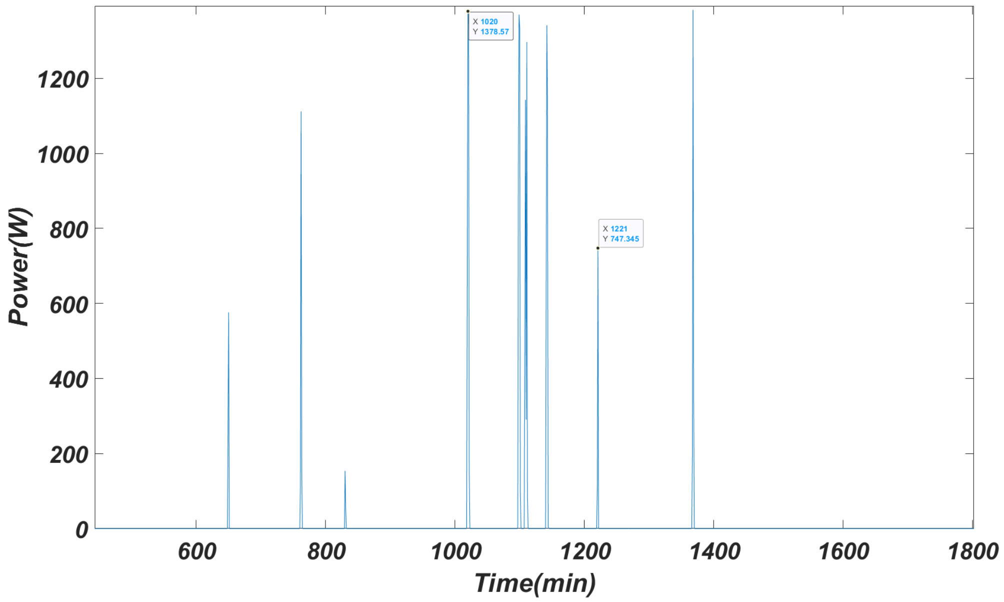


Figure 4.17: Power consumed by a Microwave during one day.

4.3.7 Coffee Maker

A Coffee maker was used typically for one week, and the power consumption was measured and logged with the help of a Voltcraft. The result can be seen in figure 4.18. The Coffee Maker warms up the water for 4 minutes, and then it consumes less power to keep the coffee warm afterward. The Coffee Maker operates at 1500 Watt at the beginning and then decreases to 75 Watt.

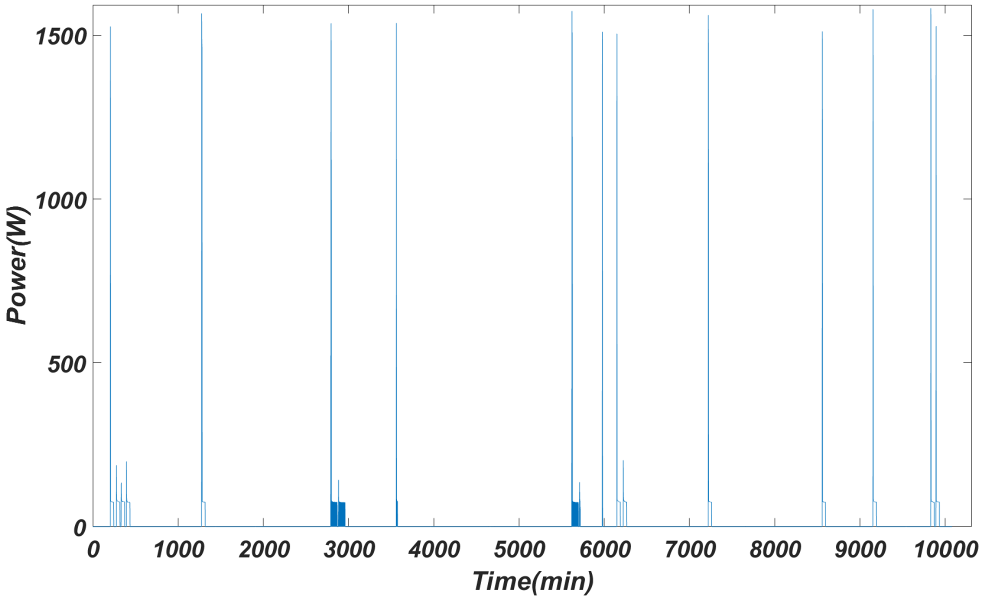


Figure 4.18: Power consumed by the Coffee Maker during one week.

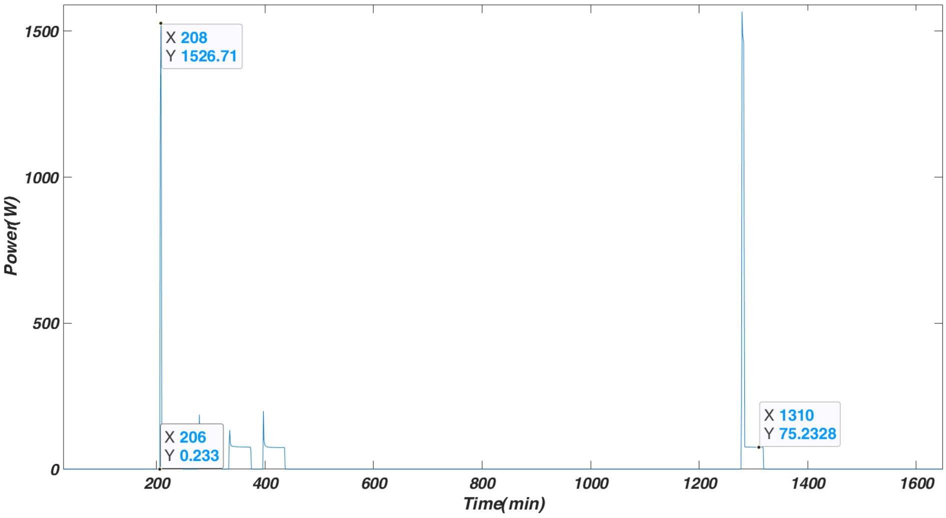


Figure 4.19: Power consumed by the Coffee Maker during one day.

4.3.8 Vacuum Cleaner

The Vacuum cleaner was used one time during the whole week. The power consumption was measured and logged with the help of Voltcraft. It operated with a maximum power of 1485 Watts and was used for 21 minutes.

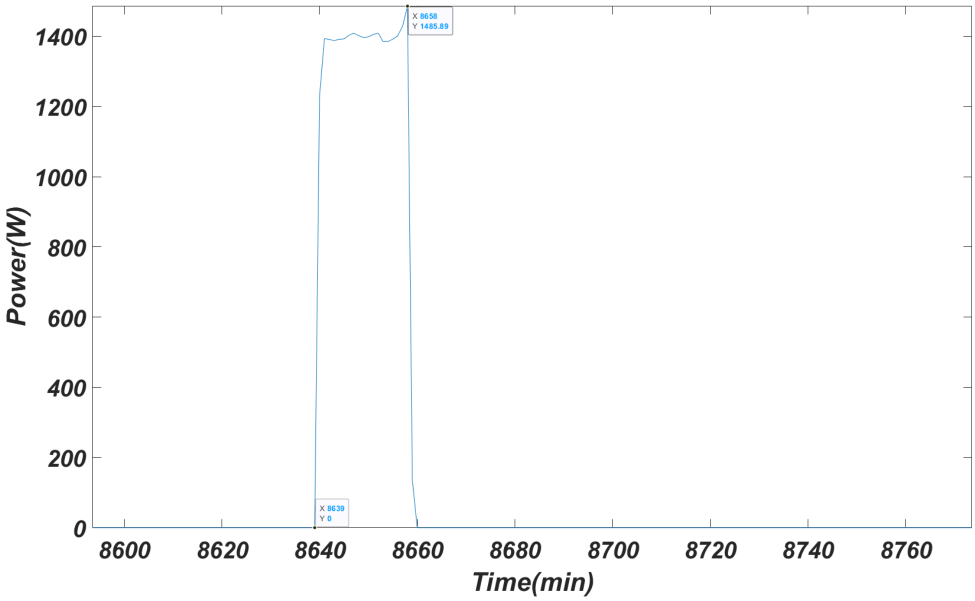


Figure 4.20: Power consumed by a Vacuum Cleaner during one day.

4.3.9 Mixer

The mixer was used on seven occasions during one week, as shown in figure 4.21. It was measured, and the measurement data was logged during the whole week. The Mixer operates between 70 to 75 Watts. Each spike shows power consumption for one day, and each day the mixer was used for 2 minutes.

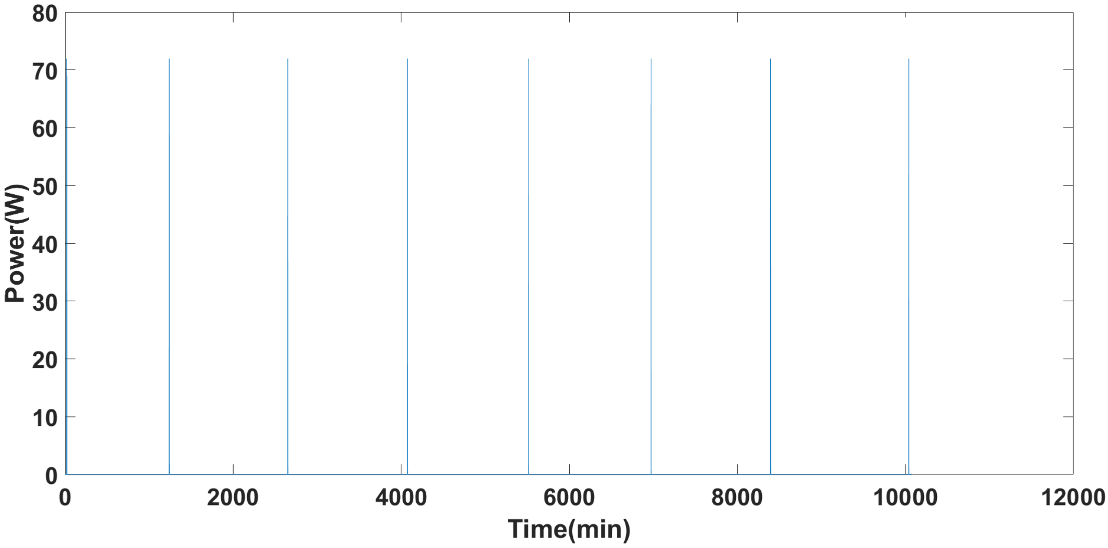


Figure 4.21: Power consumed by a Mixer during one week.

A one-day power consumption of a mixer can be seen in figure 4.22. The mixer was used for 2 minutes with a maximum power of 72 Watts.

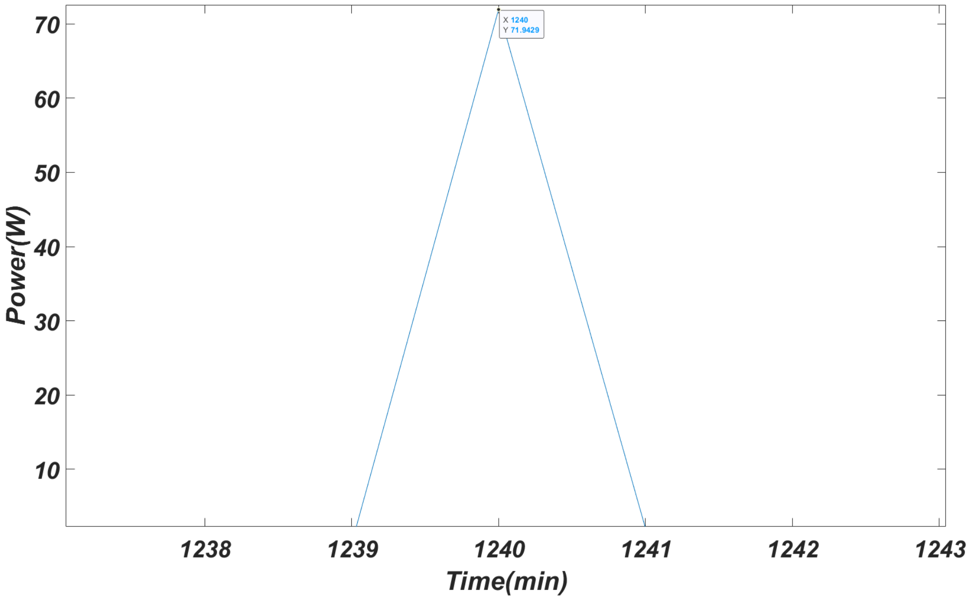


Figure 4.22: Power consumed by a Mixer during one day.

4.3.10 Toaster

The power consumption of a Toaster was measured and logged for one week. It was used seven times during the measurement period. The Toaster operates between 500 and 600 Watts.

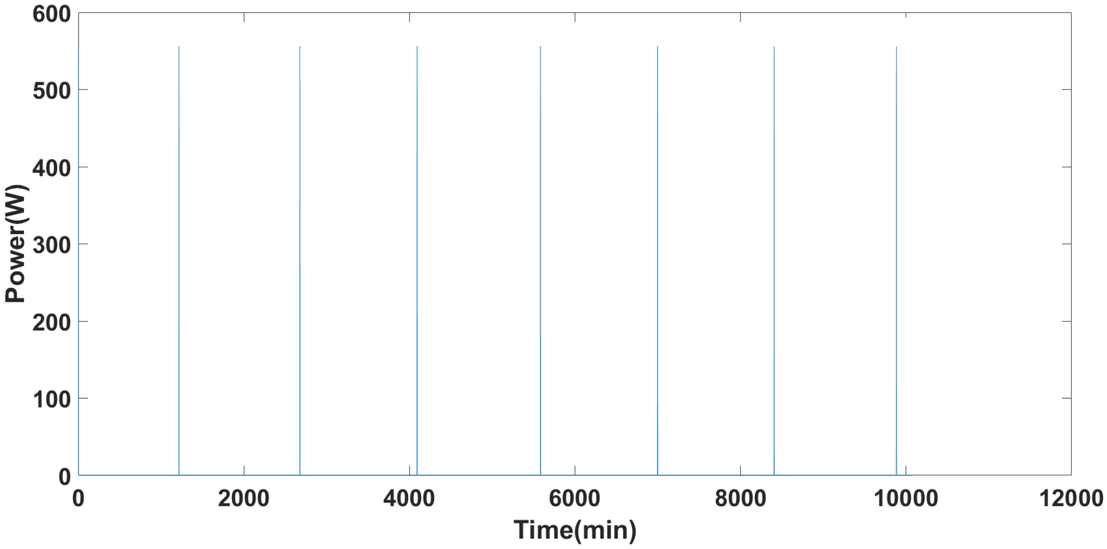


Figure 4.23: Power consumed by a Toaster during one week.

A one-day power consumption of the Toaster can be seen in figure 4.24. The Toaster operates for 3 minutes, and the maximum power it consumes is 556 Watts.

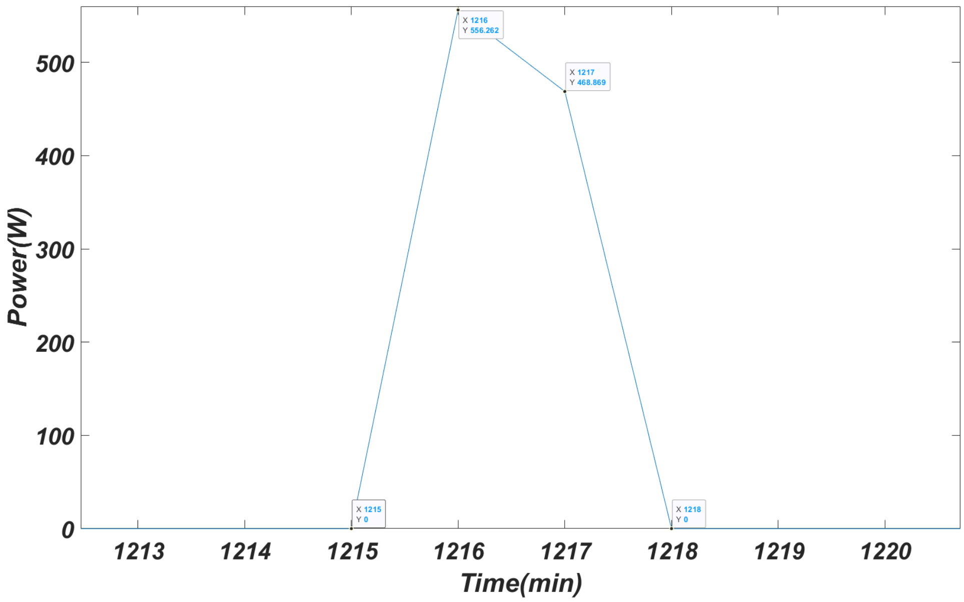


Figure 4.24: Power consumed by a Toaster during one day.

4.3.11 Refrigerator

Due to technical difficulties, measurements could not be conducted on a refrigerator in the apartment. Thus data were taken from previous measurements that were done during 24 hours. The measurements showed that a refrigerator is operational for 13 hours and 28 minutes during one day with an average power consumption of 32.61 Watts [15]. The power consumption peaks at 280 Watts for 30 minutes during the refrigerator's defrosting process. A set of data points representing the power consumption for this refrigerator will be added to the total power consumption for the apartment.

4.3.12 Total consumption of an Apartment

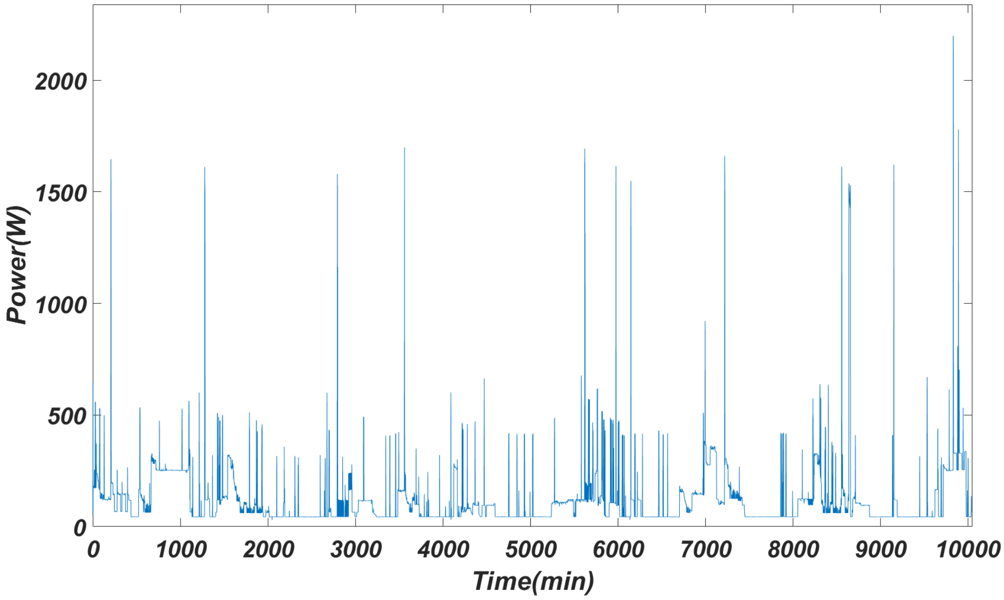


Figure 4.25: Power consumed by an apartment during one week.

The result from the household appliances and the power consumption of a refrigerator was put together to form the load profile of an apartment for one week. The result can be seen in figure 4.25. The spikes with very high power consumption can depend on using household appliances simultaneously. By integrating the power over time and correcting with a factor of 52 for all of the weeks during a year, total power consumption of 1191 kW per week was given. Since the power consumed by household appliances stands for approximately 20% of the total power consumption of a household, this value was multiplied by five. And assuming that a normal family is away from home for one month during the year, a multiplication with 0.9167 was made. This gave a total power consumption of 4746 kWh/year, which agrees with real numbers, which should be between 4 and 6 thousand kWh/year[10].

4.4 Matlab Results

As described earlier, Matlab was used to approximate functions for the power losses for the converter using different transformers at various loads. The functions are expressed as polynomial equations. This was achieved by transposing the vectors containing the data points and using the vectors as two out of the three input arguments for a previously defined function in Matlab called (fit). The last argument selects to what degree the user would like the polynomial equation to be expressed as. In this case, a ninth-degree polynomial equation.

Using the data points for the consumed power by different household appliances as input to these functions, an output of the total power losses for each time sample is received. These two sets of data points are summed and compared to each other.

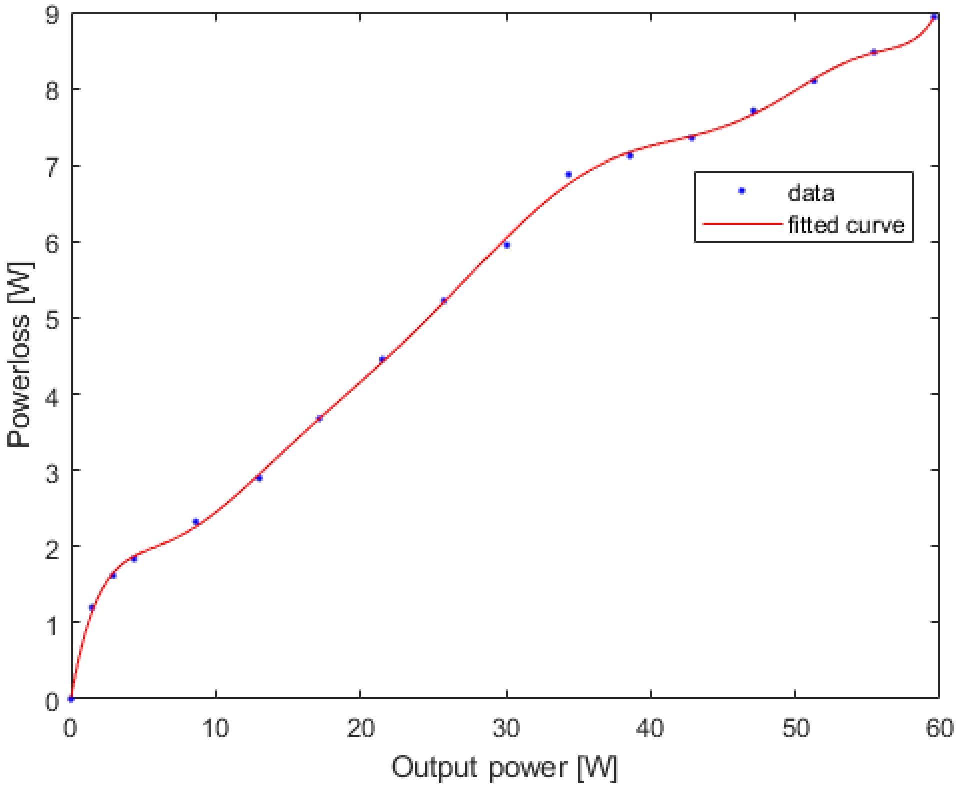


Figure 4.26: Fitted curve to the data points of the power losses in relation to the output power with the planar transformer.

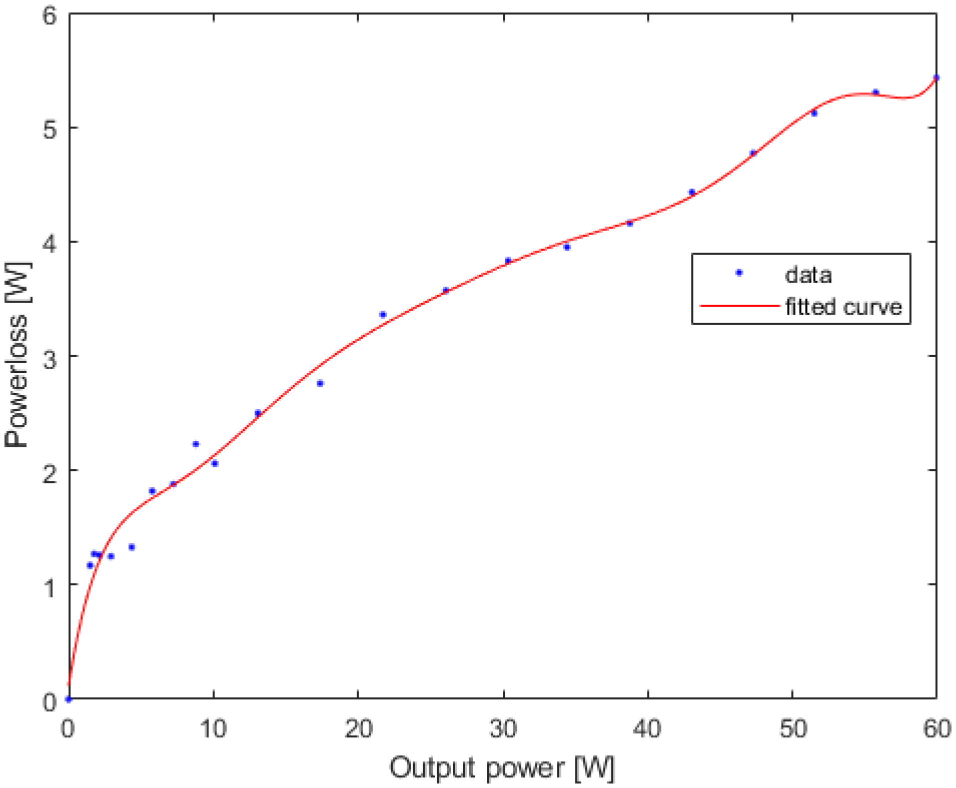


Figure 4.27: Fitted curve for the data points of the power losses in relation to the output power with the conventional transformer.

Figure 4.26 illustrates the data points for the power losses at different loads and the approximated line through the points for the converter using the planar transformer. The same is respectively illustrated in figure 4.27 for the converter using the conventional transformer.

By using the load profiles of the household appliances from 0 to 60 Watts as input to these two functions, a total power loss of 102.8 and 56.9 kW was given for the converter using the planar transformer and the conventional transformer respectively. The difference in losses summed up to approximately 45.9 kW for one week. In this case, however, loads above 60 Watts are not considered since the functions are not defined above this power level. This is because this particular flyback converter is not designed to operate above this power level.

The planar transformer that was used during this project was a prototype and improvements will be made to increase the efficiency of this transformer. By assuming that the improved planar transformer will reach an efficiency of up to 96% and by considering all load profiles of the household appliances that were measured during this project, a total power loss of 57 kW was calculated for one week period. This is the minimal theoretical limit of power losses that could be reached under the condition that all household devices are connected to different flyback converters with specific peak efficiencies for each particular device. This limit will most likely not be reached since it is unlikely that the flyback converter will have a load profile connected to it that operates at the converter's maximum efficiency. Assuming that loads between 100 and 2000 Watts operate under an efficiency of 96 percent and that smaller loads operate at the efficiency levels of the flyback converter with the planar transformer, the total losses for one week will be approximately 68 kW.

Table 4.2 shows the results of the power losses for the converter using the conventional and the planar transformer as well as an approximation of the total power losses for all load profiles of a household. This approximation is based on the power losses of the conventional transformer as well as a 96% efficiency for high load profiles.

Table 4.2: Power losses for the flyback converter with different transformers and various load profiles connected to it during a one week period.

$P_{loss.conv}$ [0 - 60 W Loads]	$P_{loss.plan}[0 - 60W Loads]$	$P_{plan.0.96}$ [0 - 2000 W Loads]
56.9[kW]	102.8 [kW]	68.2 [kW]

4.5 Life Cycle Cost Analysis

The conduction losses of the primary MOSFET may vary depending on what load the flyback converter is connected to. And the conduction losses of the primary MOSFET can be reduced by 50% by using the topology shown in figure 4.5. Assuming that a MOSFET switch costs 12 SEK, an analysis will be made of how beneficial another MOSFET switch can be when connected to various electrical loads. The loads in focus are the ones that are active throughout an entire year, such as the TV and refrigerator.

The TV is in standby mode between 18 and 20 hours during one day, which means that the conduction losses of the main MOSFET of the flyback converter will constantly be 90mW. Using the topology described in figure 4.5, a reduction of between 0.263kWh and 0.328kWh can be made throughout a year. With the current energy prices, this would mean that the consumer would save between 4 and 6 SEK every year.

Refrigerators may vary in power consumption depending on the model. However, data sheets and previously conducted measurements show that a refrigerator has an average power consumption of 32.61 W and operates at this power level for 13 hours and 28 minutes per day[15]. By connecting one refrigerator to a flyback converter with an added switch, it would be possible to save 0.407 kWh every year. It is now uncommon for large households to have two refrigerators. This would keep the flyback converter operating close to its rated load, which minimizes the total losses. By implementing paralleled MOSFET switches, it would be possible to decrease losses by 0.953 kWh every year.

5

Discussion and Conclusion

The prototype planar transformer has proven to be 4% less efficient than the conventional transformer. It is advised to develop the planar transformer further or use the conventional transformer on the flyback converter when supplying electrical loads. However, there could exist some uncertainties in the first statement. This is because the transformers were not tested at the same time and under the same circumstances. During the time between the measurements, the conventional transformer was exposed to damage. It is uncertain if any other components also were damaged, in which case this could affect the results. If the planar transformer is improved and reaches a higher efficiency for high loads, power losses will decrease significantly and perform better than the planar transformer.

Since the converter has a higher efficiency close to its rated load, it is highly recommended to keep it working as close to this point to keep the power losses down to a minimum. In addition to this, the conduction losses in the primary MOSFET can be decreased by 50% by connecting another MOSFET in parallel to the primary one. This decrease in losses will not be significant on an individual level whatsoever. But could, however, be very important from a sustainability standpoint if this system was implemented on a larger scale. How significant the decrease in conduction losses are, is highly dependent on the electrical load that is connected to the flyback converter, for how long of a time it is operational and the energy prices. The conduction losses in the MOSFET are higher closer to rated power.

The economic value for the energy reduction in the conduction losses by the added MOSFET will have to correspond to the investment cost of said MOSFET for the investment to be beneficial. It is most likely to achieve this under two circumstances. The first is that the converter must operate close to rated power. And the second is that the converter must operate for an extended period of time. Electrical devices such as refrigerator, TV and electrical heating has a higher potential to achieve this since these loads are always operational.

The measured load profiles of the household appliances proved to be an accurate representation of a standard Swedish household after adding one of the missing devices, the refrigerator, and correcting the load profiles of the microwave and electric kettle to match the consumption of an average household. An average Swedish household of this size has a total yearly energy consumption of between 4000 and 6000 kWh/year. The measured values after correcting for an entire year resulted in total energy consumption of 4350 kWh/year. The only significant power-consuming devices missing are the oven, stove, dishwasher, and washing machine. To avoid corrections and improve the measurements, all electrical loads in a household should be measured for an entire year or more to identify patterns.

The measurements of the individual devices show an accurate illustration of power consumption during various stages of the device, such as when the coffee maker is heating up and just maintaining heat, when the TV is turned on and when it is in standby mode, and when a smartphone only is charging and while it is being used while charging. Hopefully, these measurements could be used as a guideline for what power levels converters should be designed to have the optimal efficiency.

5.0.1 Ethical Aspects

Technology is everywhere in society; therefore, the ethical aspects must be considered while developing these technologies. As engineering students, it is our moral duty to follow the Engineering code of ethics. This project follows the ethical codes from the Institute of Electrical and Electronics Engineers[16].

In this project, all the processes are upheld to the highest possible standards to achieve the best possible results. However, according to the IEEE code of conduct point two, which is *"to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems"* the results comparing the two transformers that are used in the active clamp flyback converter might not be an accurate representation due to various factors discussed earlier.

According to the IEEE code of conduct point three, which is *"to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist"* there have not been huge conflicts of interest in this project, however, when the conflict of ideas arose, it was discussed between the students and the supervisor.

Moreover, according to point seven in the IEEE code of conduct which is *"to treat all persons fairly and with respect, and to not engage in discrimination based on characteristics such as race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression"* both students have been deeply indulged. They have been able to share and discuss their ideas and views during the process of this project. Both students have treated each other with respect and been treated with respect by the supervisor and all the involved persons in this project.

5.0.2 Sustainability Aspects

As the world moves toward a more sustainable future and the demand for electricity keeps increasing, it is important to ensure a sustainable development of technologies that have an impact in this sector. This is why 17 sustainable development goals (SDGs) or the Global goals were introduced in 2015. These goals are now adopted by the United Nations member countries to achieve sustainable development by the year 2030. This project has focused on two sustainability goals seven and twelve[17], which are *"affordable and clean energy"* and *"responsible consumption and production"*.

Generating and having access to clean energy will be fundamental as we move toward a sustainable future. Increasing access and electrification of different sectors also increases the demand for cheap energy. While the development of renewable energy technologies paves the path for more affordable renewable energy generation. The highly efficient DC/DC converter plays a significant role by converting renewable energy in a household with high efficiency and low power losses. The energy price can be much more affordable by reducing the energy loss in household appliances. Moreover, the high-efficiency DC/DC converter ensures sustainable consumption of energy.

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A

Tables with Results from Electrical Measurements

Table A.1: Measurement data from the active clamp flyback converter using measurement method 1.

R_{load} [Ω]	U_{in} [V]	I_{in} [A]	U_{out} [V]	I_{out} [A]	P_{in} [W]	P_{out} [W]	η[%]
14.13	370	0.095	20.54	1.454	35.18	29.87	84.90
19.71	370	0.069	20.58	1.044	25.54	21.49	84.14
24.75	370	0.055	20.59	0.832	20.35	17.13	84.18
29.6	370	0.047	20.60	0.696	17.39	14.34	82.45
39.33	370	0.035	20.61	0.524	12.97	10.80	83.28
49.93	370	0.028	20.62	0.413	10.37	8.52	82.09
58.94	370	0.025	20.63	0.350	9.26	7.22	77.95
63.48	370	0.023	20.63	0.325	8.51	6.70	78.79
73.68	370	0.020	20.63	0.280	7.41	5.78	77.95
85.25	370	0.018	20.63	0.242	6.67	4.99	74.86
87.79	370	0.017	20.63	0.35	6.30	4.85	76.97
98.24	370	0.016	20.63	0.210	5.93	4.33	73.08
109.73	370	0.015	20.63	0.188	5.56	3.88	69.79
117.22	370	0.014	20.63	0.176	5.18	3.63	70.06
126.63	370	0.013	20.64	0.163	4.82	3.36	69.85
145.35	370	0.012	20.64	0.142	4.45	2.93	65.92
174.92	370	0.010	20.64	0.118	3.70	2.44	65.77
198.46	370	0.010	20.64	0.104	3.71	2.15	57.94
217.26	370	0.009	20.64	0.095	3.33	1.96	58.80
286.67	370	0.007	20.64	0.072	2.59	1.49	57.30

Table A.2: Measurement data from the active clamp flyback converter usin measurement method 2.

R_{load} [Ω]	U_{in} [V]	I_{in} [A]	U_{out} [V]	I_{out} [A]	P_{in} [W]	P_{out} [W]	η[%]
14.13	370	0.0982	20.54	1.454	35.18	29.87	82.16
19.71	370	0.0711	20.58	1.044	25.54	21.49	81.65
24.75	370	0.0570	20.59	0.832	20.35	17.13	81.19
29.6	370	0.0480	20.60	0.696	17.39	14.34	80.67
39.33	370	0.0360	20.61	0.524	12.97	10.80	80.86
49.93	370	0.0296	20.62	0.413	10.37	8.52	79.37
58.94	370	0.0249	20.63	0.350	9.26	7.22	78.06
63.48	370	0.0235	20.63	0.325	8.51	6.70	77.22
73.68	370	0.0207	20.63	0.280	7.41	5.78	75.42
85.25	370	0.0182	20.63	0.242	6.67	4.99	74.14
87.79	370	0.0179	20.63	0.35	6.30	4.85	73.20
98.24	370	0.0163	20.63	0.210	5.93	4.33	71.84
109.73	370	0.0149	20.63	0.188	5.56	3.88	69.89
117.22	370	0.0141	20.63	0.176	5.18	3.63	69.66
126.63	370	0.0134	20.64	0.163	4.82	3.36	67.86
145.35	370	0.0119	20.64	0.142	4.45	2.93	66.01
174.92	370	0.0104	20.64	0.118	3.70	2.44	62.73
198.46	370	0.0097	20.64	0.104	3.71	2.15	59.81
217.26	370	0.0089	20.64	0.095	3.33	1.96	59.55
286.67	370	0.0072	20.64	0.072	2.59	1.49	55.79

Table A.3: Measurement data from the active clamp flyback converter usin measurement method 3.

$R_{load}[\Omega]$	$U_{in}[V]$	$I_{in}[mA]$	$U_{out}[V]$	$I_{out}[A]$	$P_{in}[W]$	$P_{out}[W]$	$\eta[\%]$
7.14	380	178.0	20.63	2.889	67.96	59.60	87.70
7.68	380	166.8	20.64	2.686	63.42	55.44	87.42
8.31	380	155.0	20.64	2.485	58.93	51.29	87.03
9.04	380	143.0	20.64	2.283	54.37	47.12	86.67
9.94	380	130.9	20.64	2.076	49.78	42.85	86.07
11.04	380	119.2	20.64	1.870	45.33	38.59	85.12
12.40	380	107.5	20.64	1.664	40.88	34.34	84.01
14.17	380	93.9	20.64	1.457	35.72	30.07	84.19
16.53	380	80.8	20.64	1.249	30.74	25.78	83.87
19.79	380	67.7	20.64	1.043	25.75	21.53	83.59
24.81	380	54.3	20.64	0.832	20.66	17.17	83.11
32.78	380	41.5	20.65	0.630	15.79	13.00	82.39
49.40	380	28.6	20.65	0.418	10.88	8.63	79.36
97.87	380	16.16	20.65	0.211	6.15	4.36	70.86
146.45	380	11.81	20.65	0.141	4.49	2.91	64.78
294.86	380	6.90	20.64	0.070	2.63	1.44	55.02

Table A.4: Results from Active clamp converter with regular transformer

$R_{load}[\Omega]$	$U_{in}[V]$	$I_{in}[mA]$	$U_{out}[V]$	$I_{out}[A]$	$P_{in}[W]$	$P_{out}[W]$	$\eta[\%]$
7.17	380	0.17	20.58	2.91	65.36	59.93	91.69
7.71	380	0.16	20.59	2.71	60.80	55.74	91.67
8.33	380	0.15	20.59	2.50	56.62	51.50	90.95
9.09	379.9	0.14	20.60	2.30	52.05	47.28	90.84
10	379.9	0.13	20.60	2.09	47.49	43.05	90.66
11.11	379.9	0.11	20.61	1.88	42.93	38.77	90.31
12.50	379.9	0.10	20.61	1.67	38.37	34.42	89.70
14.29	379.9	0.09	20.61	1.47	34.19	30.36	88.79
16.67	379.9	0.08	20.62	1.26	29.63	26.06	87.96
20	379.9	0.07	20.62	1.05	25.07	21.71	86.60
25	380	0.05	20.62	0.84	20.14	17.38	86.31
33.33	380	0.04	20.63	0.63	15.58	13.08	83.95
43	380	0.03	20.62	0.49	12.16	10.10	83.09
50	379.9	0.03	20.63	0.43	11.02	8.79	79.77
60	380	0.02	20.63	0.35	9.12	7.24	79.40
75	380	0.02	20.63	0.28	7.60	5.78	76.01
100	380	0.02	20.63	0.21	5.70	4.37	76.73
150	380	0.01	20.63	0.14	4.18	2.93	70.08
200	380	0.01	20.34	0.11	3.42	2.16	63.04
250	380	0.01	20.62	0.09	3.04	1.77	58.33
300	380	0.01	20.63	0.07	2.66	1.49	55.84

B

Matlab code

```
%Mathematical function which represents power loss vs.
%power output of the planar transformer

function  [z]=forlust_3(x)
size_x = size(x);
row = size_x(1);
col = size_x(2);
z = zeros(row, col);
    for  cols = 1 : col
        if (x(:, cols) >= 0) && ( x(:, cols) <= 70)
            z(:, cols)=  (1.575e-12)*x(:, cols).^9 + ...
            (-4.32e-10)*x(:, cols).^8 + (4.965e-08)*x ...
            (:, cols).^7 + (-3.11e-06)*x(:, cols).^6 + ...
                    (0.0001157)*x(:, cols).^5 + ...
                    (-0.002616)*x(:, cols).^4 + ...
                (0.03532)*x(:, cols).^3 + (-0.2651)*x ...
                (:, cols).^2 + 1.079*x(:, cols);
        else
            z(:,cols) = NaN;
        end
    end
end
```

```
%Mathematical function which represents power loss vs.
%power output of the regular transformer

function [z]=forlust_4(x)
size_x = size(x);
row = size_x(1);
col = size_x(2);
z = zeros(row, col);
    for cols = 1 : col
        if (x(:, cols) >= 0) && ( x(:, cols) <= 70)
            z(:, cols)= (1.131e-12)*x(:,cols).^9 + ...
            (-3.011e-10)*x(:,cols).^8 + (3.378e-08)*x ...
            (:,cols).^7 + (-2.081e-06)*x(:,cols).^6 + ...
                    (7.686e-05)*x(:,cols).^5 + ...
                    (-0.001744)*x(:,cols).^4 + ...
                (0.02383)*x(:,cols).^3 + (-0.1847)*x ...
                (:,cols).^2 + 0.8182*x(:,cols);
        else
            z(:,cols) = NaN;
        end
    end
end
```

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