DESIGN OF CAPACITIVE COUPLED TRANSFORMER FOR POWER CONVERTER APPLICATIONS

A Thesis

by

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DESIGN OF CAPACITIVE COUPLED TRANSFORMER FOR POWER CONVERTER APPLICATIONS

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ABSTRACT

Transformer types have varied over time according to the purpose of use. As it is known, these devices are coiled materials that provide power transfer by magnetic induction. The AC voltage applied to the primary is reflected on the secondary side, resulting in a voltage induced in the secondary by the magnetic field. These materials, which we encounter in many places in power systems and power electronics, are difficult to produce and take time, and are costly because a certain number of turns is required. In this study, instead of an inductive transformer model, a capacitive transformer model will be designed and tested. This device will transfer power with an electric field. With the mutual capacitance value created by the four metal plates being in the same dielectric material in a nested structure, the power transfer will be transferred from the primary plates to the secondary plates. It is expected that the capacitive transformer model here will be better than the inductive transformer in terms of manufacturing convenience and cost. This design will also provide isolation for some types of non-isolated converters. The equivalent circuit of this capacitive transformer was set up, a simulation study was performed with MATLAB Simulink, and a power transfer was performed as desired. Similarly, the experimental circuit was set up and the results were obtained. It has successfully done the purposes of step-down and isolation transformers.

ÖZETÇE

Kullanım amacına göre transformatör tipleri zaman içinde çeşitlenmiştir. Bilindiği üzere temelde bu cihazlar manyetik indüklenme ile güç aktarımı sağlayan sargılı malzemelerdir. Primer sargılarına uygulanan AC voltaj, sekonder tarafına yansır sonuç olarak manyetik alan ile sekonderde indüklenen bir voltaj oluşur. Güç sistemleri ve güç elektroniğinde birçok yerde karşımıza çıkan bu malzemelerin üretimi zordur ve zaman alır ayrıca maliyet açısından yüksektir çünkü belirli bir sarım sayısı gerekliliği vardır. Bu çalışmada indüktif bir transformatör modeli yerine kapasitif bir transformatör modeli için tasarım, simulasyon ve deneysel testleri yapılacaktır. Bu cihaz güç aktarımını elektrik alanı kullanarak yapacaktır. İç içe geçmiş bir yapıda dört metal plakanın aynı dielektrik malzeme içerisinde olmasıyla oluşan ortak kapasitans değeriyle güç aktarımı primer plakalardan sekonder plakalarına aktarılacaktır. Buradaki kapasitif transformatör modelinin üretim kolaylığı ve maliyet açısından indüktif transformatöre göre daha iyi olacağı beklenilmektedir. Bu cihaz ayrıca bazı izole olmayan dönüştürücü topolojileri için izolasyon da sağlayacaktır. Bu kapasitif transformatörün eş değer devresi çıkartılıp, bu devrenin simülasyon çalışmaları MATLAB Simulink ile yapılmıştır ve istenildiği gibi bir güç transferi gerçekleştirilmiştir. Benzer şekilde deneysel devreler de kurulup başarılı bir şekilde alçaltıcı transformatör ve izolasyon trafosu görevlerini yerine getirmiştir.

ACKNOWLEDGEMENTS

I would like to thank my advisor Asst. Prof. Gokturk Poyrazoglu all their help and advice. I would also like to thank my supervisor Huseyin Cem Kizilari in Vestel Electronics. I also appreciate all the support I received from the rest of my family.

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CHAPTER I

INTRODUCTION

1.1 Motivation

The experimental apparatus invented by Faraday in the 1830s included the principles of electromagnetic induction and the basic elements of the transformer. About 50 years later, in the 1880s, the first transformer took its present shape [4]. We know that until today, this design is almost preserved, and many types of transformers have been designed using the same electromagnetic principle on the basis. Many parameters such as dimensions, core material, winding numbers, and power values vary according to the usage areas.

Transformers in power electronics and many fields consist of coils wound on the same core. The variable current flowing through these coils creates a variable magnetic flux on the ferromagnetic material. This magnetic flux induces a voltage in the secondary winding to which the load is connected. In this way, power transfer is provided from the side where the supply voltage, called primary winding, is applied, to the side where the load is connected, called the secondary winding. With these transformers, the power transfer is made by the inductive coupling method.

Towards the end of the 1800s, one of the biggest goals of Nicola Tesla was to provide power transfer between continents, and he formed the foundations of the related Wireless Power Transfer (WPT) technology in those years [5]. Today, power transfer is done in many application areas with the wireless power transfer (WPT) method, which uses the same principle as in transformers. The difference is that there is an air gap between the windings or plates that are coupled.

This causes a decrease in efficiency and therefore requires high-frequency switching. There are 2 most commonly used methods of power transfer with WPT; Capacitive power transfer (CPT) performed with capacitive coupling and inductive power transfer (IPT) performed with inductive coupling [6]. There are also studies in which these methods are used together [7]. With the developing technology, many of the smart mobile phones we use in our daily lives charge their batteries with the IPT method.

As seen in previous studies, we see that power transfer can be done with the CPT method as power transfer is done with IPT. Similarly, we know that mutual inductance is provided and power transfer is performed with the windings wound on the same core as an inductive coupling in transformers. In this thesis, it will be examined whether it is possible to design a transformer using capacitive coupling similar to the capacitive coupling method in the CPT method.

1.2 Aims and Objectives

Coiled materials, which play a key role in power electronics, are used in almost every design. Transformers, one of these coiled materials, constitute the most important parameters of the design. Each design is created within the framework of specific requirements and it is a fact that each design needs a different transformer. For this reason, the consumption demand for these materials is quite high on an annual basis. Transformers are materials that are difficult to manufacture, high lead times, and difficult to work.

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Transformers are materials that are difficult to manufacture, high lead times, and difficult to work. For this reason, the costs of these materials are also quite high [8]. The transformer model to be applied in this thesis is much better than an inductive transformer, it does not require a special labor and production time since it does not contain a coiled material. Based on these reasons, we can predict that the capacitive transformer design here will be much more cost-effective.

In this thesis, just like a high coupling coefficient value obtained by having a transformer windings on the same core, designing a system that is well coupled with plates in the same dielectric material, and providing power transfer by keeping the mutual capacitance value high with these plates in the same electric field is the main is the goal. Various comparisons will be made by making trials to determine the advantages and disadvantages of this design compared to inductive transformers and to show its realizability. In the light of the information here, an application trial of this transformer design will be made on a sepic converter, and then the power transfer level, efficiency, and various parameters will be measured with a capacitive transformer.

1.3 Thesis Outline

In the capacitive transformer design, after the design criteria are determined first, the necessary parameters for testing this transformer on the sepic converter will be calculated. The design will have primary and secondary sides, just like the inductive transformer, and there will be dielectric material between each plate.

As shown in Figure 1, in this system consisting of four plates, P1 and P2 plates represent the primary side, namely the supply side, P3 and P4 plates represent the secondary side, namely the load side. The design criteria of this transformer will be determined according to the sepic converter requirements. The design of this sepic converter circuit will be applied as an experimental setup, and all measurements will be measured and calculated on the oscilloscope in the laboratory environment.

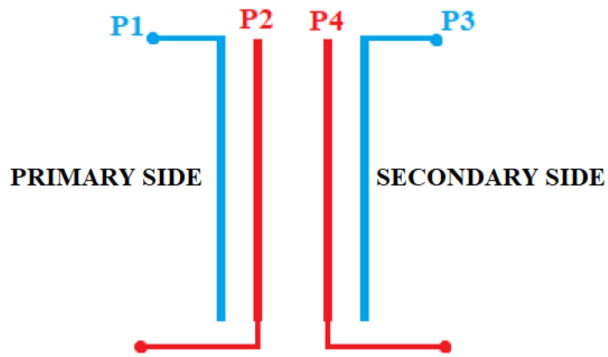

Figure 1: Schematic of Capacitive Transformer.

CHAPTER II

LITERATURE REVIEW

2.1 History of Transformers

Michael Faraday started experimenting using the electromagnetic principle in 1831. In those years he achieved to generate electricity with magnetism. He wrapped the windings in a 2-sided (Figure 2) way on an iron ring (toroid core) and when he disconnected the battery, which he connected to the ends of the wires on one side, he saw that the end of the windings on the other side oscillated. This principle is known as electromagnetic induction and it would form the basis of the modern transformer [1].

Figure 2: Faraday's First Transformer [1].

When self-inductance was discovered in 1832, Joseph Henry noticed that with the current cutoff, rapid flux change occurred, resulting in very high voltages (several hundred volts) in the coil. Figure 3 shows Henry's Coil [4].

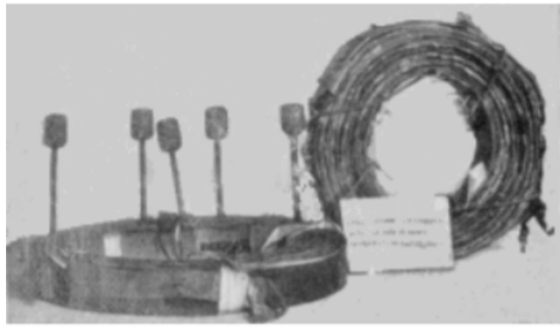

Figure 3: Henry's Coil [1].

About 50 years after these developments, a convenient transformer appeared, containing all the basic elements of the modern transformer. Developed by William Stanley, this transformer (Figure 4) was developed by George Westinghouse after a while and started to be used in power distribution transmission systems. This model has played a key role in electricity transmission and distribution. The story of the transformer doesn't end there, though. Today, some designs can reach up to 500 times the power of this design and 15 times the voltage and efficiency exceeding 99 percent. [2].

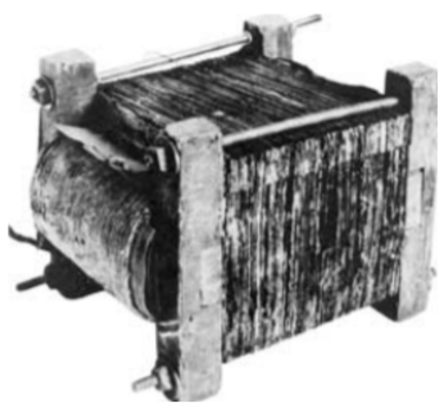

Figure 4: Stanley Transformer from First AC Power Station [2].

2.2 History of Wireless Power Transfer

The wireless power transfer (WPT) is not a new technology for science, although it seems like new technology. The first introduction of wireless power transmission which is capacitive power transfer (CPT) was made by Nicola Tesla, towards the end of the 1800s [9]. Shortly after this, the inductive power transmission (IPT) was demonstrated again by Tesla. Tesla's main goal was to transmit power between continents around the world. Using the Wardenclyffe Tower (Tesla Tower) which was designed and constructed by Tesla to transmit power without any wires was one of his greatest goals shown in Figure 5 [10]. When Tesla's funds and investment resources began to run out, wireless power transfer technology waited for decades to be developed until the 1960s [3]. After that William C. Brown introduced the first microwave power transfer (MPT) system which is electromagnetic radiation power transfer in 1963. This technology would enable the solar power transfer from solar cells of satellites in space to the ground. It can achieve the far distances for the WPT [11]. Wireless power transmission, which became popular again in the 1970s, slowed down the development in these areas due to insufficient semiconductor devices for those years [9].

Figure 5: Wardenclyffe Tower (Tesla Tower) [3].

2.3 Methods

Wireless power transfer can be done using three methods, the first of which is capacitive power transfer (CPT), the transfer made by capacitive coupling using an electric field. The second is inductive power transfer (IPT), which provides power transfer using the electromagnetic field, and the last method provides power transfer with microwaves which is microwave power transfer (MPT) [12]. The CPT method uses capacitive coupling which transferring the electrons using an electrical field.

In this thesis, power transfer will be analyzed with capacitive coupling as in the CPT method. Unlike wireless power transfer, the coupling plates here will be realized with two capacities in the same dielectric material.

Now we can talk about what inductive and capacitive coupling means when we talk about transformers.

2.3.1 Capacitive Coupling

One of the biggest disadvantages of the wireless CPT method is that coupling is very poor [12]. Since the capacitive transformer to be designed in this thesis does not require a wireless power transfer, therefore both primary and secondary capacitors to be coupled will be placed in the same dielectric material. In this way, the mutual capacitance will be created and the coupling coefficient will be increased.

We have mentioned that there is magnetic flux flowing in the core in the Inductive coupling in transformers. In the transformer model that is intended to be designed here, the capacitive coupling method will be applied and the power transfer will be provided with mutual capacitance by having the plates in the same dielectric material. Unlike the Wireless CPT method, it will be designed in the same dielectric material, so it will be like a typical inductive coupling transformer design.

The capacitive coupling equivalent circuit can be shown as in Figure 6 with mutual capacitance values [13].

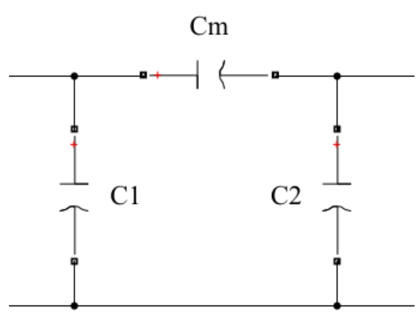

Figure 6: Equivalent Circuit of Capacitive Coupling Transformer

Here C1 and C2 capacities are the self-capacitance values of the primary and secondary sides. Cm capacity is the mutual capacitance value. The value of the k is the coupling coefficient and is calculated as follows:

$$k = \frac{Cm}{\sqrt{C1.C2}} \tag{1}$$

2.3.2 Inductive Coupling

In all transformers that using in power supplies have an inductive coupling to transfer the power from primary winding to secondary winding. The windings around the transformer's core create the value of inductance. This value, called self-inductance (L1 and L2), occurs for all windings separately in the core. We can talk about another inductance value in the windings wounded in the same core, called mutual inductance (M). The magnetic flux (phi) created by the alternating current in the windings circulates in the same core and creates this mutual inductance value. Windings that are wounded on the same core are coupled to each other with the mutual inductance value created by the magnetic flux circulating in the core. The coupling factor (K) in ideal transformers is considered to be 1. This coupling is called inductive coupling. [14]

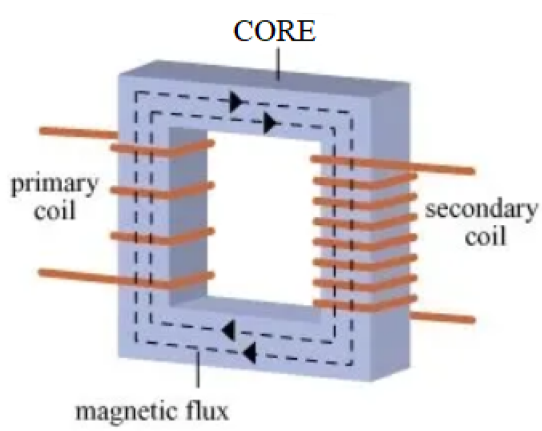

Figure 7: Schematic of Inductive Coupling Transformer

The wireless IPT method, based on the same principles as the power transmission in transformers, also transfers power in this way.

According to Lenz's law, the electromagnetic force produced in the receiving side (secondary) winding with varying magnetic flux [15]:

$$e(t) = N\frac{\partial \phi}{\partial t} \tag{2}$$

Mutual inductance (M) is calculated from self inductances as follows:

$$M = K\sqrt{L1.L2} \tag{3}$$

2.4 Types of Transformers

Many types of transformers are used in power electronic circuits and power systems today, they consist of windings wound on the same core with the inductive coupling method. In special materials such as Instrument Transformer, a single winding is sufficient because these types of transformers are used for current/voltage measurements.

As seen in Figure 8, transformer types serve many different purposes. Transformers are classified according to their application type, rated power, frequency values, voltage class, cooling type, and magnetic form [16]. Simply, step up and step down transformers are used to reflect the voltage on the primary windings to the secondary side by increasing or decreasing it. Power and distribution transformers used in power systems are used for high power transfer and distribution. These are large, heavy, and high-rated power values. Electrical transformers used in power supplies in power electronics circuits are designed to be suitable for high-frequency switching. The design decision criteria such as transformer size, winding form, and turns ratio are determined by the requirements of the converter topology to be applied.

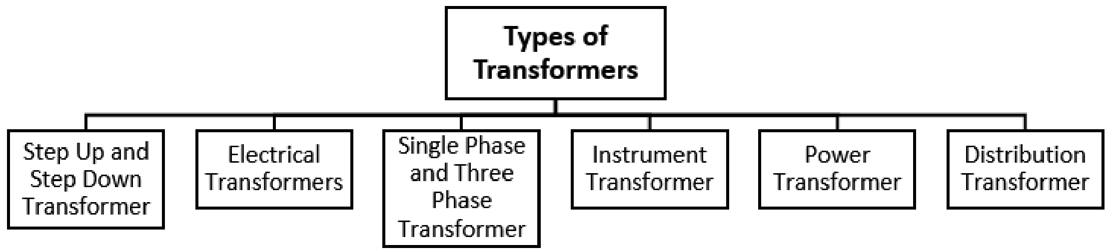

Figure 8: Types of Transformers

2.5 Sepic Converter

Sepic converters are SMPS (Switch Mode Power Supply) circuits used for DC-DC conversions. These converters are important reasons for being preferred because of their low cost, ease of application, and small dimensions. The basic schematic of the sepic converter is shown in Figure 9. As it is known, the inductor wants to maintain the continuity of the current passing through it and stores its energy with the magnetic field. In the first case, the L1 inductor stores energy over the input voltage while the MOSFET is in the on-state as shown in Figure 11. When Mosfet is off state, C1 capacity is charged through the L1 inductor, and C2 capacity is charged through L1 and L2 inductors as shown in Figure 10. Meanwhile, the diode is closed [17].

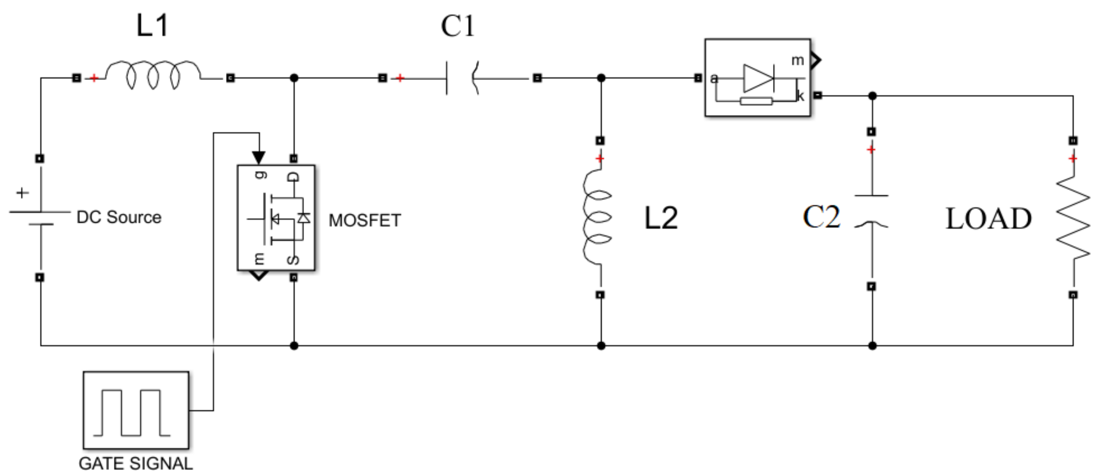

Figure 9: Basic Schematic of Sepic Converter

Sepic converter topology, which is a type of converter to be used here, does not provide any electrical isolation. Because there is normally no transformer in its design. Sepic converters do both conversions like buck-boost, step up and step down. We can calculate the relationship between input and output voltages with the parameter expressed as the duty cycle. This value is calculated as the ratio of the open time of the MOSFET to the whole period and is given in Equation (4). [18]:

$$Vo = \frac{Vi \times D}{1 - D} \tag{4}$$

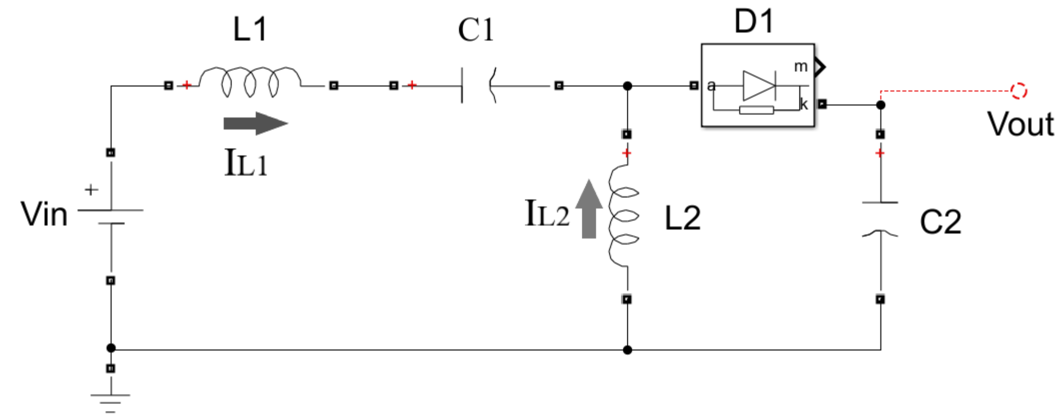

Figure 10: Sepic Converter During MOSFET Turn Off

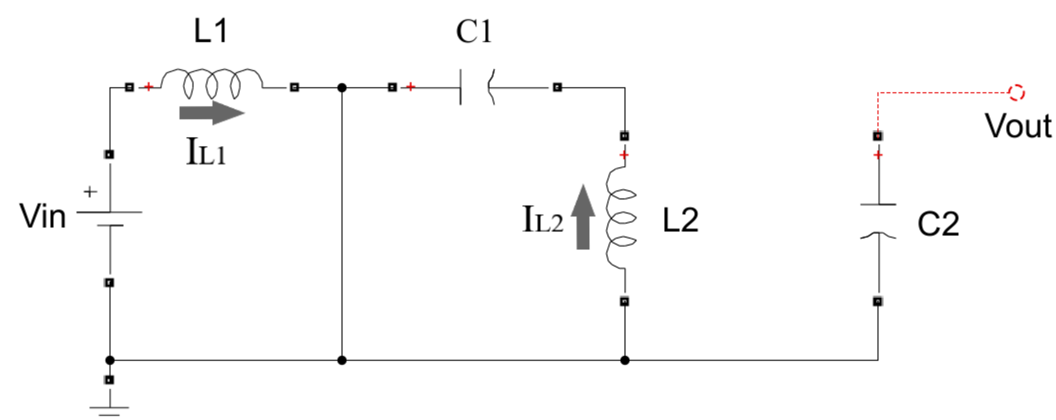

Figure 11: Sepic Converter During MOSFET Turn On

CHAPTER III

DESIGN AND MODELING

3.1 Parameters of Converter

In this section, we first need to determine the L1, L2, C1, and switching frequency parameters of the sepic converter. These values will be used in both simulation and experimental circuits.

First of all, it is necessary to determine the L1, L2, and load resistance values required for sepic converter design. Afterward, the required minimum coupling capacity (Cm) will be determined and a capacitive transformer structure will be created accordingly. The parameters will be calculated so that the sepic converter has an input voltage (Vin) equal to 12V, an output voltage (Vo) equal to 16V, and an output current (Iout) equal to 100mA. The switching frequency (fsw) is chosen as 100kHz. The duty cycle is calculated as Eq. (5). The Vd parameter that is given is the diode forward voltage value. The forward voltage value of the diode used in the experiment is 0.7V.

$$D = \frac{Vout}{Vin + Vout + Vd} \tag{5}$$

The duty cycle D is calculated as 0.582. Then the inductor and capacitor values are calculated as following equations Equation (6), Equation (7), and Equation (8).

$$\Delta i_L = Iout \times \frac{Vout}{Vin} \times 40\% \tag{6}$$

$$L1 = L2 = L = \frac{Vin}{\Delta i_L \times fsw} \times D \tag{7}$$

$$\Delta V_{Cm} = \frac{Iout \times D}{C_m \times f_{sw}} \tag{8}$$

The ΔiL value is the ripple current across the inductor is given in Equation (6) and calculated as 0.054A. Then the Equation (7) gives the inductors' values L1 and L2 as 1.29mH.

The ΔV_{Cm} value represents the ripple voltage of the coupling capacitor given in Equation (8). Finally, the coupling capacitor Cm is calculated as 290nF for the 2 volts of ripple voltage.

3.2 Capacitive Transformer

The capacitive transformer to be designed here will be formed by overlapping 4 layers of conductive material and the same dielectric material will be used between each layer. This structure is called a four-plate stacked or four-plate vertical structure. The layers used to create this structure bring 6 capacitance values in total. These capacities are shown in Figure 12. There is symmetry in the system since there will be an equal distance between layers and the same dielectric material between each layer. Due to this symmetry in this structure, some capacitance values are equal to each other. These are $C_{12} = C_{34}$ and $C_{23} = C_{14}$. All 6 capacity values in this 4-layer structure can be modelled as shown in Figure 12. If we want to convert this structure to a simpler circuit, we can use the equivalent circuits in Figure 13 and Figure 14 [19]. While performing simulations over MATLAB Simulink, the simplest equivalent circuit shown in Figure 14 will be used.

Here, four layers are labeled as P1, P2, P3, and P4 and the same-named outputs from these layers show each port of the transformer. In other words, P1 and P2 ports indicate the primary side of the transformer, P3 and P4 ports indicate the secondary side of the transformer.

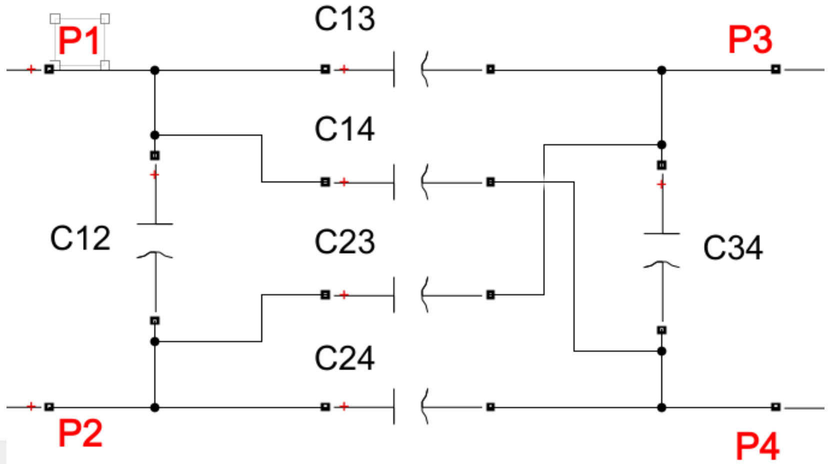

Figure 12: Circuit Model of Capacitive Transformer

If we replace the modelling shown in Figure 12 with a simplified structure, we can obtain the equivalent circuit in Figure 13. The capacitance values C_1, C_2, C_{m1} and C_{m2} in Figure 13 can be obtained with the following equations [20].

$$C_m = \frac{C_{12}C_{34} - C_{14}C_{23}}{C_{12} + C_{34} + C_{14} + C_{23}} \tag{9}$$

$$C_1 = \frac{(C_{13} + C_{14}).(C_{23} + C_{24})}{C_{12} + C_{34} + C_{14} + C_{23}} + C_{12} \tag{10}$$

$$C_2 = \frac{(C_{13} + C_{23}).(C_{14} + C_{24})}{C_{12} + C_{34} + C_{14} + C_{23}} + C_{34} \tag{11}$$

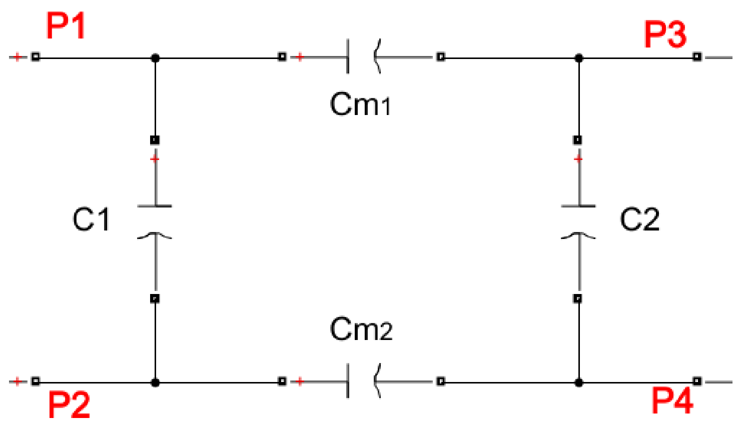

Figure 13: Equivalent Circuitry of Capacitive Transformer

The C_{m1} and C_{m2} capacities shown in Figure 13 are the mutual capacitance values of the equivalent circuit. These two capacities are connected in series with each other in the current path in the circuit and Equation (12) is used if it is required to be represented as a single C_m value. As a result, the pi equivalent circuit of the capacitive transformer has been obtained, which is the simplest form of the equivalent circuit as shown in Figure 14.

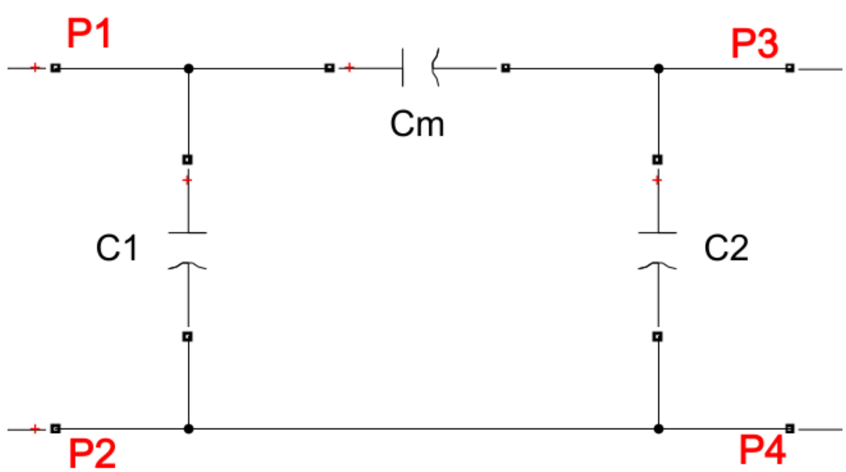

Figure 14: Π Equivalent Circuitry of Capacitive Transformer

$$C_m = \frac{C_{m1} \times C_{m2}}{C_{m1} + C_{m2}} \tag{12}$$

3.3 Modeling

In this section, the transfer function of the transformer will be created by using the equivalent capacitive transformer circuit in Figure 14. This circuit has a four-port structure. We can define the primary side and the secondary side as the input and output of the circuit, respectively. C_m, C_1, and C_2 capacitance values allow the voltage to reflect and to be seen at the output by proportioning with a coefficient given by the transfer function. In this case, the capacitive transformer equivalent circuit allows the voltage to be reflected with a coefficient, just like an inductive transformer. If we write the impedance values of the capacities the following Equations (13), (14), and (15) are obtained.

$$Z_{Cm} = \frac{1}{jwC_m} = \frac{1}{sC_m} \tag{13}$$

$$Z_{C1} = \frac{1}{jwC_1} = \frac{1}{sC_1} \tag{14}$$

$$Z_{C2} = \frac{1}{jwC_2} = \frac{1}{sC_2} \tag{15}$$

We can demonstrate these impedance values on the equivalent circuit as shown in Figure 15.

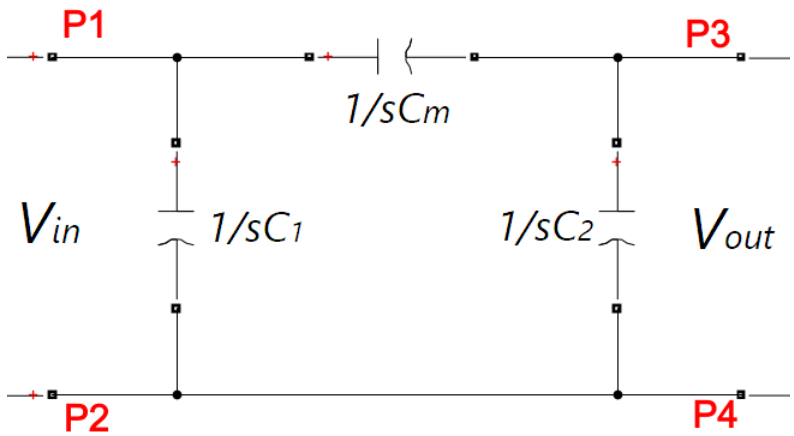

Figure 15: Equivalent Circuitry of Capacitive Transformer

The ratio of the input and output voltages (V_{in}/V_{out}) shown in Figure 15 allows us to obtain the transfer function. This transfer function will give the equation between the input and output voltage of the capacitive transformer and in this way transfer function equation provides us to find the amplitude of the voltage that will reflect the secondary side of the capacitive transformer.

$$V_o = V_{in} * \frac{\frac{1}{sC_2}}{\frac{1}{sC_m} + \frac{1}{sC_2}} \tag{16}$$

$$\frac{V_o}{V_{in}} = \frac{\frac{1}{sC_2}}{\frac{1}{sC_m} + \frac{1}{sC_2}} \tag{17}$$

$$\frac{V_o}{V_{in}} = \frac{\frac{1}{sC_2}}{\frac{C_2+C_m}{sC_2C_m}} \tag{18}$$

$$\frac{V_o}{V_{in}} = \frac{sC_2C_m}{sC_2^2 + sC_mC_2} \tag{19}$$

$$\frac{V_o}{V_{in}} = \frac{C_m}{C_2 + C_m} \tag{20}$$

We can obtain the transfer function of the capacitive transformer as in Equation (20), which is the last equation. Substituting Equation (9) and (10) in Equation (20) we obtain:

$$\frac{V_o}{V_{in}} = \frac{\frac{C_{12}C_{34}-C_{14}C_{23}}{C_{12}+C_{34}+C_{14}+C_{23}}}{\frac{(C_{13}+C_{23}).(C_{14}+C_{24})}{C_{12}+C_{34}+C_{14}+C_{23}} + C_{34} + \frac{C_{12}C_{34}-C_{14}C_{23}}{C_{12}+C_{34}+C_{14}+C_{23}}} \tag{21}$$

Using the model of the capacitive transformer in Figure 12, the transfer function with 6 capacitance values is obtained as in Equation (21).

If there is no parasitic effect, in other words, there are only pure capacitance values in the circuit, we cancel the terms $s = jw = j2\pi f$, which are the frequency component, as a result, we obtain a frequency-independent transfer function.

We determined the relationship between the input and output voltages of the capacitive transformer using the transfer function. This equation shows that the designed capacitive transformer reflects the input voltage to the output with a calculated ratio.

CHAPTER IV

SIMULATION SETUP

In the transformer designed in this thesis, a mutual capacitance value is obtained as mentioned before. As is known, a capacity called coupling capacity is used in SEPIC converter design. This capacity is charged and discharged in each switching period of the MOSFET. The coupling capacity in the sepic converter is no longer needed, when we remove this capacity as seen in Figure 16, divide the circuit into two parts, and insert the capacitive transformer, the mutual capacitance value replaces the coupling capacity. The circuit simulation here has been done using MATLAB Simulink. 12V DC voltage is applied to the input of the circuit, the output voltage and current waveform are measured on Scope 1. The PWM signal in the gate of the MOSFET is measured over Scope 2. And finally, the voltage across the mutual capacitance is measured by Scope 3.

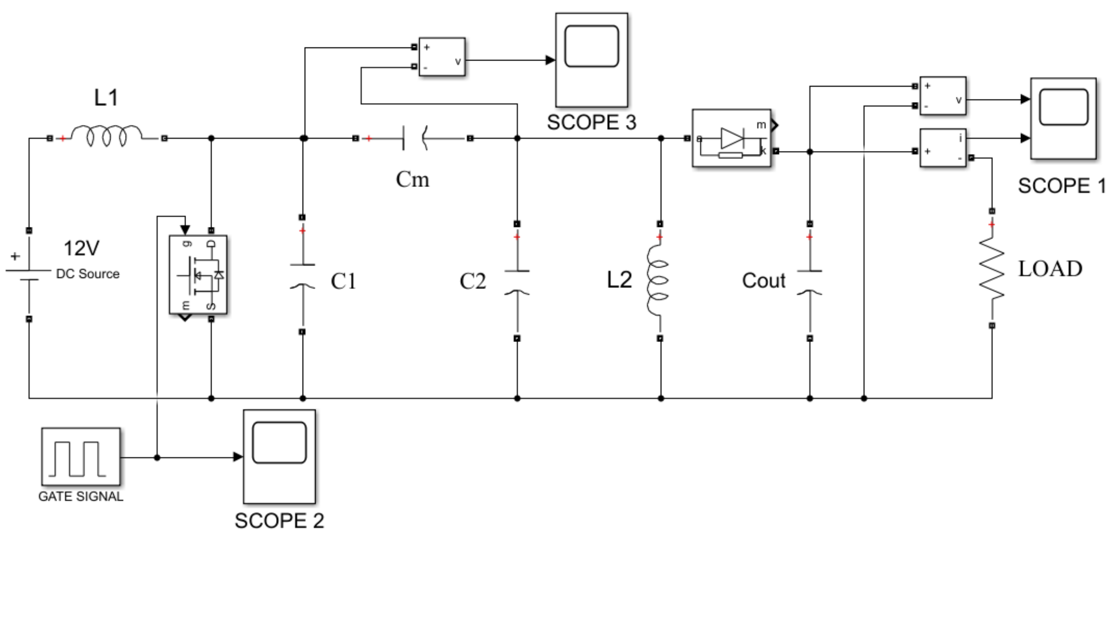

Figure 16: Sepic Converter with Capacitive Transformer

4.1 Generation of PWM Signal

The PWM (Pulse Width Modulation) signal must be applied to the gate pin of MOSFET to switch the MOSFET. Although the voltage of this signal value varies from material to material it is generally 6V and above.

In order to obtain the PWM signal, it is necessary to compare the 2 signals as shown in Figure 17. One of these signals is the reference and the other is the sawtooth signal. If we put these two signals into the comparator, the frequency of the Sawtooth signal will determine the frequency of the PWM signal that will occur at the comparator output. The amplitude of the reference voltage will determine the duty cycle of the PWM signal.

We will get the PWM signal with a duty cycle of 0.582 and a frequency of 100kHz from the output when we insert the 100kHz sawtooth signal and the reference signal with 0.582 amplitude into the comparator as seen in Figure 17. Scope 1 is measured the sawtooth signal and its output as seen in Figure 18.

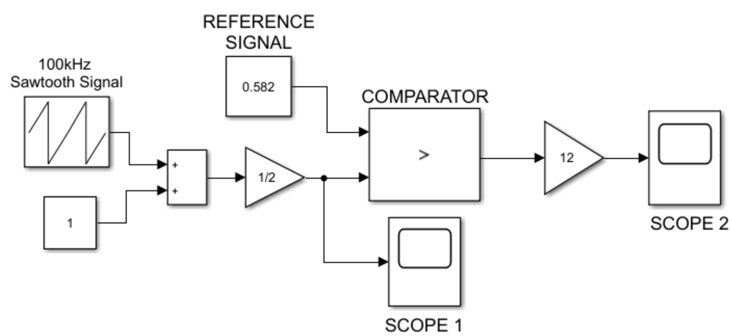

Figure 17: PWM Generation Logic

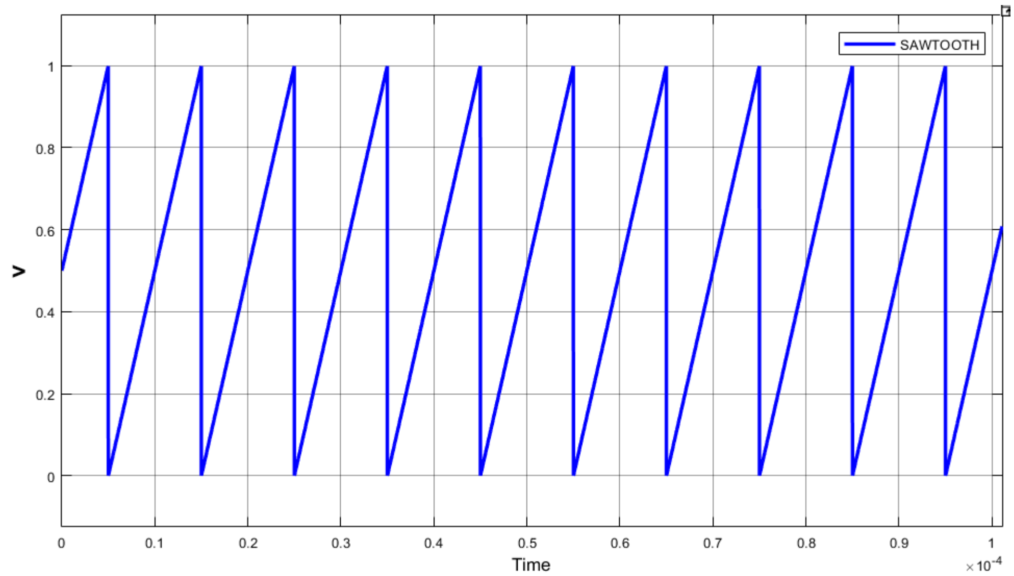

Figure 18: Sawtooth Signal

When the reference voltage level is higher than the sawtooth, the comparator output becomes high. Conversely, if the sawtooth voltage amplitude is higher than the reference level, the comparator output becomes low. Finally, the output of this logic (scope 2) is the PWM signal as shown in Figure 19.

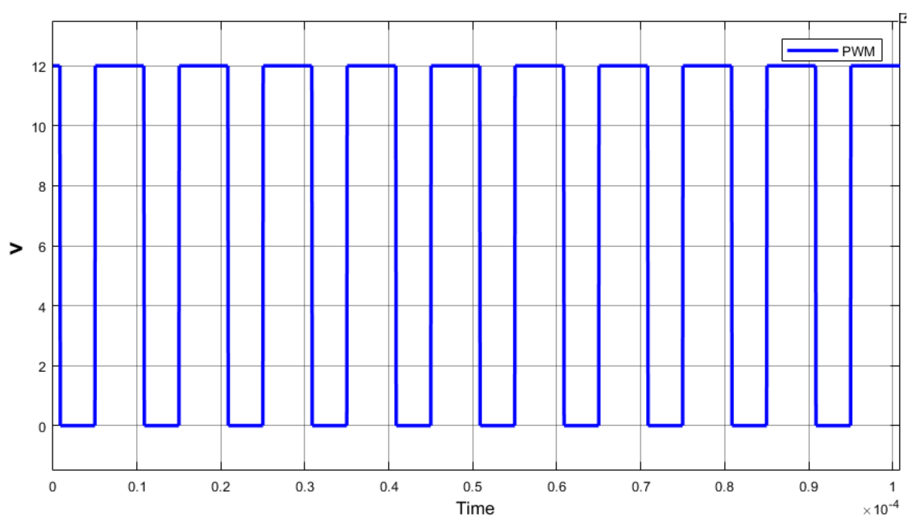

Figure 19: PWM Signal

4.2 Simulation Results

The PWM signal is applied to the gate pin of the MOSFET as shown in Figure 20. The amplitude of the applied PWM signal is 12V and its frequency is 100kHz. If we calculate the duty cycle by looking at Figure 20:

$$D = \frac{t_{on}}{T} = \frac{0.582.10^{-5}s}{1.10^{-5}s} = 0.582 \tag{22}$$

As calculated in the design chapter previously, the duty cycle value is set to 0.582 so that the output voltage is 16V. As shown in Equation (22), the ratio of MOSFET on time to the whole period gives the duty cycle.

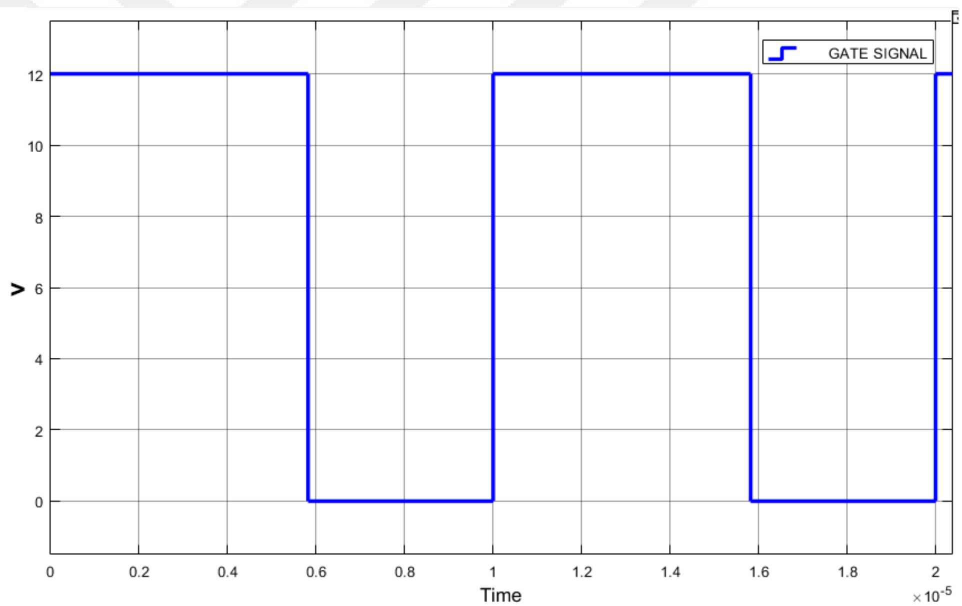

Figure 20: Turn On and Turn Off Time of the Gate Signal

As stated in Equation 20, if the value of C_m is much larger than C_2, the transfer function will be approximately equal to 1. Thus, when $C_1 = C_2 = 100nF$ and $C_m = 1uF$ are selected, output voltage and current are observed as in Figure 21. Here, since the ratio coming from the transfer function of the capacitive transformer is very close to 1, the output voltage of the SEPIC converter did not change, the calculated 16V DC voltage was obtained.

The resistance value used as a load at the output of the SEPIC converter is 150ohm. Thus, 100mA output current was obtained.

Inductance values were chosen as $L_1 = L_2 = 1.3mH$ as calculated in the design chapter.

The charge and discharge voltage waveform at each period of the mutual capacitance in the capacitive transformer equivalent circuit is shown in Figure 22.

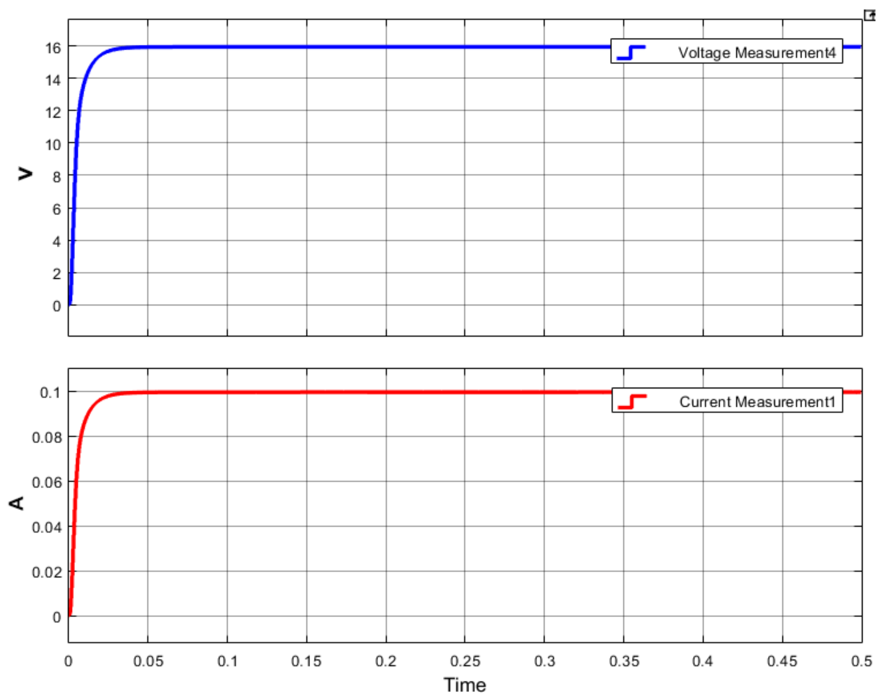

Figure 21: Output Voltage and Current Wave Forms of Sepic Converter

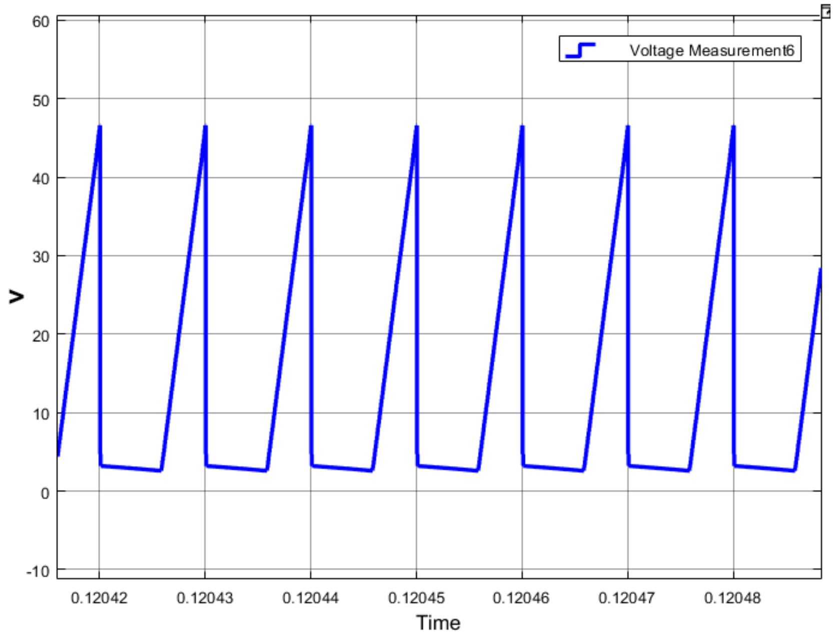

Figure 22: Voltage Waveform Across the Mutual Capacitance

Now let's change the values in the equivalent circuit. If we make $C_2 = C_m$, we get the value $V_o/V_i = C_m/(C_m + C_2) = 0.5$ from the transfer function. It was calculated and simulated with a predetermined 0.582 duty cycle value to obtain 16V output voltage. When the capacitive transformer is accepted as $C_m = C_2 = 100nF$ and simulated again, the output voltage and current are observed as in Figure 23. As can be seen, 8V output voltage is obtained by multiplying the 16V output voltage by the 0.5 coefficient obtained from the transfer function of the capacitive transformer. Thus, if the correlation between the input and output voltage of the whole circuit is written, we can express it as in Equation (23).

$$V_o = V_i \frac{D}{(1-D)} \frac{C_m}{(C_2 + C_m)} \tag{23}$$

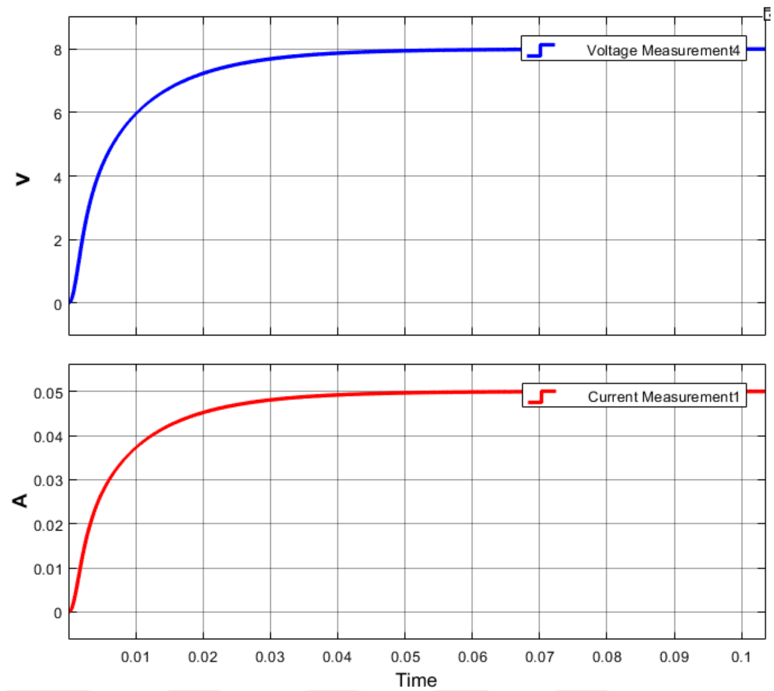

Figure 23: Output Voltage and Current When C_m and C_2 Are Selected Equal

The simulation setup in which the capacitive transformer is considered standalone and AC voltage is applied to its input is as shown in Figure 24. A 100kHz 100V peak sinusoidal signal is applied to the P1 and P2 ports, which are the inputs of the capacitive transformer, and the scope is connected to observe the input and output voltages.

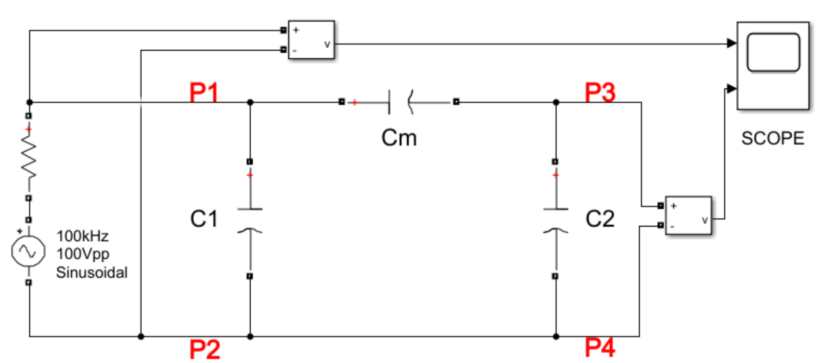

Figure 24: Voltage Applied to Equivalent Circuitry of Capacitive Transformer

When the C_m and C_2 are selected equal, the expected output voltage that comes from transfer equation is $100V \times 0.5 = 50V$. The scope is connected to P3 and P4 ports of capacitive transformer that are output ports. The blue waveform on the top shows the 100V input voltage and the red waveform on the bottom shows the output voltage, as shown in Figure 25. The output waveform is a sinusoidal signal with a 50V peak value as calculated.

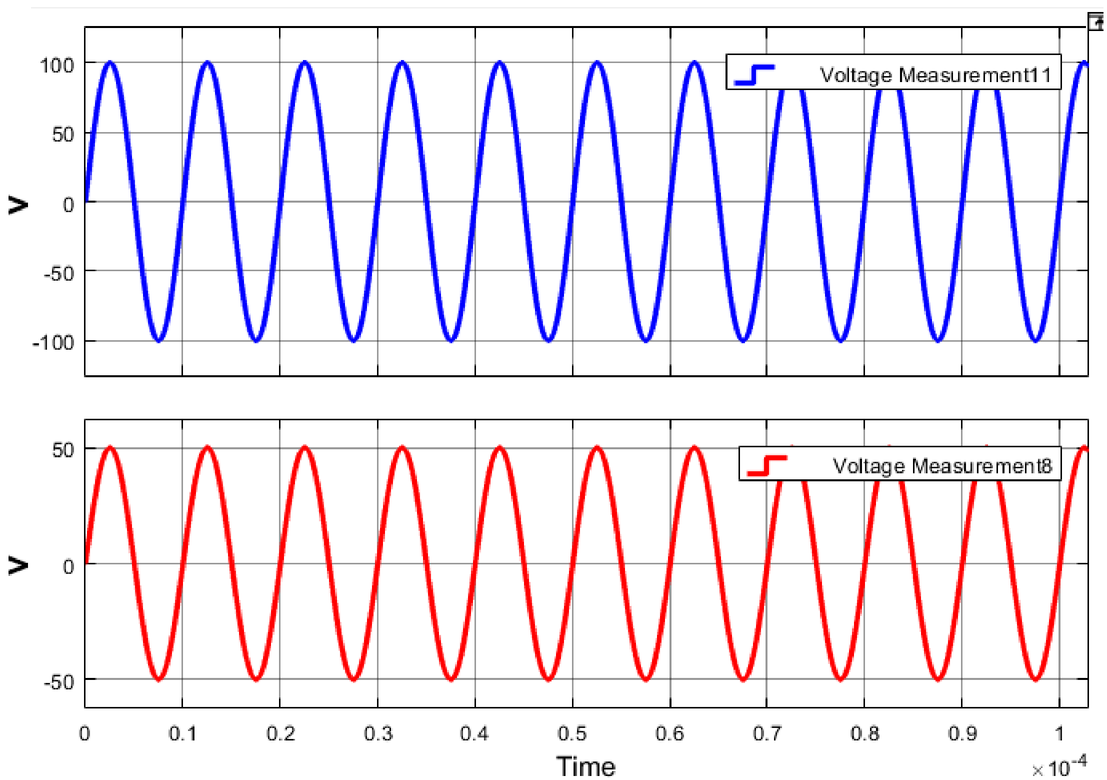

Figure 25: Input and Output Voltage Wave Forms of Equivalent Circuitry of Capacitive Transformer

Different capacity values can be selected to show that the transfer function works on the simulation. If the capacity values are $C_m = 400nF$ and $C_2 = 100nF$, the multiplier through the transfer function is calculated as $V_o/V_{in} = 400/(100 + 400) = 0.8$. As a result, $100V * 0.8 = 80V$ output voltage will be observed. The input and output voltage waveforms of the circuit are simulated in this way, as in Figure 26.

Here, the bottom red graphic is again the output voltage and it is an $80V$ sinusoidal signal as calculated.

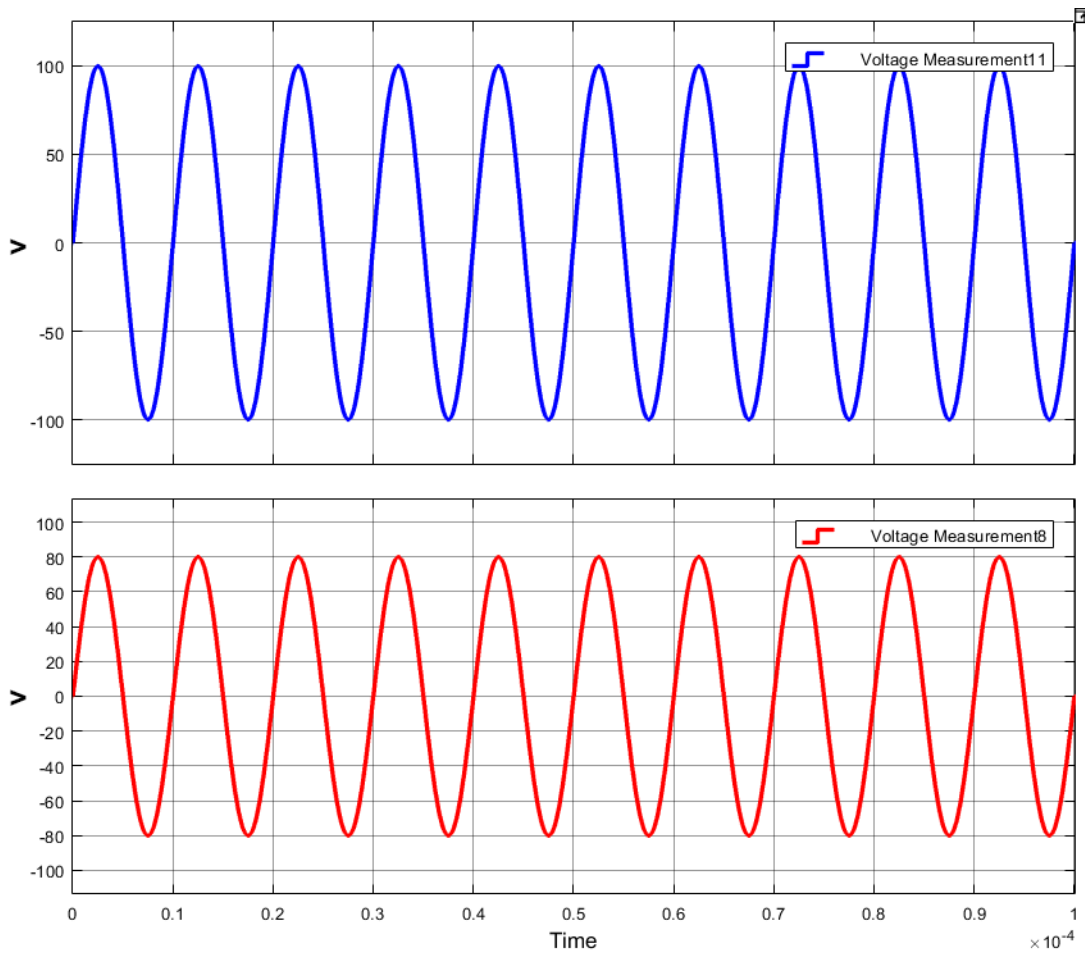

Figure 26: Input and Output Voltage Waveforms When Capacitance Values Changed

It was previously shown that if this capacitive transformer structure is created with pure capacitance only, there is no frequency-dependent component in the transfer function. Thus, when different frequency values are applied to the input of the structure, it is expected that there will be no change in the output voltage amplitude. Cm and C2 values are kept the same as in Figure 26 where the output voltage is observed as 80V, and when a 100V 10kHz sinusoidal signal is applied from the input instead of a 100V 100kHz sinusoidal signal, the output voltage waveform is the red graph in Figure 27. As seen here, the output voltage value of 80V, which is the result of the previous simulation, has not changed. As a result, when this structure is formed with pure capacitance values, it is expected that there is no frequency dependency at the output voltage.

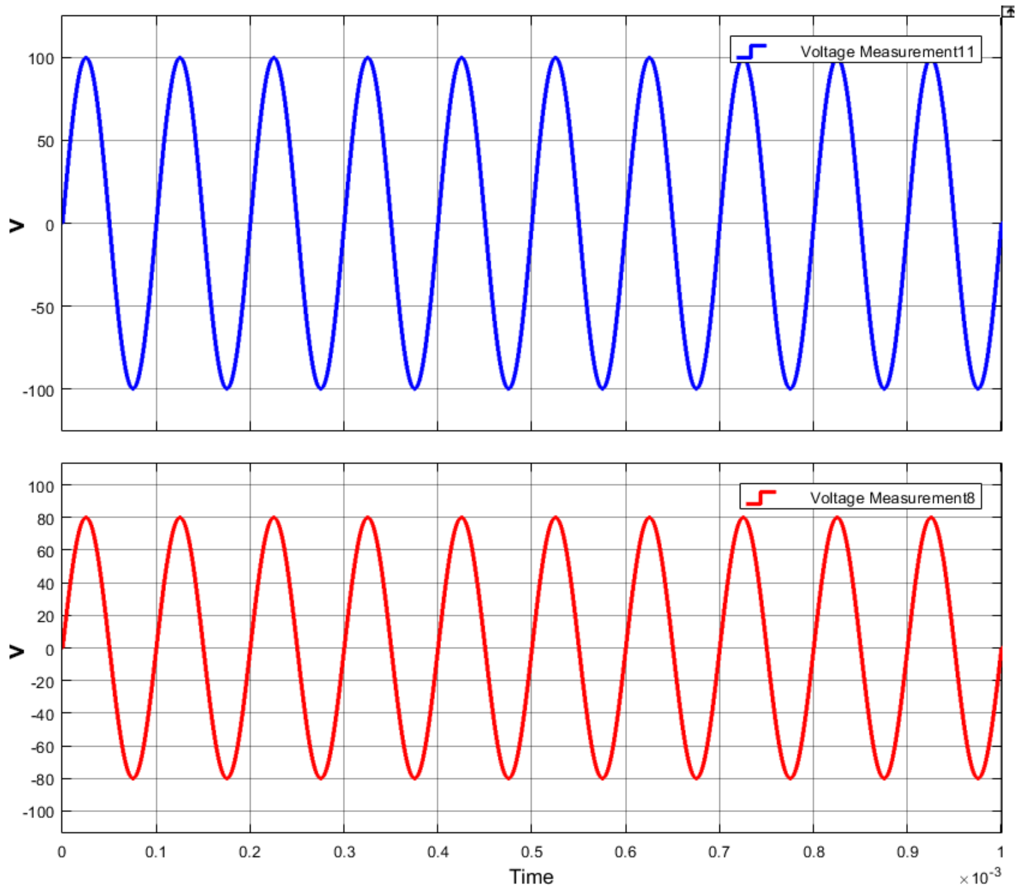

Figure 27: Input and Output Voltage Waveforms When Frequency Changed

CHAPTER V

EXPERIMENTAL SETUP

In this chapter, the experimental circuits of the capacitive transformer, which have been simulated before, will be set and the test results will be reported. First, the test results will be reported over the designed SEPIC converter, and then the test results will be reported when the transformer is alone.

If we divide the SEPIC converter topology into two parts in Figure 28 and call them primary and secondary sides, the ports of the capacitive transformer that will design should be connected to these two sides.

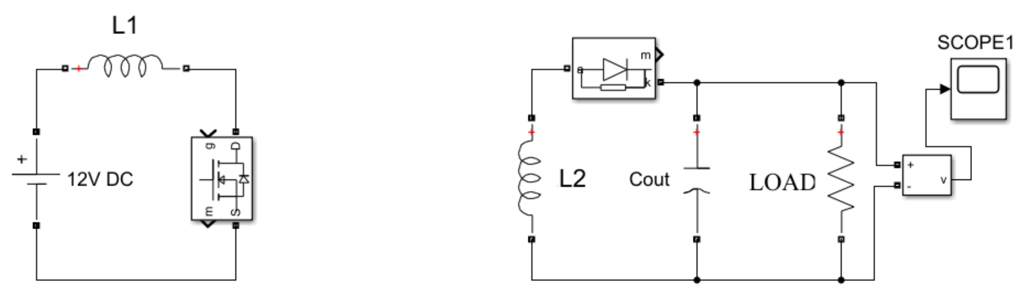

Figure 28: Primary and Secondary Sides of SEPIC Converter

The connections of the 4 layers of the capacitive transformer are made as in Figure 29. The P1 and P2 ports are the input of the primary side of the transformer. The ports P3 and P4 ports are the output of the secondary side.

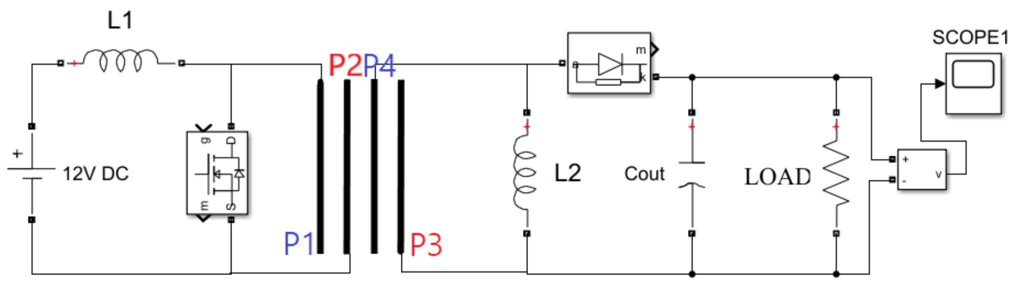

Figure 29: Schematic of SEPIC Converter with Capacitive Coupled Transformer

The push-pull circuit amplifies the $3V_{pp}$ PWM signal from the signal generator to $12V$, the output of this circuit is connected to the gate of the MOSFET, as seen in Figure 30. As mentioned before, this circuit is necessary to ensure sufficient voltage for switching the MOSFET's gate and for lower turn on and turn off times.

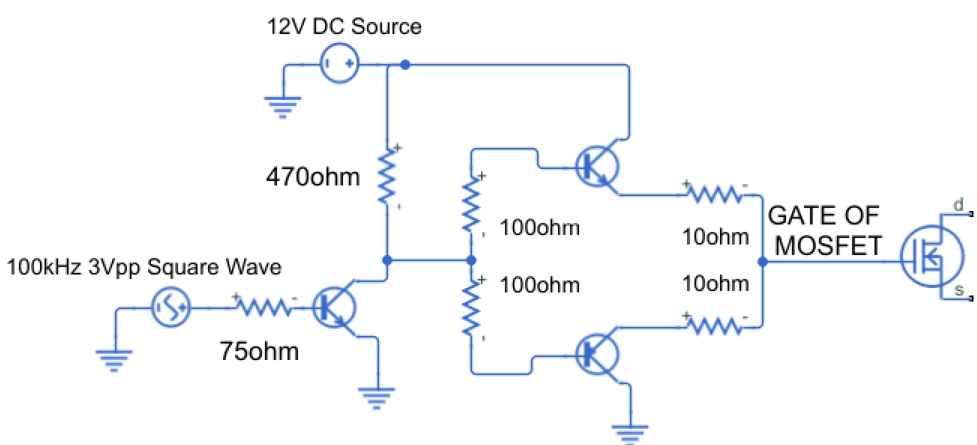

Figure 30: Push-Pull Circuitry for Gate Driver

The capacitive coupled transformer, which is wrapped with 4 layers of aluminium tape and the paper used as the dielectric material between each of them, is as shown in Figure 31 and Figure 32. The 4 layers of aluminium used here are stacked and wrapped together as shown in Figure 31. The cables of the primary and secondary sides of the designed transformer are as shown in Figure 32.

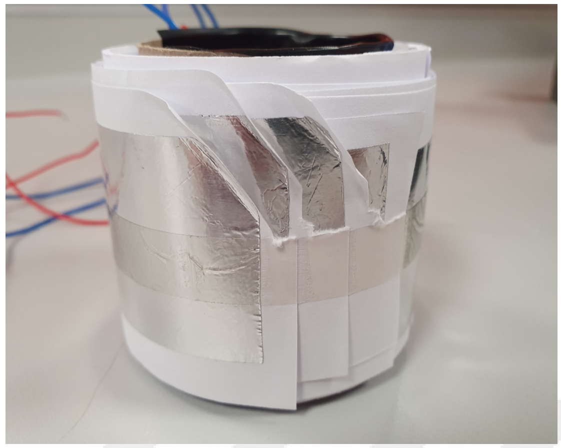

Figure 31: Four Layers of Wrapped Capacitive Coupled Transformer

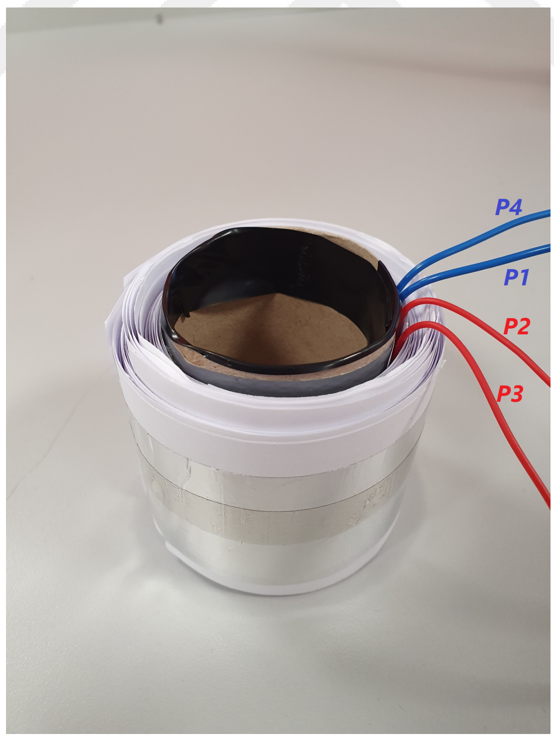

Figure 32: Primary and Secondary Ports of Wrapped Capacitive Coupled Transformer

5.1 *Experimental Results*

Experimental test results will be given in this section. The experiments here were carried out in 3 different ways. The wrapped capacitive coupled transformer has been tested both on the SEPIC converter and the standalone. After these experiments, a flat-shaped capacitive coupled transformer model was also realized.

The 6 capacitance values that occurred between each layer of the wrapped capacitive coupled transformer design were measured with an LCR meter as shown in Figure 33. The measured values of these six values are given in Table 1.

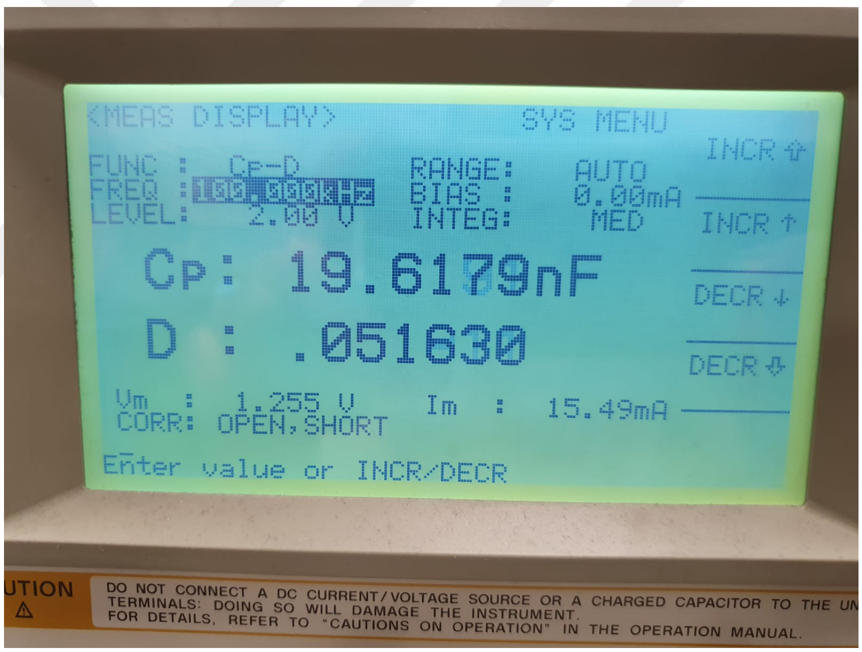

Figure 33: Measurement of C_{12} Capacity With LCR Meter

Table 1: Measured Capacitance Values of Wrapped Capacitive Coupled Transformer

C_{12}	C_{34}	C_{23}	C_{14}	C_{13}	C_{24}
19.6nF	20.4nF	14.4nF	14.4nF	16nF	19.8nF

If C_1, C_2, and C_m values in the equivalent circuit are calculated using Equations

(9), (10), and (11), the values for wrapped shape transformer are obtained as given in Table 2.

Table 2: C_1, C_2 and C_m Values of Wrapped Capacitive Coupled Transformer

C_1	C_2	C_m
34.7nF	35.5nF	2.8nF

Finally, if we calculate the voltage ratio between the output and input of the transformer using the transfer function given in Equation (20), the ratio has been obtained as given in Equation (24).

$$\frac{V_o}{V_{in}} = \frac{C_m}{C_2 + C_m} = \frac{2.8}{35.5 + 2.8} = 0.0731 \tag{24}$$

The generated PWM signal to switch the MOSFET is as shown in Figure 34. The PWM signal is the oscilloscope image taken from the output of the push-pull circuit. The PWM signal is a square wave with 12V amplitude at 100kHz frequency with an on-time of 5.8us and a period of 10us. Thus, the PWM signal with a duty cycle of $5.8us/10us = 0.58$ was created to provide the 16V output voltage from the SEPIC converter.

First of all, the experimental circuit is set up with L_1, L_2, C_1 and C_{out} values calculated in the design section. The load resistance is $150ohm$ and the input voltage is $12V$. Here, while the capacitive coupled transformer was not connected to the circuit yet, it was tested whether the SEPIC converter could provide the previously calculated $16V$ output voltage with the determined design parameters. The output voltage of the SEPIC converter was measured as 16V with an oscilloscope as it was calculated as seen in Figure 35.

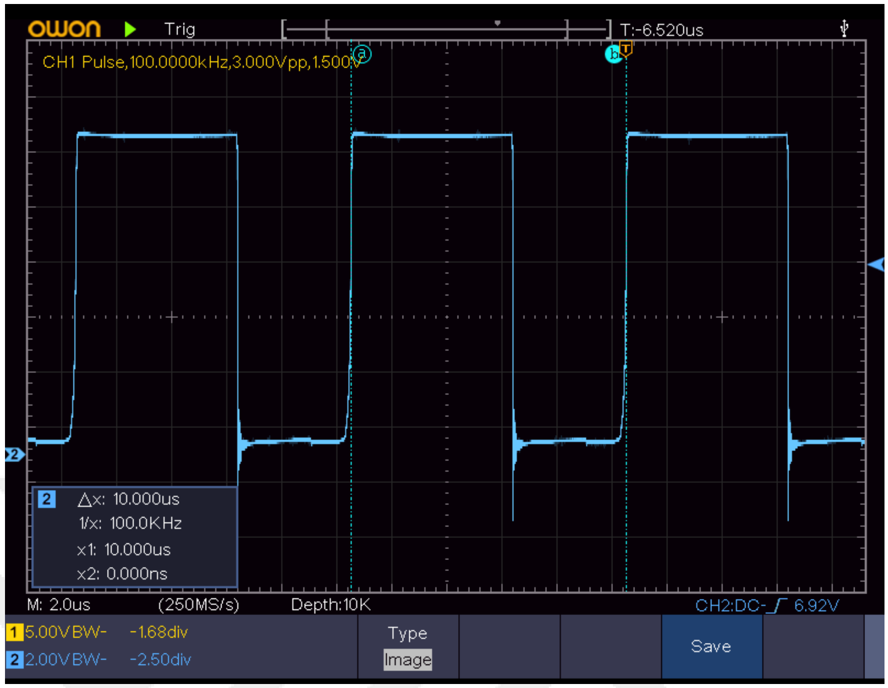

Figure 34: Output PWM Signal of Push-Pull Circuitry

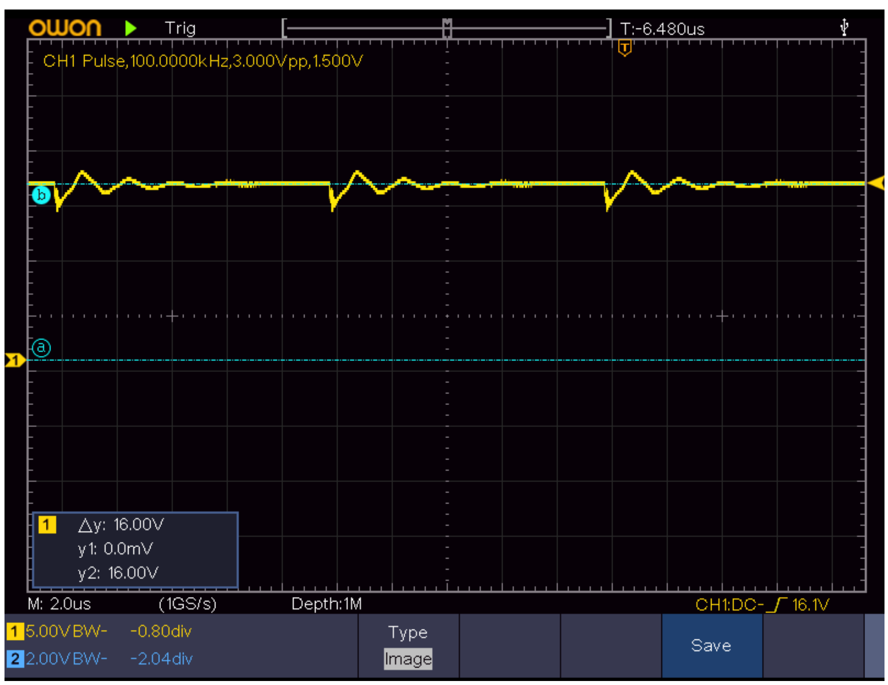

Figure 35: Output Voltage Waveform of SEPIC Converter Without Capacitive Transformer

Now, we will test the capacitive coupled transformer, which is wound in 4 layers, over the SEPIC converter. Firstly the coupling capacity (C_1) has been removed from the converter then the connections of the transformer have been made as mentioned before, so the P1, P2 layers being the primary side and the P3, P4 layers being the secondary side, as shown in Figure 36.

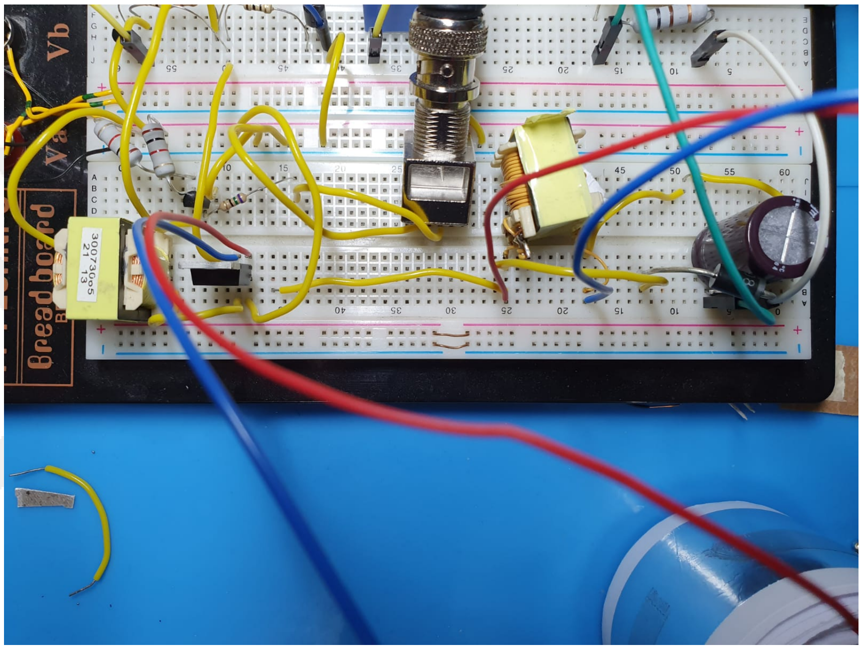

Figure 36: Connections of Capacitive Coupled Transformer to SEPIC Converter

From Equations (23) and (24) the calculated output voltage as follows:

$$V_o = V_i \frac{D}{(1-D)} \frac{C_m}{(C_2 + C_m)} = 12 \frac{0.58}{(1-0.58)} \frac{2.8}{(35.5+2.8)} = 1.2V \qquad (25)$$

When the experimental circuit was energized and the switching frequency is 100kHz the output voltage was measured as 1.08V as seen in Figure 37.

Since there is no frequency-dependent component in the transfer function of the capacitive coupled transformer, observed the 1.08V output voltage with a small change (1.02V) when the switching frequency is 200kHz as shown in Figure 38. This small change has occurred because of the parasitic effects of the wrapped shape.

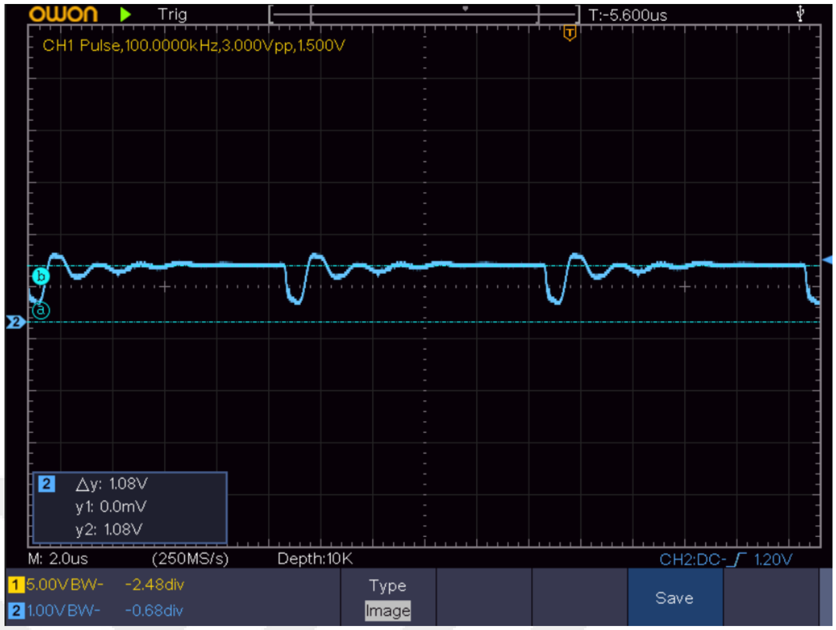

Figure 37: Output Voltage Waveform of SEPIC Converter With Wrapped Capacitive Transformer When 100kHz Switching

Figure 38: Output Voltage Waveform of SEPIC Converter With Capacitive Transformer When 200kHz Switching

This four layers wrapped shape capacitive coupled transformer design which is using on the SEPIC converter, has provided isolation to the converter and acted like a step-down transformer that reduces the output voltage with its transfer function ratio.

5.2 Standalone Operation

In this section, the four layers wrapped shape and flat shape capacitive coupled transformer will be tested as standalone without any converter topology. Firstly, the sinusoidal signals that have 100kHz and 200kHz frequency and both have 3.5Vpp amplitude will be applied to primary ports of the wrapped shape transformer. Then the secondary sides of the transformer will be measured with an oscilloscope. Finally, the same tests will be performing with four layers flat shape transformer. This time the input sinusoidal signals will have 5Vpp amplitude.

The calculated output voltage is $0.0731 * 3.5V = 255mV$ for the wrapped transformer using the transfer ratio in Equation (24).

When the input voltage is 3.5V (blue signal) the output voltage (yellow signal) is 272mV as shown in Figure 39. Then the frequency of the input signal has been increased to 200kHz with the same amplitude, again the output voltage (yellow signal) is 272mV as shown in Figure 40. So the calculated values and the experimental results are very closed to each other.

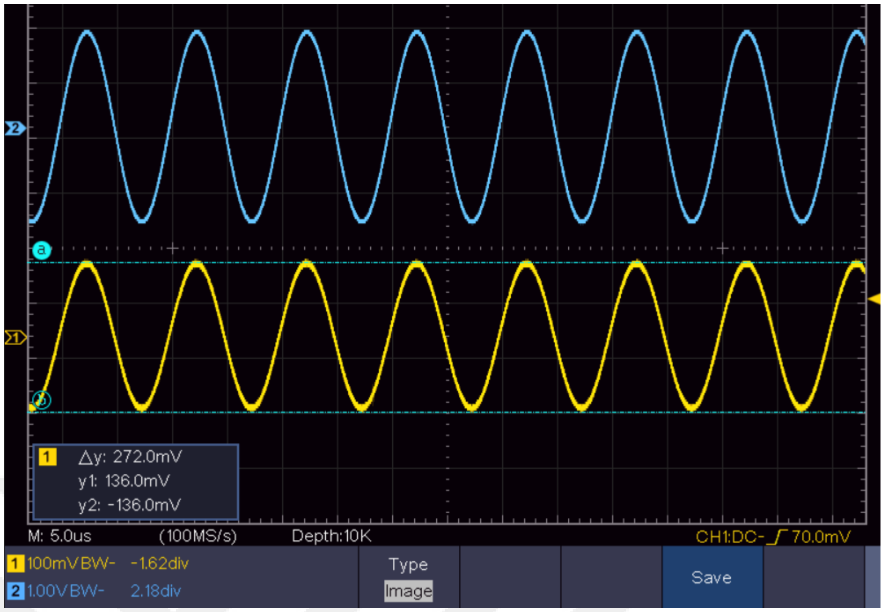

Figure 39: Output (Yellow) and 100kHz Input (Blue) Signals of Standalone Wrapped Shape Capacitive Transformer

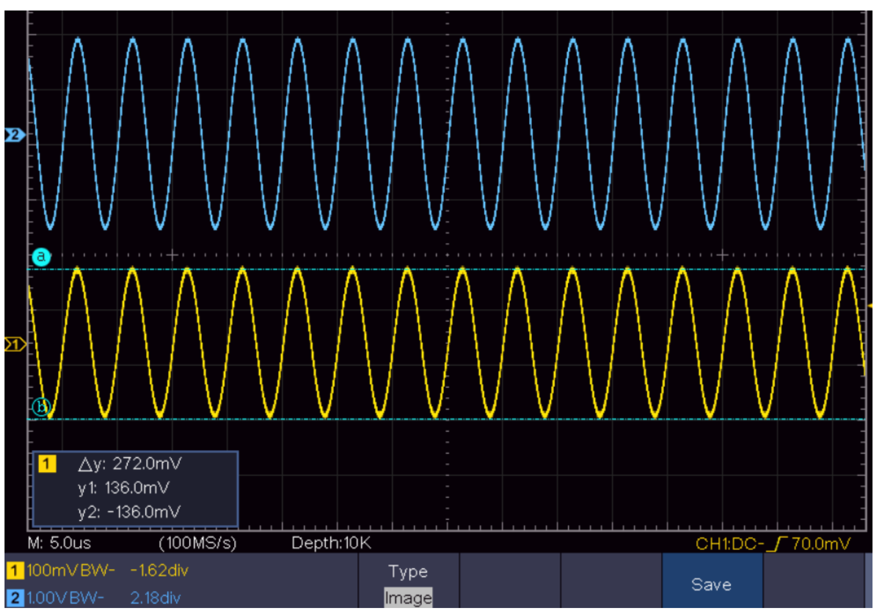

Figure 40: Output (Yellow) and 200kHz Input (Blue) Signals of Standalone Wrapped Shape Capacitive Transformer

Now the flat shape capacitive coupled transformer will be considered. The four PCB plates with FR2 dielectric material have been put in a row. The structure of four layers of copper has been obtained as shown in Figure 42.

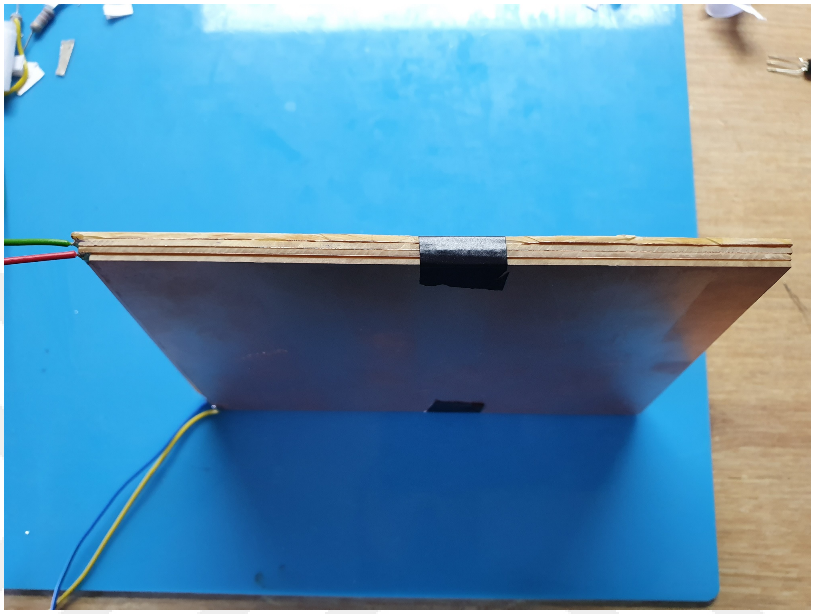

Figure 41: Layers of Capacitive Coupled Transformer in Flat Shape

The 6 capacitance values that occurred between each layer of the flat shape capacitive coupled transformer design were measured with the LCR meter. The measured values of these six values are given in Table 3.

Table 3: Measured Capacitance Values of Flat Shape Capacitive Coupled Transformer

C_{12}	C_{34}	C_{23}	C_{14}	C_{13}	C_{24}
403pF	400pF	202pF	198pF	130pF	399pF

If C_1, C_2, and C_m values in the equivalent circuit are calculated using Equations (9), (10), and (11), the values for flat shape transformer are obtained as given in Table 4.

Table 4: C_1, C_2 and C_m Values of Flat Shape Capacitive Coupled Transformer

C_1	C_2	C_m
567pF	565pF	101pF

If the calculation will be done in the same way as it has been done for the wrapped transformer before, the voltage ratio between the output and input of the transformer using the transfer function given in Equation (20), the ratio has been obtained as given in Equation (26).

$$\frac{V_o}{V_{in}} = \frac{C_m}{C_2 + C_m} = \frac{101}{565 + 101} = 0.151 \tag{26}$$

The calculated output voltage is $0.151 * 5V = 760mV$ for the flat shape transformer using the transfer ratio in Equation (26).

When the input signal is 5V 100kHz sinusoidal (blue signal), the output voltage (yellow signal) is 784mV as shown in Figure 42. Then the frequency of the input signal has been increased to 200kHz with the same amplitude, the output voltage (yellow signal) is 790mV as shown in Figure 43. So the calculated values and the experimental results are very closed to each other.

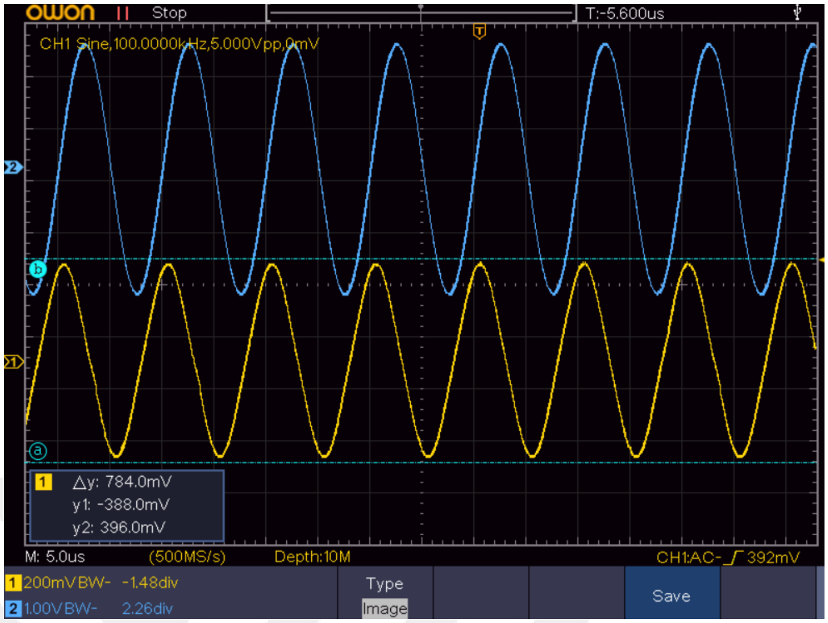

Figure 42: Output (Yellow) and 100kHz Input (Blue) Signals of Standalone Flat Shape Capacitive Transformer

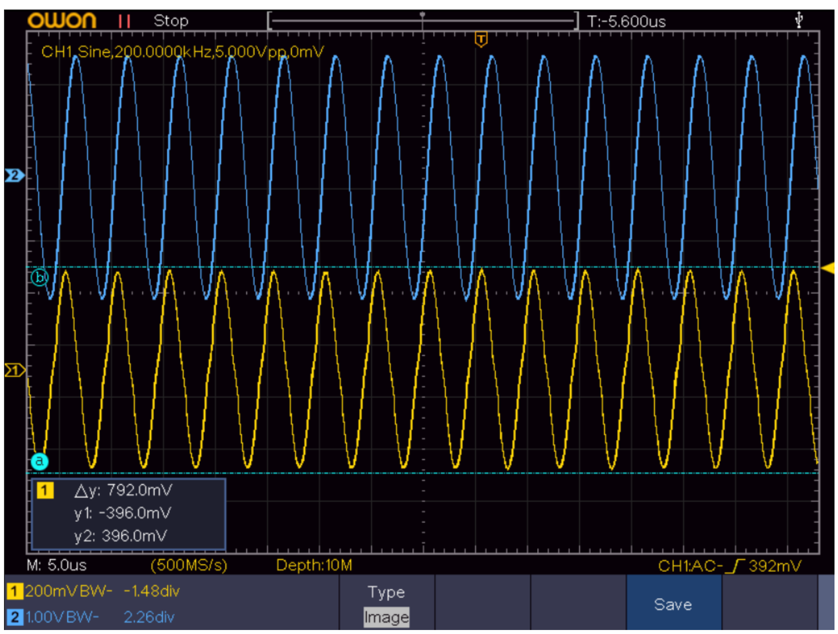

Figure 43: Output (Yellow) and 200kHz Input (Blue) Signals of Standalone Flat Shape Capacitive Transformer

5.3 Parasitic Effects

The equivalent circuitry model in Figure 15 has been analyzed before. In this section, the equivalent pi model will be analyzed again with parasitic inductance and resistance in the capacitive transformer. The parasitic parameters have been added to the equivalent circuit as shown in Figure 44.

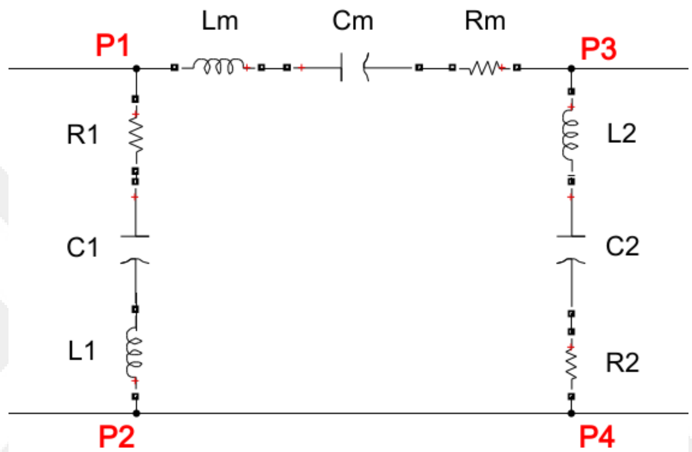

Figure 44: Equivalent Circuit with Parasitic Components

When the transfer function of this model has been calculated, Equation (29) has been obtained. This equation is representing the ratio between the output and input voltage when the parasitic parameters have been concerned.

$$\frac{Vout}{Vin} = \frac{Z_2}{Z_m + Z_2} \tag{27}$$

$$\frac{Vout}{Vin} = \frac{\frac{1}{sC_2} + R_2 + sL_2}{\frac{1}{sC_m} + R_m + sL_m + \frac{1}{sC_2} + R_2 + sL_2} \tag{28}$$

$$\frac{Vout}{Vin} = \frac{Cm(1 + sC_2R_2 + s^2C_2L_2)}{C_2 + sC_mC_2R_m + s^2C_2C_mL_m + C_m + sC_mC_2R_2 + s^2C_2C_mL_2} \tag{29}$$

CHAPTER VI

DESIGN FOR ISOLATION PURPOSE

6.1 Simulation Result

In this section, power transfer will be made by creating 2 different capacity values that are wrapped side by side, unlike the nested transformer structure as in the previous structures. This structure will only be examined to fulfill the task of isolation. In this structure, the transfer function ratio is very close to 1 because there are only two capacitance values (C13 and C24) and the other capacitance values in this structure are very small and negligible, so the SEPIC converter circuit is set up as seen in Figure 45.

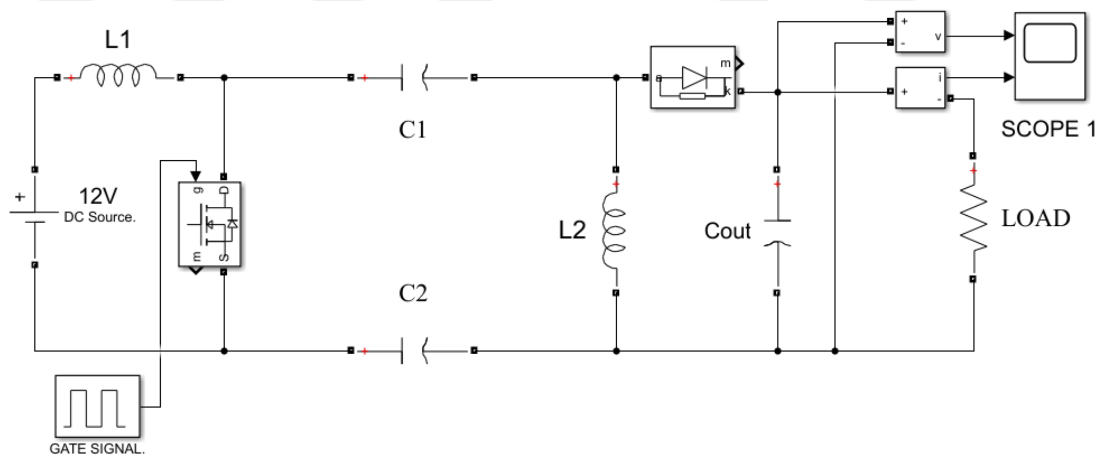

Figure 45: Simulation Setup of Capacitive Coupled Isolation Transformer

The output voltage and current waveforms are shown in Figure 46. The SEPIC converter parameters are the same as in the previous section. The output voltage is calculated as 16V from Equation (23). Since there is only mutual capacitance here, the transfer function ratio is equal to 1. Therefore the simulation result shows the output voltage as 16V which is the same as the calculated value. The output voltage was not affected by the isolation transformer.

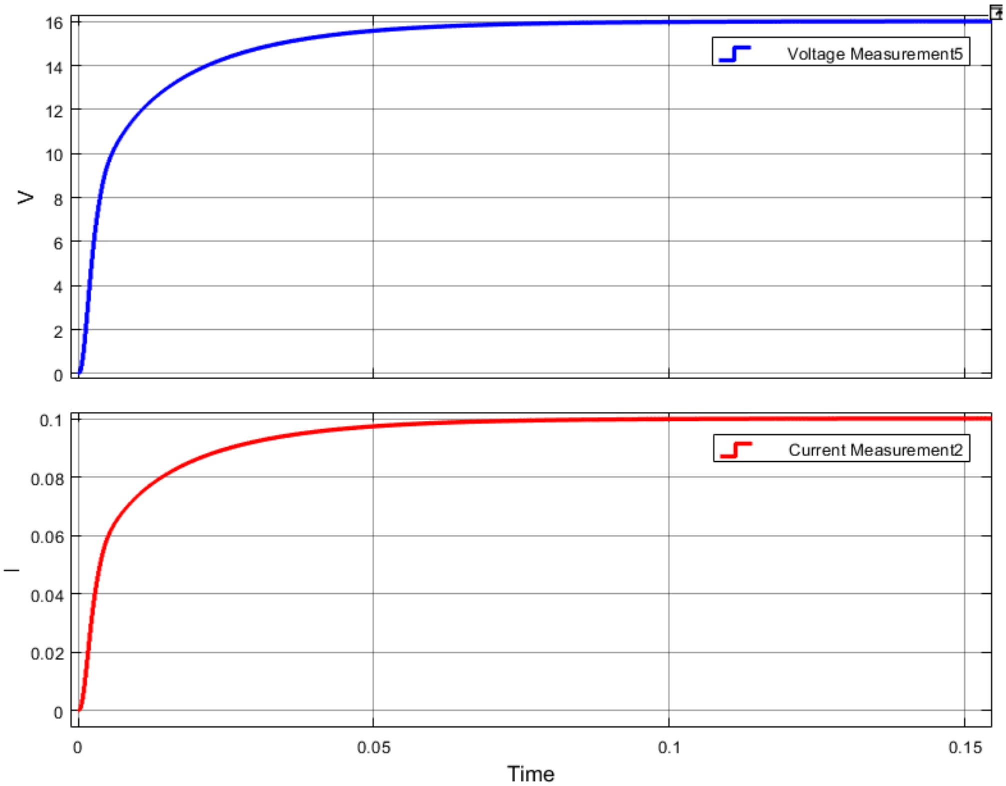

Figure 46: Output Voltage (Blue) and Current (Red) Waveforms of SEPIC converter with Isolation Transformer

6.2 Experimental Result

To execute the experimental setup the capacitive isolation transformer has been wrapped as shown in Figure 47. There are two capacitances separately in this structure. The red cables are representing the primary side and the blue cables are representing the secondary side. The measured values of C1 and C2 capacitances are 50nF and 51nF respectively.

When the SEPIC converter has been set up with the same parameters in the previous section and the connections of the isolation transformer have been done, the output voltage has been obtained as 16V as shown in Figure 48. Therefore the output voltage is the same as the Figure 35 which is no transformer setup. As a result, the isolation transformer has not affected the output voltage of the SEPIC converter because its transfer ratio is very close to 1.

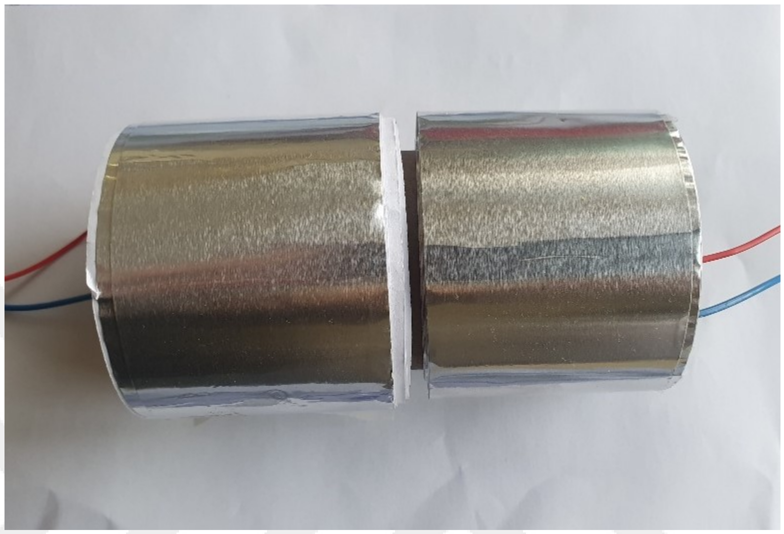

Figure 47: Capacitive Coupled Isolation Transformer Design

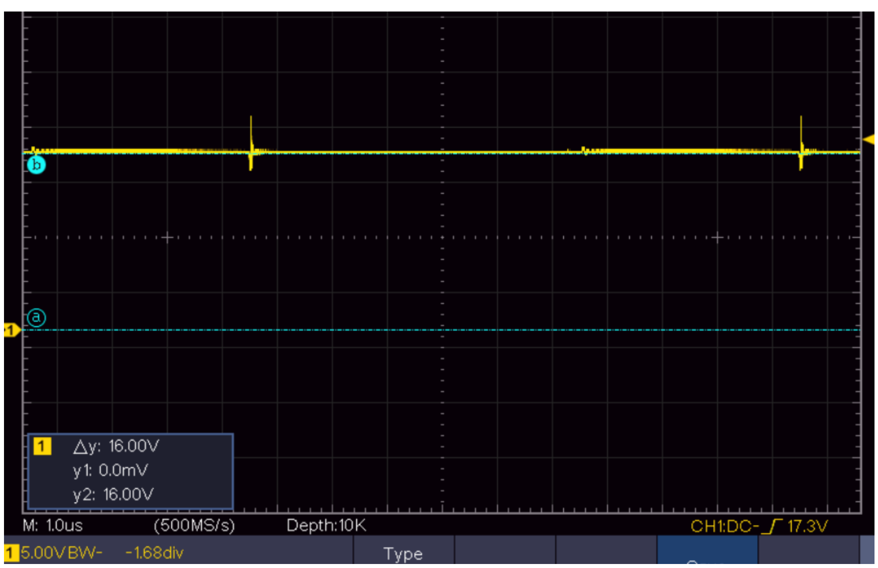

Figure 48: Output Voltage Waveform of Experimental Setup of SEPIC converter with Isolation Transformer

CHAPTER VII

DICUSSIONS

As can be seen in Figure 16, when the capacitive transformer is placed instead of the coupling capacity in the SEPIC converter, the mutual capacitance value of the transformer has fulfilled the task of this capacity. The ratio between input and output voltage amplitudes was adjusted by changing the C_m and C_2 capacitance values. In this way, the output voltage could be changed. Also, this structure provides isolation between the primary and secondary sides of the SEPIC converter.

When we examine this transformer independently from the circuit, the multiplication of the amplitude of the signal applied to its input with the transfer function ratio gives the output voltage of the transformer. Finally, when the frequency of the input signal is changed and there is no change in the output voltage it shows that the equivalent circuit gives results independent from frequency.

There are two limitations in the usage of transformer on SEPIC converter, the mutual capacitance value should be large enough to lower voltage ripple at the output of the converter and the value of C1 capacitance should be small. If it is not, the capacity that is connected between drain and source of MOSFET will cause the high switching loss and MOSFET will warm up.

While higher capacitance values can be achieved in the wrapped shape transformer, a larger surface area and thinner dielectric material are required to achieve this in the flat shape. The production processes of the Wrapped shape transformer may take a little more time than the flat shape one.

CHAPTER VIII

FUTURE WORKS

Examining the flat shaped, wrap shaped and transformer that offers only isolation purposes, it was seen that the flat-shaped transformer design provides a simpler and easier installation. Since the transfer function of the transformer design, which is used only for isolation purposes, is very close to 1, the input and output voltage ratios are equal. We can say that this type of transformer can only be used for isolation purposes in converters. In the studies carried out for the wrap-shaped transformer, it has been observed that the transfer rate is lower than the flat-shaped transformer. It has been observed that it is difficult to increase the capacitance values in the flat-shaped design in the laboratory environment. In a flat shape transformer, which seems to be easier to design, this transformer design should be developed as a continuation of this work. In this design, it would be meaningful to bring the capacitance values to higher levels to make the power transfer more successful. To achieve this, the permittivity of dielectric materials between the plates must be increased. For example, materials such as ceramics have higher permittivity. Apart from that, the distance between the plates can be reduced to the minimum distance according to the voltage in the usage area. Production trials can be made in the factory environment, higher capacitance values and smaller-sized materials can be produced quickly and easily with this structure.

CHAPTER IX

CONCLUSION

In this thesis, the capacitive power transfer (CPT) and inductive power transfer (IPT) methods have been researched. These two methods transfer the power from the transmitter side to the receiver side. This transfer is done by using wireless methods. There is be an air gap between the receiver and transmitter plates in the CPT method. And similarly, there is be an air gap between the receiver and transmitter coils in the IPT method. If this structure was done without an air gap and the coils wounded in the same core it will be an inductive transformer that we all know. What if the four plates of the CPT method were brought together without an air gap, there occurred the proposed structure of a capacitive coupled transformer. This structure claims a lower manufacturing time, cost, and ease to build as a motivation of this thesis.

In the light of these ideas, the capacitive coupled transformer has been decided to test and analyze within SEPIC converter topology and the standalone operations. Therefore the design parameters of the SEPIC converter have been calculated and the pi equivalent circuitry of the transformer has been given in the design chapter. The parameters of this equivalent circuit have been calculated from the six capacities that occurred between four layers. After these calculations, the transfer function of this equivalent circuit has been obtained. Transfer function shows the relationship between output and input voltages of the transformer. This ratio has to be less than 1 according to Equation (20). So this transformer acts as a step-down transformer. Also, this ratio has not contained a frequency-dependent component.

The simulations of the capacitive coupled transformer have been done on both SEPIC converter topology and standalone operation using MATLAB Simulink. When the Cm and C2 values are taken equally, the output voltage of the converter will be 8V and it has been calculated as given in Equation (23). Also, the simulation results show that 8V output has been obtained from the 12 V input voltage with converter as calculated. After this, the standalone operations have been executed on simulation. The input and output signals of the transformer have been observed in two different values of Cm. It has been verified that it multiplies the input voltage with the coefficient coming from the transfer function to form the output voltage. Also, the frequency of input signal has been changed therefore there is no change in the amplitude of output signal.

The wrapped shape transformer has been tested on a SEPIC converter and standalone operation as shown in Appendix A Figure 49. This transformer has been made from 4 layers of aluminum bands and there are papers between each layer as a dielectric material as shown in Appendix A Figure 52. This structure has been wrapped together in a cylindrical shape and has been measured of six capacities between each layer. The parameters of an equivalent circuit which are C_1 C_2, and C_m have been calculated using Equation (9), (10), and (11). So the transfer function ratio (0.0731) of the transformer has been calculated using Equation (20). Here the Cm capacity has been taken the place of the coupling capacity of the SEPIC converter and the connection of transformer on simulation setup has been shown in Figure 16. The output voltage of the converter calculated as 1.2V using Equation (25). Also, the experimental results have been measured at 1.02V and 1.08V in both 100kHz and 200kHz switching frequencies using an oscilloscope as shown in Appendix A Figure 51. Therefore the results are consistent with each other.

Finally, the transformer has been analyzed in a wrapped and flat shape on the standalone operation. The flat shape transformer has four layers of copper with FR2 dielectric material between them as shown in Appendix A Figure 50. Similarly, the amplitudes of output signals have been calculated using the transfer function. The input signals have been applied to the both wrapped and flat-shape transformer and outputs have been measured from the oscilloscope. Therefore it has been shown that the experimental results and the calculated values are consistent with each other in standalone operations.

As a result, simulation and experimental circuit results show that this structure can be realized and can be used for both step-down transformer and isolation transformer purposes. But the wrapped shape may not be as cost and time-effective as the flat shape.

APPENDIX A

SETUP

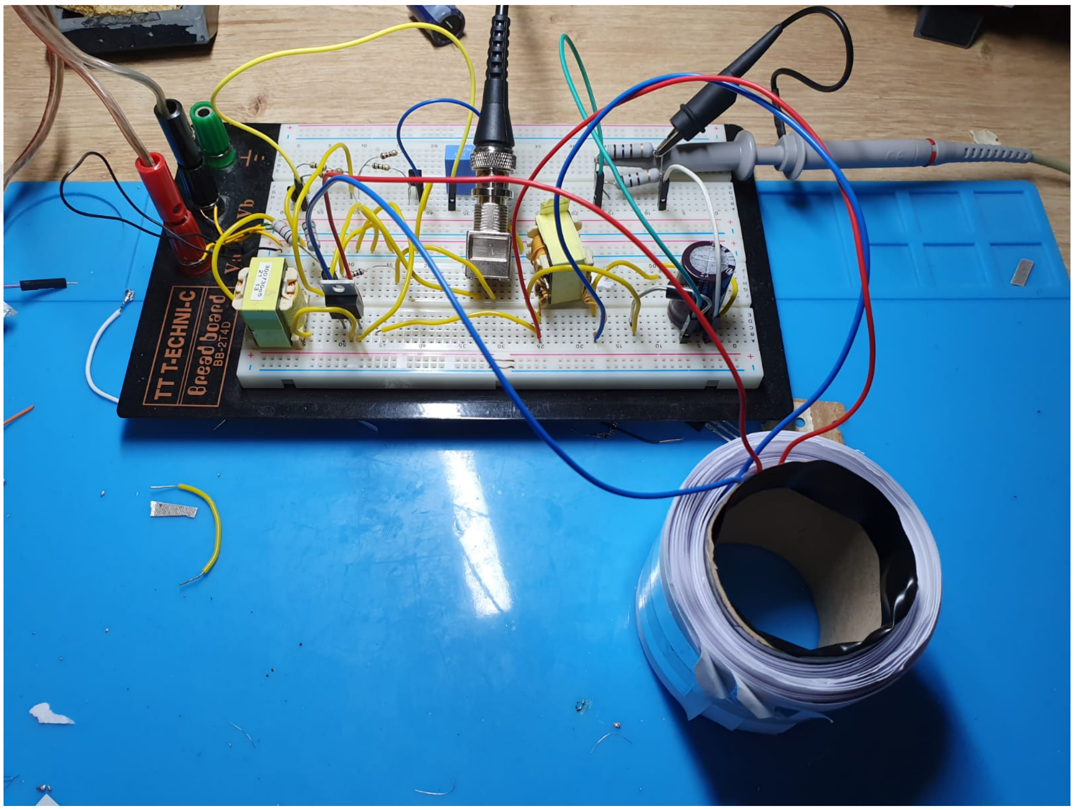

Figure 49: Experimental Setup

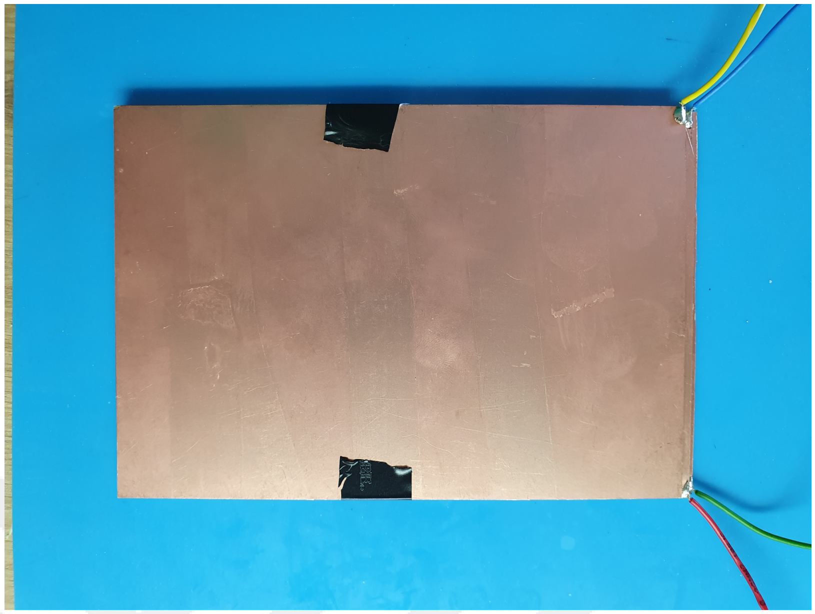

Figure 50: Capacitive Coupled Transformer in Flat Shape

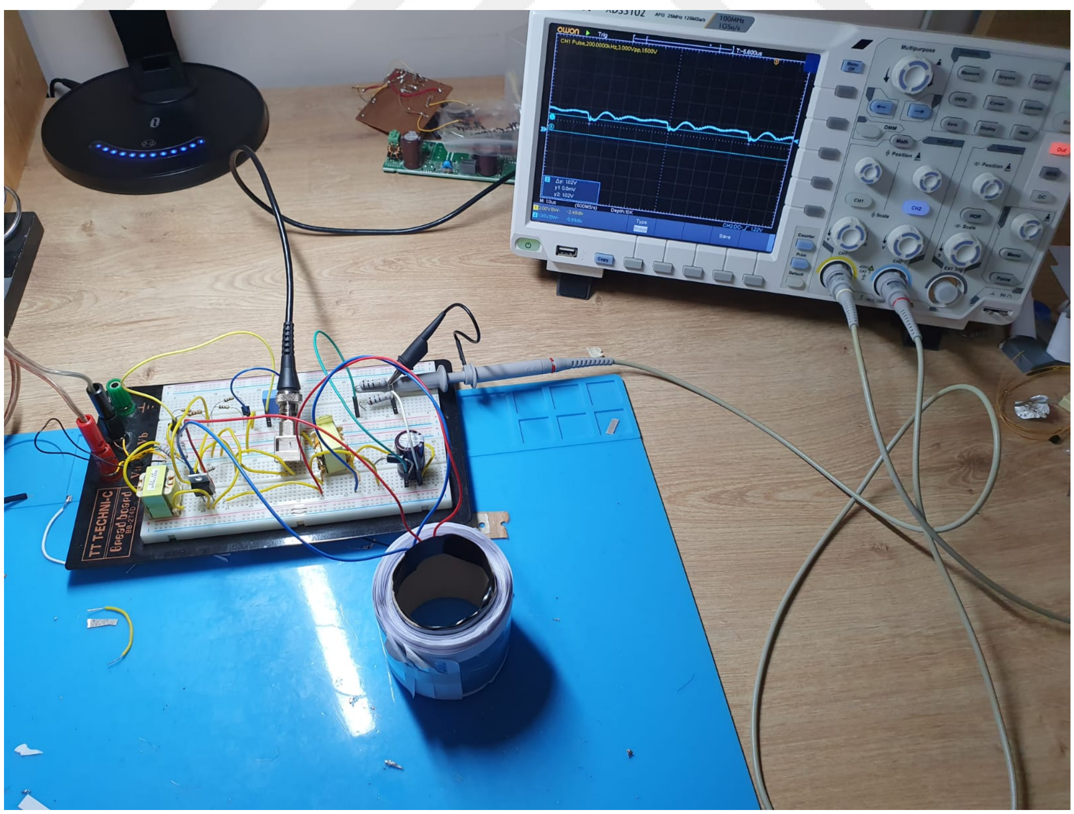

Figure 51: Experimental Setup With Oscilloscope

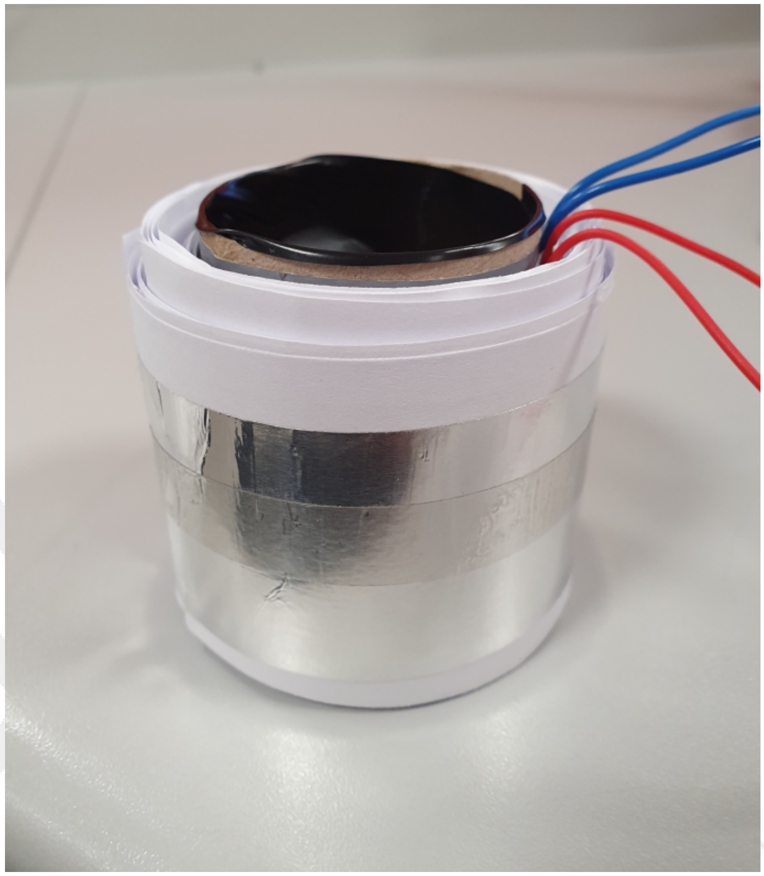

Figure 52: Wrapped Capacitive Coupled Transformer

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VITA

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