Research Article

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# An improved intermittent power supply technique for electrostatic precipitators

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**Abstract:** A cost-effective power supply design proposed for electrostatic precipitators (ESP) is presented in this work. The cost minimization is done in terms of eliminating the power transformer and reducing power consumed by the ESP unit. Usually, transformers are used to boost the voltage level in conventional systems on its input side, which is replaced by a combination of a high-frequency converter along with a voltage multiplier in a modular arrangement. By interconnecting these modules, the suitable voltage is built-up easily. An intermittent pulse energized supply is developed by the proposed system to reduce back corona and to save energy consumption. The modular arrangement also increases the lifetime of converter switches, by reducing the switching stresses developed across them during its high-frequency operation and by reducing the Total Harmonic Distortion (THD). The complete system is designed and analyzed using MATLAB SIMULINK. The obtained results are better than the existing methods used for generating intermittent energization, the THD is reduced to 35.78% and the voltage stresses also reduced to 1800 V. And a module is experimented and found that it is capable of producing 3 kV.

**Keywords:** back corona; electrostatic precipitator; energy saving; high voltage power supply; THD.

## Introduction

As population increases, the demand for products and electrical supply increases. In the process of manufacturing needed products and for generating more electricity, industries let dust particles into the air. These dust particles create health hazards and global warming. So, there is a necessity to control these dust particles Tachibana (1989). There are many devices available for controlling these dust particles like bag filters, cyclone filters etc., and among these devices Electrostatic Precipitator (ESP) is an attractive device used for controlling air pollution, in an effective manner Hall (1990). In an electrostatic precipitator, there are two electrodes, wire and plate type; mostly the wire type is used as discharge electrode and plate type is used as collection electrode. The dust particles coming out of industries are allowed to flow through these electrodes placed inside a closed chamber Klippel (2000). A very high DC voltage, preferably, a negative voltage is applied to the discharge electrode to generate corona. The dust particles get charged either due to field or diffusion charging mechanism and the charged dust particles are captured on collection electrode having positive polarity and these dust particles are collected in hoppers, by rapping the collection electrodes in a periodical manner Grass, Hartmann, and Klockner (2004). It is to be observed that small scale industries are not giving importance to effective pollution/emission control, since these emission controlling devices are not in a cost level which they can afford and also because of high energy consumption Iváncsy, Kiss, and Berta (2009). Even though the size of the ESP unit they need is small for controlling the dust particles from their outlet, a power supply unit with a high voltage in the range of 30–100 kV is needed separately, which a difficult thing for small scale industries on considering the cost to be invested for this power supply Parker, Arne Thomas Haaland, and Frode (2009). One problem associated with the ESPs is back corona, which is a significant drawback. Back corona occurs during application of continuous energization on high resistive dust particles, when these excited dust particles get deposited and accumulated on the collection electrode Soeiro, Biela, and Linnér (2010). The dust particles create a layer of materials on the collection electrodes which leads to the development of a back corona Mermigkas et al. (2012). This back corona problem can be avoided with intermittent energization. Intermittent energization also limit the energy

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consumed. To increase the voltage level during this intermittent energization production, high frequency operations are employed on the power supply converters Li et al. (2013). But, the high frequency operations create voltage and current stresses across the switches, which leads to aging of switches earlier than their normal lifetime. Another problem with the high frequency operations is, its impact on power supply in terms of harmonics Vukosavić, Perić, and Sušić (2015). This paper aims to reduce the expenditure/cost for the power supply unit used for ESPs by eliminating the high voltage power transformer, to create an intermittent pulsed supply in order to avoid the development of back corona with limited energy utilization with modular converters and to reduce switching stress for increasing the lifecycle of switches employed in the power supply side. And to reduce the THD.

ESPs were commercially introduced in the year 1884 by Walker & Co, and the power supply has undergone plenty of modifications, from Ruhmkorff's transformer to Switched Mode Power Supply (SMPS) (Mayakrishnan, Srinivasan, and Loganathan 2017; Pakala, Vijayan et. al 2017). The most successful power supply in the early periods was using Transformer/Rectifier (T/R) sets, for producing high voltage supply and in the later periods by the implementation of the SMPS, the collection efficiency is increased along with that, the power converters size is reduced by high power low-frequency transformers with high power high-frequency transformers Rajkumar and Sekar (2018). However, the cost of a high power high-frequency transformer is still high and switching stresses across each switch in SMPSs is also high, which lowers the overall efficiency of the converter Manoharan, Rameshkumar, and Ravichandran (2018). For example, the role of a high power high-frequency transformer is to boost up the voltage level from 230/440 V to 30/100 kV. This boosting voltage level can be achieved by using the cascaded technique of multi-module converters. In this work, the modular converters are developed by a Cockcroft-Walton voltage multiplier for boosting the voltage level instead of a high-frequency transformer, and in combination with a high-frequency inverter. A module having a high-frequency converter with a three-level voltage multiplier is designed for generating an output of 3 kV. By connecting three of these modules in a cascade, a block is developed, it is possible to obtain a voltage of around 10 kV a block. By connecting three blocks in the series, it is easy to generate a voltage of around 30 kV and by increasing the number of blocks any desired voltage level can be obtained. The current THD in the existing converter ranges between 43.2 and 88%, which can be reduced with the proposed converter due to the usage of voltage multipliers. In order to identify the number of harmonics generated, an FFT (Fast Fourier Transform) analysis is conducted on the supply side of each module using MATLAB. The significance of the work is the reduction of the back corona problem, by developing a new power converter for generating intermittent pulse energization. The proposed modular converter topology can operate in different level of high voltage in a flexible manner and low cost, with reduced THD and, reduced switching stresses. This facility will attract industries to use ESPs, which will ultimately reduce particulate pollution and their after effects.

## ESP power supply- a status analysis

Generation of the corona is possible with the help of high voltage DC supply applied to the discharge electrodes in non-uniform manner. For obtaining this high voltage DC, a separate power supply is needed with a continuous energization or pulsed energization or intermittent energization Madichetty, Mishra et al. (2019). Continuous energization creates a problem in the ESP named back corona when collecting high resistive dust particles. For collecting these high resistive dust particles, the dust particles are needed to be highly charged at discharge electrodes using a very high voltage, and the highly charged dust particles may retain their charges even after reaching the collector electrode and they may create a back arc towards the discharge electrode, which is the back corona phenomenon Serebryakov et al. (2019). Another problem in ESP is production of ozone during positive corona with continuous energization, which occurs on the rise in the voltage level, on the flow velocity rise and on changes of air flow directions. Ozone creates an increase in wire surface temperature and emits dangerous, harmful gas, which need to be avoided Kumar et al. (2019). The rise in temperature of flue (dust particle) gas will affect the collection efficiency of ESP and reduces the radius of corona development over the discharge electrode. This problem can be eliminated with negative corona on discharge electrode Wei et al. (2020). To avoid the above drawbacks, pulse energization are evolved, which will avoid back corona, ozone generation and the effects due to temperature changes. The negative corona with pulsed energization gives better collection efficiency than the continuous energization. The intermittent pulse energization has a better collection efficiency than the pulsed energization. Intermittent pulse energization can improve the collection efficiency for collecting high resistivity dust particles with low power consumption and also minimizes generation of back corona

Jiahui Li et al. (2020). The average current during intermittent energization is given by

$$I_{\text{iavg}} = K\frac{I_c}{D} \tag{1}$$

where $D$ is the degree of intermittent/numbness of the cycle's suppressed, $I_c$ is the continuous energization current, and $K$ is a constant factor within a range of 1–1.5. From this it is clear that, the amount of energy consumed by intermittent energization will be lower than continuous energization Zhuikov et al. (2021). The transient voltage produced across the layer collected on the electrode due to intermittent energization is given by

$$V_{ie} = RI_0\left(1 - e^{-t/t_0}\right) \tag{2}$$

where $R$ is the resistivity, t is the cycle duration, $t_0$ is the time constant given by

$$t_0 = 8.85\epsilon_s\rho_d * 10^{-14} \tag{3}$$

Where $\epsilon_s$ is the specific dielectric constant, $\rho_d$ is the specific resistivity. The time taken by the dust particles to generate back corona is given by

$$t_1 = t_0 ln\left(\frac{1}{\left\{\frac{1-E_d}{\rho_d j_0}\right\}}\right) \tag{4}$$

[1] where $E_d$ is dust layers breakdown strength, $j_0$ is the base value of current density. The intermittent pulses have to be generated in such a way that the corona need to be reduced before the time reaches $t_1$ and re-energized again for the same duration. A three phase intermittent energization with phase sequence adaptation is far better than the single phase energization, and a negative intermittent pulse energization is better than a positive intermittent pulse energization García-Díaz et al. (2021). For increasing the voltage level on power supply side step-up transformers with rectifier set were employed. The rectifiers are replaced with a Cockcroft-Walton voltage multiplier on secondary side of transformer to reduce transformer's size Yang, Sisi et al. (2021). Helical winding transformers were used to avoid the Electro Magnetic Interference (EMI) between two turns, and to reduce leakage reactance and skin effect, so that the efficiency of the power supply can be improved. But the cost of these transformers increases the overall cost of ESP system, which can be reduced with ferrite transformer for power supply of ESP Cao et al. (2021). The large size, power transformers were replaced by smaller ones with Switched Mode Power Supplies (SMPS), which improves the collection efficiency and reduced the amount of power consumed Makov et al. (2021). But, on operating SMPS with higher frequency a high voltage stress used to develop across each switch. This voltage stress creates loss and reduces the operating efficiency of ESP supply. The voltage stress problem can be resolved using a resonant converter in soft switching operation Yuan et al. (2021). The resonant converter increases the efficiency by eliminating back corona. On using a switched parallel resonant converter topology, the voltage stress across the switches can be reduced up to 56 kV/μs. By sectioning the power supply the collection efficiency can be increased, but each section draws the more amount of power from the supply. To collect more dust particles than the earlier converters a two stage ESP can be used which avoids the re-entrainment of particles. Re-entrainment is the re-entry of collected dust particles into the inner electrode spacing. Re-entrained dust particles are usually easy to collect, if they are charged appropriately with the help of two stage ESP but, two-stage ESP's are costly. With Modular Multilevel Converter (MMC) topology, it is easy to develop a very high voltage with low voltage stress, but failure of modules leads to improper operation of the power supply and so a complex controller is needed. The energy saving is another important criteria to look after in the case of using ESP, since small scale industries cannot afford large power consumption for ESP and the energy saving about 83% is possible with fuzzy logic controllers with IGBT inverter but the controller employed with fuzzy logic is costlier. The energy consumption can be obtained from Stroke's law, which gave the friction resistance on dust particles

$$F_D = 6\pi\vartheta r\omega \tag{5}$$

where $\vartheta$ is the medium viscosity, $r$ is the radius of dust particles and $\omega$ is the flow rate and the charge consumed by the particles of 10–25 μm is given by

$$Q = 6\pi\mu r\omega S \tag{6}$$

But the reduction in energy consumed is not supposed to affect the collection efficiency of the ESP section, the ESP collection efficiency given by White's equation is

$$\eta = 1 - e^{-K1P_c/A} \tag{7}$$

where $P_c$ is the corona power, $K_1$ is constant, and $A$ is the amount of flue gas. To save energy pulse energizing can be used with proper monitoring. Using computer based pulsed energization, energy saving is possible along with back corona elimination. On saving the power, the power quality is also needed to be monitored with a suitable control technique. The high frequency operations of the ESP power supply create parasitic capacitance in transformer windings, and this can be controlled with the help of fuzzy logic controllers. For the fuzzy controllers, algorithms are generated using numerical analysis to calculate the electric field, current density, and efficiency. Energy saving can be achieved by the Genetic Algorithm (GA) to monitor the load side voltage. Ripples are another phenomenon which is present in the output of ESP power supply, which can create irregular energization of the dust particles. Multi pulse with active filter can avoid these ripples and improve the power quality. In the conventional Transformer/Rectifier set based supply, the current Total Harmonic Distortion (THD) is 51.27%, on using pulse energization the THD is found to be 58.39%, and on using a 12- pulsed supply the THD is found to be 42.54%.

## Circuit description

The proposed converter consists of three 415 V, 50 Hz supply each connected to an isolation transformer followed by a rectifier, and then it is fed to the cascaded modules. In each module, a high-frequency inverter is present along with a voltage multiplier to boost its voltage level to higher values. In total, there will be nine modules as shown in Figure 1 involving the boosting operations. For example, the switches $S_1$, $S_2$, and $S_3$ are operated instantaneously to combine the voltage together to obtain a high voltage for 10% of a cycle, the remaining 90% of the cycle the voltage across the ESP is allowed to drop up to its base value (corona starting value) and thereby the corona generation at the electrode can be controlled for obtaining an intermittent pulse energization. On starting the next cycle, the switches $S_1$, $S_2$, and $S_3$ are again turned ON, and this process is repeated in each cycle. The purpose of

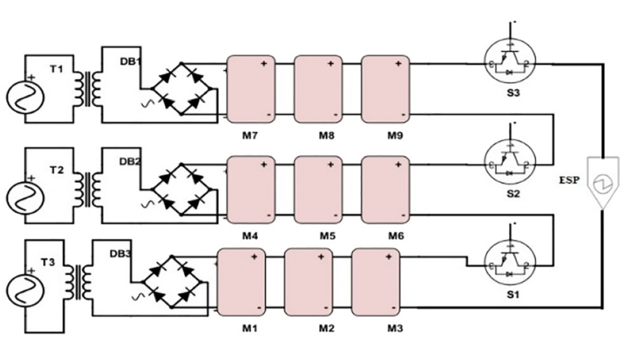


**Figure 1:** Block diagram of proposed system.

converting the AC input into DC using a bridge rectifier and then to the AC is for the operation of the voltage multiplier by converting the frequency to the suitable value. Figure 2 consists of nine modules, which have a block of three modules connected in series to obtain 10 kV, and three blocks are cascaded to generate 30 kV. Each block is supplied with a 415 V supply, the supply is connected to an isolation transformer of 415 V/415 V followed by a bridge rectifier, and then it is fed to the first module of the block.

In each module, there are four switches, an inductor, and a voltage multiplier as shown in Figure 3a, where the inductor smoothens the ripples produced during the switching operation. The output of one module is given as input to the next module, to boost its voltage level. For example, the switches *S*1, *S*2, *S*3 are operated instantaneously with a switching time of 10% of the cycle value. The remaining time the ESP is allowed to get back to its nominal value i.e. the voltage below the base value with discharge action of the load.

Figure 3a shows the module diagram having four switches, $T_1$, $T_2$, $T_3$, $T_4$ with three level voltage multiplier. $T_{1,}$ $T_2$ and $T_{3,}$ $T_4$ are operated alternatively to obtain high voltage output, and the switching waveform is shown in Figure 3b. The switches, $T_{1,}$ $T_3$ operate in higher switching frequency while other two switches are in OFF condition.

There are four modes of operation.

### Mode 1

In mode 1 the switches, $T_1$ and $T_4$ are in ON condition, the inductor connected in series to the input charges and the current flows in a closed loop. The switches $T_2$ and $T_3$ are in OFF condition. All the diodes in voltage multiplier are in reverse biased condition, the capacitors $C_4$, $C_5$, and $C_6$ discharge and give their output to the next module which is connected in cascade, and the capacitors $C_1$, $C_2$ and $C_3$ are floating as shown below. The switches $S_1$, $S_2$ and $S_3$ are in ON condition, they add the voltages by series connection and the combined voltage is given to ESP. The voltage across the ESP raises to 33 KV.

### Mode 2 (i)

In mode 2(i), the switches, $T_1$ and $T_2$ were turned ON, and the switches $T_3$ and $T_4$ are in OFF condition. The boost inductor discharges, which produces a positive half cycle into the voltage multiplier, it makes all even order diodes to be forward biased, they start conducting, the capacitors $C_4$,

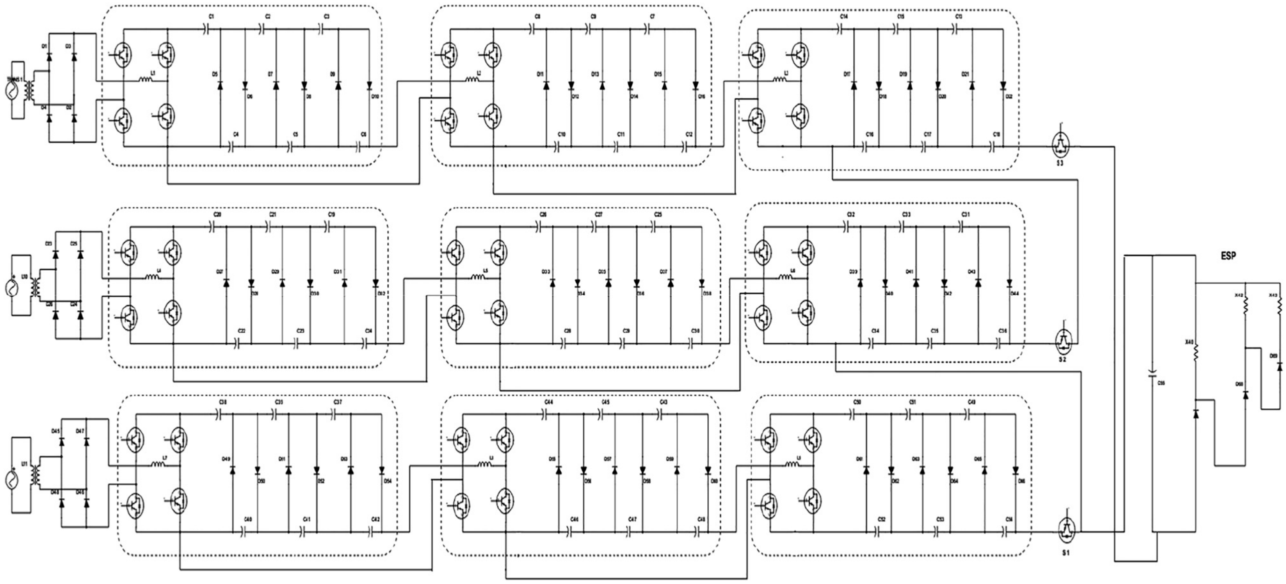

**Figure 2:** Detailed circuit diagram of proposed System.

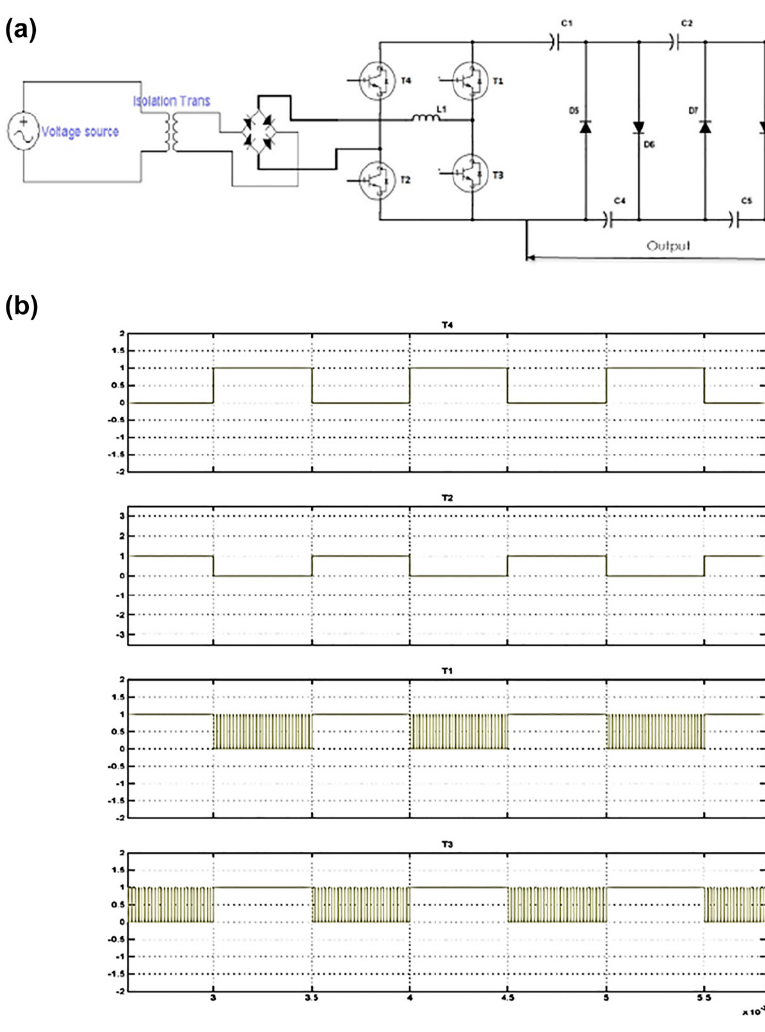


**Figure 3:** Operation of proposed system. (a) Module circuit diagram (b) switching waveform of $T_1$, $T_2$, $T_3$, $T_4$.

$C_5$, and $C_6$ are charging through these diodes, and the capacitors $C_1$, $C_2$ and $C_3$ are discharging their charges to next capacitors ($C_4$, $C_5$, and $C_6$).

## Mode 2(ii)

Here the capacitor $C_3$ is discharged, so the flow will bypass it and the current will flow through diode $D_8$.

## Mode 2(iii)

Here Capacitor $C_2$ and $C_3$ get bypassed together and current will flow through diode $D_6$

## Mode 3

It is similar to the Mode 1 operation, in this mode the switch $T_3$ and $T_2$ are turned ON and switch $T_1$ and $T_4$ will be in OFF condition. So, all the diodes in voltage multiplier are in reverse biased condition (Figures 4–11). The voltage stored in the lower arm ($C_4$, $C_5$, and $C_6$) of voltage multiplier in each module gets discharged and combined due to cascade

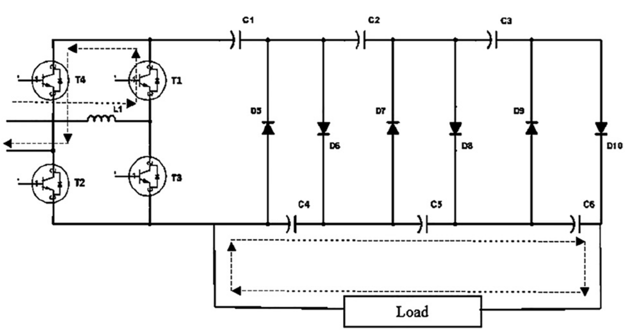


**Figure 4:** Mode 1.

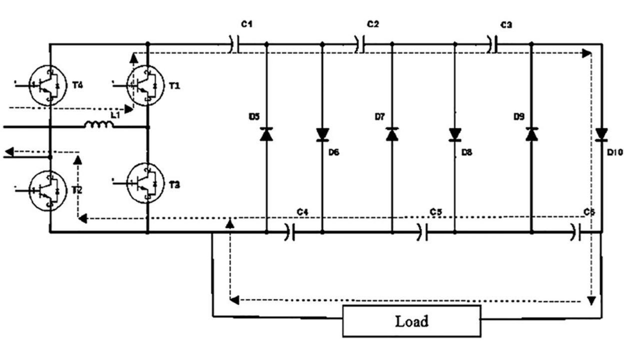


**Figure 5:** Mode 2(i).

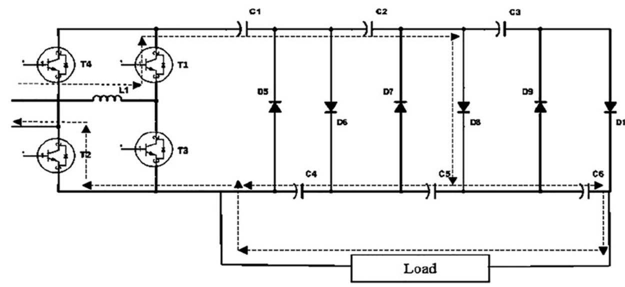


**Figure 6:** Mode 2(ii).

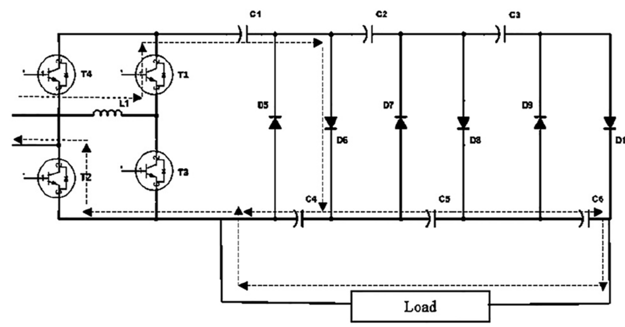


**Figure 7:** Mode 2(iii).

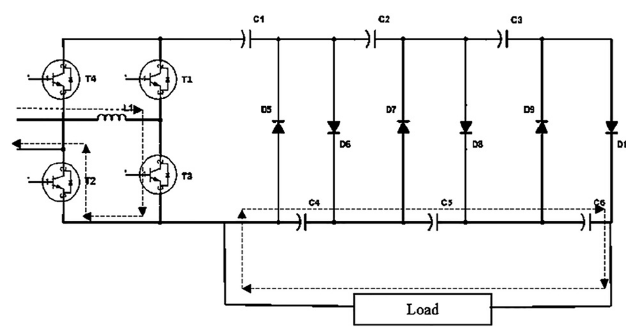


**Figure 8:** Mode 3.

and series connection applied to the ESP. The switches $S_1$, $S_2$ and $S_3$ are turned to developing voltage across the ESP above the corona onset value.

## Mode 4 (i)

It is similar to Mode 2 operation, the switches, $T_3$ and $T_4$ are in ON condition, the switches, $T_1$ and $T_2$ are in OFF condition, Inductor discharges in the negative side, creates a negative half cycle as input to the voltage multiplier with all the odd order diodes to be forward biased and they charge the capacitors $C_4$, $C_5$, and $C_6$ from the charges of input supply with capacitors $C_1$, $C_2$ and $C_3$. The switches $S_1$, $S_2$, and $S_3$ are in OFF condition, and voltage gets discharged by the ESP to the nominal level of voltage.

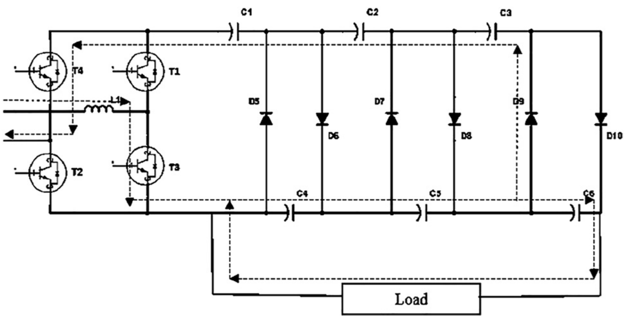


Figure 9: Mode 4(i).

## Mode 4(ii)

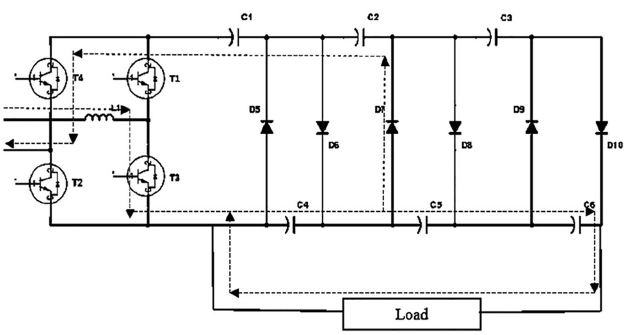


Figure 10: Mode 4(ii).

## Mode 4(iii)

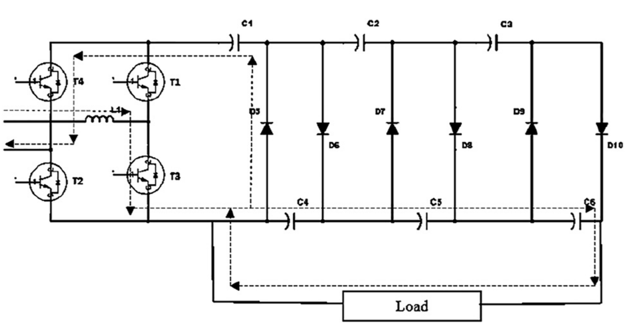


Figure 11: Mode 4(iii).

## Load design

An ideal ESP load is simulated using MATLAB as shown in Figure 12, with a huge capacitor in parallel with a Zener diode and a resistor and once-again with the same combination across the first resistor, in order to obtain a non-linear variation between voltage and current drawn by the load. The resistors gets added-up, when the voltage across the capacitor/resistor crosses the Zener breakdown voltage, thereby the resistors get added in a linearly variable manner as shown in Figure 13. From the Figure 13, it is clearly noticed that the ESP load used in the simulation matches the practical ESP V-I characteristics.

## Simulation and results

Simulation is prepared using MATLAB 2013a SIMULINK (Figure 14). There are nine modules in total which are grouped as three and each group is supplied by an individual AC source. The output produced by each group gets

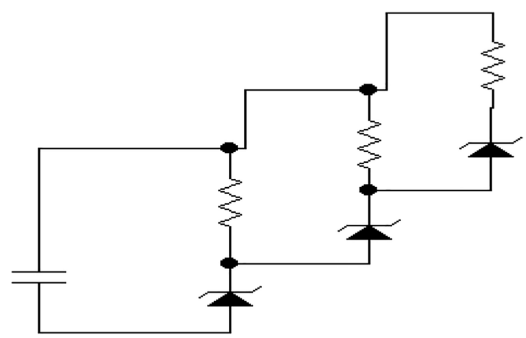

Figure 12: ESP load.

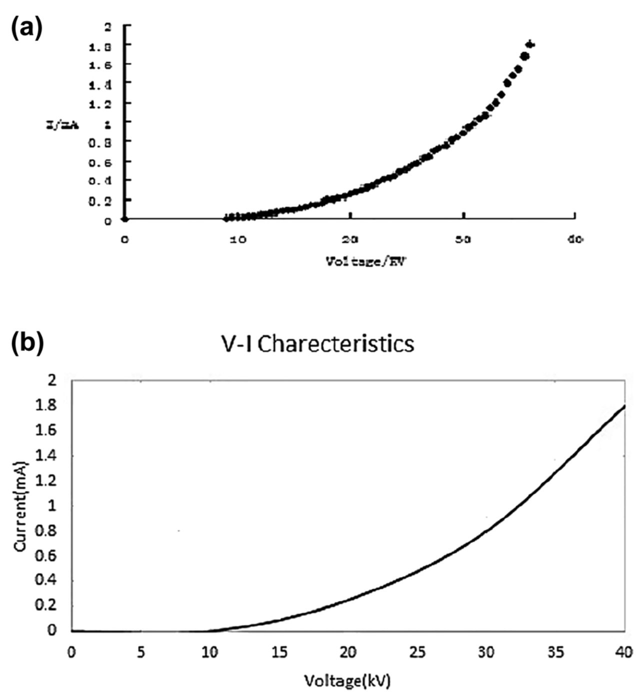


Figure 13: V-I characteristics of ESP load. (a) V-I characteristics of practical ESP, (b) V-I characteristics of simulated ESP.

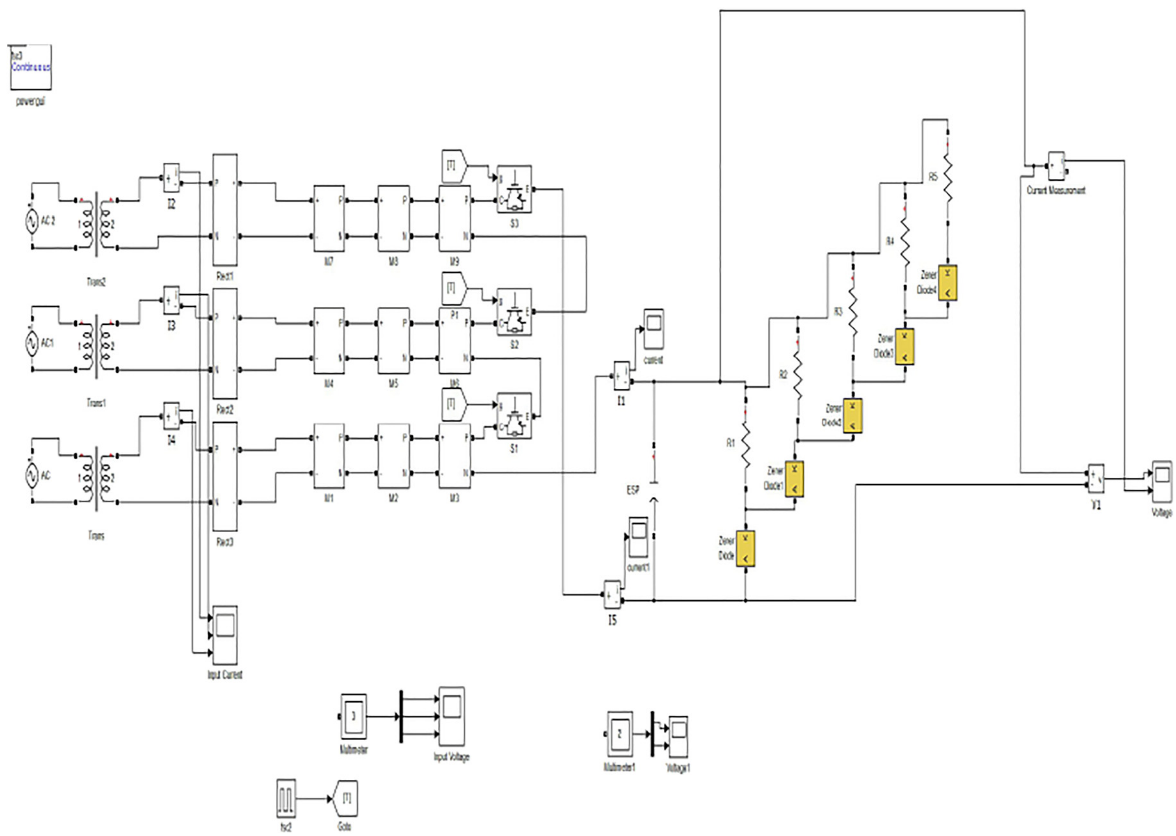


**Figure 14:** Simulation diagram.

added together using a switch which is operated instantaneously for 10 ms to obtain an output voltage of 33 KV with an interval of 140 ms as shown in Figure 15. The power supply specifications and design results were shown in Table 1.

From the output, it is clear that 33 kV is reached in 33 ms, and the time between two successive pulses is 140 ms. The output voltage is a set of intermittent pulses which can be tuned, it will reduce back corona problem. At starting of ESP, the rise time to reach maximum peak

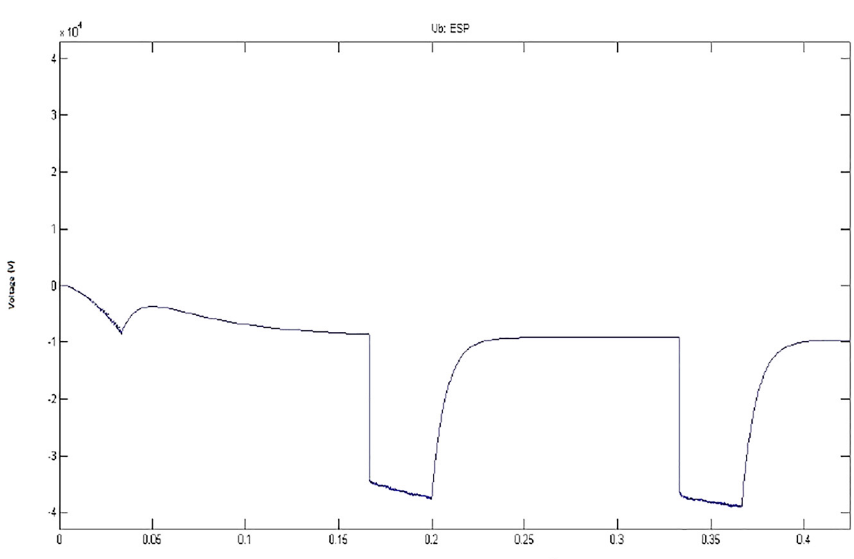


**Figure 15:** Intermittent output voltage to ESP from proposed converter.

Table 1: Power supply Specification and Design results.

| S. No. | Parameter | Value |
|---|---|---|
| 1 | Input voltage | 415 V |
| 2 | Capacitor | 470 μF |
| 3 | Inductor | 1.5 mH |
| 4 | Switching frequency | 1 kHz, 60 kHz |
| 5 | Output voltage | −33kV |
| 6 | ESP capacitance | 200 nF |

voltage is 170 ms, and later the voltage value is maintained at the peak level. The time taken by ESP to reach its base value is 45 ms at every interval. The zoomed view of output voltage is shown in Figure 16 and the peak output current produced during the voltage development is shown in Figure 17. With the same parameters, the Transformer/Rectifier based and SMPS-based power supply units were simulated and compared with the proposed converter and the results were shown in Table 2.

The Figure 18a, b, and c shows the switching stresses developed across the modules $M_1$, $M_2$ and $M_3$ operated with lower switching frequency and Figure 18d, e, and f shows

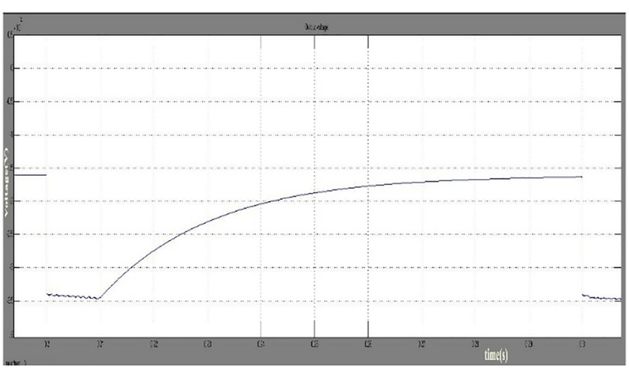

Figure 16: Output voltage.

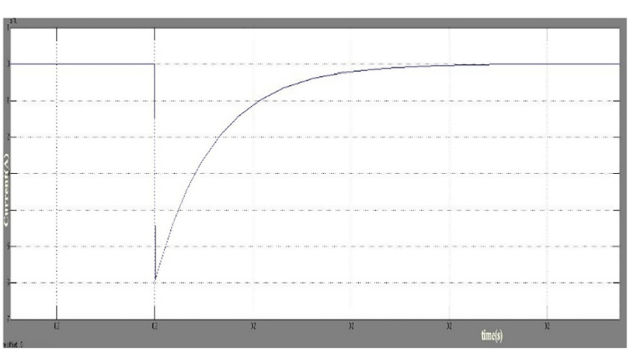

Figure 17: Peak output current.

Table 2: Comparison of simulation results.

| Parameters | T/R Set | SMPS | Proposed system |
|---|---|---|---|
| Output voltage | 33 kV | 33 kV | 33 kV |
| ESP capacitance | 200 nF | 200 nF | 200 nF |
| Rise time to reach the first peak voltage | 220 ms | 290 ms | 170 ms |
| Time taken to reach successive peak voltage | 38 ms | 36 ms | 33 ms |
| Time taken to reach base voltage | 62 ms | 55 ms | 45 ms |
| Maximum voltage stress | 140 kV | 8.6 kV | 1800V |
| THD | 51.27% | 58.39% | 35.78% |

stresses of the switches operated in higher switching frequency belonging to the same modules. From the figures it is clear that the stress developed across each switch is comparably lower than the stresses developed in existing converters which was around 15 kV across a switch. Moreover, the stress developed across in each switch of proposed converter is measured in terms of V having a maximum of 1800 V whereas the stresses developed in existing converters are measured in terms of kV. Similarly, Figure 19 shows the voltage stress developed across Switches $S_1$, $S_2$ and $S_3$, from that it is clear that the stress across all switches are uniform.

Since the switching is done in higher frequency, the THD introduced into the supply will be more. The THD level on the supply side of the proposed system was analyzed using Fast Fourier Transform analysis in MATLAB SIMULINK and found as shown in Figure 20. The current THD value is found to be 35.78% and the voltage THD is found to be 0%, which are lower than the values for existing converters, the value of current THD is 44.6% and voltage THD is 1.48%.

A single module is developed to analyse the simulation output. Figure 21 shows the Hardware prototype of one single module unit, here the Arduino (1) is used to generate the PWM pulses for the MOSFET switches (2). A bridge rectifier arrangement (3) is provides the power supply for the converter. A three level Cockroft-Walton Voltage Multiplier module is provided at (4). A digital voltmeter is used to measure the high voltage developed by the converter (5).

A voltage of 3.3 kV is obtained from the hardware prototype and it is measured using a digital voltmeter as shown in Figure 22. Which proves that, the proposed converter topology is capable of producing the desired voltage levels.

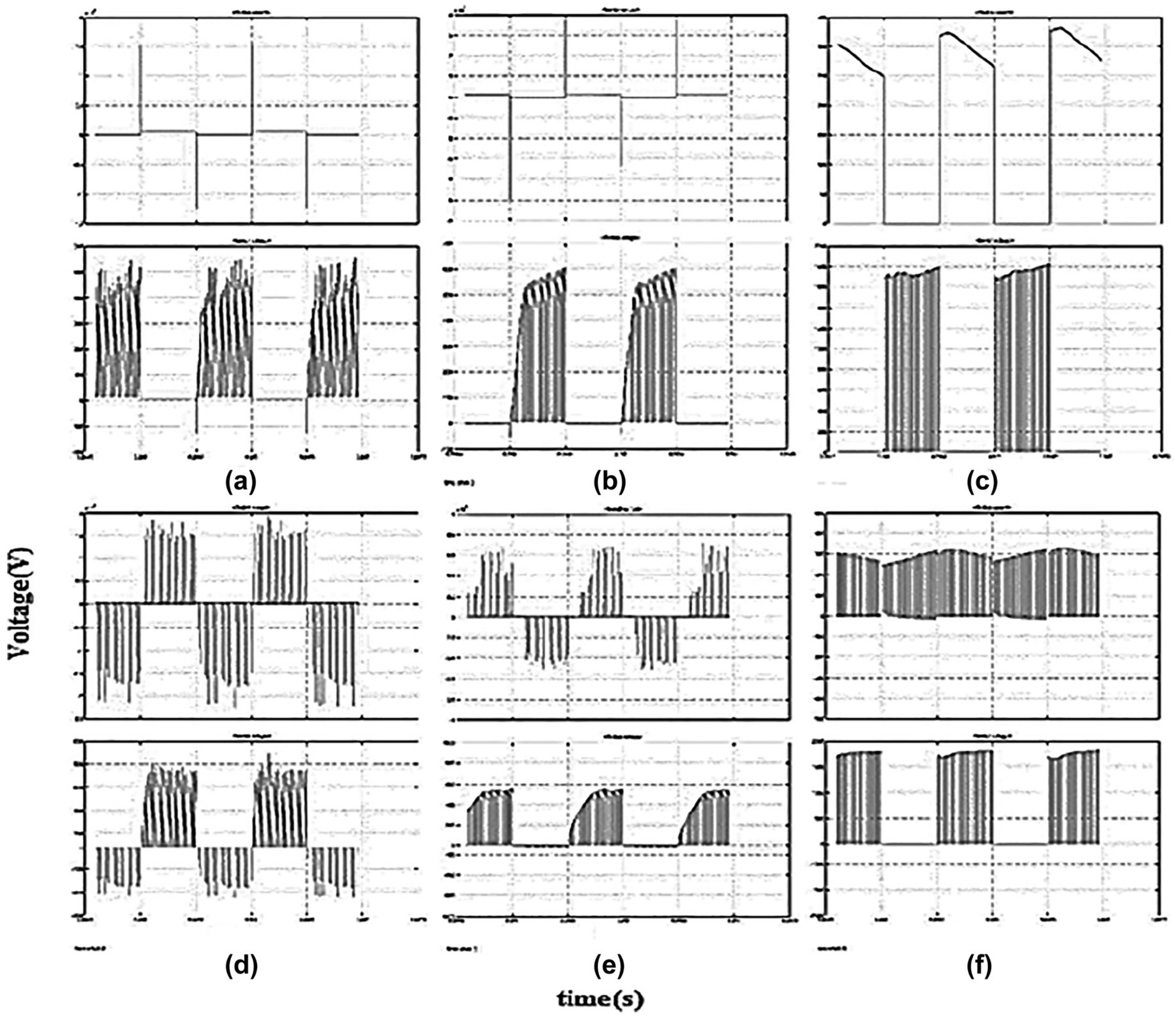


**Figure 18:** Switching stress across various modules.

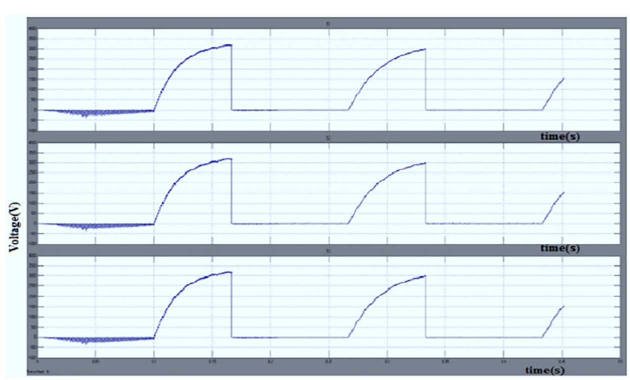


**Figure 19:** Voltage stress across switch $S_1$, $S_2$, and $S_3$.

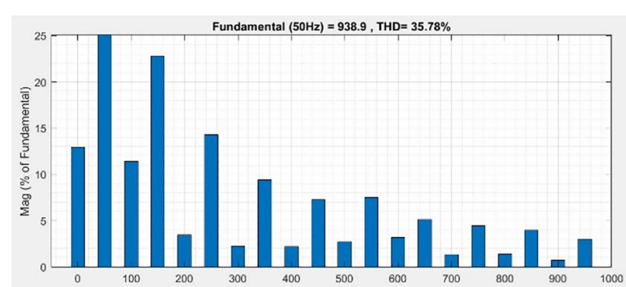


**Figure 20:** Current THD levels.

## Conclusions

The proposed converter is more cost effective due to the elimination of power transformers and having the isolation transformer alone. The output of the proposed converter can be increased to any desired value by adding more modules in cascade (if needed). The voltage stresses produced across the switches are found to be low in comparison with the conventional systems so that the losses during the converter operation will also be low. Since the

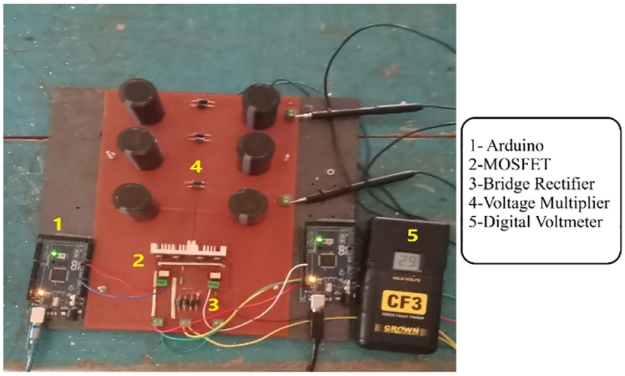


**Figure 21:** Hardware Prototype.


**Figure 22:** Prototype output.

output pulses delivered to the ESP are intermittent, the amount of energy drawn from the supply is reduced. The THD is also found to be reduced than the conventional converters. A Hardware Prototype of a single module is developed, tested and found it is capable of generating the required output.

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