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


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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.


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/diacode, 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 50-100 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 has 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.
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Input voltage : 22 kV ± 10 % , 50 Hz</td>
</tr>
<tr>
<td>Output</td>
<td>HVPS for HPA-2 14-18 kV , 250 kW</td>
</tr>
<tr>
<td></td>
<td>HVPS for HPA-3 16-27 kV , 2800 kW</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 1 % of maximum value of particular stage</td>
</tr>
<tr>
<td>Resolution</td>
<td>100 Volts</td>
</tr>
<tr>
<td>Ripple</td>
<td>± 1 % of maximum value of particular stage</td>
</tr>
<tr>
<td>Rise Time</td>
<td>100 μs to 5 ms (Programmable)</td>
</tr>
<tr>
<td>Transient Response</td>
<td>Less than 1ms (18 kV to 27 kV)</td>
</tr>
<tr>
<td>Energy dumped into a fault</td>
<td>The load must be remain less than 10 J</td>
</tr>
</tbody>
</table>

### TABLE III. COMPONENTS FOR HVPS

<table>
<thead>
<tr>
<th>Components</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-secondary Transformers</td>
<td>Transformer-1 with 32 (16 star &amp; 16 delta) secondary windings</td>
</tr>
<tr>
<td></td>
<td>Transformer-2 with 16 (8 star and 8 delta) secondary windings</td>
</tr>
<tr>
<td>SPS Modules</td>
<td>32 Modules with 690 Vdc,190A</td>
</tr>
<tr>
<td></td>
<td>16 Modules with 690 Vdc,175A</td>
</tr>
<tr>
<td>Controller</td>
<td>1 controller with dual control loops , both works independently with synchronisation</td>
</tr>
</tbody>
</table>
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       | 16 Numbers       |
| (alternate D-Y)  | (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. Switched 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 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].
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. Measurement 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_{pp}) is well under specified limits of ± 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(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: Resolution
Ch-3 (x10000)
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. 12(a): HVPS output at no load Ch-3 (x10000), Ch-4 (x1000)](image)

![Fig. 12(b): HVPS output at rated load Ch-1 (x10000), Ch-3 (x1000)](image)

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

![Fig. 13(b): Short Circuit Current at HPA-3](image)

![Fig. 14: HVPS operation for 7200 seconds](image)

**TABLE V. EFFICIENCY & PQ PARAMETERS**
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