Design & Development of 1 kV, 1 A DC Power Supply

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Abstract- This paper presents the design and development of a Switch-Mode Power Supply (SMPS) with a 1 kV and 1 A DC output. This paper provides detailed information on designing a resonant half-bridge converter that uses two inductors (LL) and a capacitor (C), known as an LLC configuration. This paper also includes the use of Frequency Modulation (FM) and Pulse Width Modulation (PWM) techniques for achieving different voltage levels. The SMPS utilizes an LLC resonant converter and closed-loop control with frequency modulation (FM) and pulse-width modulation (PWM). The LLC resonant converter offers high efficiency and reduced EMI, while FM and PWM control ensure stable operation and precise voltage regulation. Simulation and experimental results demonstrate the effectiveness of the design, achieving high efficiency, excellent voltage regulation, and fast response. The system is suitable for power electronics, industrial automation, and renewable energy applications.

Keywords- SMPS; LLC; Converter; PWM; FM

I. INTRODUCTION

Switch-Mode Power Supplies (SMPS) have revolutionized the field of power electronics by offering high efficiency, compact size, and versatility for a wide range of applications. The demand for high-voltage, high-current DC power supplies has been on the rise, particularly in industries such as power transmission, renewable energy systems, electric vehicles, and industrial automation. Designing an efficient and reliable SMPS capable of delivering a 1 kV and 1 A DC output requires careful consideration of various factors, including converter topology, control strategies, and component selection.

The aim of this paper is to present the design and implementation of a Switch-Mode Power Supply with a 1 kV and 1 A DC output, utilizing an LLC resonant converter and closed-loop control with frequency modulation (FM) and pulse-width modulation (PWM). The LLC resonant converter is a popular choice for high power applications due to its high efficiency and ability to handle high power levels.[1] The LLC resonant converter, known for its superior performance in terms of efficiency and electromagnetic interference (EMI), is employed to ensure efficient power transfer while operating at high frequencies. By carefully selecting the values of the resonant components, the converter can achieve the desired 1 kV DC output voltage. To maintain stable and precise output voltage and current levels, closed-loop control is implemented using a combination of frequency modulation (FM) and pulse- width modulation (PWM). The closed-loop control system ensures stable and accurate output voltage regulation by comparing the output voltage to a reference voltage and adjusting the frequency and duty cycle of the converter [1]. FM and PWM techniques are used in combination to achieve optimal performance, including reduced EMI and good transient response. The closed-loop control system continuously monitors the output voltage and adjusts the switching frequency and duty cycle to regulate the power transfer. Frequency modulation enables efficient power transfer over a wide load range, while pulse-width modulation allows for fine-grained control and rapid response to changes in the load.

The design process involves careful consideration of component selection, such as power MOSFETs, resonant inductors, and capacitors, to handle the desired voltage and current ratings.

Simulation and experimental validation play a vital role in assessing the performance of the designed SMPS. The efficiency, voltage regulation, transient response, and EMI emissions are evaluated under various load conditions and compared against design specifications. The results demonstrate the effectiveness of the proposed design, showcasing high efficiency, excellent voltage regulation, and fast response to load variations.

The significance of this research lies in its contribution to advancing the field of high-voltage, high-current SMPS design. The incorporation of the LLC resonant converter and closed-loop control with FM and PWM enables improved efficiency and precise voltage regulation, making the SMPS suitable for demanding applications requiring stable and reliable power supplies [2]. Moreover, the design can be applied in power electronics, industrial automation, renewable energy systems, and other fields where high- voltage DC power is essential.

The experimental results demonstrate the effectiveness of the proposed SMPS design, with high efficiency and excellent stability. The proposed SMPS design is based on an LLC resonant converter topology that consists of a resonant tank circuit, a full-bridge power switch, and a transformer. The resonant tank circuit comprises of a capacitor, an inductor, and a resonant network that provides zero-voltage switching for the full-bridge power switch. The transformer is designed to provide isolation between the input and output of the SMPS, and to step up the voltage to 1 kV. The closed-loop control system is implemented using a microcontroller that reads the output voltage of the SMPS and compares it to a reference voltage. The error signal obtained from the comparison is used to adjust the frequency and duty cycle of the converter. FM and PWM techniques are used in combination to achieve optimal performance [3]. FM is used to regulate the output voltage by adjusting the switching frequency, while PWM is used to control the duty cycle of the half-bridge power switch. The experimental results demonstrate that the proposed SMPS design achieves high efficiency, excellent stability and low EMI.

In the following sections, we will delve into the specific design aspects of the SMPS, including the LLC resonant converter, closed-loop control strategies, component selection, and experimental validation. The results and analysis presented herein aim to provide valuable insights into the design and implementation of high-voltage SMPS systems, contributing to the advancement of power electronics technology.

II. LITERATURE SURVEY

This literature survey focuses on the design and control strategies for a 1 kV, 1 A DC power supply switch-mode power supply (SMPS) using an LLC resonant converter. The survey explores the advancements in closed-loop control techniques involving frequency modulation (FM) and pulse width modulation (PWM) to enhance the performance and efficiency of the power supply.

Several research studies have addressed the design considerations for LLC resonant converters operating at high voltage and low current levels. These works propose optimal design methodologies for selecting resonant inductors, resonant capacitors, and resonant tanks to achieve high efficiency and power density while meeting the desired voltage and current requirements.

Frequency modulation control techniques have been investigated to regulate the output voltage of LLC resonant converters. These methods dynamically adjust the switching frequency to maintain stable output characteristics under varying load conditions. Researchers have proposed closed-loop control algorithms based on feedback signals from the output voltage to achieve precise frequency regulation [2].

PWM control is another commonly used technique in LLC resonant converters. It involves adjusting the duty cycle of the switching signals to regulate the output voltage. Closed-loop PWM control methods utilize feedback signals to dynamically modulate the duty cycle, ensuring accurate voltage regulation and improved transient response.

To further enhance the performance of the power supply, some studies have explored the integration of FM and PWM control strategies in LLC resonant converters. These hybrid control schemes combine the advantages of both techniques, allowing for improved efficiency, reduced output voltage ripple, and enhanced load regulation. The closed-loop control algorithms dynamically adjust both the switching frequency and the duty cycle based on feedback signals from the output voltage.

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Several research works have experimentally validated the proposed closed-loop control strategies for 1 kV, 1 A DC power supply SMPS with LLC resonant converters. These studies include performance analysis in terms of efficiency, output voltage regulation, transient response, and harmonic distortion. Experimental results demonstrate the effectiveness of the closed-loop control techniques in achieving high-performance power supplies.

The literature survey highlights the advancements in the design and control strategies for a 1 kV, 1 A DC power supply SMPS using an LLC resonant converter. The integration of closed-loop control techniques involving frequency modulation and pulse width modulation enables precise voltage regulation, improved efficiency, and enhanced transient response. The surveyed studies provide valuable insights for researchers and engineers involved in the design and development of high-performance power supplies based on LLC resonant converters.

LLC resonant converters are a type of power converter topology that has gained popularity in recent years for their high efficiency and ability to handle high power levels. The LLC converter is a type of resonant converter that uses an inductor, a capacitor, and a transformer to convert DC power into AC power with high efficiency. There are several topologies of LLC resonant converters, which can be classified based on their operation modes. The most common types include full-bridge, half-bridge, and series-parallel resonant converters. The full-bridge LLC resonant converter has a symmetrical structure, making it a popular choice for high-power applications. The control strategy of LLC resonant converters plays an important role in their performance. The most common control methods used for LLC resonant converters include frequency modulation, phase-shift modulation, and hybrid modulation. Frequency modulation adjusts the resonant frequency of the converter to maintain a constant output voltage, while phase-shift modulation adjusts the phase of the input voltage to regulate the output voltage [3].

Hybrid modulation combines the advantages of both frequency and phase-shift modulation to achieve optimal performance. Combined FM and PWM techniques have also been researched for closed-loop control of SMPS which combines the advantages of both FM and PWM to achieve optimal performance [4]. The SMPS control loop is closed using a feedback signal, which is compared to a reference voltage. The error signal obtained from the comparison is used to adjust the switching frequency and duty cycle of the SMPS. The advantages of this technique include improved efficiency, reduced EMI, and good transient response [5]. LLC resonant converters are used in a wide range of applications, including renewable energy systems, electric vehicles, and telecommunications. In renewable energy systems, LLC resonant converters are used for solar and wind power applications due to their ability to handle high power levels and high conversion efficiency. In electric vehicles, LLC resonant converters are used for battery charging and motor control. In telecommunications, LLC resonant converters are used for power supplies, which require high efficiency and compact size. In conclusion, LLC resonant converters have gained popularity due to their high efficiency, ability to handle high power levels, and suitability for a wide range of applications. The research conducted on LLC resonant converters is focused on designing strategy to improve their performance, developing new control strategies and exploring new applications [6-8].

III. SIMULINK MODELS

SMPS stands for Switched-Mode Power Supply, which is an electronic power supply that uses switching regulators to convert electrical power from one form to another. A typical SMPS circuit includes a rectifier, a filter capacitor, a switching element, and a transformer. The proposed circuit is first simulated and tested on MATLAB Simulink Software. After the analysis of the results obtained from the simulation, the hard model is implemented. The complete Simulation of our project is described in the following sub-sections.

A. Three-phase input

Firstly, a 3-phase, 415 Vrms, 50 Hz, AC supply is obtained by using "Three-phase Source" block. Simulink model is shown in Fig. 1. Fig. 2 presents the 3phase input waveforms obtained. Here Vrms = 415 V, Vpeak = 586.89 V.

B. Three-phase Full-wave Diode Rectifier:

A three-phase full-wave diode rectifier is obtained by using two half-wave rectifier circuits.[2] MATLAB model is shown in shown in Fig. 1. The advantage of this circuit is that it produces a lower ripple output than a half-wave 3-phase rectifier. This is because it has a frequency of six times the input AC waveform.

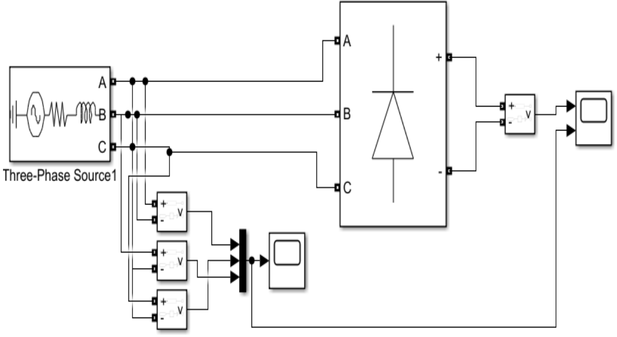


Fig. 1 Simulink model of three-phase full-wave diode

The magnitude of the DC voltage is the sum of the magnitude of the voltages in the two diodes that are conducting at any instant, which is incidentally also a particular line voltage depending on which diode pair is conducting. The average output voltage across the resistive load is given by [Vo = 396.325 Volts] and the percentage ripple obtained is 12.627 %.

The resultant waveforms for the output of three-phase full-wave diode rectifier are shown in the Fig. 2.

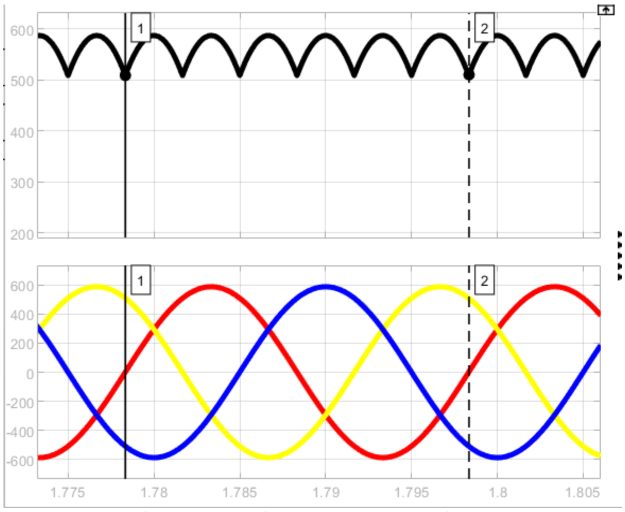


Fig. 2 DC output of three-phase full-wave diode rectifier in black with respect to the Three-phase input shown in Red, Yellow, Blue.

IV. DESIGNING COMPONENTS

The LC filter is obtained by connecting an inductor in series and capacitor in parallel as depicted in the Fig. 3.

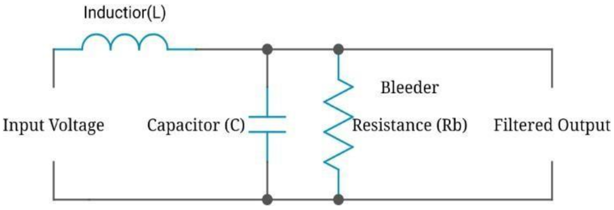


Fig. 3 LC Filter

The output dc waveforms of three-phase full-wave diode rectifier includes ripples of around 48 % and now we are designing the LC filter to filter out the ripples and get the output voltage to the level with minimum ripples around only 1 %.

$$\frac{V_{fundamental.rms}}{V_{output.dc.avg}} = 48\ \%$$

$$\frac{V_{o(s)}}{V_{i(s)}} = \frac{\frac{1}{sC}}{sL+\frac{1}{sC}}$$

$$LC \approx 47$$

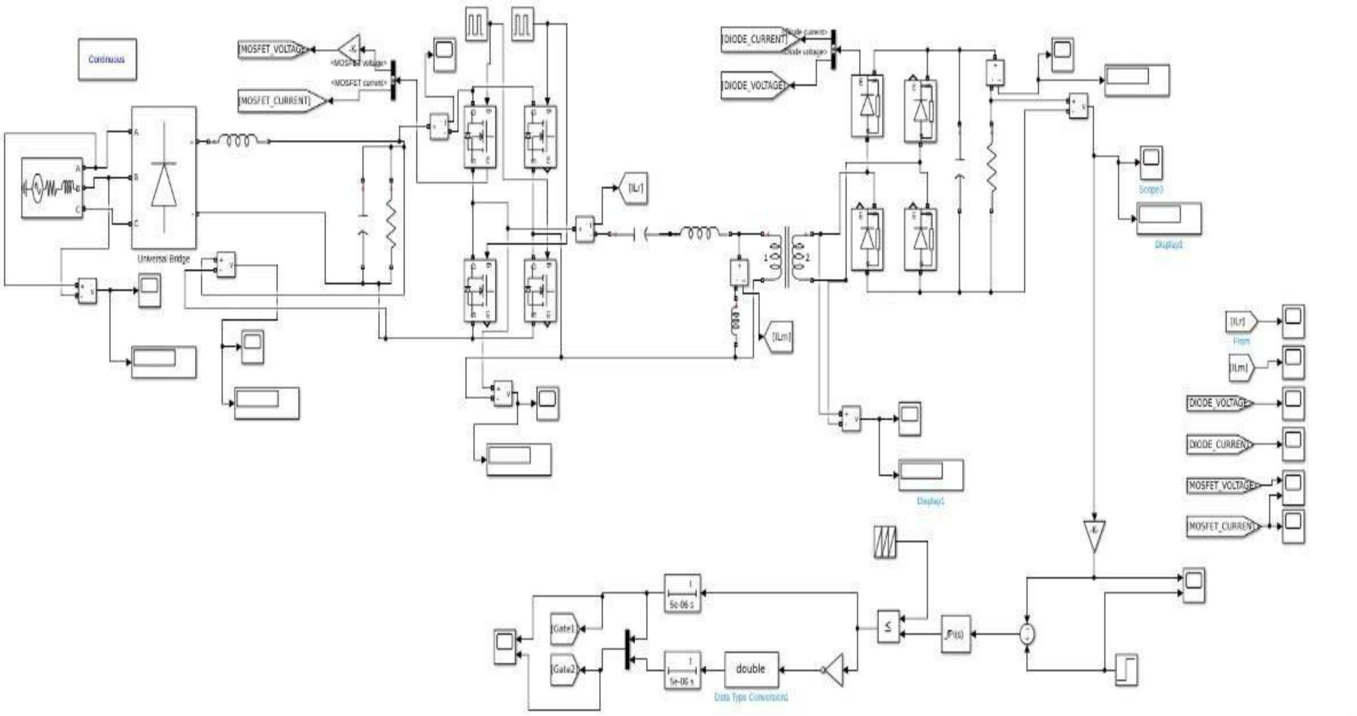


Fig. 4. Final Complete Simulink Model of the SMPS

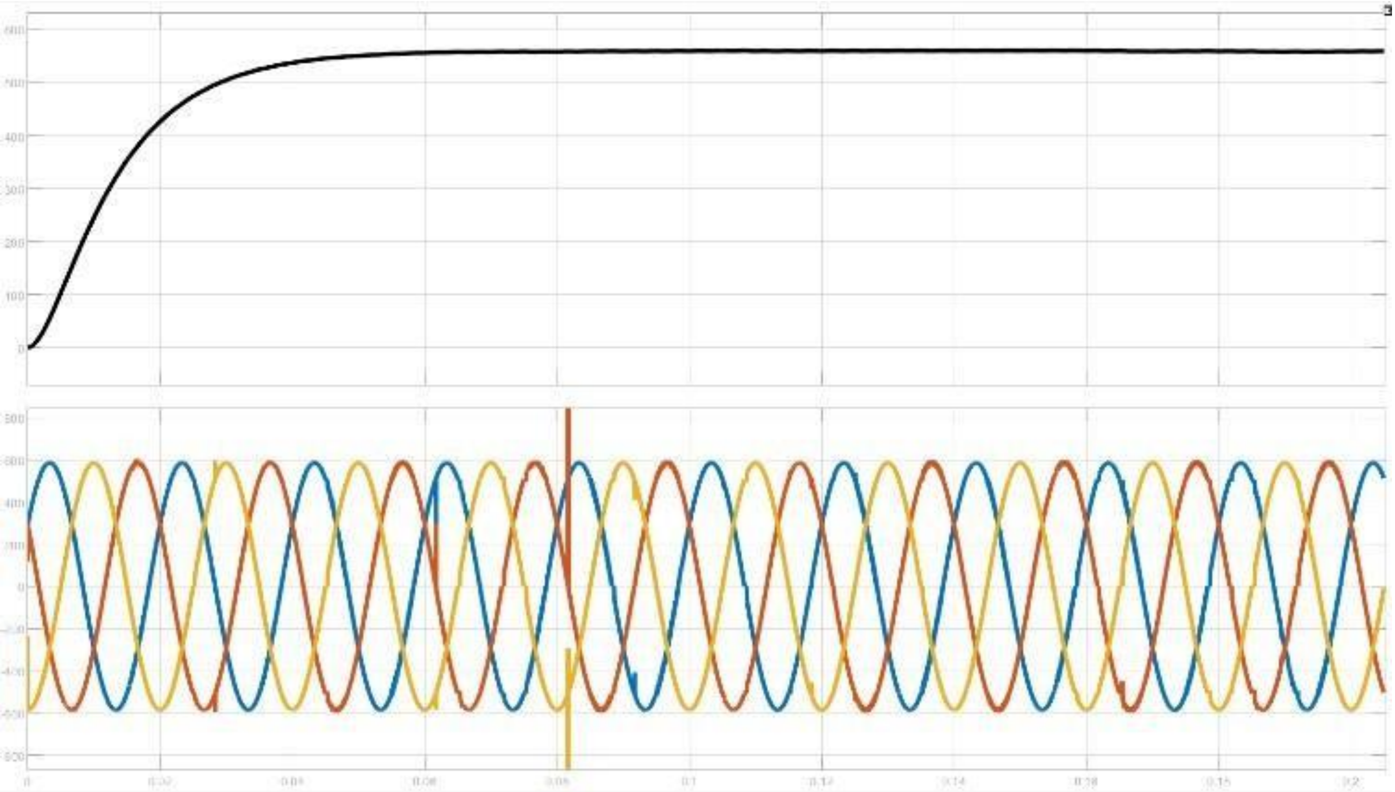


Fig. 5. Final DC output and the three-phase input

The final complete Simulink Model is shown in Figure 4. The final output waveform is shown in Figure 5, where the waveform in black is the final DC output waveform with respect to the red, blue and yellow input waveforms.

LC filter is designed to filter out the ripples and get the output voltage to the level with minimum ripples around only 1 %.

$$\frac{V_{fundamental,rms}}{V_{output,dc.avg}} = 48\ \%$$

$$\frac{V_{o(s)}}{V_{i(s)}} = \frac{\frac{1}{sC}}{sL+\frac{1}{sC}}$$

$$LC \approx 47$$

a) Inductor Designing

Assuming Vdc to be approximately equal to 600 V.

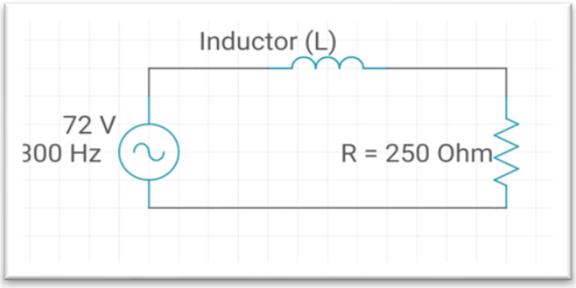


Fig.6 Inductor Designing

Ripple at output of 3-phase diode rectifier = 12 % of 600 = 72 V
Desired ripple output = 1% of 600 V = 6 V
$X_L = 2\pi f L$
Ripple frequency (f_r) = 6*50 = 300 Hz
$X_L = 2\pi * 300 *L$
Current without ‘L’ = 72/250 Amp Current with ‘L’ = 6/250 Amp

$$66 = 2 \times \pi \times f \times L \times \frac{6}{250}$$

$$L = \frac{66 \times 250}{6 \times 2\pi \times 300}$$

$$\underline{\underline{L = 1.4589\ H}}$$

b) Capacitor Designing

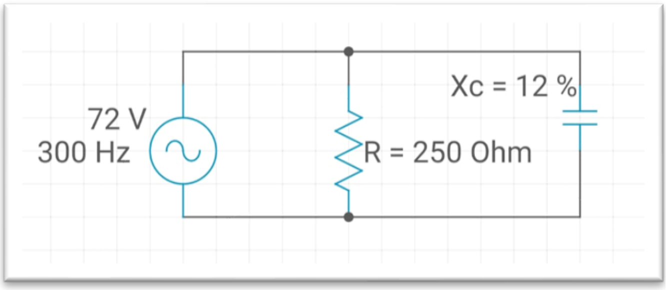


Fig. 7 Capacitor Designing

$I_{ac} = 75/250$ *Amp*
$I_{dc} = 2$ *Amp*
Ripples are in ratio of 1:12
$X_c = 250/12 = 20.833\ \Omega$

$$X_c = \frac{1}{2\pi \times f \times C}$$

$$C = \frac{1}{2\pi \times f \times X_C} = \frac{1}{2\pi \times 300 \times 20.8333} = \underline{\underline{25.46479\ \mu F}}$$

The values designed for minimizing ripples to around 1% are [L = 1.4589 mH] and [C =25. 46479μF].

c) Single-Phase Full Bridge Inverter

A full bridge single phase inverter is a switching device that generates a square wave AC output voltage on the application of DC input by adjusting the switch turning ON and OFF based on the appropriate switching sequence, where the output voltage generated is of the form +Vdc, -Vdc, Or 0.

In the Simulink model of the MOSFET Inverter, a diode is connected across each MOSFET in parallel which provides a path for inductive load current to by-pass the MOSFET during its “OFF” state.

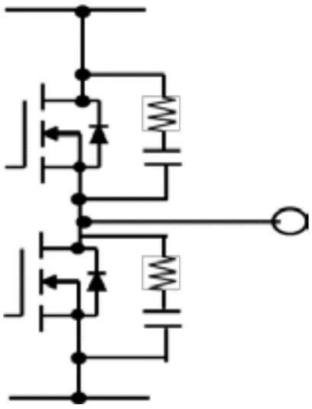
For simulation, the MOSFETs are driven with “Pulse Generator” block, in which the period for pulses is set to (1/100kHz = 10e-5) for all the MOSFETs. The MOSFET is driven for pulse width of 45 % of the period for the purpose of providing some “dead-time” to the MOSFET inverter. This is provided intentionally for providing path to through-currents flowing through the switches.

The MOSFET switches S1 & S3 are provided with no phase delay whereas the S2 & S4 are provided with phase delay of 180 degrees by {[180/360] * [10e-5]} in the phase delay block.

The generated AC waveforms from the Simulink Model provided with maximum voltage of 560.00 Volts and minimum voltage of -560.00 Volts. This output voltage is with the frequency of 100 kHz.

1) Designing of Snubber Capacitors for MOSFETs

Surge voltage is produced by stray inductances of a circuit. A snubber should be connected in parallel with a switching device to absorb the surge voltage.



The snubber circuit used in project is RC snubber circuit, as shown in Fig. 10. It is ideal for chopper circuits. The power loss caused by an RC snubber resistor is so large that an RC snubber is not suitable for high frequency switching applications.

MOSFET range of medium switching frequency in DC/DC converters is of 100 kHz to 1 MHz. An RC snubber for a high capacitance switching device needs to have a resistor with a small value, which causes drain current to increase during turn-on.

The power P dissipated by the snubber resistor is calculated as follows:

$$p = C_s \,.\, E_d^2 \,.\, f$$

Standard formula for calculating filter capacitor:

$$L = L_{eqv.} = L_p + L_s^2 = 3.89 * 10^{-3} + (1/4) * 19.133 * 10^{-3}$$
$$= 8.67325 * 10^{-3}\, H = 8.67325\, mH$$

Lp = Primary Inductance
Ls = Secondary Inductance
$L = L_{eqv} = 8.67325\, mH$

$$\tfrac{1}{2} Li^2 = \tfrac{1}{2} Cv^2$$
$$Li = Cv$$
$$8.67 * 10^{-3} * 2^2 = C * 500^2$$
$$C = \frac{8.67 * 10e-3 * 4}{250000}$$
$$\underline{\underline{C = 128.77\, nF}}$$

2) Designing of Driver circuit for MOSFETs:

In Simulation, the MOSFETs are driven with the “Pulse Generator” block in MATLAB Simulink. The Pulse Generator block is set for Period of 10e-5 and pulse width is set to 45 % for providing “Dead-time”.

In Hardware implementation, the gate pulses can be generated using ATMega328 Microcontroller Board. In which it is programmed for generating pulses for gate of the MOSFETs of Inverter.

V. LLC RESONANT CONVERTR

The basic parameters of LLC Resonant Tank are Capacitance (C), Resonant Inductance (Lr) connected in series with the transformer and Magnetizing Inductance (Lm). The ideal transformer has its magnetizing inductance in parallel with its primary winding. So, we can use this inductance in parallel with the resonant tank, this is called Mutual Inductance (Lm). Practically, the transformers always come with Leakage Inductance in series with the transformer winding.

If we somehow use this inductor as a resonant inductor, we can reduce the cost of the circuit [4-5]. The main purpose of the Resonant tank is to filter out the harmonics in the square wave input to the transformer and give a sinusoidal waveform as output at the frequency of 100 KHz.The resonant tank has a gain that varies according to the load connected at the secondary side of the transformer and frequency[6].

The Gain versus Frequency plots are obtained from MATLAB for different values of Gains at different values of loads quality factor (Q).

Design of LLC parameters

We know the output parameters viz., Output voltage (Vo) = 1 kV, Output power = 1 kW, Switching frequency (Fsw) = 100 kHz, Vin(min-max): Vnominal = 560V, Vmax = 616V , Vmin = 504V. Assuming value of gain (M) to be 6. Firstly, we need to determine transformer turns ratio. Turns ratio of the Transformer can be calculated as N1/N2

$$\frac{N_1}{N_2} = \frac{560}{1000} = 0.56 = 1/2$$

We need to ensure that the LLC resonant converter has a high enough voltage gain with minimum input voltage and maximum output voltage at a full load so a unified transformer ratio n=0.56 is selected for LLC resonant converters to provide a fair compensation and ease the transformer design. We are designing the converter to have the 100 kHz switching frequency.

The maximum and minimum values of Amplitude are calculated as below –

$$G_{max} = \frac{560}{504} = 1.12 \qquad G_{min} = \frac{560}{616} = 0.91$$

The quality factor (Q) depends upon the load current means the heavy load conditions operate at the high Q values while the lighter loads is having low Q value, so the moderate Q value is to be taken to satisfy the voltage gain requirement that to in a specific case. Maximum Q=0.35 from graph

$$Re = \frac{V_i nMax^2}{p} = \frac{(616)^2}{1000} = 379$$

$$Z = Q \times Re = 0.3 \times 379 = 113.7$$

$$Z = \sqrt{\frac{L_r}{C_r}} = 114$$
$$L_r = (114)^2 \times Cr = 12996 \times Cr$$

Resonant frequency = 100 kHZ

$$f = \frac{1}{2\pi\sqrt{L_r Cr}} \qquad 10^5 = \frac{1}{2M\sqrt{(114)^2 (Cr)^2}}$$

Cr=13.96nF = 14nF

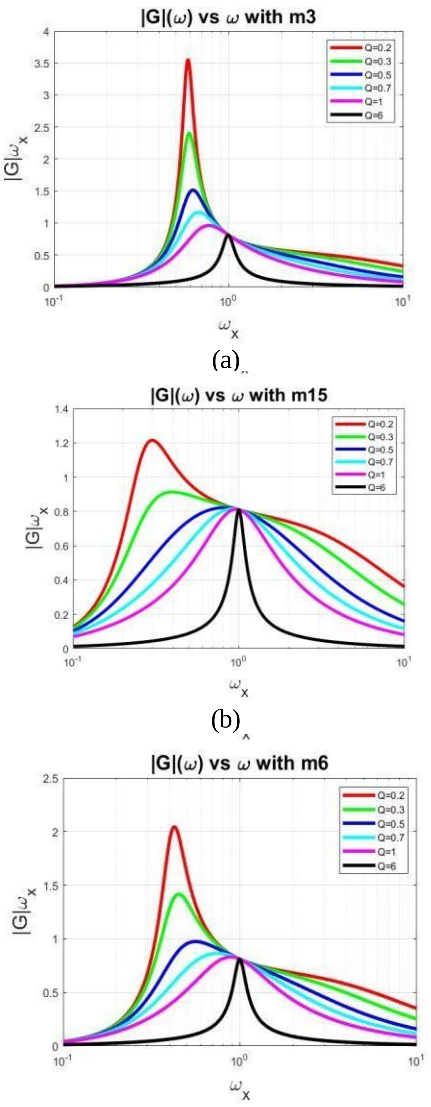
$$L_r = (114)^2 \times c_r \qquad L_r = 12996 \times 14 \times 10^{-9}$$
$$L_r = 182\mu H$$

We have calculated resonant tank elements values as above.

Value of Gain (M) can also be calculated by following formula,

$$M = \frac{Lm + Lr}{Lr}$$

The M is the static parameter that is used to start the design by optimizing its value. Below figures show the same resonant tank gain plots but having different M values so it is seen that the lower value of M can achieve higher boost gain. In addition, it also provides narrower range of the frequency modulation, it means it is having more flexibility and more regulation so it can be used in an application with a wide voltage range.[7] Low values of M with the same quality factor Q and the resonant frequency (*fr*) means the smaller magnetizing inductance (Lm) whereas in case of the high Mvalues the value of circulating current is low but it is having higher magnetizing inductance and higher efficiency



(a)

(b)

(c)

Fig. 9 Gain Curves (a) with m=3, (b) m=15 and (c) m=6

VI. WORKING OF CLOSED LOOP CONTROL

The closed-loop control of an SMPS involves the use of a feedback loop that continuously monitors the output voltage and adjusts the duty cycle of the switching converter to maintain a constant output voltage. The feedback loop typically consists of a voltage sensing circuit, an error amplifier, and a pulse-width modulation (PWM) circuit. The voltage sensing circuit monitors the output voltage and provides a voltage signal to the error amplifier. The error amplifier compares the output voltage with a reference voltage and produces an error signal that represents the difference between the two voltages. The PWM circuit uses the error signal to adjust the duty cycle of the switching converter, which in turn adjusts the output voltage to match the reference voltage.[8]

Closed loop control of an SMPS DC power supply using an Arduino Uno can be achieved by using both variable frequency and variable PWM. This approach allows for precise control of the output voltage and current, which is important in many applications such as electronics testing, battery charging, and motor control. To implement closed loop control, we need to measure the output voltage and current and use that information to adjust the PWM duty cycle and frequency. Here's a basic overview of how this can be done:

Measure the output voltage: We can use a voltage divider to scale down the output voltage and measure it using an analog input pin on the Arduino. Measure the output current: We can use a shunt resistor in series with the load to measure the output current. The voltage drop across the shunt resistor can be measured using another analog input pin on the Arduino. Adjust the PWM duty cycle and frequency: We can use the analogRead() function to read the voltage and current values and use that information to adjust the PWM duty cycle and frequency using the analogWrite() function. The duty cycle determines the amount of time that the PWM signal is high compared to the total time period, while the frequency determines how often the PWM signal is repeated.

Implement a closed loop control algorithm: We can use a PI(proportional-integral) controller to adjust the PWM duty cycle and frequency based on the difference between the desired output voltage/current and the measured values. The PI controller calculates an error value based on the difference between the desired and measured values and uses that error to adjust the PWM duty cycle and frequency.

Control Methodology

LCC resonant converter is widely adopted in industrial applications due to its advantages of zero voltage switching (ZVS) of power switch. However, conventional variable frequency controlled LCC resonant converter suffers from various problems. Variable frequency controlled LCC resonant converter suffers from wide variation of switching frequency. Although fixed frequency controlled LCC resonant converter benefits from constant switching frequency, it suffers from narrow zero voltage switching (ZVS) range of power switch and high circulating energy. A pulse width modulation – pulse frequency modulation (PWM-PFM) hybrid controlled LCC resonant converter is proposed to achieve wide ZVS range of power switch with narrow variation of switching frequency.

LLC resonant topology has a simple structure and reduced EMI. Moreover, switching losses can be decreased by extending the zero voltage switching (ZVS) and zero current switching (ZCS) range of MOSFETs and power diodes respectively. If the LLC converter has to meet such a wide voltage range, the switching frequency (*fs*) needs to be varied and deviates from resonant frequency (*fr*). Hence, Pulse Frequency Modulation is suitable for control purpose with constant Pulse Width. In this model, the variation of frequency ranges from 10 kHz to 100kHz with constant duty cycle of 45%. If voltage gain is low required, then power diodes will lose ZCS, leading to an increased switching loss. Therefore, it is necessary to operate the switches at fixed frequency with variable duty cycle. If high voltage gain is required, LLC converter must operate at much lower frequency than resonance. This leads to the problems in designing optimal circuit magnetic such as transformer core. So to avoid this problem, we here used Pulse Width Modulation with variable frequency for output voltage control.

The control strategies for the proposed converter are demonstrated in Table 1. In PWM mode, the output voltage ranges of 0-400V has been met with a constant switching frequency.

TABLE I
Control and Configuration Characteristics

Vo(volt) Output	Modulation Mode	Inverter Side Configuration	Pulse Width Range	Operating Frequency Range
0-400	PWM	Full Bridge	10%-45%	Fixed Frequency 100kHz
400-1000	PFM	Full Bridge	Fixed - 45%	10kHz-100kHz

VII. HARDWARE IMPLEMENTATION

After successful designing and testing of essential components such as High Frequency Transformer, Inductor and Capacitor, the components are mounted as well as connected as shown in the Fig. 10.

Figure 11(a) & (b) are depicting input waveforms of LLC resonant converter at different switching frequencies.

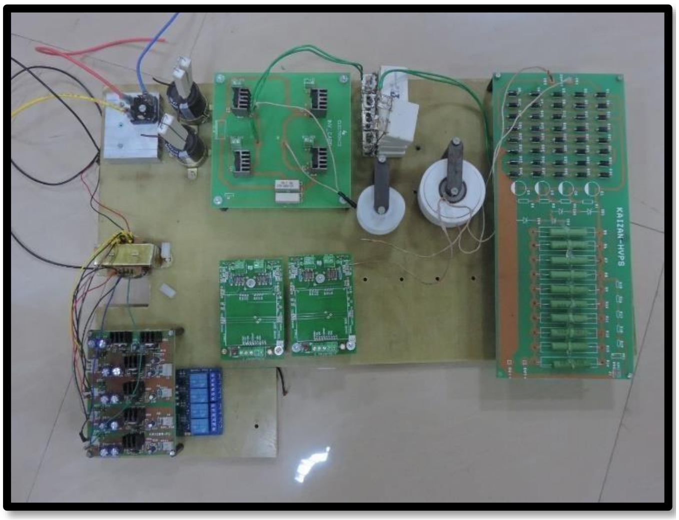


Fig. 10 Hardware implementation

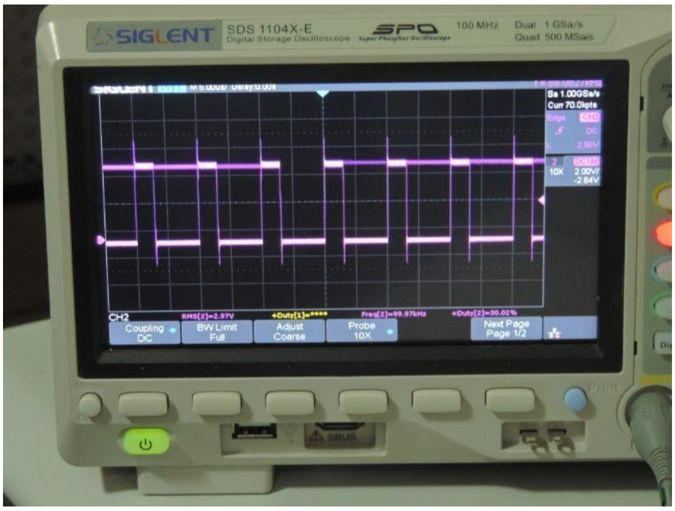


Fig. 11(a)

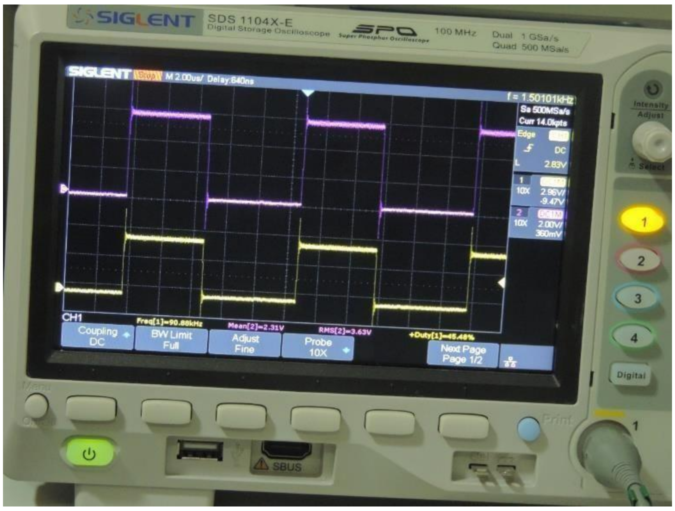


Fig. 11(b)

Fig. 11 Output of Arduino UNO showing variable PWM wave with different duty cycles.

VIII. CONCLUSION

The development of a 1KV, 1A Resonant Converter-based DC power supply using LLC converter with Frequency modulation and PWM technique for varying voltage has been successfully achieved. The LLC resonant converter topology has been implemented to achieve high-efficiency power conversion with minimum switching losses. The use of frequency modulation and PWM technique enables the voltage to be varied within a certain range with high accuracy and stability. The simulation and experimental results demonstrate that the proposed power supply provides excellent performance in terms of efficiency, output voltage stability, and low output ripple. Moreover, the proposed power supply has a wide range of applications, including powering sensitive electronic devices, electric vehicles, and renewable energy systems. Overall, this project has successfully demonstrated the design and implementation of a highly efficient and versatile DC power supply.

IX. REFERENCES

[1] Texas Instruments, "Survey of Resonant Converter Topologies," reproduced from 2018 Texas Instruments Power Supply Design Seminar SEM2300, Topic 1, TI Literature Number: SLUP376, © 2018 Texas Instruments Incorporated.
[2] P. C. Sen, *Principles of Electric Machines and Power Electronics*, Wiley Publication.
[3] M. H. Rashid, Ed., *Power Electronics Handbook*, University of West Florida, Pensacola, Florida.
[4] U. Khalid, M. M. Khan, M. Z. Khan, M. A. U. Rasool, and X. Jianming, "Pulse Width and Frequency Hybrid Modulated LLC Converter Adapted to Ultra- Wide Voltage Range."
[5] P. JS, Y. P. Obulesh, and C. S. Babu, "Closed Loop Control of Zero Voltage Switching DC-DC Converter to Generate Three Outputs."
[6] S. Abdel-Rahman, "Resonant LLC Converter: Operation and Design," Infineon Technologies North America (IFNA) Corp.
[7] H. Wang, "Design and Control of Series Resonant Converters for DC Current Power Distribution Applications," Utah State University.
[8] Texas Instruments, "Design Guide-Two-Phase Interleaved LLC Resonant Converter Design with C2000™ Microcontrollers."