Development of 3 MW Dual Output High Voltage Power Supply for ICRH System

A.Patel, H. Dhola, D.Upadhyay, B. Raval, K.Mehta.N. Goswami, N. P. Singh, A.Thakar, D. Parmar, S.Gajjar, R. Dave, V. Gupta, U.K.Baruah
Power Supply Group
ITER-India, Institute for Plasma Research
Ahmedabad, INDIA
Email: ampatel@ipr.res.in

S.Athaullah, Y.Dileep, A. Rajakiran D.H. Rathod,N.Appa Rao, K.Mahadev
Power Electronics Projects Section
Electronics Corporation of India Limited
Hyderabad, INDIA
Email: pep@ecil.co.in

Abstract*—High voltage power supply (HVPS) based on pulse step modulation (PSM) topology has already demonstrated its ability for broadcast transmitters, accelerators using radio frequency (RF) source and neutral beam injectors. Typical ion cyclotron resonant heating (ICRH) system composed of cascaded connection of driver stage and end stage would need two power supplies. A novel concept of tapping two outputs from single PSM based HVPS is attempted for the first time. A PSM based HVPS is developed with dual output to feed driver and end stages of a high power RF amplifier. This article discusses the development of a HVPS, capable to provide 14-18 kV, 250 kW to driver stage and 16-27 kV, 175-105 A, 2800 kW to end stage RF amplifier chain. Here dual output are controlled independently by single FPGA based PXI controller which support all pros of PSM based HVPS like low ripple, fast dynamics and very short time to turn-off. Discussed HVPS supports non-linear demand from ICRH system i.e. lower current (105 A) at higher voltage (27 kV) and higher current (175 A) at lower voltage (18 kV), which developed as indoor compact solution. As an add-on specification, HVPS facilitates 1 kHz RF power modulation. The HVPS is composed of two cast resin multi-secondary transformers (CRT), 48 numbers of switched power supply (SPS) modules; FPGA/real time based controller and other auxiliaries including passive protection devices. Present article describes technical details of HVPS components which are manufactured to IEC standards. HVPS with dual output is an effective replacement to conventional solutions, as it offers optimized solution for equipment bulk as well as economy.

Keywords—High Voltage Power Supply, Pulse Step Modulation, Multi-secondary transformer, Switched Power Supply Module, Radio Frequency Amplifier.

I. Introduction

High temperatures inside tokamak for fusion research is achieved from auxiliary heating systems like neutral beam injectors (NBI), or RF heating devices, viz., ion cyclotron (IC), electron cyclotron and lower hybrid systems (using high power vacuum tubes, tetrode/diacrode, gyrotrons and klystrons respectively) [1-4]. The ion source and vacuum device need HVPS for its operation [1], [5-10]. These systems are typically with voltage ratings in the range 30-100 kV and power level in 3 to 8 MW. The operation requirements of these HVPS include strict specifications in voltage regulation, ripple, accuracy and short circuit energy [1-4]. In addition, the HVPS must support fast dynamics, i.e. rise and fall time of µs order, fast turn-off (<10µS) and transient responses. PSM based HVPSs using fast power semiconductors accomplishes such specifications simply by its control and topology. A dual output HVPS had additional advantage of being two HVPSs feeding two stages of a RF amplifier chain being merged into one, which is proposed to be used in ITER [1], [15-16].

II. ICRH System for ITER

For ITER, each chain of ICRH RF source has to provide 1.5MW power in frequency range of 35- 65 MHz for 3600 seconds [2], [15-16]. The system must be capable to operate both at matched and mismatched load condition (VSWR 2). A cascade chain of amplifier is a practical solution due to limiting level of power of available vacuum tubes. As shown in Fig.1, the ICRH system at ITER-India experimental setup consists of high power amplifier-1 (HPA-1), HPA-2 and HPA-3 where input power is amplified from few watts to 1.5MW [2]. For HPA-2 and HPA-3, HVPSs are required with voltage and power requirement of 14-18 kV, 250 kW and 16-27 kV, 2800 kW, respectively. From system point of view, 2 numbers of closely synchronised PSM based HVPSs are required to support the cascade of power amplifiers as in configuration shown in Table I.

However, in the present development two such HVPSs have been merged into a single dual output system with a controller designed to run two independent control loops. Present article focusses on the most recent evolutions and achievements with the HVPS having two outputs.

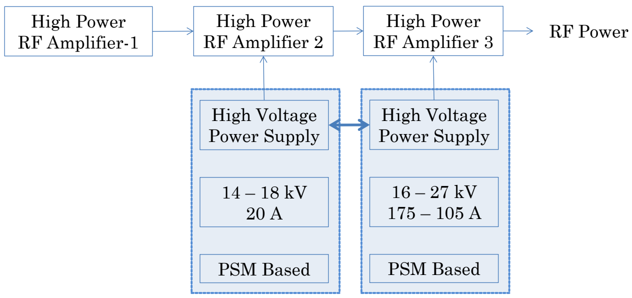

Fig. 1 : ICRF System Block Diagram

TABLE I. RF AMPLIFIER CONFIGURED WITH 2 HVPSS

Components	**HVPS for HPA-2**	**HVPS for HPA-3**
	14-18 kV , 250 kW HVPS	***16-27 kV , 2800 kW HVPS***
Multi-secondary Transformer	1 Number having 32 secondary winding , 22 kV class	1 Number having 48 secondary winding ,22 kV class
SPS Module	32 numbers of 690 V ,15 A	48 numbers of 690 V ,175 A

III. DUAL OUTPUT HVPS FOR ICRF

To overcome the requirement for different HVPS for different stages of RF amplifiers, the dual output HVPS was developed with intermediate tapping to feed HPA-2 as shown in Fig.2. First 32 SPS modules along with transformer form a HVPS for HPA-2, addition of another 16 SPS modules and a transformer form the HVPS for HPA-3. For ease of manufacturing and for proper load sharing on all secondary windings, two multi-secondary transformers are used. In general terms, higher side SPS modules, i.e. 33^{th} to 48^{th} SPS modules contribute the ΔV above the output V for HPA-2, to feed V+ ΔV for HPA-3.

The dual output configuration holds several advantages over conventional scheme. Adaption of single HVPS for full cascaded chain increases power density remarkably, as creepage distance and clearances for compliance to HV installation practices are to be maintained for single HVPS only. Another important advantage is savings on equipment and effective capacity utilisation. Conventional scheme would have demanded 2 HVPSs with 80 (32+48) SPS modules and most of them (32 numbers of SPS modules) operating at very low power level (15A) compared to available capacity of 100A (semiconductor devices at 690 V class). HVPS with dual output requires only 48 SPS modules, where SPS modules from 1 to 32 carry additional current of 15A without affecting investment in semiconductor capacity selection or on the auxiliaries like cables, etc. Operational benefits include ease of synchronisation between two outputs that can be managed from same controller.

However, there are challenges associated with control of dual output for both stages by single controller. When the RF load of the amplifier is in mismatch condition, voltage requirement for both stages [1] (HPA-2 and HPA-3) become identical, loading transformer-1 in excess (Fig.2).

IV. HVPS SPECIFICATIONS & CONFIGURATION

Specifications for the developed dual output HVPS are mentioned in Table II, the configuration is as in Fig.2 while major components used are mentioned in Table III. The HVPS installation at our laboratory consists of two CRTs at ground level and HV cabinets (housing SPS module and other accessories) located on mezzanine floor, as shown in Fig 3.

TABLE II. SPECIFICATIONS OF HVPS

Parameter	**Value**	
Input	Input voltage : 22 kV ± 10 % , 50 Hz	
Output	HVPS for HPA-2	14-18 kV , 250 kW
	HVPS for HPA-3	16-27 kV, 105 – 155 A ,2800 kW
Accuracy	± 1 % of maximum value of particular stage	
Resolution	100 Volts	
Ripple	± 1 % of maximum value of particular stage	
Rise Time	100 µs to 5 ms (Programmable)	
Transient Response	Less than 1ms (18kV to 27 kV)	
Energy dumped into a fault in the load must be remain less than 10 J.		

TABLE III. COMPONENTS FOR HVPS

Components	**Details**	
Multi-secondary Transformers	2 numbers of 22 kV class transformers	Transformer -1 with 32 (16 star & 16 delta)secondary windings
		Transformer -2 with 16 (8 star aand 8 delta) secondary windings
SPS Modules	48 numbers of 690 V AC input Class	32 Modules with 690 V_{DC},190A
		16 Modules with 690 V_{DC},175A
Controller	1 controller with dual control loops , both works independenly with synchronisation	

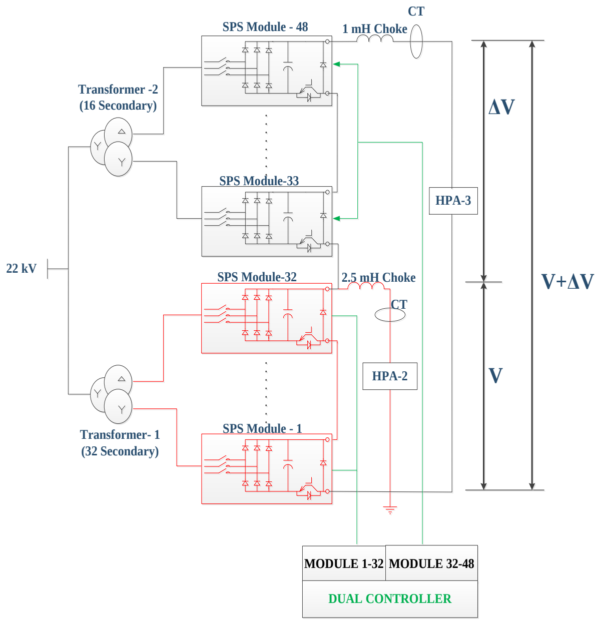

Fig. 2: Dual Output HVPS

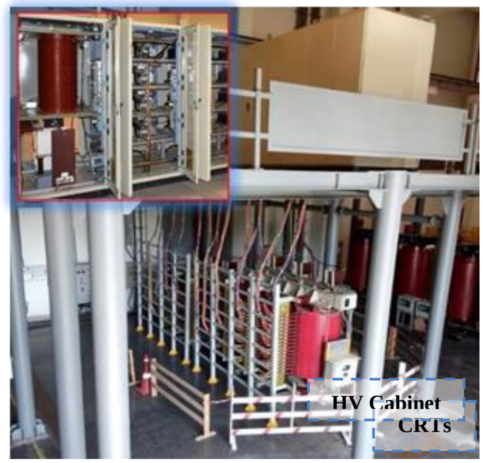

Fig. 3: Installed HVPS

IV. Description of HVPS

The HVPS was configuration using readily available components minimising customised components as described in subsequent sections.

A. *Multi-Secondary Transformers*

In PSM based HVPSs, multi-secondary transformer provide required power with essential isolation between each series connected SPS modules.

Different types of multi-secondary transformers are popular, viz., oil cooled transformers [6-7], dry type, either, vacuum pressure impregnated (VPI) or cast resin transformer (CRT) [8-9]. Oil cooled transformers are popular for higher insulation voltages though stray capacitance among secondary windings may be a concern at light load operations [11]. CRT having low inter-winding capacitance are better suited for the indoor installation specified for the application.

The CRTs meets the necessary fire safety requirements for indoor installations. With advancement in CRT technology, manufacturing of transformers up to 140kV has already been reported [12].

For dual output HVPS, specifications for manufactured transformers with IEC60076-11 and IEC61378 conformance, are mentioned in Table IV.

TABLE IV. Transformer Specifications

	Transformer - 1	**Transformer -2**
Rating	2800 kVA	1200 kVA
Primary Voltage	22 kV , 50 Hz (Star)	22 kV , 50 Hz (Star)
Secondary Voltage	542 V AC	542 V AC
Number of windings	32 Numbers (alternate D-Y)	16 Numbers (alternate D-Y)
% Z	8 %	7.2 %
Voltage withstand	50 kV DC from Ground	
Voltage withstand	3 kV DC with adjacent secondary windings	
Insulation Class	Class – F	
Cooling	AN/AF	

B. *Swicthed Power Supply Module (SPS Module)*

A SPS module consists of input rectifier followed by buck converter generating pulsating dc output in accordance to PWM pulses from HVPS controller. Each SPS module dc link voltage is 690 V_{DC} and is able to provide continuous peak current of 200 A. Semiconductor selections was done following manufacturer's recommendation on derating and thermal design. Input voltage class (close to) 690V enabled selection of components (i.e., contactors, diode, capacitors and IGBT) in their standard range. Power schematic for SPS module is shown in Fig. 4, while manufactured SPS module is shown in Fig.5. The SPS modules are open architecture type and water cooled for minimum heat dissipation in air. Two contactors at input allow for soft charging and isolation of SPS from input supply. SPS modules communicate with HVPS controller with 4 numbers of fibre optic links. The SPS modules are designed with high efficiency and compliant to IEC60146 and IEC61000-6-2.

C. *Physical Layout*

PSM based HVPS are formed by series connection of cascade SPS modules need progressive isolation from ground and among adjacent modules. Voltage withstand capability was designed in the transformer and physical layout including clearances of cable works and mounting structure. In the present design, the HVPS is a metallic enclosure at ground potential with SPS modules installed on fibre-reinforced plastic (FRP) structures. Design of internal creepage and clearance followed prescription of IEC61936 and UL840 standards and tested for 40 kV dc voltage withstand. Outer dimension of the HVPS cabinet is 8m (L) x 1m (W) x 2.4m (H), it houses 48 numbers of SPS modules, 2 numbers of inductors, output disconnector switch and hydraulic network with instrumentation. The transformers are installed below the HV cabinet as shown in Fig.3.

D. *Controller*

In PSM based HVPS, desired output voltage is generated by applying PWM pulses to SPS modules [5-10]. A single controller handles two independent voltage control loops for dual outputs. Switching frequency is same for all SPS modules while PWM duty and phases are distinct for the two outputs. Controller architecture and hardware is as shown in Fig.6 and Fig. 7 [13].

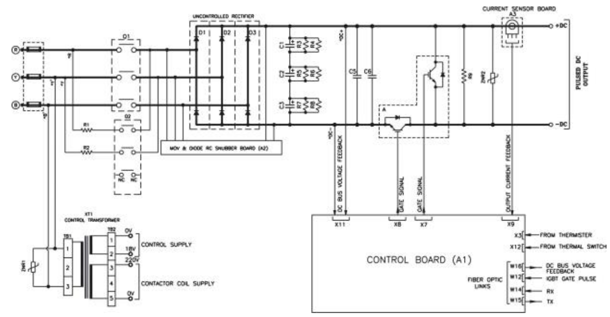

Fig. 4: SPS Module Power Diagram


Fig. 5: Manufactured SPS Module

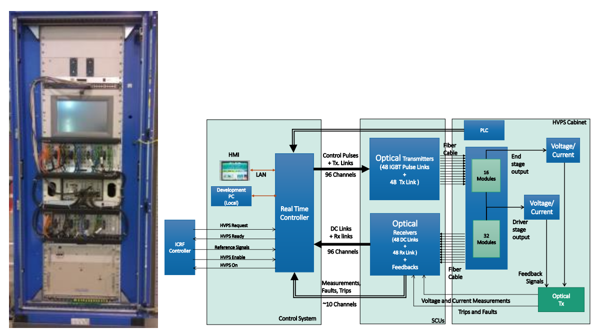

Fig. 6: PXI based HVPS Controller

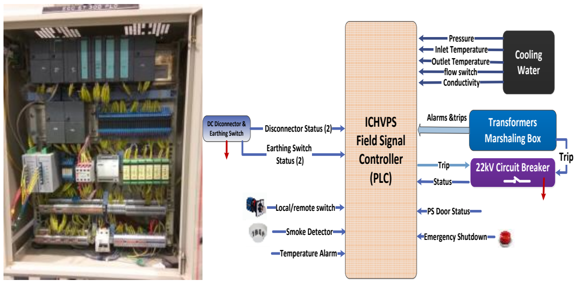

Fig. 7: PLC based HVPS Controller

The controller is implemented on a FPGA module on PXI based hardware. The voltage control and fast protection functions are implemented on this controller. It generates PWM pulses for SPS modules and takes care for load protections i.e. fast turn-off. All other safety, monitoring and interlock protection (e.g., safety switches, cooling water parameters, etc.) functions are implemented on a separate PLC based slow controller.

E. Measurment and Passive Protection

Voltage and current measurements with isolation to the operating voltage level were used at each output of the HVPS. The electrical signals from sensors are converted to optical form for transmission with isolation and used for feedback corrections and load protections [14]. As current and voltage monitoring units serve part of load protection, these are developed to IEC61000-4 with “Class A” qualifications. Air core inductors, one 2.5 mH (at output of HVPS for HPA-2) and another 1 mH (at output of HVPS for HPA-3) are used for filter of the high frequency ripple at the output as well as reducing the rate of rise of current in case of a fault in the RF Amplifiers.

V. TESTING ON RESISTIVE LOAD BANKS

The HVPS was subject to validation tests with resistive pulse duty load banks and simulated fault conditions. Fig. 8 (a) is an oscillogram showing both outputs of the HVPS at 14.3 kV (15 A) and 27 kV (105 A). Similarly, Fig. 8 (b) presents dual output of HVPS at 14.6 kV, (15 A) and 15.7 kV, (155A). Fig.9 (a) and Fig.9 (b) are for the attributes of rise and fall times, both are 500 µs in this case. Fig.10 shows ripple voltage at HVPS for HPA-3 operating at 17kV, 155A. The measured ripple (336 $V_{P\text{-}P}$) is well under specified limits of $\pm$ 270 V. Fig.8 (b) and Fig.11 shows the achievable resolution in step of 100V. For load regulation test, output voltage waveforms (of HVPS for HPA-3) were observed at no load and full load conditions keeping other parameters unchanged. In both cases, average output voltages remain same as shown in Fig.12 (a) and Fig.12 (b). It may be noted that at no load, due to use of only an L-R type filter at output, the ripple observed is higher.

To demonstrate low energy dump (<10 Joules) during a fault, wire bun test was performed. The test setup used a fuse wire of specified length in series with a short circuit switch, across HVPS output. Following the short circuit in each case, the controller detects and blocks all IGBT pulses to bring the HVPS output voltage to zero within 10µs. The action is fast enough to leave the fuse wire intact during the test. Test results for short circuit test on HPA-3 of HVPS are shown in Fig.13. The plot (a) shows the time elapsed for activation of the protection and plot (b) shows the rise and decay of fault current in the HVPS.

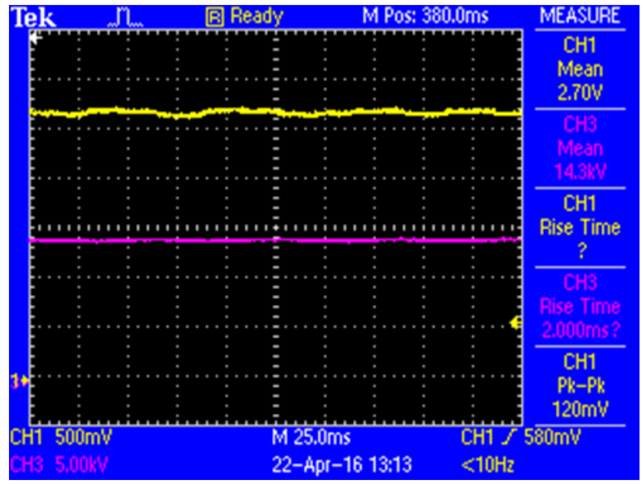

Fig. 8(a): HVPS output
Ch-3 (x10000), Ch-4 (x1)

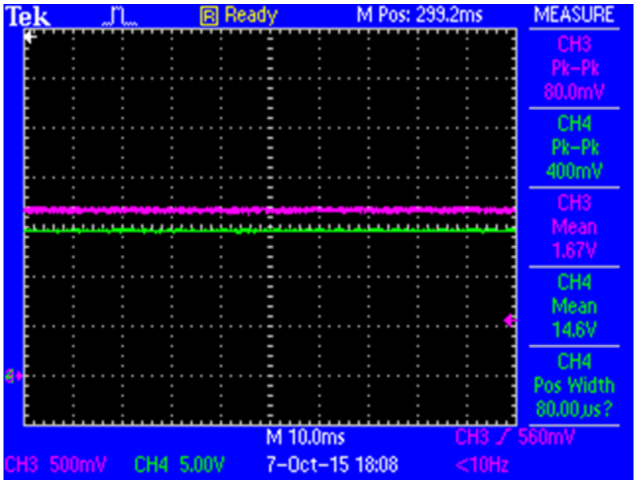

Fig. 8(b): HVPS output
Ch-3 (x10000), Ch-4 (x1000)

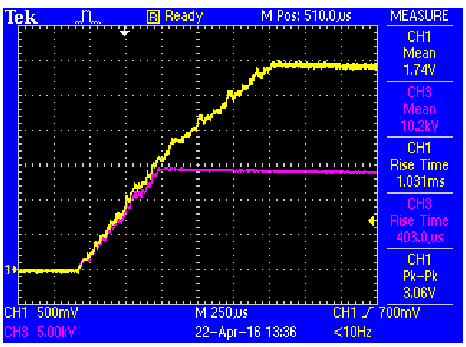

Fig. 9(a): Rise time
Ch-1 (x10000), Ch-3 (x1)

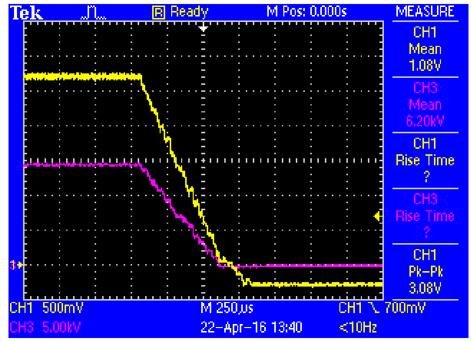

Fig. 9(b): Fall time
Ch-1 (x10000), Ch-3 (x1)

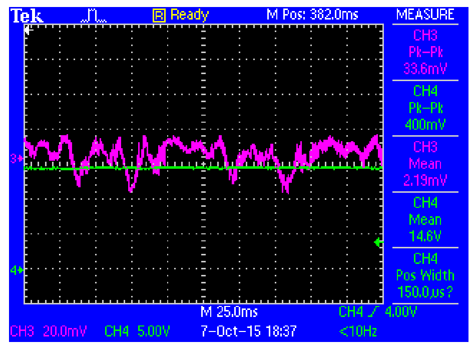

Fig 10: HVPS ripple
Ch-3: (x10000), Ch-4: for trigger

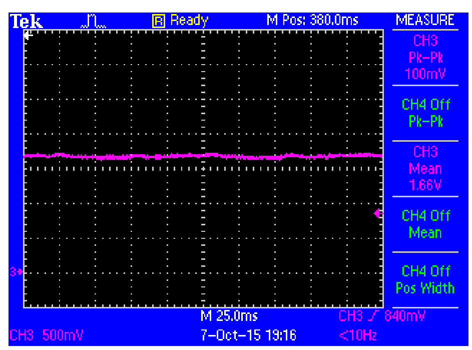

Fig.11: ResolutionCh-3 (x10000)

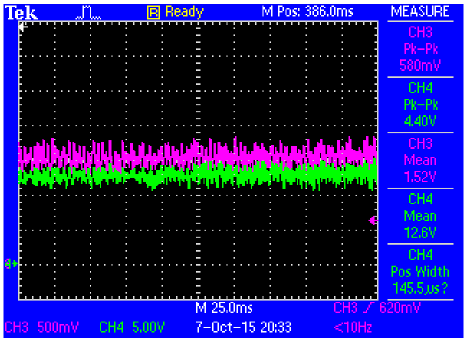

Fig. 12(a): HVPS output at no load
Ch-3 (x10000), Ch-4 (x1000)

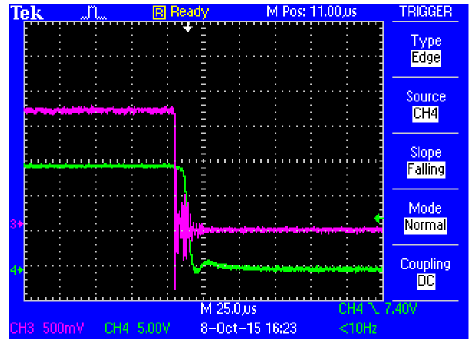

Fig. 13(a): Short Circuit Test-HPA-3, Ch-4 (x1000)

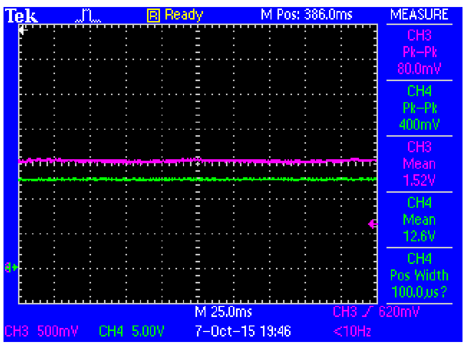

Fig. 12(b): HVPS output t rated load
Ch-1 (x10000), Ch-3 (x1000)

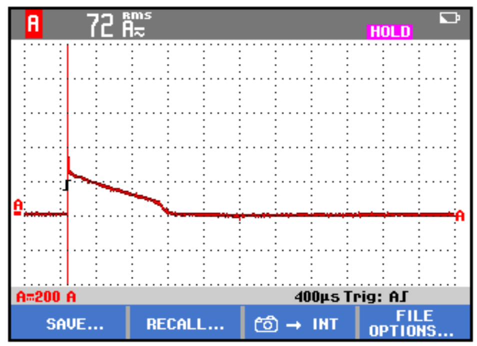

Fig. 13(b): Short Circuit Current at HPA-3

VI. Operation on RF Amplifiers

Following the validation on dummy load, the Dual Output HVPS has been integrated with the high power RF amplifiers and being operated for extended duration of 3600 seconds continuously at rated power as shown in Fig.14. HVPS efficiency and power quality parameters are presented in Table V.

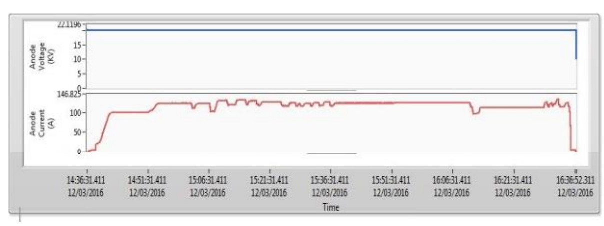

Fig. 14: HVPS operation for 7200 seconds

TABLE V. Effeicinecy & PQ Parameters

Parameter	Value
Observed Efficiency (%)	96 %
THD (Current @ 22 kV Side)	8 %
Voltage (@ 22 kV Side)	22 kV
Current (@ 22 kV Side /Per Phase)	76 A
Overall Power Factor	0.99

VII CONCLUSION

Development and initial operating experience of a dual output high voltage power supply has been described. Novelty of obtaining dual output is achieved by implementing a controller capable of running two independent control loops. The solutions save one complete HVPS which would otherwise have been necessary to run two stages of the High power RF amplifier.

REFERENCES

[1] T. Gassmann, B. Arambhadiya, B. Beaumont, U.K. Baruah, T. Bonicelli, C. Darbos, D. Purohit, H. Decamps, F. Albajar, F. Gandini, M. Henderson, F. Kazarian, P.U. Lamalle, T. Omori, D. Parmar, A. Patel, D. Rathi, and N.P. Singh, "High voltage power supplies for ITER RF heating and current drive systems," Fusion Eng. Des., vol.86, pp 884–887, Oct. 2011.

[2] A. Mukherjee et al, "Status of R&D activity for ITER ICRF power source system," Fusion Sci. Technol., vol. 96-97, pp. 542-546, Oct. 2015.

[3] P.K.Sharma et al,"Proposed high voltage power supply for the ITER relevant lower hybrid current drive system," Fusion Eng. Des., vol.86, pp. 819-822, Oct. 2011.

[4] T.Omori et al, "Overview of the ITER EC H&CD system and its capabilities," Fusion Eng. Des., vol.86, pp. 951-942, Oct. 2011.

[5] J. Alex, W. Schminke, "Fast switching modular high-voltage DC/AC-power supplies for RF-amplifiers and other applications", in Proc. 16th Symp. Fusion Eng., 1995, pp. 936-939.

[6] P. J. Patel, N. P. Singh, V. Tripathi, L. N. Gupta, and U. K. Baruah,"A regulated high voltage power supply for accelerator driven system," International topical meeting on nuclear research applications and utilization of accelerators, May 2009, Vienna.

[7] P. J Patel et al, "Regulated high voltage power supply (RHVPS):integration, operation, and test results with LHCD system of SST-1," IEEE Trans. Plasma Sci., vol. 42, no. 3, pp. 651-655, Mar. 2014.

[8] P. J. Patel et al, "Development overview of solid-state multimegawatt regulated high-voltage power supplies utilized by NBI and RF heating systems," IEEE Trans. Plasma Sci., vol. 41, no.1, pp. 263-268, Jan. 2013.

[9] W. Xu, W. Xuan, L. Yao, and Y. Wang, "Development of 8 MW power supply based on pulse step modulation technique for auxiliary heating system on HL- 2A," Plasma Sci. Technol., vol.14, no.3, art. no. 263, Mar. 2012.

[10] D. Fasel et al, "5MW CW supply system for the ITER gyrotrons test facility," Fusion Eng. Des., vol.86, pp. 872-875, Oct. 2011.

[11] N. P. Singh et al, "Studies on the behavior of multisecondary transformers used for regulated HV power supplies," Fusion Eng. Des.,vol.75-79, pp. 127-133, Nov. 2005.

[12] V. Tripathi, N. P. Singh, L. N. Gupta, K. Oza, P. Patel, and U. K. Baruah, "Development of cast resin multisecondary 1600kVA transformer for regulated high voltage power supply- A prototype," J. Phys.: Conf. Ser., vol. 208, art. no. 012005, 2010.

[13] H. Dhola et al, "Data transfer methods in real time controller of ion cyclotron high voltage power pupply," in Proc. NPSS Real Time Conf., Padua, Italy, June 6-10,2016.

[14] H. Dhola et al, "Using voltage to frequency conversion for close loop control in HVPS," DAE-BRNS National Symposium on Nuclear Instrumentation (NSNI 2013).

[15] F. Kazarian et al, "RF sources for ITER ion cyclotron H&CD system," Fusion Eng. Des., vol.86, pp. 888-891, Oct. 2011.

[16] P. Lamalle et al., "Status of the ITER Ion Cyclotron H&CD system," Fusion Eng. Des.,vol. 88, pp. 517-520, Oct. 2013.

[17] "NI R Series for "PXI" datasheet.

[18] IEC60076 : Power transformers.

[19] IEC61378:Converter Transformers.

[20] IEC60146: Semiconductor converters.

[21] IEC61936: Power installations exceeding 1 kV.

[22] UL840 : Standard for Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment.