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Development of IGBT based High Voltage Power Supply for ESP Application

G. Balawanth Reddy, Alla Koteswara Rao, G.S.Naik, Shoubhik Mukherjee, G.Avinash and Bishnu P. Muni
BHEL, Corporate R&D, Hyderabad – 500093, India
e-mail: balawanth@bhelrnd.co.in

Abstract – This paper presents the development of Insulated Gate Bipolar Transistor (IGBT) based High Voltage (HV) power supply for Electro Static Precipitator (ESP) Application. With the fast switching power semiconductor devices like IGBT enable us to develop inverter based high voltage power supply for ESP application. Compared to conventional Silicon Controlled Rectifier (SCR) based technology the average corona power can be increased to improve the precipitator efficiency. In this development, Digital Signal Processor (DSP-TMS320F2810) has been used for PWM generation, protection, HMI interface and control algorithm implementation for ESP operation. The developed system is tested on the existing 50 Hz High Voltage Rectifier (HVR) unit with ESP load. The testing is performed at various frequencies ranging from 50Hz to 500 Hz for no-load, load and short-circuit condition. It is observed that the average DC voltage has increased with frequency and at the same time de-rating of the transformer is observed. During flashovers the fast current control of IGBT power inverters improves the precipitator performance due to fast voltage recovery resulting in further increase in corona power.

Key Words: Insulated Gate Bipolar Transistor, Electrostatic Precipitator, Digital Signal Processor, High Voltage Rectifier Transformer, Pulse Width Modulation, Inverter, Medium Frequency Power Supply.

1. INTRODUCTION

The most common power supplies for the ESP currently feed by standard single-phase line-commutated thyristor-based HV power supplies, which are not able to provide the optimal waveforms of the high voltage and current supply. The circuit diagram of line commutated Thyristor power supply is shown in Fig 1. The voltage ripple ΔV (ΔV = Vmax - Vmin) of the precipitator voltage depends on the electrical capacitance and resistance of the precipitator, which result from the process conditions and from the mechanical dimensions. In addition, it is governed by the power supply frequency, which unfortunately, is determined by the mains voltage and can't be varied. It can be seen that the ripple in

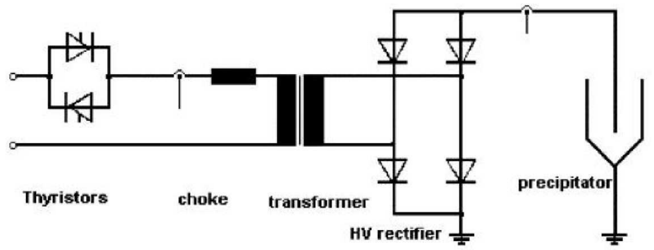

Fig. 1. Thyristor based HV power supply system for ESP [1]

the voltage is quite high in Thyristor based power supplies which is around 30% of the peak. Since flashovers in precipitators usually occur close to the peak value of the precipitator voltage, Vmax is limited by the Voltage Flashover voltage (Vmax < VFO). This means that, as the ripple increases, the maximum permissible voltage and, therefore, the average corona discharge power decreases as does the performance of the precipitator. The authors [1] also point to the high flashover current even after the voltage is removed as shown in Fig 2. In spite of these drawbacks, the main reason for using this topology is its simplicity of operation and lower investment cost. Due to the line frequency operation the control delay is in the 10 ms range (50 Hz). Further, upon the detection of a spark, the Thyristor will switch off only after the switch current ceases.

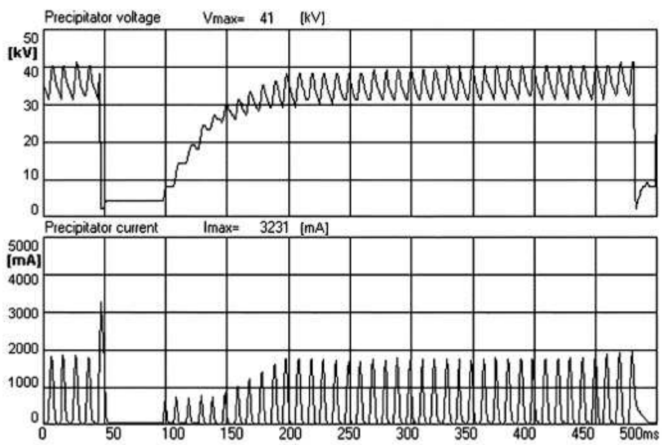

Fig. 2. Thyristor based Precipitator Voltage and Current [1]

Apart from the Thyristor based HV power supply systems, three other concepts are discussed in the literature – IGBT based high frequency system (hard switched), IGBT based resonant converter based system (soft switched) and pulsed power supplies [2]. A typical IGBT based power supply system is shown in Fig 3[3].

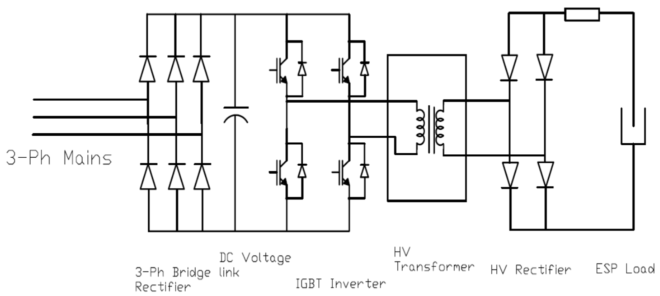

Fig. 3. Typical IGBT based HV power supply system

This paper presents the development of IGBT based medium frequency power supply system.

2. IGBT BASED HV POWER SUPPLY SYSTEM

IGBT based HV power supply system has three major components/subsystem viz. (i) 3Ph diode bridge rectifier, DC link Capacitor and 1Ph IGBT inverter (ii) High voltage rectifier unit (Step-up transformer and high voltage diode bridge rectifier) and (iii) DSP Controller with keypad and display unit (HMI).

By using a 3-phase bridge rectifier, a balance loading of the mains can be achieved. The line current also improves from the point of power quality compared to a Thyristor based power supply system. . Initially the system is energized with pre-charge circuit contactor and then shifts to main contactor to avoid inrush currents to charge the DC link. The output of the diode bridge rectifier is filtered by a filter capacitor bank. The filtered DC voltage is fed to the inverter. The inverter is operated with PWM switching technique to obtain a 1-phase variable voltage and variable frequency ranging from 50 Hz to 500 Hz. The 1-phase output of the inverter is stepped up by the transformer of the HVR unit and converted to DC using a high voltage 1-phase diode bridge rectifier. The DC output of high voltage rectifier is connected to positive and negative plates of ESP. The entire system is controlled by Texas instrument DSP TMS320F2810 based controller. The schematic of the developed system is shown in Fig 4.

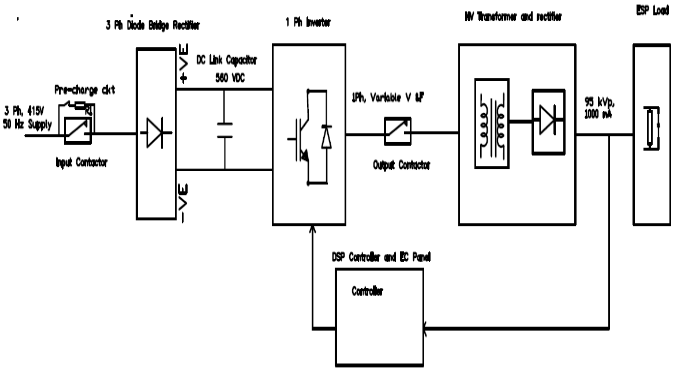

Fig. 4. Block diagram of the developed IGBT based HV power supply system

3. CONTROL TECHNIQUES IMPLEMENTED IN IGBT BASED HV POWER SUPPY SYSTEM

The following controls were implemented or the operation of ESP system.

i. **I_s Control:** To vary the ESP load current, the value will be selected based on the quality of the coal used for combustion. This control is achieved by varying the Modulation Index (M.I) of the inverter (shown in Fig 5.) with the pot mounted on the front panel of the developed system at different frequencies ranging from 50 to 500Hz.

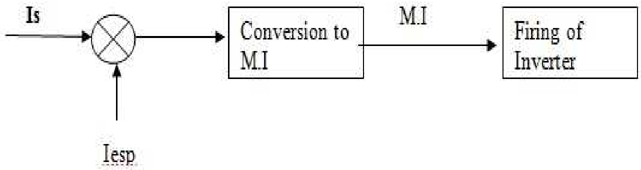

Fig. 5. Is Control implementation in IGBT system

ii. **Intermittent charging:** The ESP system is not energised continuously because of back corona problem, so intermittent charging is preferred to avoid this effect. This control in implemented by selecting the charge ratio. Fig 6. shows the output voltage for a charge ratio of 1:5.

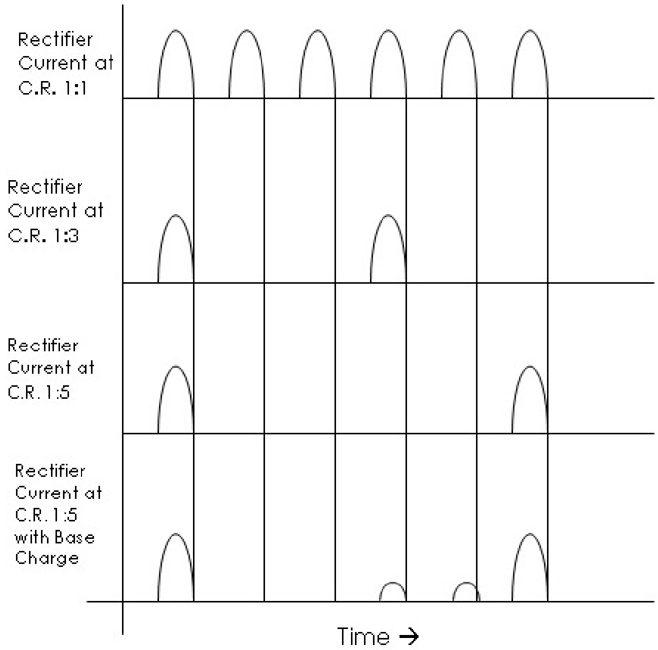

Fig. 6. Intermittent and base charge Control

iii. **Base Charging:** This is similar to intermittent charging but the amount of energisation is less in magnitude in order to maintain minimum ionization. This is achieved by firing the inverter with a less and fixed MI at regular intervals of time based on the base charging ratio. In Fig 6. base charge is also shown.

iv. **S&T Control:** This control is required to control the spark rate that eventually controls the performance of the collecting efficiency. This control is implemented by sensing the ESP load currents and also based on settings of S-control and T-control. Suppose, if a spark has occurred, then the ESP load current (Iesp) at that particular instant will be sensed and reduced to Iesp*[1 - (S-control*I_s(rated)/100)] and the same will be ramped up to next spark in T-control time (Proportional to the time and increment of Iesp will remain same). The S & T control implementation is shown in Fig 7.

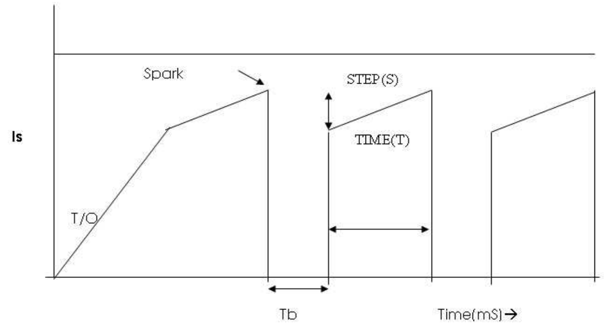

Fig. 7. S & T Control implementation

These control techniques were implemented in the DSP controller. The control software was written in Code Composer Studio IDE for the operation of IGBT based HV power supply for Electrostatic Precipitator.

CONTROL HARDWARE:

The control hardware consists of a) DSP (TMS320F2810) controller b) ESP interface Card, c) LCD & keypad Interface card d) LCD & Keypad (HMI) unit and e) Is setting pot. The user settings are set through LCD & keypad unit, these parameters are communicated to DSP controller by serial communication, the controller inturn process the requirements and generates the firing pulses for the inverter operation. The sensed signals (voltage and current) are conditioned through ESP interface card. The interface between DSP and HMI system is shown in Fig. 8.

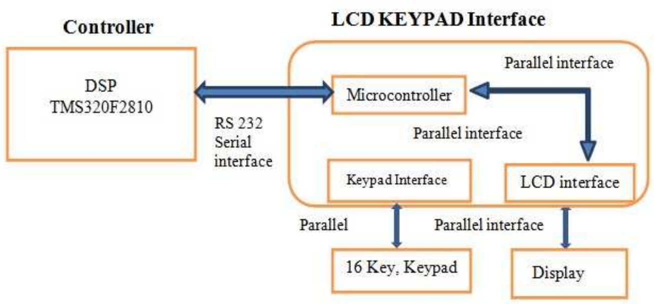

Fig. 8. Interface between DSP and Keypad/Display unuit

4. SIMULATION RESULTS

In order to study the performance of the system in simulation, a suitable model for ESP load needs to be implemented. The ESP is a highly non-linear system as shown by *v-i* characteristics [4] of Fig. 9. A simpler model of an ESP is assumed to be a parallel combination of a Resistance and a Capacitance [4]. The electrode system provides the capacitance and the Corona components provide the resistance. The corona current is influenced by the properties of the flue gas. This is the model used for our studies, the values for the R0 and C0 are decided based on field experience. The mean load current is 1000 mA. The values used for simulation are

R0 = 60 kΩ,

C0 = 120 nF

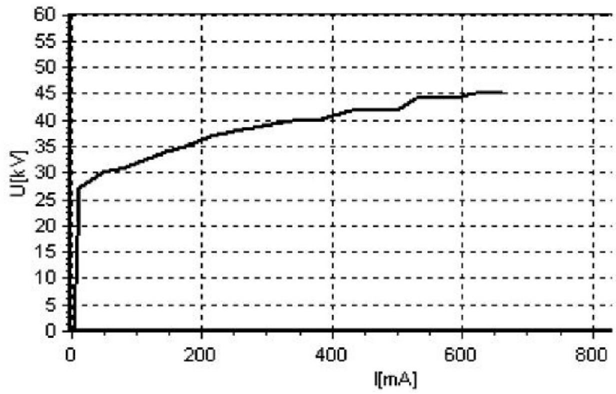

Fig. 9. Response of 50Hz supply system [4].

The simulation studies were carried out using MATLAB/Simulink tool. The Simulink model of IGBT based HV power supply is shown in Fig. 10. The proposed development is simulated for I_s control with HVR parameters similar to test setup. The PI controller is used for tracking the current in the ESP and the inverter is set to generate SVPWM (3rd harmonic injection) wave and is switched at 6 kHz for different frequencies ranging from 50 Hz to 500Hz.

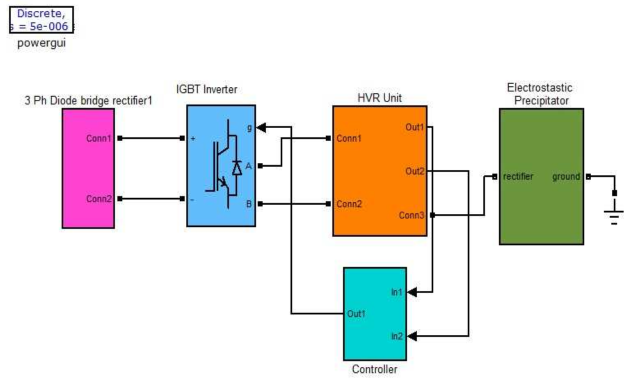

Fig. 10. Simulink model of IGBT based HV power supply

The simulation results are given in Fig. 11 – 13. The plots contains I_s Reference and actual current, inverter output voltage and current, DC link voltage, ESP actual and average load voltage and current waveforms respectively. From the plots, for the 50 Hz supply, the system response appears to be stable and the control is well established. The current rises gradually and appears to follow the reference current. For 500Hz supply system, actual current is not following the reference current because of the increase in impedance of the HVR system and hence, the rating of the power supply system is reduced. It is also observed that ripple is decreased and ESP average output voltage is increased. The response for spark condition is also simulated and found satisfactory (created at 0.8 sec). The intermittent energisation of the system is done for a charge ratio of 1:6 and the same is shown in Fig. 13

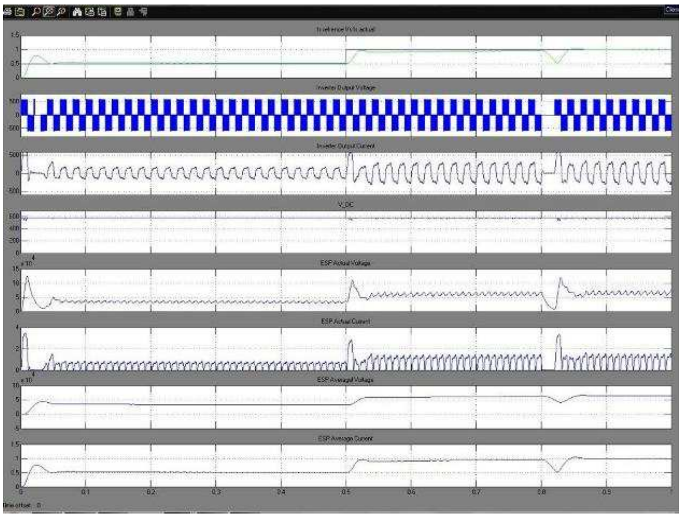

Fig. 11. Response of 50Hz supply system.

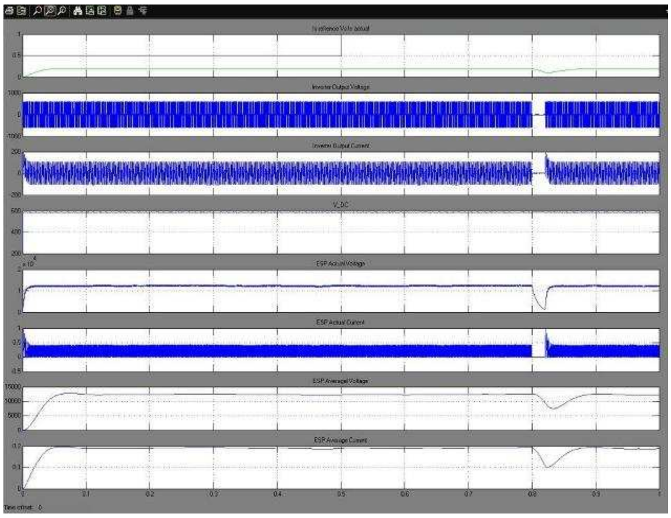

Fig. 12. Response of 500 HZ supply system.

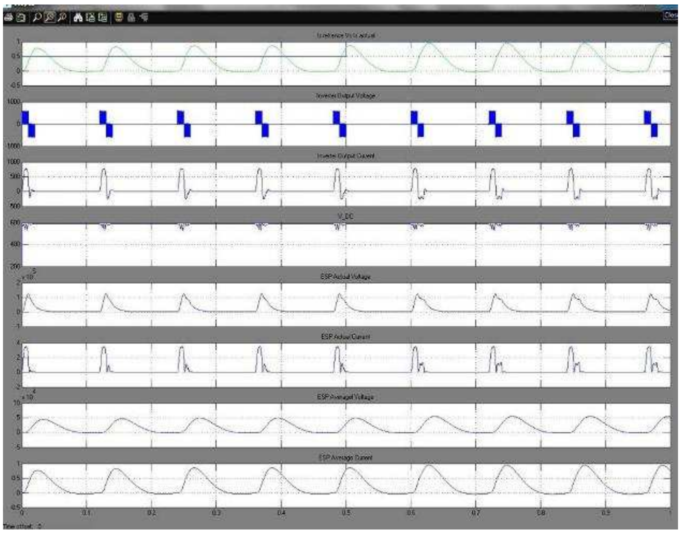

Fig. 13. Intermittent energisation of the system.

5. EXPERIMENTAL/TEST RESULTS

The developed IGBT system (shown in Fig 14.) is designed for output voltage of 95kVp. This system is integrated with the existing HVR (52 $kV_{avg,}$, 600mA) and ESP load setup of BHEL test bed at Ranipet.

Fig. 14. Developed IGBT power supply system (front & back view)

The following tests are conducted on the developed IGBT based HV power supply system.

i. **No load Test** with variation in M.I and switching frequency at various frequencies ranging from 50 to 500Hz.
ii. **Load test** (connected to ESP load setup) with variation in M.I at various frequencies ranging from 50 to 500Hz.
iii. **Short circuit Test** with HVR secondary terminals shorted with variation in M.I at various frequencies ranging from 50 to 500Hz.

The waveforms of the above tests are shown in Fig. 15- 17.

The no-load and short circuit test results are tabulated in table 1 and 2 respectively.

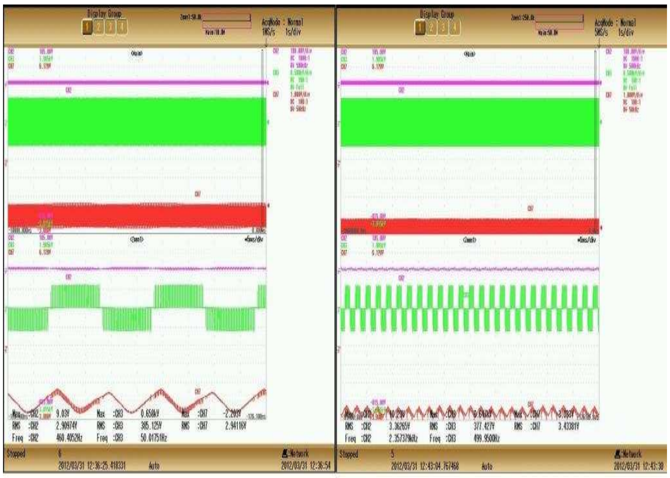

Fig. 15. No-load waveform @ fs = 6kHz, for F=50 & 500Hz.

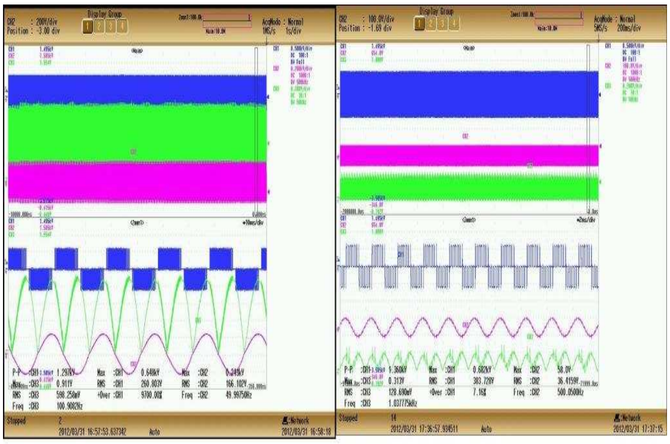

Fig. 16. SC waveform @ fs = 6kHz, for F=50 & 500Hz.

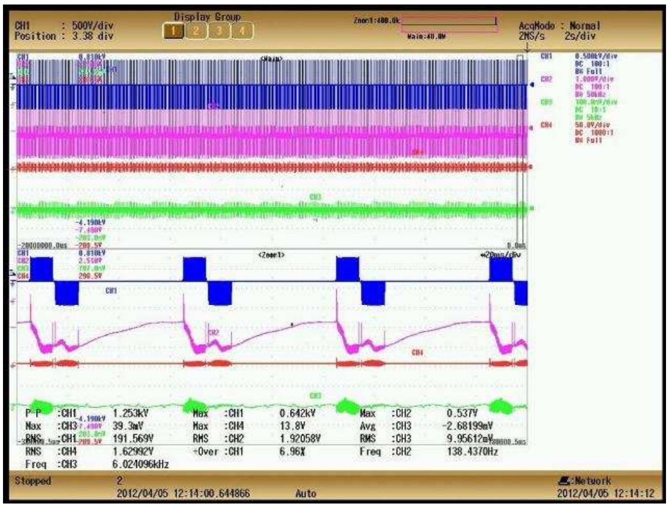

Fig. 17. Intermittent charging waveform with a charge ratio of 1:3.

Table 1: No-Load Test Results

	50Hz Output	500Hz Output
M.I	V DC_{avg} in % of rated (HVR Secondary)	V DC_{avg} in % of rated (HVR Secondary)
0.15	21.15	28.85
0.2	32.69	38.46
0.3	46.15	55.77
0.4	65.38	75.00
0.5	76.92	92.31
0.6	92.31	109.62
0.65	100.00	115.38

Table 2: Short circuit Test Results

	50Hz Output	500Hz Output
M.I	I DC_{avg} in % of rated (HVR Secondary)	I DC_{avg} in % of rated (HVR Secondary)
0.16	36.67	3.33
0.2	51.67	5.00
0.28	83.33	9.17
0.36	98.33	11.67
0.40	101.67	13.33
0.48		16.67
0.56		18.33
0.64		21.67
0.68		23.33

6. CONCLUSION

The developed IGBT based HV power supply system is tested for loaded, no-load and short circuit conditions. It is observed that with increase in frequency the output voltage of HVR contains fewer ripples compared to thyristor based power supply. Hence, average voltage is 15% higher for 500 Hz system. This will benefit ESP for low dust resistivity application like Soda Recovery Boilers / Biomass. In short circuit condition, the HVR secondary current has decreased with increase in fundamental frequency from 50 Hz to 500 Hz for the same M.I. With the increase in M.I (till primary rated voltage) under 500 Hz operation, the secondary current has increased. This concludes that the derating of the system is happened with increase in frequency. Due to better spark quenching (because of DSP & forced commutated device like IGBT), there is an increase in average corona power which leads to better dust collecting efficiency.

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