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Control Logic, Interlock And Monitoring System For 1 MHZ Tetrode Tube Based Pulse High Power RF Amplifier System

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ABSTRACT

A high power Radio Frequency (RF) system is always equipped with control logic, interlock, and monitoring with protection circuit for its reliable and safe operation. In RF system cooling system, all bias supplies and RF input need to be switched ON/OFF in a certain predefined timing sequence to prevent damage to the high power RF device and its subsystem. This is ensured by a properly designed control logic, interlock, and monitoring with protection circuit. Additionally, a protection circuit senses the fault conditions such as over/under voltage parameters, over-current parameters, coolant fault and generates trips which switch off the supplies in a controlled sequence. For better reliability and stability, a PLC based system is being developed. Processing of predefined operation sequence, cooling interlocks with various voltage and current interlocks have been realized by using Siemens make S7-CPU-315-2DP (CPU) based programmable logic controller (PLC) system. Siemens make operating panel KPT1000 is being used as a human machine interface (HMI) device for command, data, alarm generation and process parameter monitoring. This paper describes in detail, the design scheme of PLC based interlock and protection systems for tetrode based pulse RF power amplifier system.

1. INTRODUCTION

In this paper we are using PLC to realize a Control logic, interlock and monitoring system for Thales make tetrode tube TH561 based radio frequency (RF) high power pulse amplifier system at 1 Mhz. TH561 tube based high power radio frequency (RF) system has 30 kW maximum pulse output power, and 300 MHz maximum operating frequency. The main aspect of the paper is to automate the process of ON and OFF the amplifier and generate interlock, alarm and trip the amplifier in of case of any abnormal condition.

A programmable logic controller (PLC) is an industrial computer control system that continuously monitors the state of input devices and make decisions based upon a custom program to control the state of appliances. It is designed for multiple inputs and output arrangements, high temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Almost any production process can highly enhanced using this type of control system, the biggest benefit in using a PLC is the ability to change and replicate the operation/process while collecting and communicating vital information. Another advantage of a PLC is that it is modular i.e. we can add and match the types of input and output devices to best suit our application.

2. OVERVIEW OF AMPLIFIER SYSTEM

TH561 Tube Based High Power Radio Frequency (RF) Amplifier system has maximum 30 kW pulse output power, at maximum 300 MHz operating frequency. The rating of plate high voltage (HV) supply for this amplifier is 7 kV. The sensing signals interfacing of this HV supply are essential part of the interlock system. This high voltage is appear across the anode and cathode (which is at ground potential) of the amplifier tube. Tetrode based RF amplifier schematic is shown in the figure-1.

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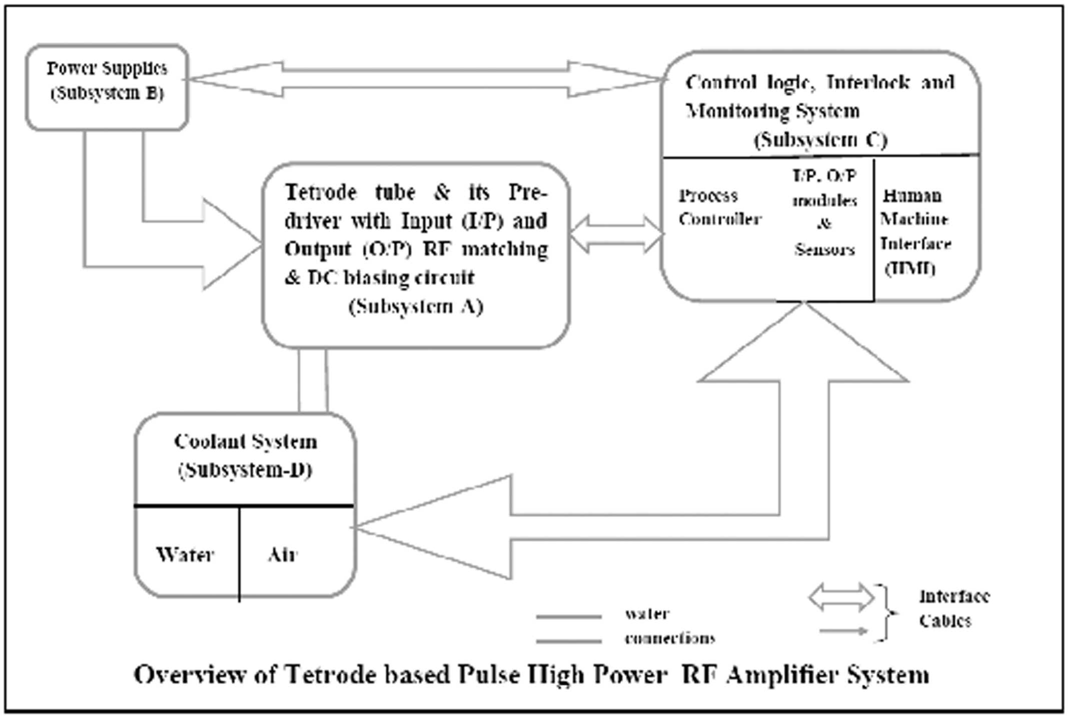

Figure 1: Overview of Tetrode tube base Pulse High Power RF Amplifier System

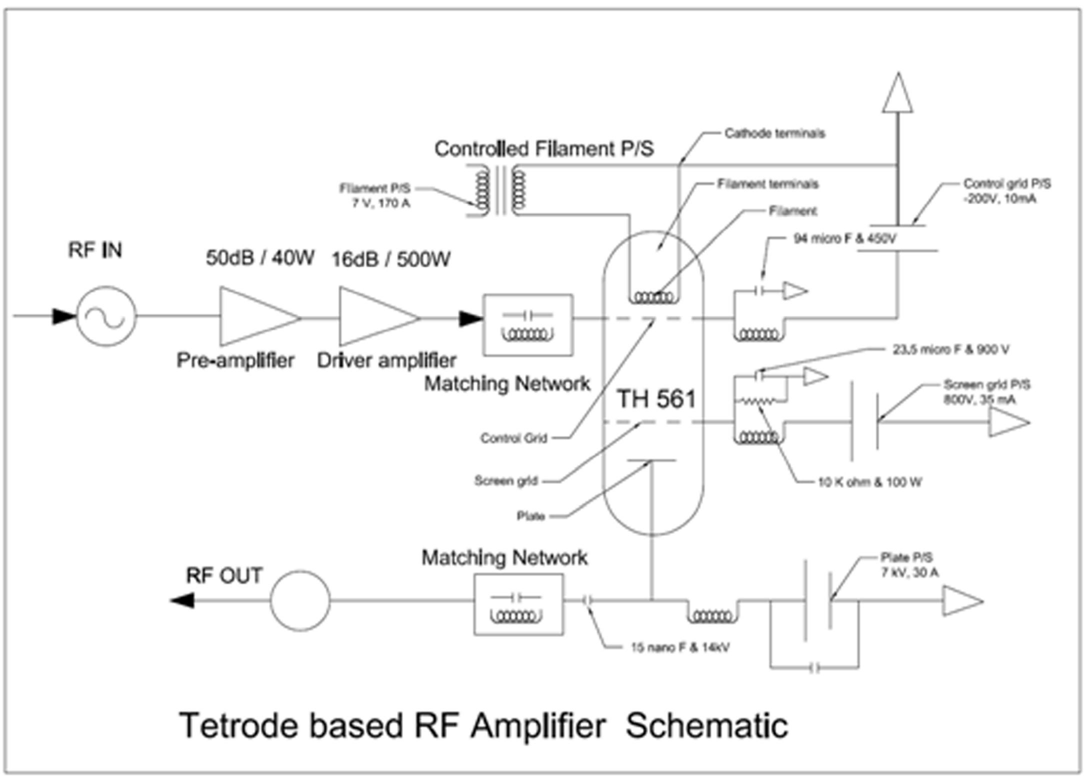

Figure 2: Tetrode tube base Pulse High Power RF Amplifier Schematic

This amplifier has various power supplies as electron gun filament supply (6.6 V, 135 A), control grid power supply (-200 V, few mA), screen grid power supply (800 V, hundreds of mA), and plate voltage power supply (7 kV, 5 A) which are mounted on separate isolated cabinet. Forced air cooling is used for the cooling of electron gun, however low conductivity water (LCW) is used for the cooling of plate of amplifier tube. The plate is at HV which needs to be safely handled for water cooling so, a special cooling is used to rectify this, which is called hypervapotron cooling. The RF monitoring system is also incorporated in control logic, interlock and monitoring system. The high power based amplifier system has been tested up to 15kW RF power. The overview of Thales make tetrode tube TH561 based radio frequency (RF) high power pulse amplifier system at 1 MHz and Tetrode tube with all sub system & power supplies (sub system –A & B) are shown in figure-1 and figure-2 respectively.

This amplifier system consists following subsystems:

2.1. Tetrode tube and its input (I/P) and output (O/P) RF matching and DC biasing circuits;

2.2. Power supplies

- Electron gun filament power supply (6.6 V, 135 A),
- Pyrolatic control grid supply (-200 V, few mA),
- Screen grid power supply (800 V, hundreds of mA),
- Plate voltage power supply (7 kV, 30 A).

2.3. Control logic, interlock & monitoring system

This subsystem includes

- Process controller device,
- I/P, O/P digital & analog modules and sensors,
- Human machine interface (HMI) device,
- Interfacing wires and cables.

2.4 Cooling system-

- Water cooling for plate (Hypervapotron cooling),
- Forced Air cooling for filament.

2.5 RF monitoring system-

- Direct coupler
- Attenuator
- Detection scheme (It may be diode detector, IC based/ FPGA based peak power detector)

3. INTERLOCK AND PROTECTION SCHEME FOR 10KW RF SYSTEM

To energize the RF system in a safe and reliable mode, all the bias supplies, RF driver and cooling circuits need to be switched ON/OFF in a predefined time sequence to prevent damage to the high power RF devices. A suitable interlock and protection circuit has been designed and developed which takes care of these feature. The RF system has been tested maximum upto 15 kW power.

3.1. Scope of interlock and protection

Scope of the interlock and protection circuit has been built as per the guidelines laid out in the data sheet of main RF power device TH 561. The necessary electrical signals are derived from sensor incorporated in each of the bias supplies. The Thales make tetrode tube TH561 based radio frequency (RF) high power pulse amplifier system at 1 MHz setup is shown in figure -3.

Figure 3: Tetrode tube TH561 based radio frequency (RF) high power pulse amplifier system at 1 MHz setup

This high power pulse RF amplifier system can't be put on/off directly, rather it has a systematic procedure to put on and off. This system requires unattended and automatic reliable operation which need of a control system. Cooling is the most important aspect for protection of RF amplifier. Before switching on the amplifier, normal cooling conditions are need to be ensured. Interlock circuit takes care of this. After verification the cooling conditions availability, the circuit starts its operation. It also requires fault/ interlock detection, data and command logging, processing and monitoring of various Voltage (V), Current (I), Radio Frequency (RF) parameters for assuring reliable operation of the amplifier system. In this way control logic, interlock and monitoring system is needed to meet objectives as under:

- Controlling and sequencing of operation, this include startup, shutdown and various operation sequences,
- Generation and processing of interlocks (faults), (interlock means faults which will be latched so that user can acknowledge it),
- Monitoring various parameters, safety alarm generation, command and data logging

3.2. Criticality to be handled

3.2.1. This amplifier has directly heated thermionic thoriated tungsten cathode (filament) based tube. It has an exclusive activation profile for optimization of cathode life. Controlling analog signal of this profile will be generated by control logic system as black heat mode and full heat mode. Activation and deactivation profile (filament V/I Vs. time) are realized according to time activation profile given in datasheet and is shown in figure-4 & 5. The cooling of filament is performed by forced air which is operated in post cooling mode after shut down operation from black heat mode. This ensures proper cooling operation of filament.

3.2.2 This amplifier system has hypervapotron anode cooling, for anode which has 7 kV dc potential. Anode is cooled by Low conductivity water (LCW) to get safety in cooling from high voltage shorting/ discharge the conductivity. The LCW conductivity needs to be monitored during all course of amplifier

system operation. In case of any abnormality occurred in this cooling operation plate current increases which can be monitored in HMI and coolant alarm will be generated. If flow rate is decreased from its normal range water interlock is generated and PLC system is put off the RF, SG & plate supply.

Since this amplifier system has various operation stages and commencement of any stage will be dependent upon normal operation of previous stages (as described in the description of flow chart), in case of abnormal operation of any of the previous stage system will generate fault/interlock signal. Hence each stage should to be properly commenced.

3.3. Control logic sequencing and interlocking processing flow chart

A detail sequence control scheme including all the fault parameters was evolved. The entire operation sequence of the Tetrode tube based RF system has been divided into six modes such as Black Heat mode, Full Heat mode, Control Gird power supply ON mode, Plate power supply ON mode, Screen Grid power supply ON mode, and RF ON mode. The sequence starts with monitoring the air flow conditions. After satisfy the predefined conditions, it proceeds to Black Heat mode after put on the filament supply and starts ramping upto 1.7 V, 35 A of filament voltage in 2 minutes (Black Heat ramp mode). This constant supply of 1.7 V, 35 A rating apply for 10 minutes in Black Heat mode. After completion of Black Heat mode, the filament supply again ramp from 1.7 V, 35 A to 6.6 V, 135 A which is called Full Heat ramp mode of filament. After commencement of Full heat ramp mode, this constant supply of 6.6 V, 135 A rating apply for 1 minutes in Full Heat mode. After commencement of Full Heat mode, the Control Grid supply can be put ON at its rated parameters (-150 V, few mA). After commencement of Control Gird ON mode, check the cooling water flow and put ON plate power supply at its rated parameters (7 kV, 5 A). After commencement of Plate power supply ON at desire parameters, put ON Screen Grid power supply at desired voltage (800 V, hundreds of mA). After commencement of Screen Grid power supply ON mode at desire parameters, the RF mode can be put on where low level RF drive is switched ON. Throughout this entire sequence, cooling air and water flow parameters are continuously monitored.

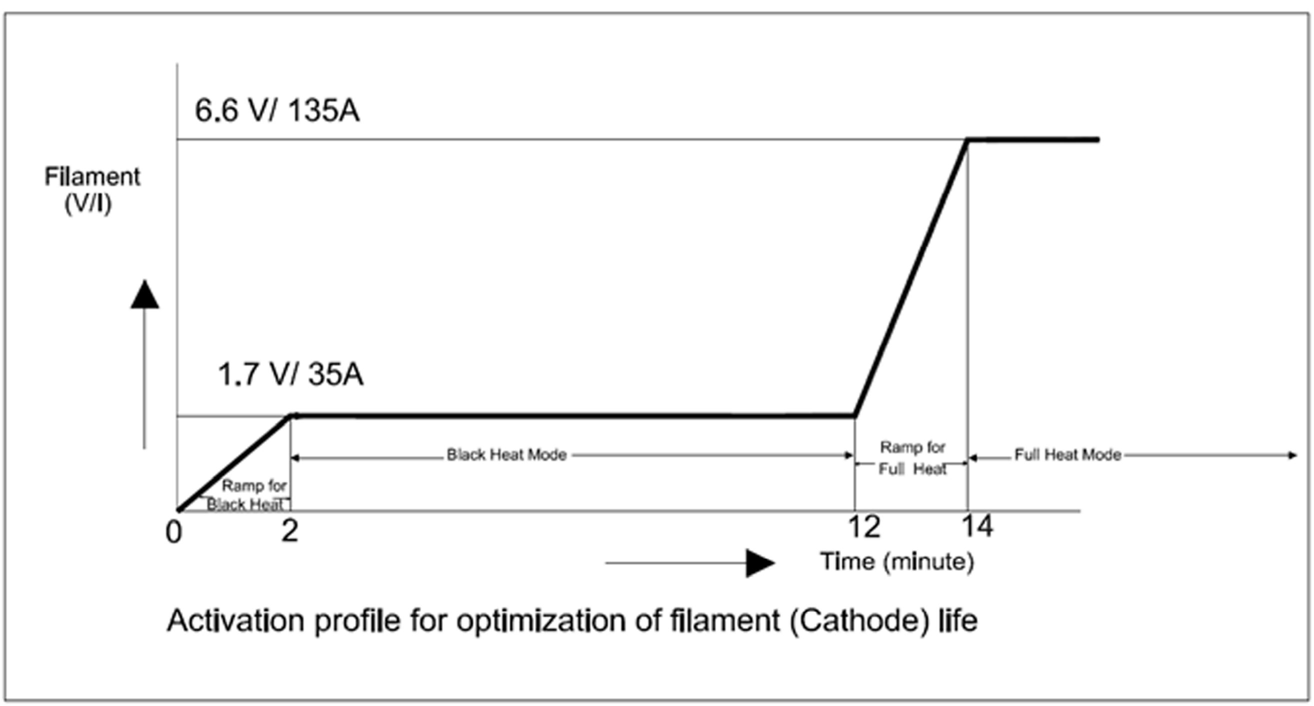

Figure 4: Activation profile for optimization of filament life

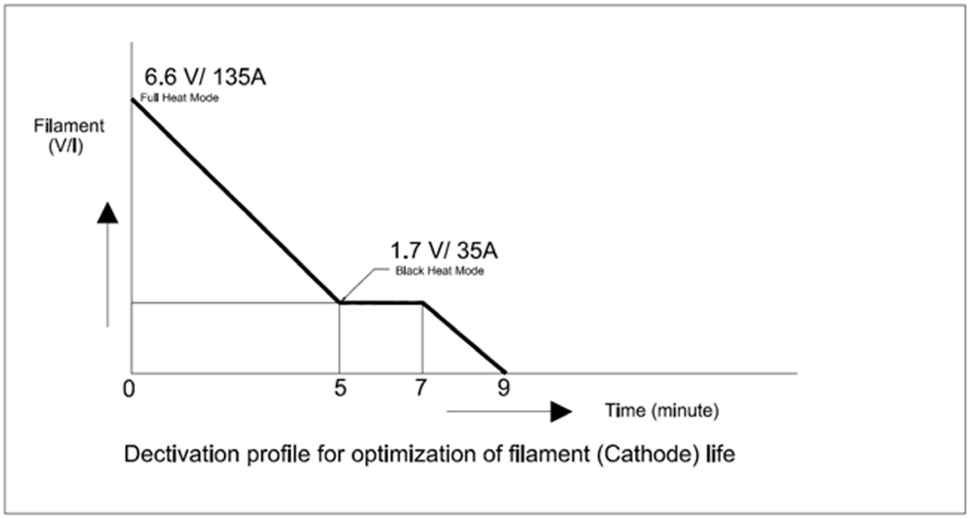

Figure 5: Deactivation profile for optimization of filament life

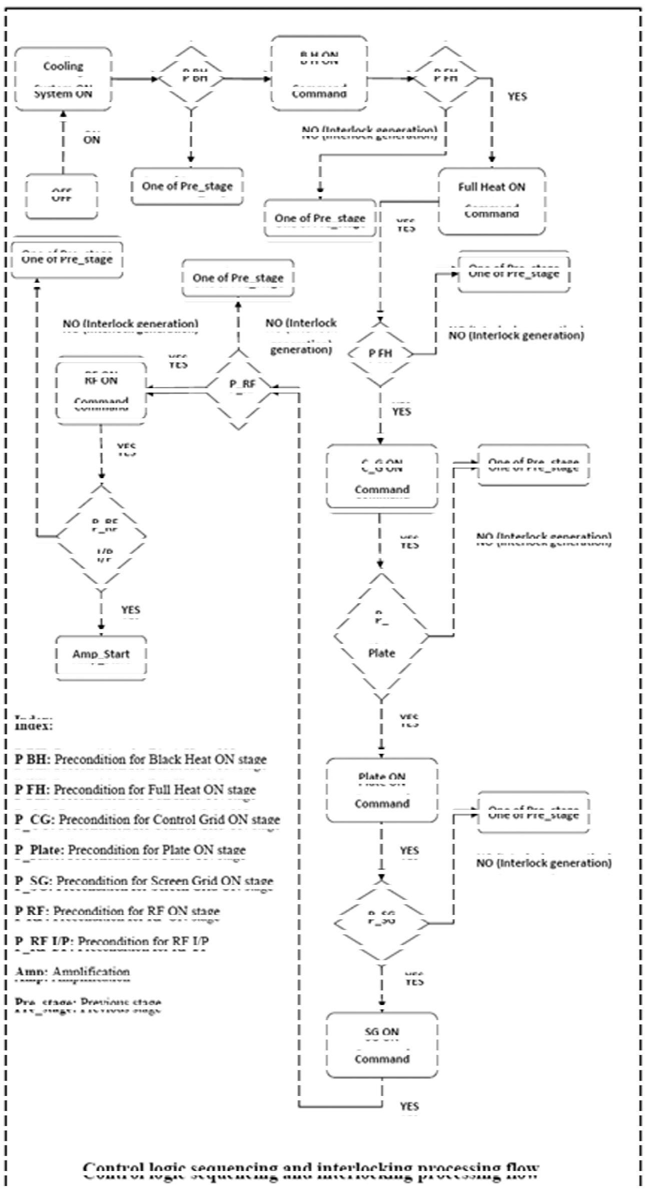

Figure 6: control logic sequencing and interlocking processing flow chart

The sequence starts with checking of air flow for filament, water flows for anode, screen grid and temperature of cooling water. When the interlock circuit receives cooling verification signal, it compares this with the reference value and switches on the filament supply. The filament supply then slowly ramps the filament voltage in as per graph in 14 minutes and then control grid voltage is switched on at predefined set value. After stabilisation period of 1 minutes and confirmation of read back signal from both supplies, a signal switches on the anode supply. The read back signal (10 V) from anode supply confirms that anode bias is established. Then, Screen Grid supply is switched on and the amplifier system is ready to accept the RF input drive.

4. EMPLOYED PLC BASED SCHEME

For better system reliability and stability, it has been thought of using programmable logic controller (PLC) based system. PLC works as per the logic implemented in the program, determines which actions need to be executed. It accept commands from command logging system & senses the inputs from transducers/ sensors & actuates the o/p to perform the function by amplifier subsystems. It is designed for multi input and output arrangement and the output should be produced in response to input conditions within a bounded time. This time period should be less than maximum allowed overload period for the Tetrode tube.

The hardware for interlock system is based on Siemens make PLC. The processor used for this is S7-300, CPU315-2DP. This system can be controlled by touch screen with high level Human Machine Interface (HMI) interface in local mode. The touch screen is handled by the user via MPI communication with PC and PLC. The whole PLC system consists of various modules of digital input, digital output, analog input, analog output, power supply, input and output interfacing modules etc. 19 digital inputs, 08 digital outputs, 13 analog inputs and 08 analog outputs are used in the ssytem. The PLC programming is done by using ladder logic and the software used is Simatic STEP-7 TIA. In table 1 the total signals incorporated in PLC system are shown.

Table 1
Incorporated signals

Nature of signals	No. of signal	Signals description
AI, 0-10 V	13	These are voltage & current (V&I) sense signals of electron gun auxiliary supplies, control grid supply, screen grid supply and plate power supply
AO, 0-10 V	8	These are voltage & current (V&I) signals of electron gun auxiliary supplies, control grid supply, screen grid supply and plate power supply for HMI and calibration of voltage & current (V&I) sense unit
DI, Logic-'0' - 0 V,'1' - 24 V	18	These signals are used for remote control of amplifier and cooling air and water status.
DO, Logic-'0' - 0 V, '1' - 24 V	8	These are used for relay operation of various power supplies of amplifier

5. EMPLOYED CONTROL DEVICES

To generate control logic start-up sequence and safety interlocks CPU 315-2DP has been used with its S7-300 series digital and analog I/P, O/P modules as shown in figure 7.

It is FPGA based control system having digital input and output channels. CPU is connected to its input and output (I/O) modules via backplane bus. CPU and all the I/O modules are operated by 24 V dc supply. All the devices of figure 3 are specified in table 2.

KPT1000 is a panel mounted Human Machine Interface (HMI). It operates by 24 V dc supplies which is taken from PLC supply and programmed by using Simatic Manager WinCC RT Professional V13.

Figure 7: Employed PLC system in amplifier system.

Table 2
Specifications of employed devices

S. No.	*Device Name & Model Number*	*No. of Channels*	*Signal levels*
1	CPU315-2DP 6ES7-315-2AH14-0AB0	–	–
2	Digital input (DI) module SM321-1- BH10-0AA0	16	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
3	Digital input (DI) module SM321-1- BH10-0AA0	16	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
4	Digital output (DO) module SM322-1BH10-0AA0	16	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
5	Digital output (DO) module SM322-1BH10-0AA0	16	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
6	Analog input (AI) module SM331-7KF02-0AB0	8	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
7	Analog input (AI) module SM331-7KF02-0AB0	8	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)
8	Analog output (AO) module SM332-5HF00-0AB0	8	Logic 0 (-30 to 5 V), Logic 1 (13 to 30 V)

Language used for programming is ladder diagram (LD) language, while HMI device is programmed by using Simatic WinCC RT Professional V13 software. PLC and HMI communicates via MPI cable by serial transmission cable.

HMI is used to log commands from local panel such as select local/remote (L/R) operation, Complete off, Reset, B_H on, F_H_ on/off, C_G_ on/off, plate on/off, screen_ on/off, RF_ on/off and normal/ diagnostic mode. Whenever the voltage and current of various power supplies cross defined range it generates alarm. It also indicates all the faults/interlocks.

Here all preconditions are necessarily included monitoring of cooling air and low conductivity cooled water flow status. At any stage of operation cycle whenever any precondition is not satisfied control system detects the fault, latches it and takes the amplifier system to a predefined safe stage according to program of PLC.

6. RESULTS AND CONCLUSION

It is noteworthy that PLC operates in cyclic fashion where the one cycle execution time of PLC is 3.4 to 4.5 ms. The timing range is meeting the requirement regarding maximum allowed overload period of the amplifier system.

This system has been tested up to about 10 hours satisfactorily without any false tripping. It saved a lot of wiring and maintenance efforts. It has standard signal levels for digital and analog signals. So it is found

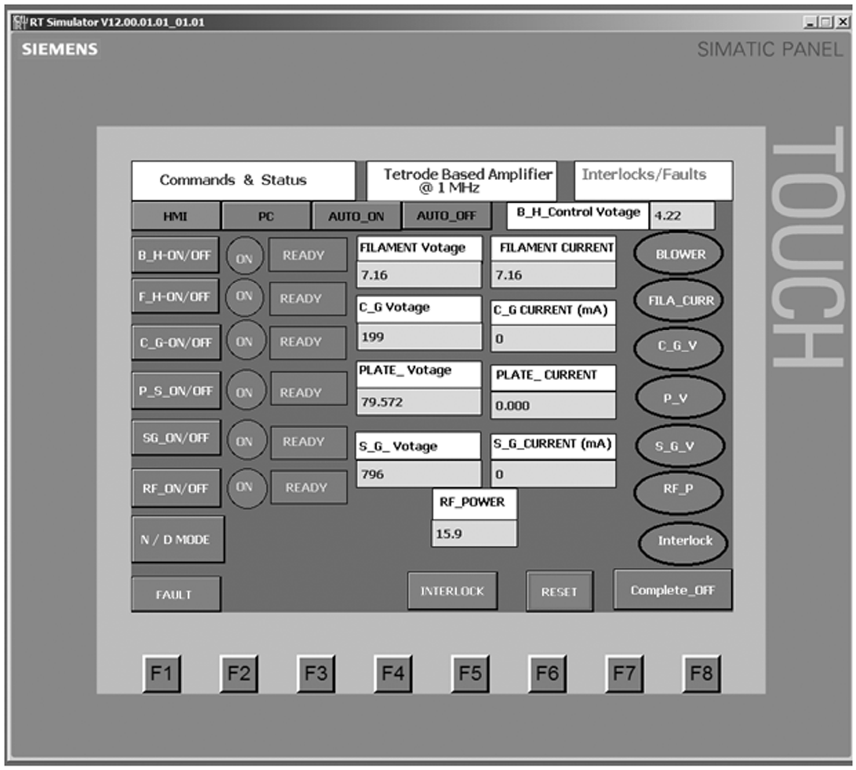

Figure 8: Employed HMI device KPT1000 in amplifier system

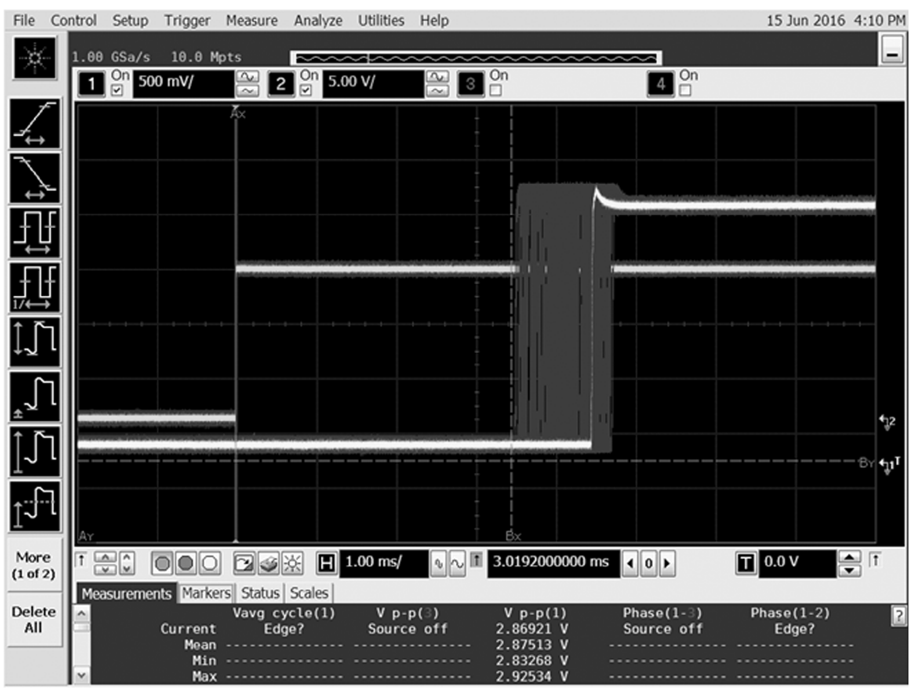

Figure 9: Overall execution time of PLC in amplifier system

suitable as control, interlock and monitoring system of 10 kW high power amplifier system. The system is providing unattended reliable & safe operation. It facilitates the provision of auto and manual operation. This system is compact, rugged, and easy to handle, easy to program and user friendly. Whenever user needs it is able to change/upgrade the system program and hardware. The maximum power achieved by this amplifier is 14.76 kW with is 9.4 dB gain and 40.16 % efficiency.

The main aim of project is to automate a system. The project engulfs the study of various types of automation components such as relay contact logic, PLC's, PAC's, analog circuit based system & several other devices have been studied. This study has helped us to choose PLC which is best suited for the required application. PLCs are dominant in fields where outputs are governed /controlled by the inputs. The PLC based system reduces the analog based circuitry and the hardwired complexities. These are amazingly robust and are able to withstand all sorts of difficult environments such as extreme temperature and dusty conditions. Since the PLC doesn't have any contacts like relays, so there is no problem of their wearing out; hence have a very large operational lifespan. PLCs prove to be one of the best controllers in industries worldwide because of its simplicity and robustness. It reduces the manual work by automating a process and its computational abilities also allow more sophisticated control. Finally SIMATIC S7-300 has been selected for the application.

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