Compact Power Supplies for Tokamak Heating

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ABSTRACT

As extension of power transformers, efficient large-scale contactless power transfer between stationary and reference frames is a problem of world-wide importance, to such applications as electric vehicles, materials handling and plasma heating for fusion science. Tokamak is the common developed fusion device where heating is recognized as one of its key technologies for its future reactor roadmap. Snubber is often used as protection device in NBI system for Tokamak heating [1-3]. The present NBI generally use 50/60 Hz High Voltage (HV) Insulation Transformers to configure its dc power supply to offer the bias current to the snubber, which could use the full flux swing of the core from the negative saturation point to the positive one of its BH major loop. The snubber weight could then be decreased to its half by using the bias power supply. But this 50/60Hz HV insulation transformer is much heavier than High Frequency (HF) High Voltage (HV) Insulation system. The paper gives the requirement, design and test of this Compact Power Systems based on HF HV Zero Current Switching (ZCS) technologies for Experimental Advanced Superconducting Tokamak (EAST) NBI snubber as well as its potential for its compact HVDC power supply. Its new control strategy is also implemented with one macro pulse composed by the digital defined continuous micro pulses. Some experimental evaluations have been done to verify the analysis results, which have been extended to over 100s and could be used for detail engineering design of power supplies for EAST based on IGBT.

Index Terms - **Compact power supplies (PS), core snubber, experimental advanced superconducting Tokamak (EAST), international thermonuclear experimental reactor (ITER), inductively coupled power transfer (IPT), high voltage (HV) insulation transformers, high frequency (HF), neutral beam (NB), microwave, pulse mode, IGBT, zero current switching (ZCS)**

1 INTRODUCTION

THE Experimental Advanced Superconducting Tokamak (EAST) is being upgraded with 4 MW microwave (4.6 GHz/10-1000 s) and 4 MW neutral beam (NB, 50-80 keV/10-100 s) heating systems as a part of the ongoing EAST Enhancement Programme. This is one of the largest upgrades of the EAST machine carried out within the EAST framework, two positive ion neutral injectors will be implemented in the near future as illustrated in Figure 1. In order to get the solid test foundation of the complex engineering system for about 100 s long pulse or even 3600 s, just as the requirement of ITER [1-4], one test platform is being constructed, which includes the HV snubber as well as its bias power supply. This system will be inserted between the ion source and 80 kV HV Pulse Step Modulator (PSM) power supply [5-6], as a means for protecting the expensive ion source while sparking in operation. Due to the narrow space around the EAST machine, one compact power supply is developed based on high frequency HV insulation transformer implemented with IPT, i.e. inductively coupled power transfer technology. IPT can be used for bi-directional contactless power transfer between one frame and another reference one, and has the merits of being clean, spark free, environmentally benign and low maintenance. It is a solution to the power transfer problem, which has been investigated using coaxial transformers at the University of Wisconsin-Madison, USA [7] and a coupled coil arrangement at Auckland University, New Zealand [8]. This paper describes a new system structure for plasma heating, which gives the requirement, design and test of this bias Power Systems implemented with power electronics based on IPT, where its theories are essentially the same as that of the transformers although IPT deals with the motion case with varied coupling factor. Its control strategy is also described. Some experimental evaluations have been done to verify the analysis results, which could be used for detail engineering design for plasma heating.
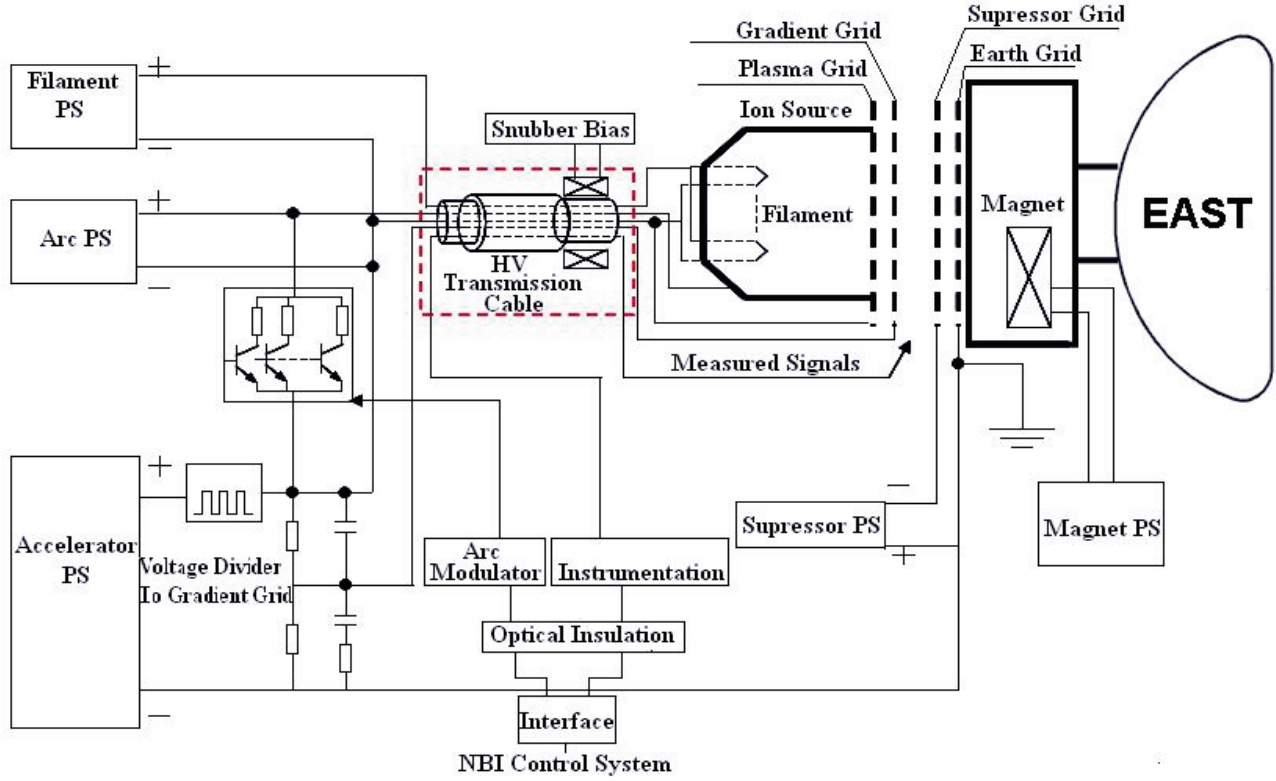
Figure 1. The EAST NBI Configuration with Power Supplies.

The inductively coupled system can be modeled by the equivalent circuit shown in Figure 2. The induced voltage in the secondary coil is given by:

$$V_2 = j\omega M I_1 \tag{1}$$

The maximum possible real current, i.e. the short circuit current

$$I_{sc} = \frac{j\omega M I_1}{j\omega L_2} = \frac{M I_1}{L_2} \tag{2}$$
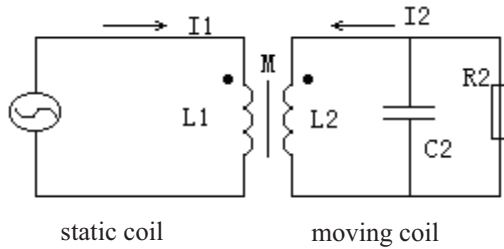

Figure 2. Equivalent circuit of the inductively coupled system.

while the load voltage is

$$V_2 = j\omega M I_1 Q_2 \tag{3}$$

The potential Volt-Ampere capacity for the system can be expressed as [5]:

$$S_2 = V_2 I_{sc} = \frac{j\omega M^2 I_1^2 Q_2}{L_2} = \frac{j\omega k^2 L_1 L_2 I_1^2 Q_2}{L_2} \tag{4}$$

$$= j\omega k^2 L_1 I_1^2 Q_2 = k^2 V_1 I_1 Q_2$$

where k is the coupling factor of the IPT system.

Due to higher insulation requirement in HV IPT system, the leakage inductance is generally fabricated much larger than common transformers. This limits the maximum input primary current and leads to a little low coupling factor between the primary coil and the secondary coil suspended in HV potential. At fixed input voltage, these parameters are two keys to implement IPT theory into power engineering. Increasing the frequency can scale down the physical size of the IPT system, but present IGBT limit realistic operating frequencies below 100 kHz for power levels up to 500 kW. It is clearly shown from equation (4) that the peak power transfer is proportional to the square of the coupling factor. Therefore, increasing the coupling factor between the static frame and the HV one is essential for high power systems.

2 THE MAIN REQUIREMENTS OF EAST NBI POWER SUPPLY

As shown in Figure 1, the power supply system of EAST NB injector includes power supplies for ion source, power supplies for extracting beams and power supply for bending magnet where Ground grid with less than $0.4\,\Omega$ ground resistance is used instead of Earth grid for the 100 kV system. Power supplies for ion source are composed by Filament PS, Arc PS, PS for gas supply and Langmuir probe PS. Their functions are supply electricity to these sub systems of ion source by floating on the accelerated PS as specified in Table 1. So, all these power supplies require HV insulation to the ground. Power supplies for extracting beams include Accelerated PS, Gradient PS, Suppressor PS and Snubber PS as listed in Table 1, where stability is the Voltage/Current ripple to their rated values during long pulse period.

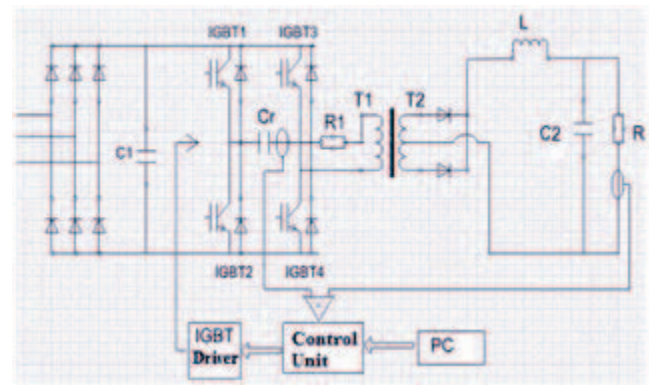**Table 1.** Specifications of beam system power supplies for EAST-NBI.

	Power Supplys	Voltage/Current	Insulation to ground	Operation Mode	Ramping up/ switching off time	Stability	Power
1	Snubber Bias	20 VDC/125 A	100 kVDC	continuous	------	1%/1%	2.5 kW
2	Filament	20 VDC/5.5 kA	100 kVDC	continuous	ramp	3%/3%	110 kW
3	Arc PS	200 VDC/3 kA	100 kVDC	10~100 s	<1 ms	1%/13%	600 kW
4	Accelerator PS	80kVDC/70A (rated)		10~100 s	20 us/10 us	1%/1%	5.6 MW
5	Gradient PS	100 kV Voltage divider		10~100 s			
6	Suppressor PS	-5 kVDC/20 A	10 kVDC	10~100 s	5 us/10 us	3%/3%	100 kW
7	Magnet PS	80 VDC/600 A	----	Continuous at 100 A	------	1%/1%	50 kW
Total						About 6.2 MW	

3 DESIGN OF THE MAIN CIRCUIT

The main circuit, which selects full bridge circuit, is shown in Figure 3. The 50/60 Hz ac utility supply is first rectified to get the dc energy storage in capacitor, then the positive and negative half cycle of high frequency oscillations are got by switching IGBT1 IGBT4 pair and IGBT2 IGBT3 pair in turn with the leakage inductance of transformer and resonant capacitor C_r. The induced voltage of the secondary winding in the high frequency 100 kV insulation transformer is rectified again to charge the capacitor, used as the snubber bias power supply. Typical parameters of the main circuit are listed in Table 2. The load voltage in the capacitor and the load current are detected and transmitted to the local control unit by optical fibre through standard RS232 interfaces. Based on PC, the local controller provides two control modes, namely open loop voltage control and closed loop current control. Current is used as fast feedback signal to switch on or off the IGBT triggers. Open load voltage is only monitored by PC. By selecting the leakage inductance of transformer and resonant capacitor C_r, the switching frequency can be designed in the mode of zero current switching (ZCS). The circuit impedance $\sqrt{L_\delta/C_r}$ from primary side is determined by matching leakage inductance L_δ of transformer and resonant capacitor C_r. Roadmap of increasing the charging accuracy of the load voltage is to enhance the frequency of coherent circuit for more voltage steps in one charging cycle.

Figure 3. The main circuit of the Compact Bias PS.

3.1 CURRENT FAST DETECTION AND REGULATION

The flow charter of the driving signal for one half cycle, which is used to drive IGBT1 IGBT4 pair or IGBT2 IGBT3 pair in the main circuit to generate one micro current pulse, is shown in Figure 4. The minimum driving time of one IGBT pair is defined as 3 μs, which can be changed in the PC monitor and control interface and is automatically extended to the value when the detected current signal is not zero. The ZCS is realized by switching off the driving signal of the IGBT pair when the detected current is zero, which corresponds to half period of the coherent circuit and be numbered one micro pulse to the load. Two continuous micro pulses compose one period of the coherent circuit. One string of micro pulses composes one required macro pulse which can be defined by PC interface while in operation. The bandwidth of the current detector is 200 kHz and the detected delay of the current signal is less than 0.3 μs. So, the maximum frequency of the driving system could be as high as 200 kHz by tuning down the minimum driving time from 3 μs to 2 μs. The working logic is implemented in one logic chip, which can be changed from the PC through fiber optic cable.

Table 2. Typical Parameters of the main circuit.

Circuit Elements	Resonant Parameters
Leakage Inductance/μH	7.11
Resonant Capacitor/μF	0.6
Resonant Frequency/kHz	77
Micro Pulse Time/μs	6.48
Impedance/Ω	3.44
Load resistance (Ω)	0.25
Load inductance (mH)	2.8478

3.2 TEMPERATURE RISE UNDER RATED LOAD

Unlike conventional ZCS technology for charging electric vehicles [9], a special continuous pulse mode is developed for NBI power supplies. One string micro pulses compose the required one NBI macro pulse which is about 100 s for EAST or 3600 s [1, 10] for ITER. The adiabatic temperature rise of all circuit devices can be designed with the required longest pulse in order that heat sink of all components is enough.

The adiabatic temperature rise of the conductor due to one pulse is derived by [11]:

$$\Delta T = \frac{Pt}{cm} = \frac{t\rho J^2 sl}{cslf_w} = \frac{t\rho J^2}{cf_w} \qquad (5)$$

where, $t=100s$ is the period of the current pulse; $c=390$ J/ (kg K) is the specific heat of the copper conductor; $f_w=8.9 \times 10^3$ kg/m^3 is the specific weight of the copper conductor. $\rho = 2.17 \times 10^{-8} \Omega m$ is the resistivity of the copper conductor at 75^0 degree.

Inserting the roughest operation parameters of the NBI parameters into equation (5), the adiabatic temperature rise of the copper conductor could be calculated. Total temperature rise is designed to below 100^0 degree C by selecting suitable current density.
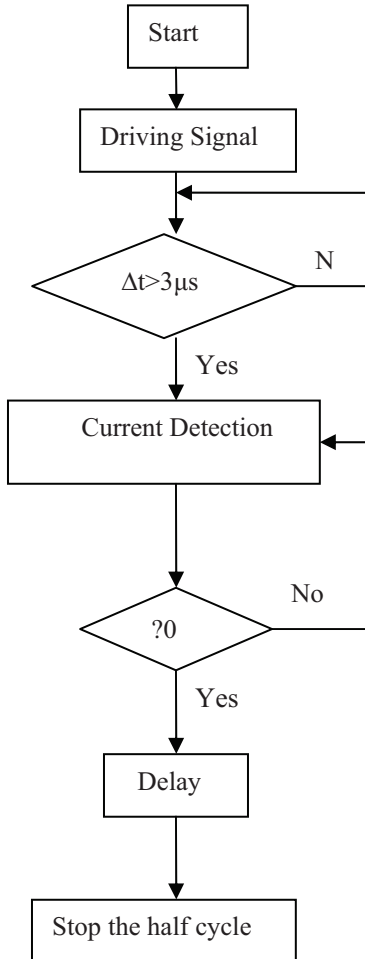
4   TESTS TO THE COMPACT BIAS POWER SUPPLY

Figure 5 illustrates the programmed monitor and control Interface to the main circuit of Figure 3 based PC. All parameters could be tuned in it which includes the number of micro and macro pulses as well as the delayed triggered time to the IGBT pair in Figure 3.
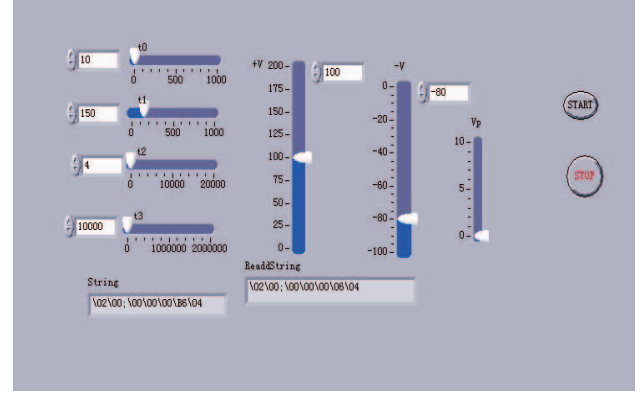

Figure 5. PC Interface.

4.1 High Voltage test to the insulation transformer

In order to check the insulation strength of the designed transformer, one 100 kV HVDC test platform was setup. The insulation strength of the test model has no problems at 90 kV HVDC for one minute in air. One oil tank of the HF insulation transformer is being fabricated now to accommodate it for over 100 kV insulation voltage test.

4.2 tests to the Power supply parameters

In order to check the possibility of high voltage system driven by above high frequency resonant pulsed power supplies, the circuit illustrated as Figure 3 is developed. The load is one resistance series with one reactor, which simulate the snubber load. The peak current in the primary side of the HF HV transformer is monitored in the control interface, which is used as feedback as well as over current protection signals. The tuned output current is measured by hall probe. The output macro pulse period could be defined in real time in the PC from one micro pulse period to any arbitrary time, which includes 10-100 s for EAST or even 3600 s for ITER NBI.
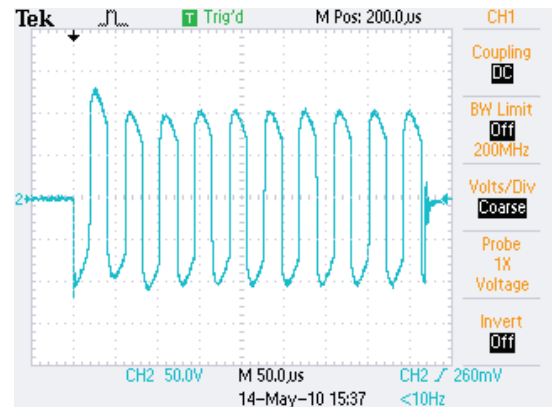

Figure 6. One macro current pulse in the secondary side.

Figure 4. The flow charter of current signal for one half cycle.

The power transfer capacity of the system is first tested with one dummy load. One current macro pulse in resonant capacitor C_r is measured by 40 A/1 V current probe, which is calibrated by one PEARSON^{TM} CURRENT MONITOR from Pearson Electronics, Inc. The macro pulse composed by 20 micro pulses is shown in Figure 6. In Figure 6, the operation parameters in Figure 5 are inputted as t_0=10 (x0.1 μs=1 μs); t_1=200 (x0.1 μs=20 μs); t_2=20; t_3=100000 (x0.1 μs=10000 μs), where t_0 is the locked dead time between switching IGBT1, IGBT4 and IGBT2, IGBT3 in turn for avoiding triggering one half bridge at the same time, which is 10 x 0.1 μs=1 μs; t_1 is the micro pulse time which is 200 x 0.1 μs=20 μs; t_2 is the continuous micro pulse number which has no unit; t_3 is the macro pulse period which is 100000 x0.1 μs=10000 μs. 166 A peak current in the secondary side is excited by 310 V dc rectified voltage in the primary side from 220 V single phase ac. In the future it will be changed to 3 phase 380 V ac line voltage. After further rectifying the current in the secondary side as shown in Figure 6, any arbitrary defined pulse time by PC could be developed. After Schottky rectifier 409CNQ150 and HF filter, the macro current pulse is rectified as dc current pulse as shown in Figure 7, which have been extended to over 100s for bias power supply of EAST NBI snubber by setting larger micro pulses in one macro pulse.

Figure 7. One macro current pulse after rectifier.

Layout of the compact NB power supplies are illustrated in Figure 8, where load 1, load 2, load 3, load 4, load 5 are respectively Snubber Bias PS, Filament PS, Arc PS, control PS and Suppressor PS. It could eliminate all 50/60 Hz isolation transformers for Arc, Filament as well as the control PS on HV side, which use HV HF power pick-ups to compact the whole PS system, just as the traditional IPT system which will be developed in our future work for HV insulation purpose.
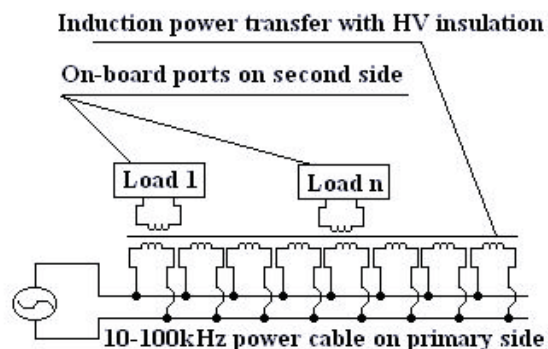

Figure 8. Layout of the Compact PS system for Tokamak heating.

5 CONCLUSION

1. The PC controlled power supply with high insulation voltage is designed, built and tested by implementing unique automatic adaptive ZCS IPT technology. The frequencies of macro pulses and micro pulses can be arbitrarily tuned below resonant frequency to digitalize the HV pulse power, which satisfies arbitrary needs of different loads. Design and tests to its application as snubber testing bias PS shows that insulation over 90 kV for EAST NBI can be achieved with HV HF transformer, which is soundless and much more compact than conventional 50/60 Hz insulation transformer due to that it is working on over 20 kHz, the same technology could be scaled up to all NB pulsed power supplies, which makes the system compact and easy to be used. Owing to avoiding the 50/60 Hz HV insulation transformer with noise, new soundless and space saving insulation possibility is suggested to be implemented with high frequency distributed transformers, i.e. IPT for plasma heating power supplies, where traditional voltage tuning with variable frequency is avoided and power could be more accurately and safely transferred to the different loads by requirements.

Presently three 50/60 Hz isolation transformers are embedded in Figure 1 for arc, filament and snubber bias and control power supplies. In the new version, Figure 8 gives one concept to eliminate all 50/60 Hz isolation transformers for arc, filament, snubber as well as the control PS on the HV side, which usees HV HF power pick-ups to compact the whole PS system, just as the traditional IPT system which will be developed in our future work for HV insulation purpose.

2. The Tokamak is generally a very high energy density device where extra high voltage at 1 MV and super high current at 68 kA are existed at the same time [10], together with the plasma current at 17 MA in ITER. The issue of 1MV insulation could be implemented by solid state insulation with over 50 mm thickness, where windings in different voltage potential are magnetically coupled on their respective high frequency cores. Developing these compact HV ZCS power supplies is necessary and useful for all Tokamak experimental system, such as NB, Radio Frequency or other plasma heating, fast control [13] and diagnosis system. Together with high Q_2 voltage multiplication of LC series resonant circuit [8, 12], these compact HV PS could find their places not only in Tokamak, but also in industry application, such as electric vehicles and uninterruptible power systems [14, 15].

ACKNOWLEDGMENT

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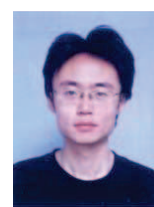
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