Chapter 5

Cathode Heating Power Source for EB Guns

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Welding and Melting are unavoidable unit practically for every manufacturing industry. Electron Beam welding & Melting (EBW/EBM) are very important unit of some specific manufacturing processes. In order to get high degree of accuracy in melt product and flawless welding, the EB applications are drawn attention from aerospace and nuclear engineering. The power supply unit (PSU) used for EBW/EBM are essential unit, for which high degree of stability and accuracy is a must. The EB Power source is the combination of multiple power supplies, each responsible for a specific function in EB machine such as cathode heating, beam acceleration, beam control and the power source for EB lenses to maneuvering the EB spot. Besides, It includes the control for Vacuum system and job handling system. The characteristics of EB gun must be considered while designing EB power source. With advancement in solid state device and increasing demand of SMPS over linear regulator, the EB power source, now a days, are made up of switching regulators. Consequently, this helps in, reduction in overall size and stored energy, and improves the performance of EB machine by introducing fast response and ease of control.

5.1 Overview of EB Power Source

Accelerator and pulse power division, BARC, Mumbai is being working on development of Electron Beam system for melting and welding applications. The EB systems are in the range of 10 kV to 80 kV and currents are from 10 mA to 4 A depending on application requirement. The EB systems of different power rating have their specific power supply requirement. The EB power source developed for EB application comprises of many power supplies, each having some specific purpose. These report summaries the functional and structural aspects of those power supplies. The line diagram indicating interconnection of EB power source with a most complex form of EB gun are depicted below.

5.1.1 Floated Power Source in EB System

The power sources used for wire cathode heating and to provide grid voltage for beam current controlling are to be connected to acceleration potential. As a result the effective voltage is lifted to the acceleration potential with respect to ground. Therefore, the components selected for these power source has to be suit to acceleration potential. However, increasing insulation level between winding and core up to acceleration potential swells leakage inductance. This also leads to large ratio error making the system more non-linear. The control circuit is to be protected from the high voltage transients by providing suitable isolation. The complexity introduces the complexity in measurement of output voltage and current from a HV terminal can be overcome by sensing voltage and current from HV terminal by using optical fiber and Hall sensor respectively.

5.1.2 Wire Cathode Heating Power Source

The most fundamental and essential part of an electron gun is to generate electrons from a wire cathode made up of tungsten or tantalum by passing current in the range of 15 A to 70 A decided by the geometry of the cathode. The electrons are escaped from their orbit by rising temperature of cathode (I^2R heating) to overcome work function W. This is possible by applying both AC and DC current also. But, to avoid the effect of oscillating magnetic field of ac current on stability of beam spot, the DC current is preferred in case of welding. The specifications of the power source are outlined in Table 5.1.
Today, SMPS based topology with medium frequency (around 5-20 kHz) switching schemes are being used to reduce output ripple and stored element. The PWM control are adopted to

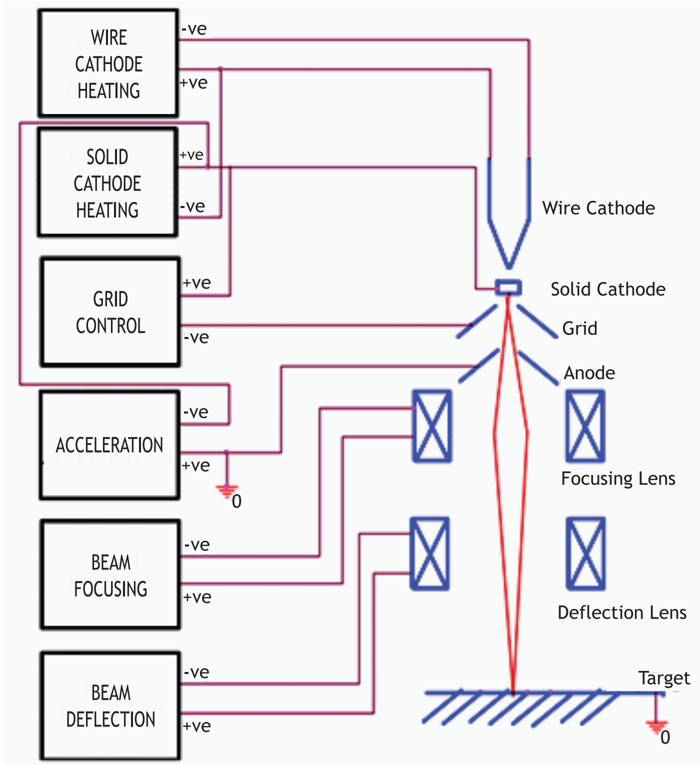

Figure 5.1: The Interconnection of EB power source with EB gun.

Table 5.1: General Specification of Wire cathode heating Power Supply.

Input:	**Output:**	
Voltage: 230 V ±15%, 1-Φ, 50 Hz	Voltage range:	10-20 V DC
	Current range:	15-70 A
	Floating Voltage range	10 kV to 100 kV
	Output Ripple:	1% peak-peak
	Regulation:	1% line and load
Control Type:	Current Control	
Topology:	PWM control inverter with suitable DC link followed by Transformer-rectifier.	

get better regulation of output current. The structure of the SMPS are depicted in simplified block diagram show in Fig. 5.2.

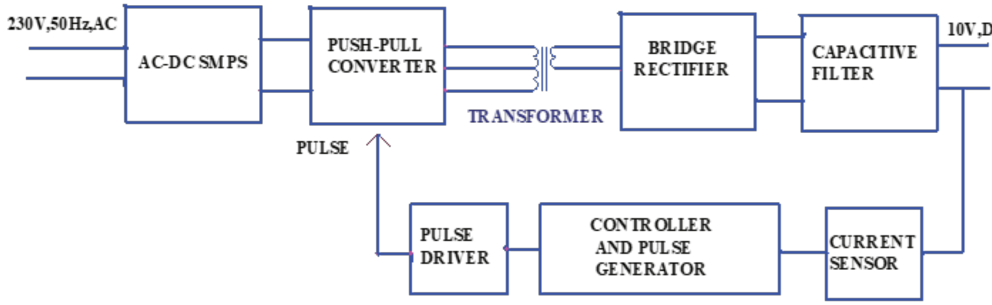

Figure 5.2: Block diagram of Wire cathode Power supply.

5.2 Development of EB Power Source

The EB power source for indigenous developed Electron Beam Gun is an ensemble of inter-dependent power sources, their control and protection. The conceptual diagram of an EB system and its interconnection to the power source is given in Fig. 5.1. But, the first step in production of an e-beam is to somehow generate the free electrons. This task is accomplished by a V-shaped tungsten filament or cathode of 0.5 mm wire diameter [15]. These cathodes are usually heated to emission temperature by electric Joule heating. The Wire cathode heating power supply designed and developed should be, compatible to V-I characteristics of tungsten filament, depicted in Table 5.2. During the design stage the maximum emphasis was given to reduce overall size, output ripple, on state losses, electromagnetic interference (EMI) and acoustic noise. The focus was also given to improve the beam stability and cathode life by sensing the output current from the floated terminals.

Table 5.2: Characteristics of 0.5 mm diameter Tungsten wire-cathode.

T (K)	**Heating Power (W)**	**R (Ω)**	**Heating current, I_h (A)**	**Heating voltage, V_h (V)**
293	0	0.03	0	0
1700	15.97	0.23	8.36	1.91
1800	21.38	0.24	9.35	2.29
1900	28.06	0.26	10.37	2.71
2000	36.18	0.28	11.43	3.17
2100	45.93	0.29	12.51	3.67
2200	57.50	0.31	13.61	4.22
2300	71.14	0.33	14.75	4.83
2400	86.98	0.34	15.90	5.47
2500	105.26	0.36	17.06	6.17
2600	126.24	0.38	18.25	6.92
2700	150.10	0.40	19.46	7.71
2800	177.07	0.41	20.67	8.57
2900	207.55	0.43	21.92	9.47

5.2.1 Power Supply Specifications

From conceptual diagram of an EB system shown in Fig. 5.1, it can be understood, the presence of acceleration power supply implies that the power source for the wire cathode heating is floating and one of its terminal is connected to HV terminal. Therefore, the secondary of the power source must be designed with high isolation capability. In order to obtain the HV isolation, considerable large gap has to be provided between secondary and core. This introduces significant parasitic [16] such as leakage inductance that the power source has to cope with. Due to low turn ratio of the transformer, the parasitic capacitance is neglected. The operating temperature of the cathode, as given in Table 5.1, has a direct bearing on Beam quality. Therefore, thermal stability of the cathode is maintained by close loop regulation of the heating current (I). The current feedback from the floating terminal was taken by means of a Hall sensor directly mounted over the HV cable. In order to enhance the filament life the operating temperature is fixed at 2800 K. The some of the major design considerations required for EB applications and development of a switching mode power converter (SMPC) with following specifications are given in following section.

- Input voltage: V_{DC} = 50 V
- Output Voltage, sinusoidal: V_{rms} = 12 V
- Controlled Output voltage: V_{odc} = 10 V
- Output current: I_{orms} = 21 A
- Switching frequency: f_{sw} = 8 kHz
- Isolation secondary and core: 30 kV
- Load regulation: 5%
- Output Ripple: 5%

5.3 Converter Topology

The dynamics of the load governs the topology selection procedure in any electrical system. During selection of topology, the attention was given to understand the application requirement and site constraints. During design the measure effort was concentrated to make the power source compact and suit to site layout. The basic block diagram of filament heating power source is given in the Fig. 5.2. The use of push-pull inverter over other available inverter topology, facilitates the use of only two numbers of ground referenced switching components that leads to simple driving circuit. The DC link voltage for the IGBT based push-pull inverter is produced by AC-DC converter. Though an inductor filter is most suitable for this application, a capacitive ripple filter is selected to reduce the foot print of HV components. The output current as a control parameter, sensed from the floated terminals to get better stability in cathode temperature and consequently in beam current.

5.4 Steady State Operation

The Fig. 5.3 shows the circuit configuration of the proposed voltage fed push-pull converter. There are 12 numbers of turns in each primary winding. The secondary winding, floated at -30 kV has only three turns. To make the analysis simple, the front end AC-DC converter has been replaced by a standard DC source V_{DC}. Considering ideal power devices the average output voltage can be given by Eq. (5.1).

$$V_{out} = K\delta V_{DC} \tag{5.1}$$

where, K = Transformer turn ratio, and δ = Duty cycle.

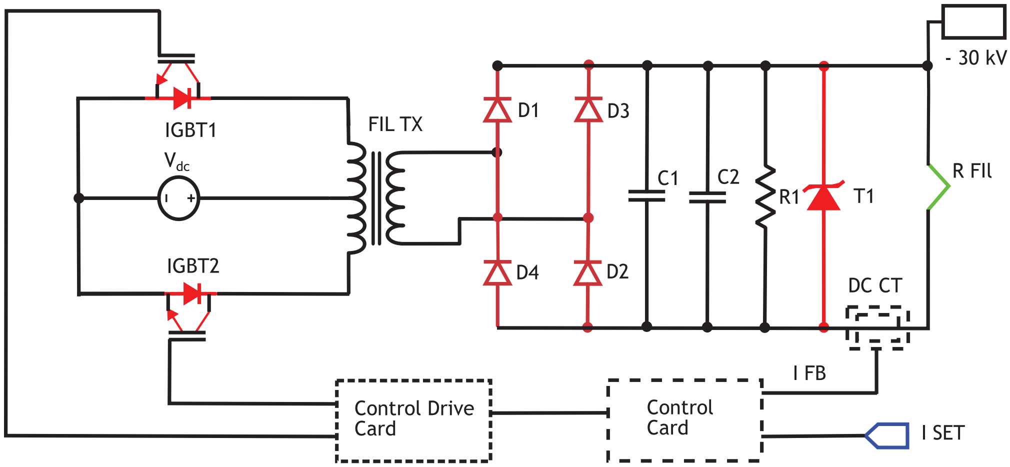

Figure 5.3: The Circuit Diagram of WC-SMPC.

The steady state operation of the power supply can be analyzed by dividing the converter operation into following intermittent steps. This increases the spike appeared across the device [17–19] during switching OFF.

Step-01: Switching of IGBT1 when IGBT2 is OFF

When IGBT1 is turned on the upper half of the transformer conducts which pushes the core flux in forward direction. The steady state voltage appear across the IGBT2 is given in the following expression.

$$V_{IGBT2} = V_{source} + V_{lower} = 2V_{DC} \tag{5.2}$$

During the turning off of IGBT1, the transient voltage appear across it is given by following expression

$$V_{IGBT1} = V_{source} + V_{upper} + L_{leak}\frac{di}{dt} = 2V_{DC} + L_{leak}\frac{di}{dt} \tag{5.3}$$

Step-02: While IGBT1 and IGBT2 are OFF

When there is a dead band between two devices, the output current free wheels, the energy stored in core gets dissipated. The primary voltage also becomes zero.

Step-03: Switching of IGBT2 is While IGBT1 is OFF

When IGBT2 turned on the lower half of the transformer conducts which pushes the core flux in forward direction. The steady state voltage appear across the IGBT1 is given in the following expression.

$$V_{IGBT1} = V_{source} + V_{upper} = 2V_{DC} \tag{5.4}$$

During the turning off of IGBT1, the transient voltage appear across it is given by following expression.

$$V_{IGBT2} = V_{source} + V_{lower} + L_{leak}\frac{di}{dt} = 2V_{DC} + L_{leak}\frac{di}{dt} \tag{5.5}$$

5.5 Hardware Implementation

The proposed push–pull inverter topology is operated with a DC link voltage $V_{DC} = 50$ V. Selecting low DC link voltage enables to maintain the output ripple within acceptable limit by maintaining a higher duty cycle. In the present application turn ratio of the transformer has been selected ($K = N_s/N_p = 1/4$). The primary side current will be around 7 A. As the secondary winding is floated at -30 kV, the corresponding insulation introduces a large gap between core and winding. This increases the leakage inductance of the transformer and hence the magnetic current. The large leakage inductance (25 H) caused a large switching spike across the devices. In order to withstand the high spike Punch through (PT) type IGBT of a voltage rating 1200 V and 50 A are selected. Though the output voltage of this power source is rated 10 V, the rectifier are selected to with stand the steady state reverse voltage of 1.2 kV, same as grid voltage. Atypical steady state fault condition is depicted in Fig. 5.4, where a broken filament came in contact with grid cup. Consequently, the full grid voltage (1.2 kV) is appeared across the cathode supply.

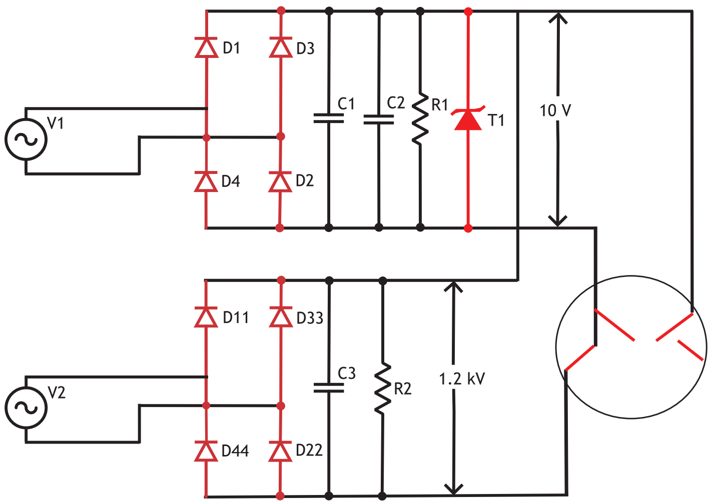

Figure 5.4: Interconnection of WC Heating and Grid power supply.

To smoothen the output, capacitor filter is preferred over LC filter, to reduce the overall size and to stay away from the fabrication complicacy of the inductor (21 A DC) floated at -30 kV. The crucial component of this power source is step-down transformer with turn ratio 5. In this work, a novel idea has been implemented to minimize the stray magnetic flux and leakage flux. Here, a toroid core (T10220, 2 in parallel) is selected to operate at maximum flux density of 0.15 T. The use of toroid core instead of UU core yields the following advantages.

1. Reduced leakage flux and magnetizing current
2. Reduced switching spike across the devices
3. Reduce acoustic noise
4. Reduced interference with surroundings

By putting a toroid core arises a new difficulties for secondary winding which is floated at -30 kV. The winding warped over a insulated bobbin [15] is nearly impossible. Therefore, an co extruded flexible HV cable as shown in Fig. 5.5, has been used as secondary winding. The litz wire prepared by bunching the enameled SWG21 copper wire to serve as primary winding. In both the windings, the current is fixed as 3 A/cm^2 after considering skin depth at a switching frequency of 8 kHz.
The output current is sensed from the DC end of the secondary by directly passing the above cable of 9 mm diameter through a hall sensor (Make: ABB, Model: EL25P) based DC CT with 10 mm hole diameter. This current is being processed further through a Type-2

Figure 5.5: Transformer with toroid core.

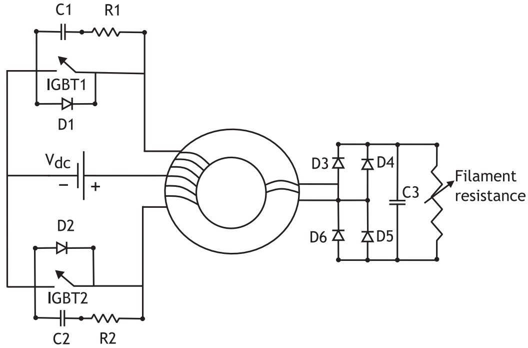

Figure 5.6: Converter with Snubber.

error amplifier followed by PWM [20] pulse generator. The large spike voltage across the switching devices due to considerable large leakage inductance was optimized by using the snubber circuit as shown in Fig. 5.6. Though a capacitive snubber is enough to mitigate the spike voltage but it introduces high frequency ringing voltage across the winding by creating a tank circuit consisting of CDC_{link}, Csnubber and Primary inductance (L_p). This compelled to put a resistor (R) in series to damp the HF ringing and also to limit the turn on current through devices. However, this additional component compelled to make a trade off between ringing and spikes. The stress due to optimized spike voltage (around 600 V) is compensated by selecting an IGBT of higher (1200 V).

5.6 Experimental and Simulation Results

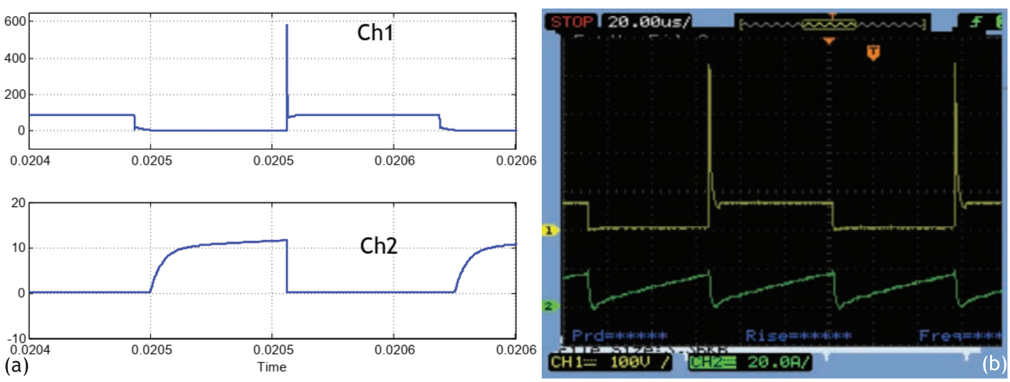

Figure 5.7: (a) Simulation result - (Ch1) Device Voltage and (Ch2) Device current, and (b) Experimental result - (Ch1) Device Voltage and (Ch2) DC link Current.

The experiments were carried out to verify the design. The spike voltage appeared across the switching devices are optimized by using RC Snubber. The primary voltage and current of the transformer, are shown in Fig. 5.7. From the experimental result, it was found that the magnetizing current is 0.4% while a load current is of 21 A. The percentage of magnetizing current with respect to primary current was calculated to be 6% similar to a conventional ground referenced transformer. The toroid core is the key to achieve the low magnetizing current. The output DC Voltage and current are also measure at full load and with minimum supply voltage (190 V). The Fig. 5.8 shows the voltage across the switching devices and the current through device. The simulation voltage wave form is quite similar to the actual voltage. But the current wave form shown in the simulation is the current passing through the devices. But the switching module consists of two switches making impossible to measure individual current. Therefore, the actual current shown here is slightly different than the simulation one.

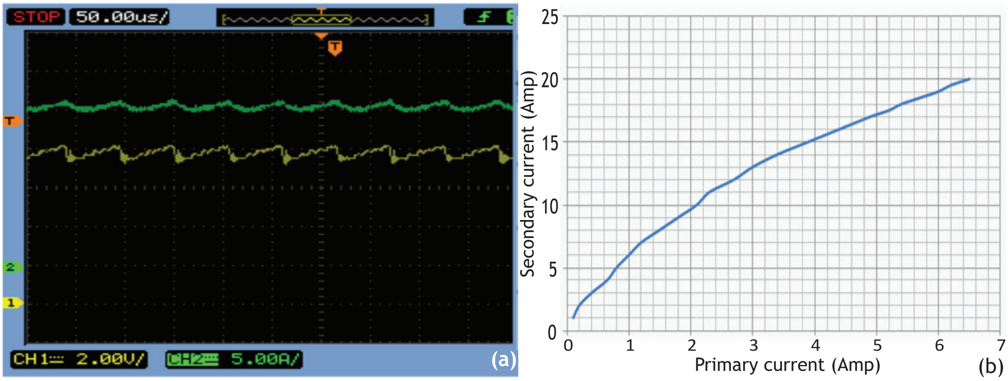

Figure 5.8: (a) Output voltage and current, and (b) Output Vs input current.

5.7 Conclusion

The push-pull inverter with a toroid core type transformer discussed is having low leakage and better linearity with compared to UU ferrite core and found more suitable for a floated power source used in EB system. The overall size of the power source is also optimized by switching at 8 kHz. The performance of the power source is superior than that of line frequency based topology. Also, the sensing of current from the floated terminals is introducing additional stability and established better linearity.

Suggestions for Further Reading

a) [4, 21, 22]