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A NEW INTERMITTENT ENERGIZATION GENERATION TECHNIQUE FOR ELECTROSTATIC PRECIPITATORS

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Abstract- This paper aims in the development and analysis of a cost efficient and low power consuming power supply for Electrostatic Precipitators (ESP) in oilers, the analysis is performed using Matlab/Simulink then with a prototype. A transformer less topology is proposed to generate a very high voltage for developing corona in ESP with the help of a boost converter and voltage multiplier (VM). Instead of using a transformer for increasing the voltage level, a voltage multiplier is used, which reduces the installation cost of ESP power supply. The control strategy implemented here is very simple which can replace the use of intelligent controllers, leads to reduction in cost. And the intermittent energization technique is used to provide excitation to the ESP which avoids the back corona problem and energy consumed. The reduction in switching stresses is achieved by using the charge pump for increasing the voltage. The proposed system is analyzed using Matlab and found that the Total Harmonic Distortion (THD) generated is 43.15% and the voltage stress is limited within 3 kV.

Keywords: Cost-effective, Electrostatic Precipitator, Voltage multiplier, Energy Saving, Intermittent energization.

1. INTRODUCTION

With the increase in demand of electricity, the number of power generation units was increased. Most of these power generations depend on the conventional energy sources like coal, coconut shells, husk etc. Among that, the boilers were utilized by small scale industries for their own power supply. The flue gas (exhaust gas) from large scale thermal power plant was controlled using many methods like filtering, gravity separation, separation with cyclones, electrostatic precipitator (ESP) etc. Among the separation methods, most of the industries prefer the ESP due to its higher collection efficiency. Electrostatic Precipitator is a device connected at the industries emission outlet. It has two electrodes, one for discharging a corona over the particulate matters (dust particles of smaller size less than 0.1 μm diameter) and one collector electrode to collect the particulate matters.

The boilers were operated by small scale industries, they are not giving importance in emission control because i) The cost of the ESP unit is high due to their controller, ii) A separate high voltage power supply is needed to produce static electricity with a transformer.

On reviewing the different power supplies at the present scenario. By using the Plate type, ESP with IGBT inverter, harmonics were generated and for reducing this passive filter can be used, but it is capable of limiting few specific frequencies [1]. On implementing Switched Mode Power Supply (SMPS), the Total Harmonic Distortion (THD) can be reduced, but due to the high frequency transformer, the cost gets increased [2].

Meanwhile the SMPS is capable of decreasing the outlet concentration by 28% than the conventional transformer rectifier (T-R) combination [3] and fed 21.9% less power than *T*/*R* set [5]. Automatic voltage Regulators (AVR) with DSP processors were used to operate the power supply unit in an efficient manner, but, the intermittent regime is better than this AVR [4]. Flash over and deionization time can be controlled properly by introducing Fuzzy logic controllers [6] also the THD can be reduced to 57.9% but the overall cost will be increased [16]. By implementing automated power monitoring system, it is possible to save energy, to 78.67% [7]. The ripples produced during the high frequency operation, can be reduced by using high frequency multiphase topology [8].

The THD was found to be 44-88% in the existing power supply [9]. The usage of shunt active filter for eliminating harmonics is also analyzed, but it reduces the overall system collection efficiency to 96.3% [10]. Using Pulse Width Modulation (PWM) technique, it is possible to reduce the harmonics generation to a minimal level, but it increases the overall system cost [11]. By implementing the 12-pulse converter, the THD generated can be reduced by it will reduce the output power delivered by the system [12]. With self-adoption spark detection system in three phase system, it is possible to get a maximum efficiency of 92.8% [13]. By having resonant converters, 20% of energy saving are possible, but still the collection efficiency is 95% [14].

In some converters the ozone is developed and decreases the flow velocity which can be reduced by intermittent pulse energization [15].

2. DESIGN ANALYSIS

The ESP collection efficiency should not be affected on applying the proposed converter. To retain the ESP collection efficiency, the following parameters have to be considered in the design [16]. The applied electric field E, at the discharge electrode

$$E = \frac{V}{r\ln\left(\frac{d}{r}\right)} \tag{1}$$

where, V is the potential difference across the electrodes, d is the distance between the discharge and collection electrode. The electric field acquired by each particle during the energization is through diffusion charging, since the particulates having a high resistivity and diameter less than 10 µm have a good diffusion charging. The electric field obtained is given by

$$E_{diff} = \frac{d_p kT}{2KEe^2}\ln\left[1+\frac{\pi K_E d_p C_i e^2 n_i t}{2kT}\right] \tag{2}$$

where, k is Boltzmann's constant, C_i is the thermal speed of ions, T is the temperature, d_p is the diameter of particulates, K_E is the vacuum permittivity, N_i is the concentration of ions, e is the charge of an electron (1.602×10^{19} coulomb), and it is the charging time. The velocity of the particulate matters has to be considered on using an intermittent pulse energization, and velocity is

$$\omega = \frac{n_p e E C_c}{3\pi\upsilon d_p} \tag{3}$$

where, n_p is the average elementary charge number, C_c is the Cunningham correction factor. The average corona current generated over the electrode is given by

$$I_{avgc} = \frac{\pi\varepsilon_0 Z_i HL}{CS^2\ln\left(\frac{d}{r}\right)} V_0\left(V_0 - V_c\right) \tag{4}$$

where, V_0 is the output voltage at discharge electrode, V_c is the corona onset voltage, H and L are the height and length of collection electrode, Z_i is the mobility of electrical ions, and ε_0 is the free space permittivity (8.854×10^{-12} F/m). The corona onset voltage is given by

$$V_c = rE_c\ln\left(d/r\right) \tag{5}$$

where,

$$E_c = \delta\left[32.2+\frac{0.864\times10^5}{\sqrt{r\delta}}\right] \tag{6}$$

The CCW voltage multiplier in each module has the same design and the voltage across the first capacitor of each CCW voltage multiplier will have the value of $V=V_m$ and the capacitors other than the first will have a voltage of $V=2V_m$. If there are n number of capacitors, then the voltage across the nth capacitor is;

$$V_n = \sum_{x=2,4,..}^{N} V_x = NV_m \tag{7}$$

where, N is the number of stages

$$N = \frac{V_0}{V_m} \tag{8}$$

There is an inductor in series with the input of the boost converter, this inductor boosts the current and smoothens out the ripples, and

$$i_L = \frac{V_i}{L}DT \tag{9}$$

where, D and T are the duty cycle and the time period of the first arm switches. The voltage gain of each module is given as

$$V_{gain} = \frac{V_0}{V_i} = \frac{N}{1-D} \tag{10}$$

For calculating the voltage loss across each switch, the instantaneous power loss is given by $P(t)=i(t)v(t)$. During the conduction period. The IGBT has some conduction losses given by

$$P_{\text{loss}} = \frac{2}{T}\int_0^{T/2} P(t)\,dt \tag{11}$$

where, T is the time period of current, and the charge delivered to the ESP (capacitor) is given by

$$Q_c = C_{esp}V_0 \tag{12}$$

The current drawn by the intermittent energization,

$$I_{IE} = K\frac{I_{dc}}{D} \tag{13}$$

where, K is a constant, I_{dc} is continuous energization, and D is duty cycle. The current drawn during pulse energization is given by,

$$I_p\left(t\right) = I_p\sin\left(\omega t\right) \tag{14}$$

where, I_p is peak current, and ω is angular frequency.

To generate the pulsed and intermittent pulsed energizing the converters has to be operated at higher switching frequencies this develops voltage stress across every operating switch that has to be avoided to retain the higher collection efficiency through various methods.

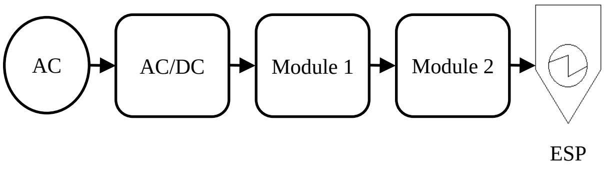


Figure 1. Block diagram of the proposed converter [16]

The idea of the proposed converter is to generate intermittent energization with voltage multiplier for boilers. The input is given from 230V AC which is then rectified to DC to make it suitable for boosting operation. There are two modules which are connected in such a way that, the output of the first module is fed as input to the second module, thereby the cascading of converters is done to boost the voltage to very high level. That high voltage is given as input to the electrostatic Precipitator (ESP) it is shown in Figure 1.

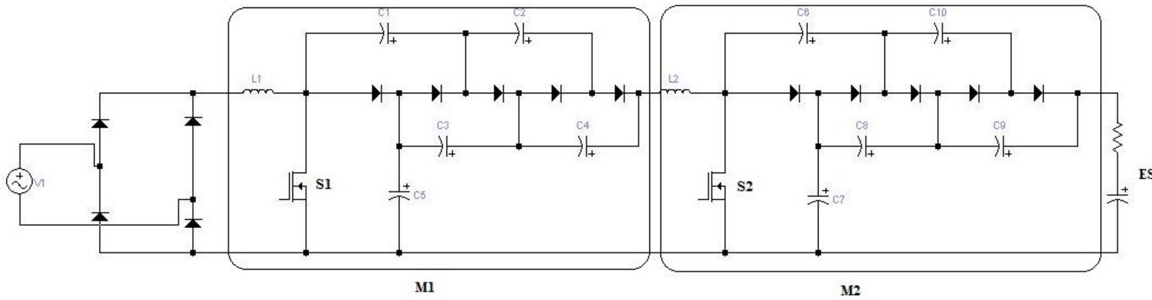


Figure 2. Circuit diagram of proposed system

Figure 2 shows the circuit diagram of the proposed system, a single AC voltage source is connected to rectifier for converting AC to DC, and it is given as input to module M$_1$ which contains a boost converter and the high gain boost operation is carried out with the switch S$_1$, inductor L$_1$, and capacitor C$_5$. The output of the boost converter is given as input to a two-level voltage multiplier constructed with capacitors and diodes for increasing the output voltage level. The output of Module M$_1$ is given as input to the module M$_2$ (contains the same setup as that as module M$_1$) which is connected in cascade to the first module. The output from module M$_1$ is given by,

$$V_0 = V_i + nV_x \tag{15}$$

where, V_i is the input voltage given to the voltage multiplier, n is the number stages in voltage multiplier, V_x is the voltage across each multiplier capacitors, In both module the number of stages used for voltage multiplication is two, i.e., n=2. So, the voltage across each capacitor is equal to the input voltage given to the voltage multiplier.

$$V_x = V_{in} \tag{16}$$

$$(15) \Rightarrow V_0 = (n+1)V_i \tag{17}$$

$$V_i = \left(\frac{1}{1-D}\right)V_d \tag{18}$$

where, D is Duty cycle of switch G, and V_d is the required DC output voltage of a module.

$$(17) \Rightarrow V_0 = \left(\frac{n+1}{1-D}\right)V_d \tag{19}$$

$$\frac{n+1}{1-D} = \frac{V_0}{V_d} \tag{20}$$

$$(1-D) = (n+1)\frac{V_0}{V_d} \tag{21}$$

$$D = 1 - \left((n+1)\frac{V_0}{V_d}\right) \tag{22}$$

This duty cycle D is to calculate the switching of G switch. Corona onset Electric Field, that is the minimum field required by the discharge electrode for generating corona will be given by,

$$E_c = \delta\left[3.22 + \frac{0.864\times10^5}{\sqrt{r_0\delta}}\right] \tag{23}$$

where, the r_o is gas density.

Based on the above equations the Module design was made

$$2\delta V_{2n} = \frac{q}{C_{2n}} \tag{24}$$

where, $2\delta V$ is sum of ripple voltage delivered by a capacitor, q is charge transferred and n is number of stages.

$$2\delta V = q\left(\frac{1}{C_{2n}} + \frac{1}{C_{2n-2}} + ... + \frac{1}{C_2}\right)$$

$$2\delta V = \frac{q}{C}\left(\frac{n(n+1)}{2}\right) \tag{25}$$

$$2\delta V = \frac{I}{fC}\left(\frac{n(n+1)}{2}\right)$$

where, I is load current and f is frequency of input voltage.

The voltage drop across the smoothening capacitors are given by

$$\Delta V_2 = \frac{q}{C}n$$

$$\Delta V_4 = \frac{q}{C}\left[2n + (n+1)\right]$$

...

$$\Delta V_n = \frac{q}{C}\left[2n + (n+1) + ... + 2\times2 + 1\right]$$

On adding all the voltage drop

$$\Delta V_{tot} = \frac{q}{C}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{n}{6}\right)$$

$$\Delta V_{tot} = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{n}{6}\right) \tag{26}$$

The optimal value

$$n_{opt} = \sqrt{\frac{V_s(\max)fC}{I}} \tag{27}$$

The maximum accessible voltage is given by

$$V_0(\max) = 2n_{opt}V_s(\max) - \frac{I}{fC}\left(\frac{2}{3}n_{opt}^3 + \frac{1}{2}n_{opt}^2 - \frac{n_{opt}}{6}\right)$$

3. PERFORMANCE ANALYSIS

The proposed converter is simulated using Matlab2013a Simulink as shown in Figure 3. It has two AC supply of 230 V, 50 Hz as input which is rectified using a diode rectifier, and the output is given to module M, which the module M and M$_1$ are in cascade connection so the output of M is fed to M$_1$. Similarly, the module M$_2$ and M$_3$ were cascaded and then it is given to ESP through a switch having a capacitor with Zener diode and resistor for analyzing a practical ESP as shown in Figure 3. By controlling these G switch, it is possible to generate varying energization, i.e., Continuous or pulsed or intermittent. Here this system aims to develop the intermittent energization, due to its focus over the energy saving with better collection efficiency. In order to match the practical ESP, a ladder made of Zener diode and resistors is created to simulate the corona current. The system is capable of generating 150 kV in an intermittent manner. The intermittent energization is obtained by reducing the output voltage of the converters to below the base value of corona development (below 20 kV).

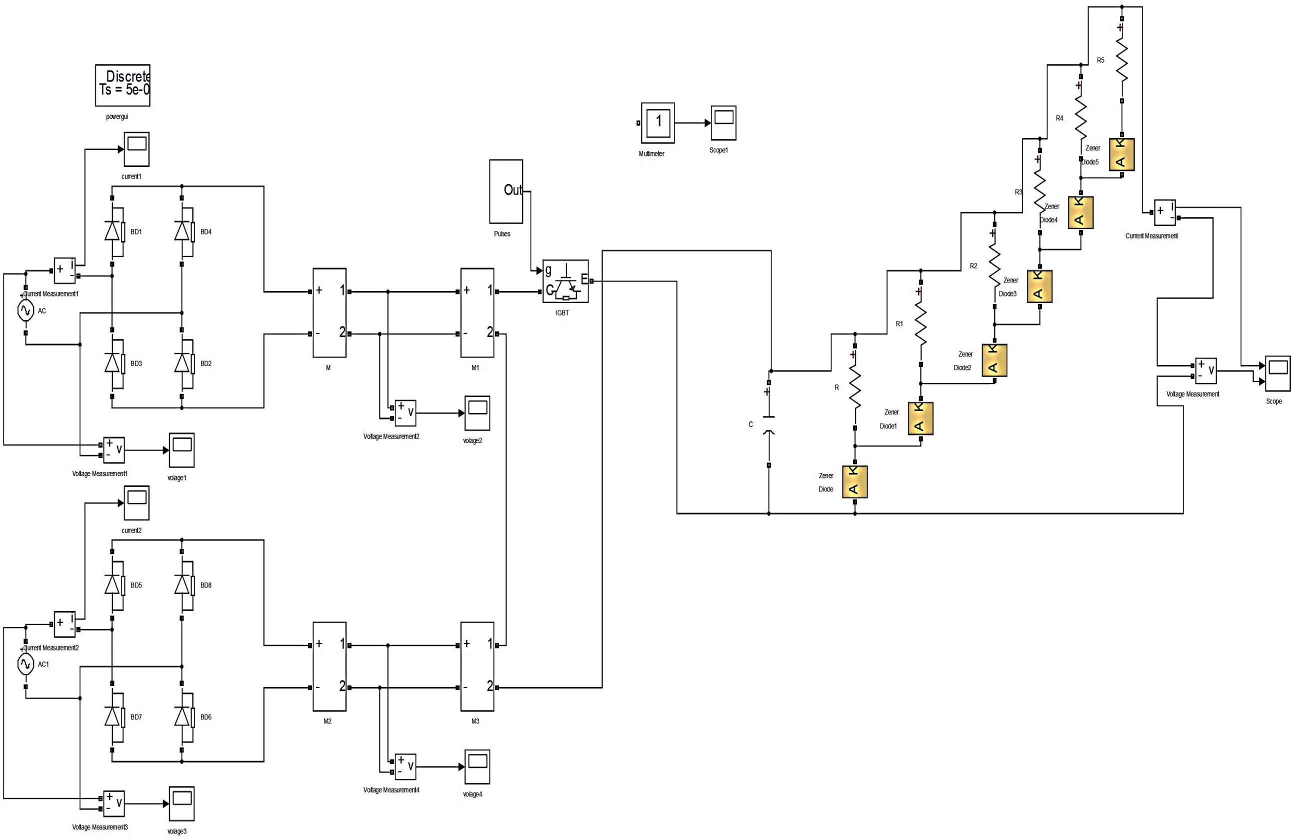


Figure 3. Proposed converter simulation

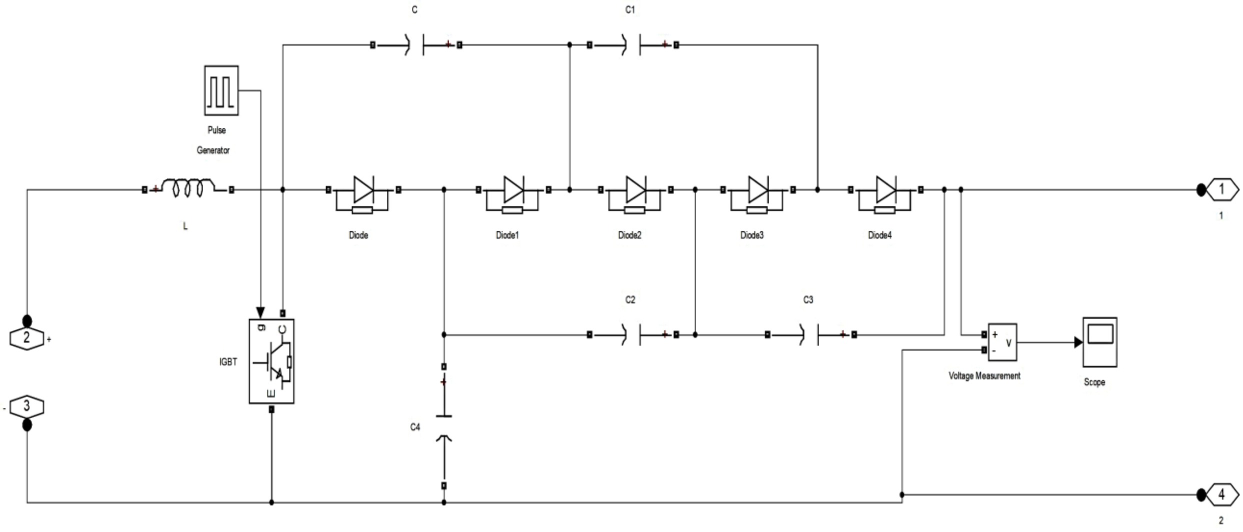


Figure 4. Connection inside the module [16]

The connection in the module is given in Figure 4. It contains an inductor L, IGBT switch and a capacitor C_4 together operated as a boost converter, followed by a two-stage voltage multiplier to boost the voltage to higher levels. A simple pulse generating controller is enough to generate intermittent energization technique without any need of a complex control strategy. The simulation specifications are shown in Table 1.

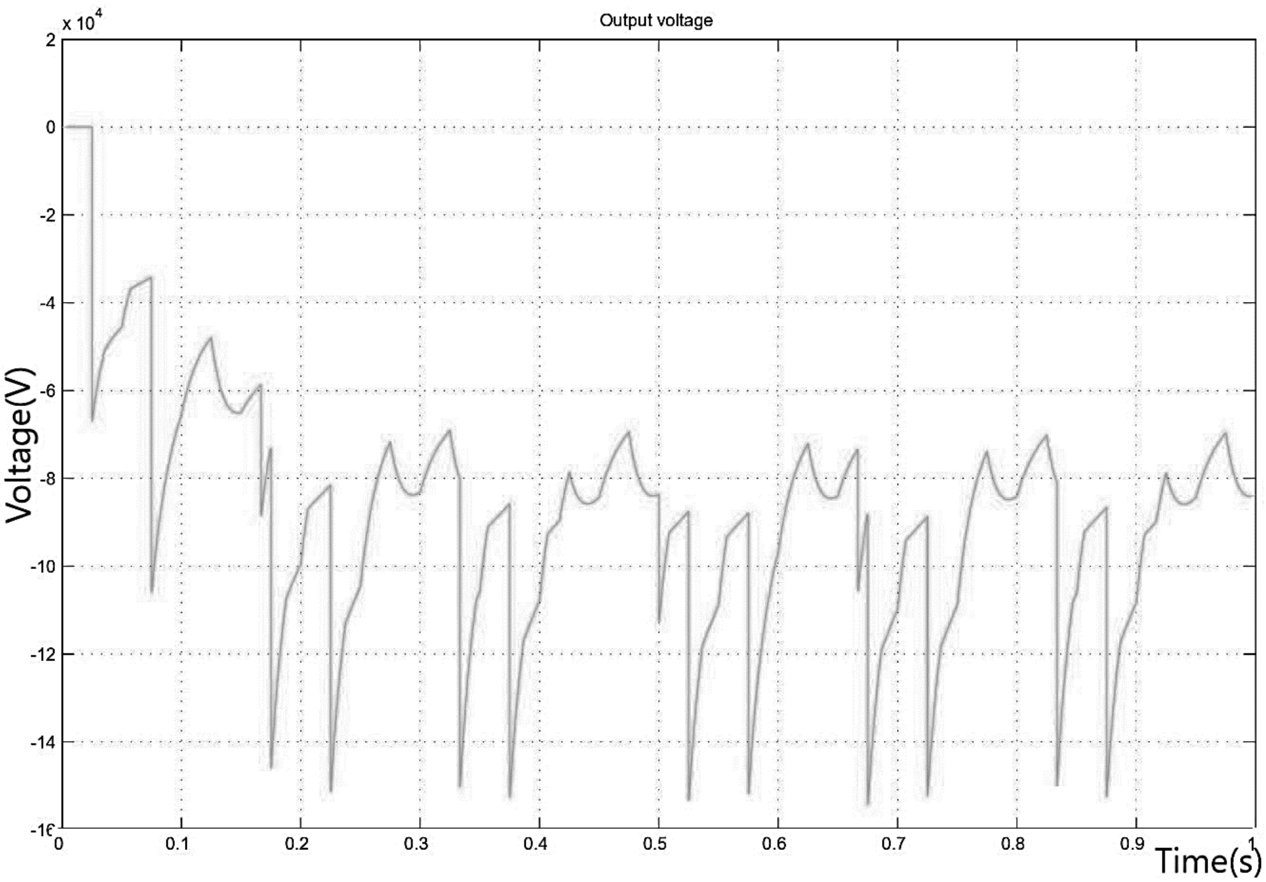


Figure 5. System output

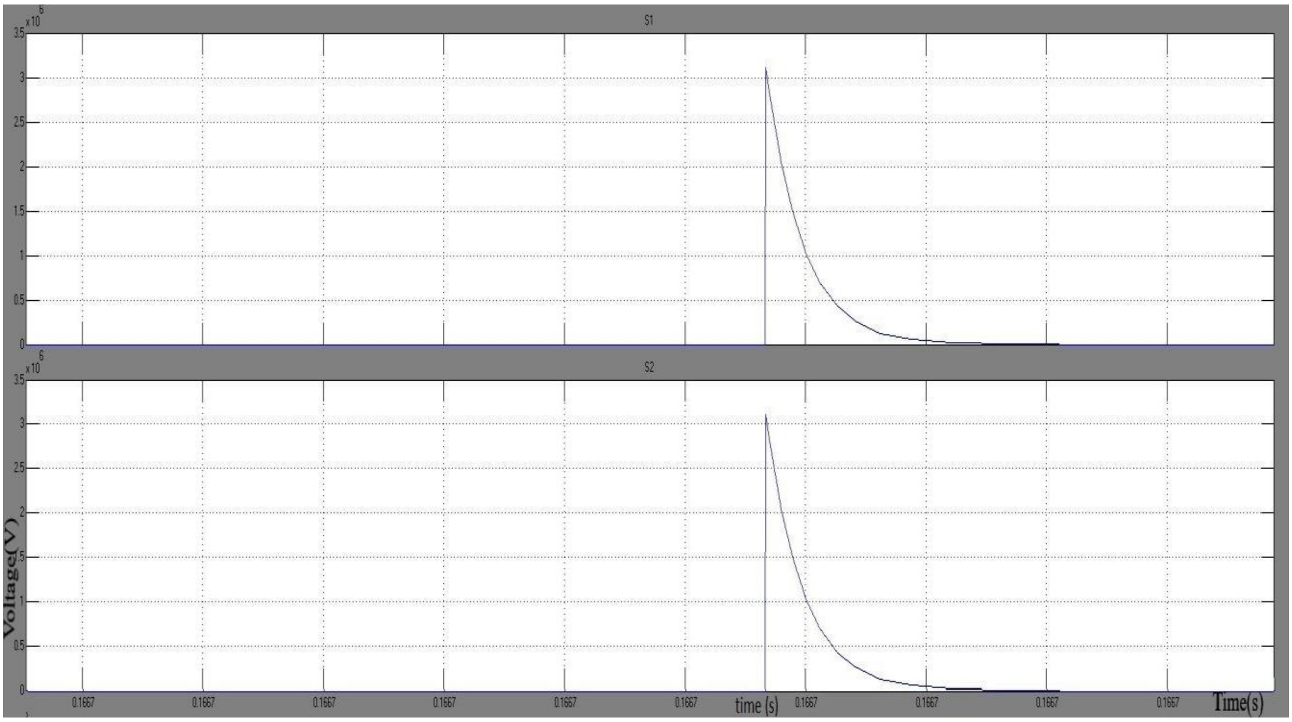
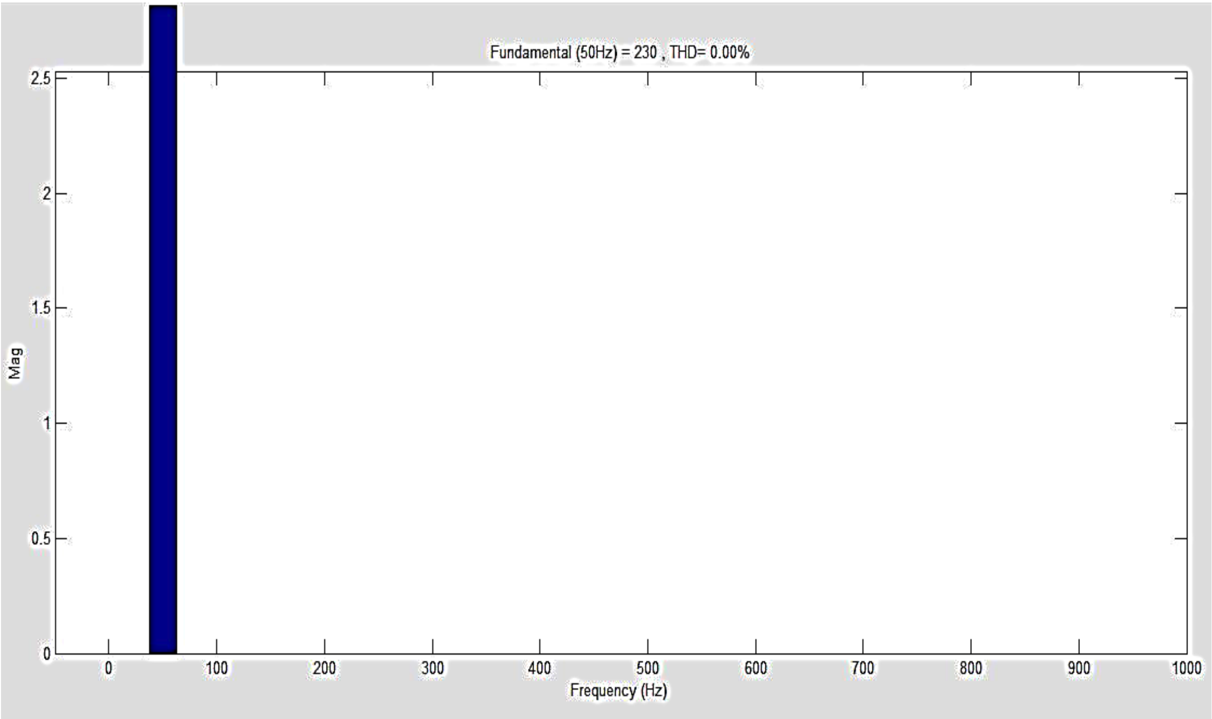
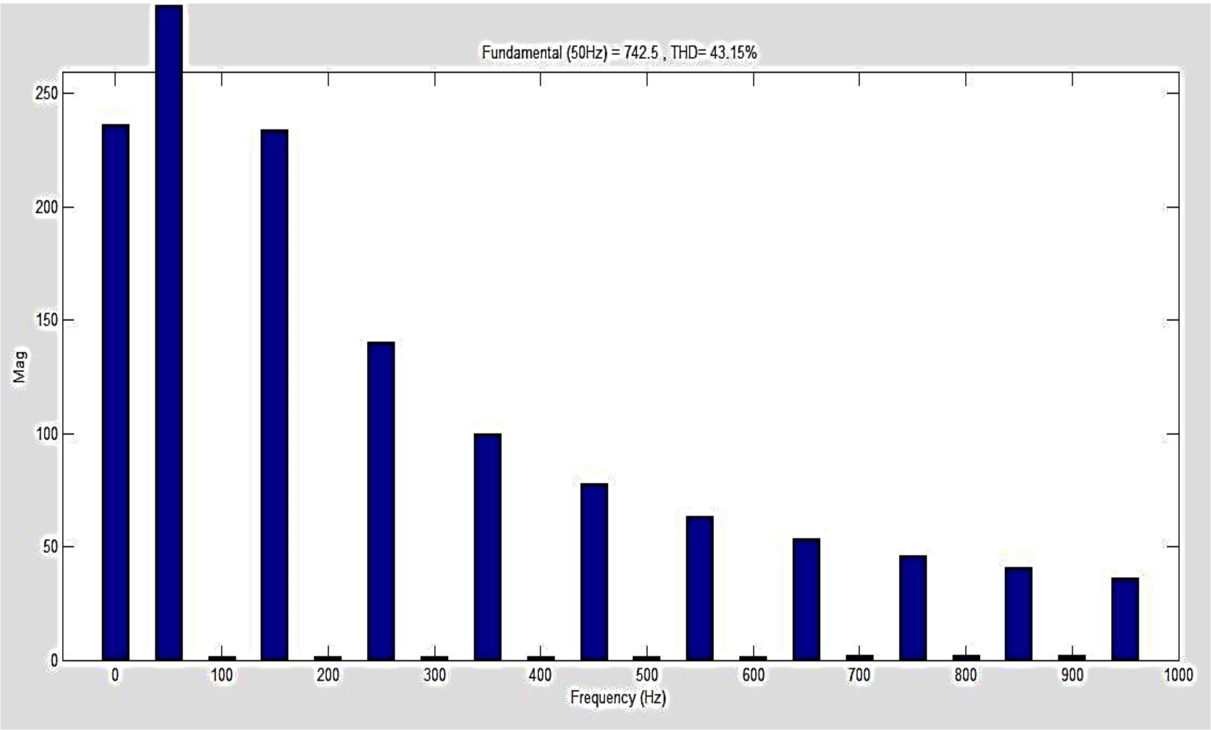


Figure 6. Voltage Stress across switches S_1 and S_2



(a)



(b)

Figure 7. (a) voltage THD, (b) current THD

Table 1. simulation specifications [16]

S. No.	Component	Value
1	Input Voltage	230 V, 50 Hz
2	Output Voltage	150 KV
3	Inductors	3m H
4	Capacitors	0.8 µF
5	Resistor	10 kΩ
6	ESP capacitor	20 µF

Figure 5 shows the output of the proposed system, from the figure it is clear that the system is capable of generating 150 kV as intermittent pulses. The time between the successive pulses can be varied by adjusting the switching time of S_1 and S_2. The only criteria to be considered on this variation is the timing provided between the pulses should ensure that the voltage across the ESP falls below the base voltage.

Figure 6 shows the voltage stresses developed across the S_1 and S_2. It has a maximum peak voltage of 3 kV developed during the high frequency operation.

Figures 7a and 7b show the voltage and current THD generated by the proposed system over the supply. The voltage THD generated over the supply is found to be 0% and the current THD found to be 43.15%, which is lesser than the existing methodologies. On comparing the parameters of the proposed system with the existing system, the comparative study is found as follows:

The existing system having transformer/rectifier set based power supply for the ESP is simulated with same parameters and analyzed as follows.

Figure 8 shows the Transformer/Rectifier based power supply with the same parameters. Its output voltage and THD analysis are shown in Figures 9 and 10, respectively.

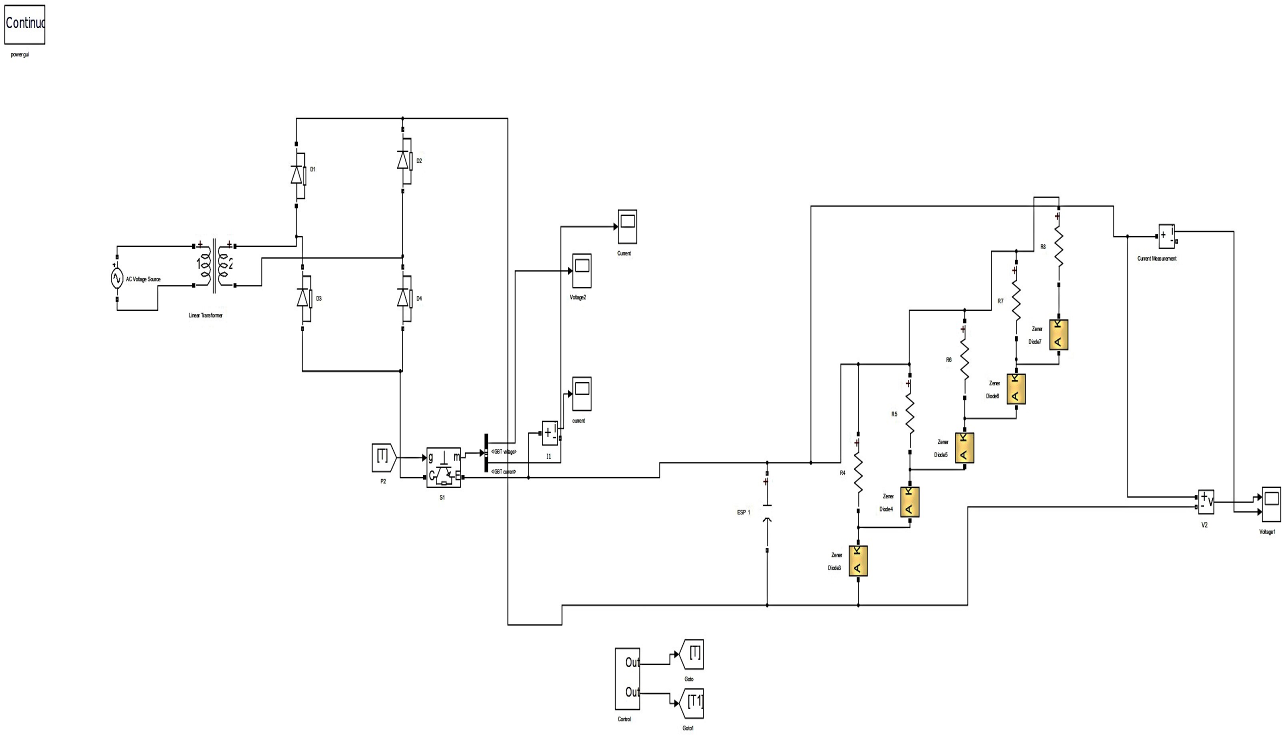


Figure 8. Simulation of *T*/*R* sets based power supply

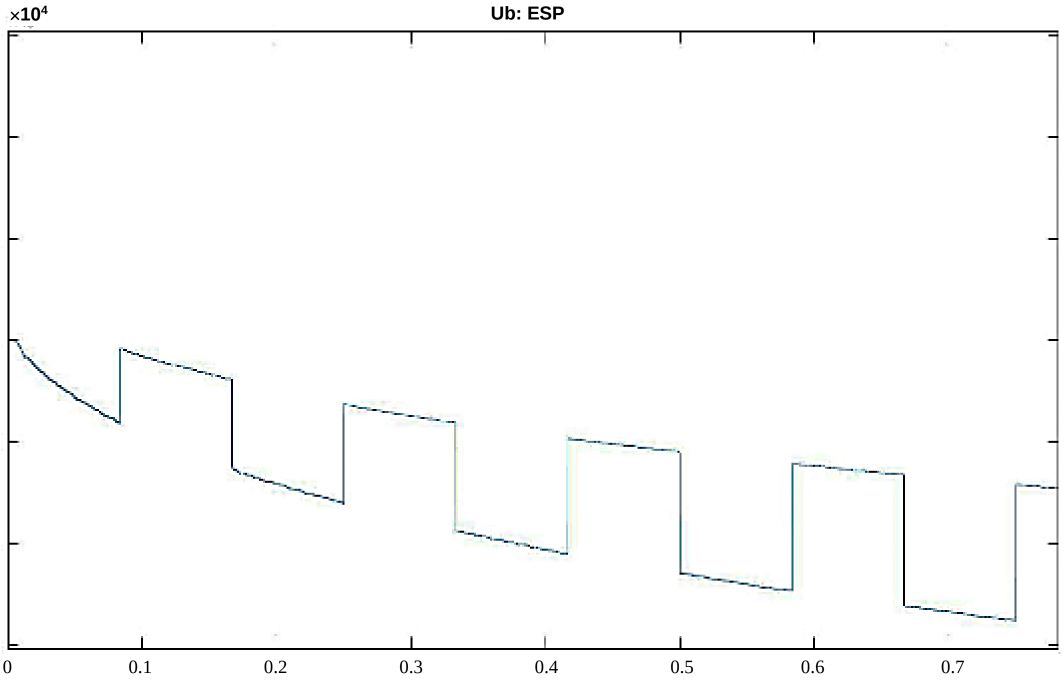


Figure 9. Output of *T*/*R* sets based power supply

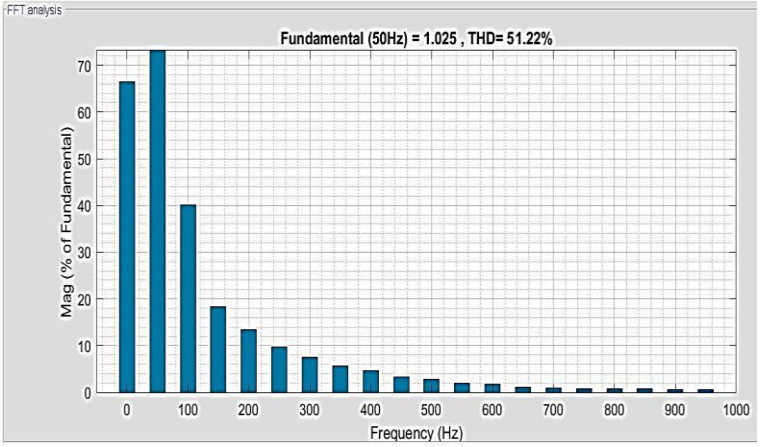


Figure 10. THD of *T*/*R* set based power supply

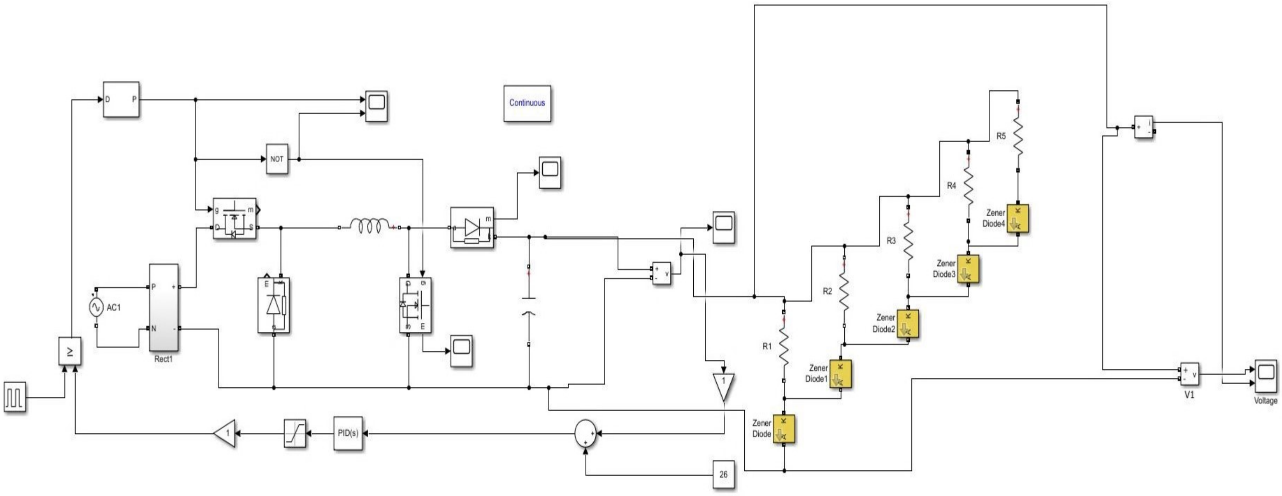


Figure 11. SMPS based power supply

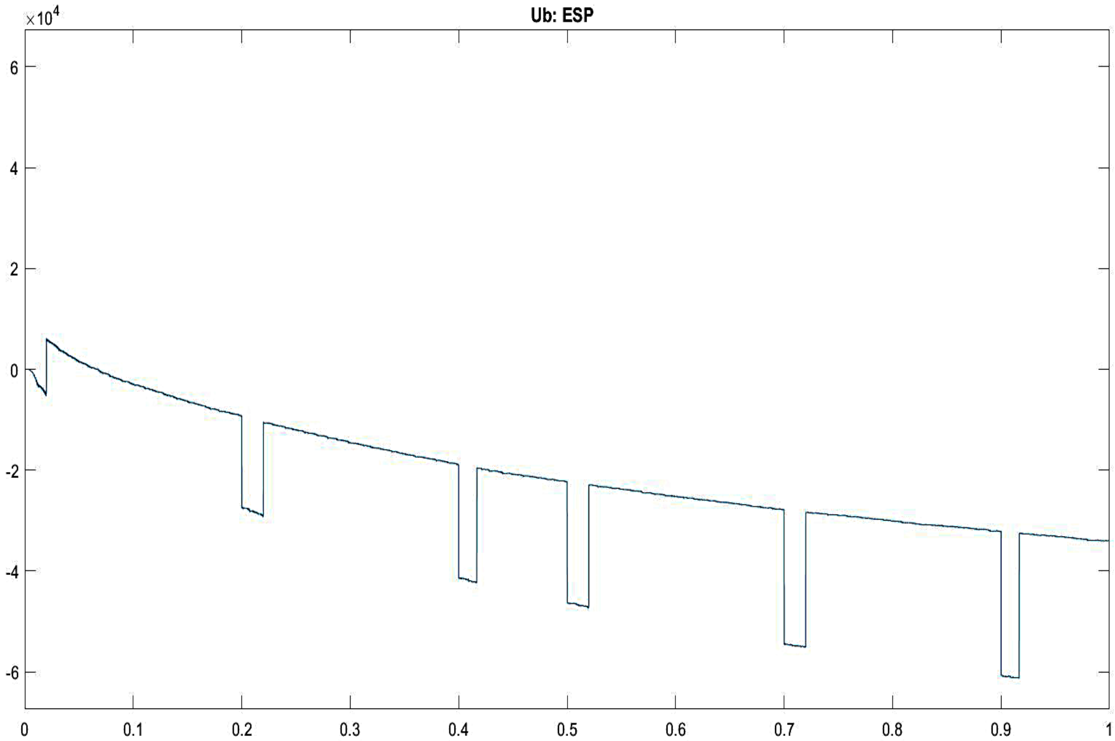


Figure 12. The output of SMPS based power supply

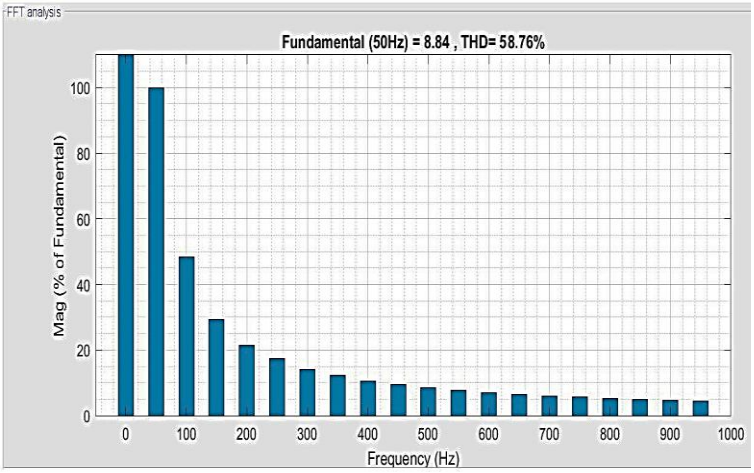


Figure 13. THD of SMPS based power supply

The main disadvantage of *T*/*R* set is, it cannot provide any flexible intermittent pulse energization. Also, the cost involved in the erection of the transformer will be high.

The SMPS based power supply is also simulated as shown in Figure 11. The output voltage and THD were analyzed as shown in Figures 12 and 13, respectively.

The SMPS is having the advantage of better energy utilization and more flexibility in the generation of intermittent pulses. But it has the disadvantage of producing more harmonics. The proposed system as in Figure 3 is capable of operating flexibility, low THD on compared to the existing systems, and cost will be low due to the absence of transformer. Based on the analysis of the different power supplies, Table 2 is formulated.

Table 2. Comparison between existing system and proposed system

	Existing systems		Proposed System
Parameters	T/R Set	SMPS	MMC
Output Voltage	150 kV	150 kV	150 kV
ESP capacitance	20 μF	20 μF	20 μF
Maximum voltage stress	140 kV	8.6 kV	3 kV
THD	51.22%	58.76%	43.15%

From the Table 2 it is clear that, the proposed system is far better than the existing systems. For the experimental verification, a single module is constructed and output is analyzed as shown in Figure 14. The module has rectifier units for different power supplies, Voltage multiplier ladder and a signal generator unit as shown in Figure 14.

4. CONCLUSIONS

The intermittent pulsed power output is produced with a magnitude of 150 kV without having any transformer, with the help of boost converter and voltage multiplier is achieved, this reduces the cost of the power supply unit as well as it reduces the power consumption of the ESP unit which can be easily purchased and maintained by all boilers; thus, this voltage multiplier-based cascade converter is more efficient in terms of cost and less power consumption then the conventional converters. Since only two active switches are involved in this power supply, the cost involved in the complex control system for switching can also be reduced. Due to the usage of the intermittent energization technique the back corona problem is also eliminated. The simulation and the experimental analysis are done to verify the performance of the proposed system. And it is found that, the voltage stress and THD gets reduced as shown in Table 2. The modular converter topology reduced the switching stresses and the less active switched usage will reduce the THD. And it will be cost-effective due to the absence of transformer.

Figure 15 shows the output of a module, this will become intermittent while passing through the switches the G switch connected in series to the modules.

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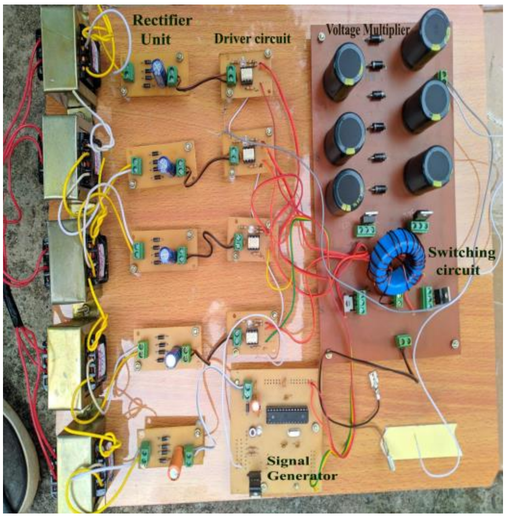

Figure 14. Experimental setup of one module [16]

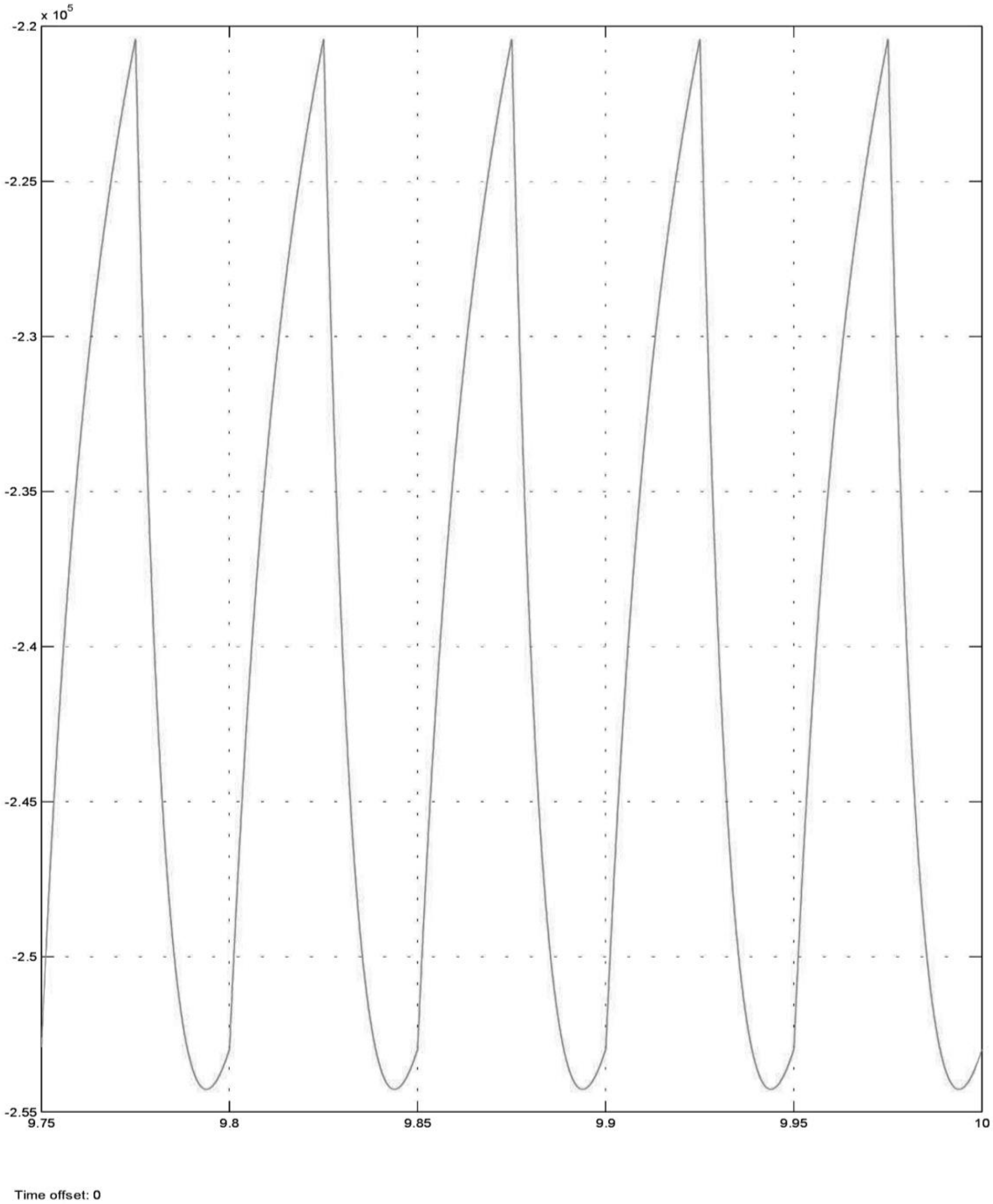

Figure 15. Output waveform

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BIOGRAPHIES

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Sekar Srinivasan was born Chennai, India, in 1955. He completed his B.E and M.E degrees in IIT, India in 1977 and 1979, respectively. He completed his Ph.D. in the area of ESP and he has a deep knowledge in high voltage research. He joined and worked as Corporate Research in BHEL, India. He is a Professor in Hindustan Institute of Technology and Science, Chennai under Hindustan University, India.