HIGH POWER SOLID STATE RF GENERATOR FOR NEUTRAL BEAM INJECTOR

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Abstract

Neutral Beam Heating Injector of 1 MW beam power for the TCV tokamak (Lausanne, Switzerland) was developed in BINP. The plasma is formed in a plasma box with inductively coupled RF power at frequency about 4MHz. Required RF power in the plasma box is up to 40kW during the period of 2 seconds with 5 minutes intervals [2]. Solid state RF generator with such capability has been developed in BINP. Description of the RF generator design, main features and the test results are presented in the report.

INTRODUCTION

The TCV tokamak (literally "variable configuration tokamak") is a research fusion reactor of the Federal Institute of Technology in Lausanne (EPFL). The upgrade program that is underway on TCV extends the power range of existing Electron Cyclotron Resonance Heating (ECRH) and adds direct ion auxiliary heating using Neutral Beam Injection [1]. At this time Neutral Beam Injector (NBI) is installed and the first 1 MW neutral beam is being commissioned. Plasma emitter of the NBI is powered with RF energy up to 40 kW from the solid state RF Generator.

GENERATOR LAYOUT

The Solid State RF generator is a modular system, it consists of 16 identical RF modules (placed in 2 racks), control modules, combiners, DC power supply – RFG DC PS. Output signal through coaxial feeder, matching network and decoupling HV transformer is applied to plasma emitter. Plasma emitter inductance with additional capacities form a resonant circuit tuned to the operating frequency of 4 MHz. "Matching network" converts subsequent circuit impedance to the characteristic impedance of the feeder at this frequency.

Generator's block diagram is shown in Fig. 1. Output signal is formed by summing the voltages of two identical generators RFG20 in "Final combiner". Both generators are working in-phase. The only difference is that one of them operates in "Master" mode while another one in "Slave" mode. Mode of operation is defined by operation mode of RF Control modules.

Block diagram of one of generators RFG20 is shown in Fig. 2. Generator is placed in one electronic rack and consists of 8 identical units "RF Module", output signals of which are summed in two stages of summation: first stage is Combiner1 and second is Combiner2. Both stage's combiners are implemented by identical scheme of 4-inputs combiner with 50 ohm input and output impedances. Each 4-inputs combiner of the first stage is supplied by in-phase signals from two "RF Modules" with two identical power cells inside. Similarly, the second stage's Combiner2 is supplied by signals from two combiner modules of the first stage.

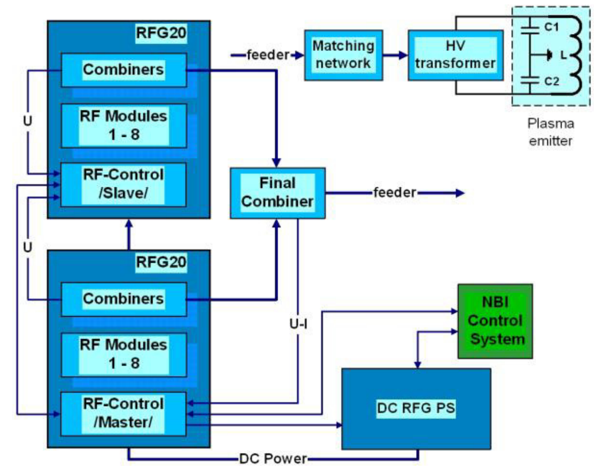

Figure 1: Generator layout.

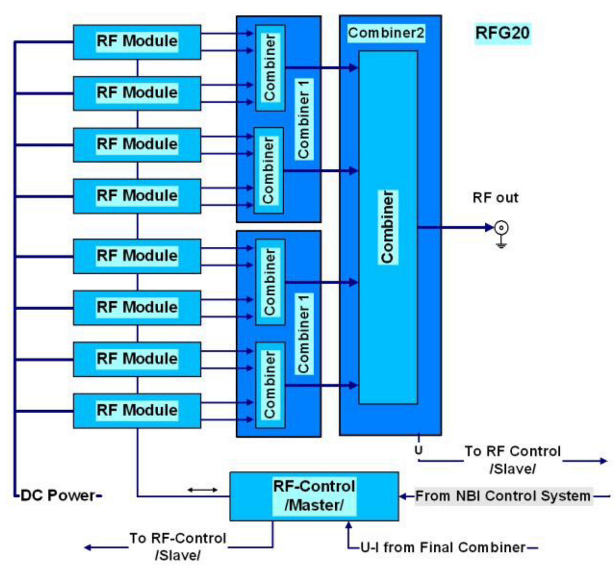

Figure 2: Block diagram of RFG20 generator.

DC power supply unit provides power cells of RF modules with adjustable power voltage. Output RF voltage of 4 MHz in the load is proportional to DC power supply voltage. The NBI system must be able to on/off modulate the beam with a minimum on/off-time of a few ms and to gradually vary the power injected into the tokamak in the range of 30-100% of full nominal power. Beam current from Injector is modulated by changing RF

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power in the plasma emitter which is performed by changing the voltage of RFG DC PS.

ELEMENTS OF THE RF GENERATOR

All the elements of RF generator are placed in four 19” racks with dimensions 600*800*2000 mm. RFG20 generators are placed into two of them and DC Power supply with the Output combiner occupy the rest two. The system does not need water cooling and uses forced air cooling.

RF Modules

All RF Modules contain two identical power cells, control circuit and protection circuits. Each power cell is based on push-pull configuration with fast power transistors manufactured by IXYS RF, operating in the switching mode class DE. Such mode allows obtaining a high efficiency (about 85%). The cells have local protection from overloading by voltage, current or temperature. If one of these parameters exceeds the established threshold, transistors close. The over current protection for each cell is performed by measuring DC power current of the cell with current sensors. Fast protective diodes connected to transistor’s drains with comparison circuit serve as overvoltage protection. Thermal switch mounted on the cooling radiator protects against over temperature. There is also protection from input clock signal disappearance. Control circuit accepts input signals from RF Control modules and forms signals for power cells drivers. It also provides the necessary protections and communication with RF Control modules. Every module is assembled in 3U chassis and has forced air cooling.

Combiners

The combiners of both stages of RFG20 generator are realized by cascading two 2-input combiners with current summation followed by 2-input combiner with voltage summation. This configuration forms 4-inputs combiner of in-phase signals with independent and isolated to each other 50-ohms inputs.

The final combiner circuit is based on Wilkinson schematic. At 4 MHz central frequency it has 50 ohm input impedance for the load of 50 ohm. In-phase signals from two RFG20 are applied to its inputs. Output signal is measured by current and voltage measuring transformers. Measured signals are transmitted to RF Control module for further processing.

RF Control

RF Control modules perform following tasks: distribution of the control signals, clock frequency generation for RF modules, measuring parameters of output signal and protection of the generator. Two control modules have identical structure, one of them operates as control unit in "Master" mode, and another one operates in "Slave" mode. Block diagram is shown in Fig. 3.

Module contains two fast ADCs with 100 MHz sampling frequency for voltage and current measuring, reference oscillator, DAC for making analogue signals to transfer to NBI control system and output drivers to form clock and control signals for RF modules. All necessary digital signal processing is fulfilled inside the FPGA Cyclon 3 (ALTERA).

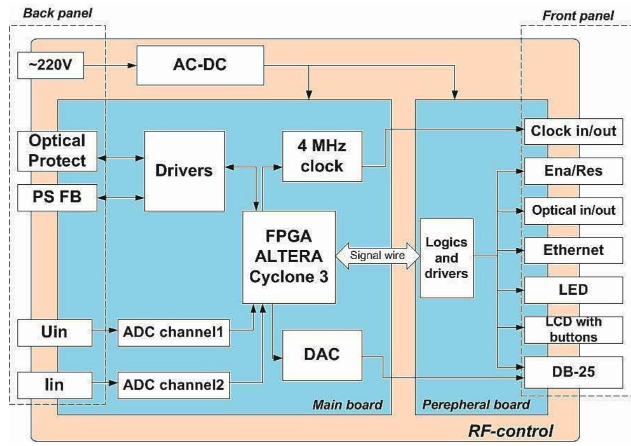

Figure 3: Layout of RF Control module.

RF Control module performs state data reading from RF modules in the case of protection take place. Every RF module has its own local protections. The single optical protection line connects all the modules serially into the ring. If protection in any block takes place RF Generator is blocked and DC power supply switches off the voltage. There is also protection against voltage disbalance between two RFG20 and against long time working without burning plasma (>50 ms).

DC Power Supply

RFG DC PS serves as the source of DC power voltage in the range of 100 ... 300 V and up to 80 kW power. Power supply is a stabilizer of two independently adjustable voltages U(LOW) and U(HIGH), which can be set by two references DAC1 and DAC2. Block diagram of the source is shown in Fig. 4.

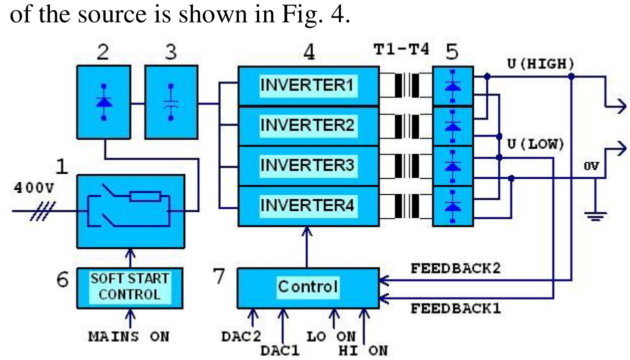

Figure 4: DC power supply layout.

Power supply consists of soft switching device of a network rectifier (1) with control (6), capacitive filter (3) of a network rectifier (2), four IGBT - inverters (4). Inverters provide a rapid regulation of the output voltage for low or base level U(LOW) and high level U(HIGH). The voltage of the inverters is regulated by pulse-width modulation at 20 kHz frequency and fed to decreasing

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high-frequency transformers (T1...T4), rectified using diode rectifiers (5). Output voltage stabilization scheme (7) provides independent control for U(LOW) and U(HIGH) levels.

RF Power Ttransmission Path

The plasma is formed in a plasma box with inductively coupled RF power. Burning plasma changes parameters of plasma emitter as a load. It shifts the frequency of the resonant circuit and changes the active load depending on plasma parameters and RF power modulation. The most effective power transfer is for matched load. In this case it was decided to work at fixed frequency with fine matching at high nominal power level and tolerate degradation at lower ones. So plasma emitter resonant circuit has constant reactive elements. High voltage DC decoupling RF transformer is used for electrical insulation from the RF antenna biased to 30 kV potential during ion source operation. It has ferrite magnetic core and is placed in tank with Middel-isolating material. Matching network before the input of HV transformer has C-L-C structure with fixed elements tuned for exact matching at high power level.

RESULTS

During the period from June 2015 to January 2016 NBI was assembled and tested on TCV. In the end of January 2016 first NBI shots in TCV were made with plasma, and neutral beam heated plasma on TCV.

Photography of the RF generator is shown in Fig. 5.

Figure 5: Four cabinets of RF generator. Nearest two racks are occupied by RFG20, next two contain DC power supply and final combiner.

The generator gave RF power up to 40 kW with the pulse duration 2 sec. Fig. 6 demonstrates measured power and phase shift between voltage and current at generator output in one of the shots. Power level was modulated in steps from 15 to 37 kW by changing DC power supply

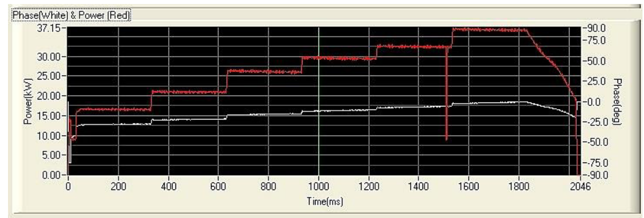

Figure 6: RF power (red) and phase shift between voltage and current (white) at generator output.

voltage. Matching is good enough at high power level and degrades at lower levels. Impedance measured at feeder input for high power level is 49.9 ohm with angle -2.2 degrees, at low level angle increases to 25 degrees. Output power and VSWR dependence from DC power supply voltage is shown in Fig. 7 where one can see good matching at Power=38 kW with VSWR=1.05. Matching was tuned at the fixed frequency of 4.022 MHz

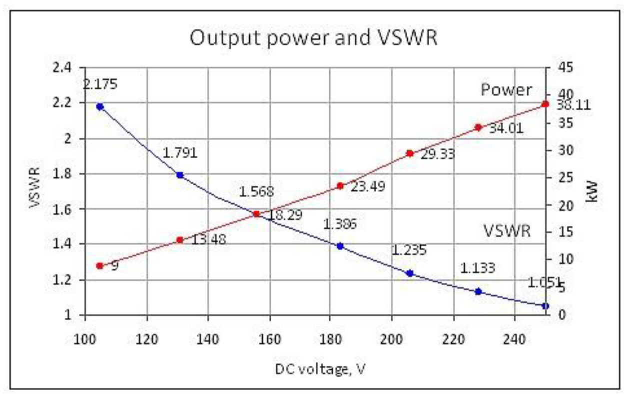

Figure 7: RF power and VSWR vs. DC power voltage.

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