Calibration of New I&C at VR-1 Training Reactor

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ABSTRACT

The paper describes a calibration of the new instrumentation and control (I&C) at the VR-1 training reactor in Prague. The I&C uses uncompensated fission chambers for the power measurement that operate in a pulse or a DC current and a Campbell regime, according to the reactor power. The pulse regime uses discrimination for the avoidance of gamma and noise influence of the measurement. The DC current regime employs a logarithmic amplifier to cover the whole reactor DC current power range with only one electronic circuit. The system computer calculates the real power from the logarithmic data. The Campbell regime is based on evaluation of the RMS value of the neutron noise. The calculated power from Campbell range is based on the square value of the RMS neutron noise data. All data for the power calculation are stored in computer FLASH memories. To set proper data, it was necessary to carry out the calibration of the I&C. At first, the proper discrimination value was found while examining the spectrum of the neutron signal from the chamber. The constants for the DC current and Campbell calculations were determined from an independent reactor power measurement. The independent power measuring system that was used for the calibration was accomplished by a compensated current chamber with an electrometer. The calculated calibration constants were stored into the computer FLASH memories, and the calibrated system was again successfully compared with the independent power measuring system. Finally, proper gamma discrimination of the Campbell system was carefully checked.

1 INTRODUCTION

The VR-1 reactor at the Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague is a pool-type light-water reactor based on enriched uranium (under 20%). Its thermal power is rated up to 5kW. The reactor is utilized primarily for training university students and future nuclear power plant staff. The training at the VR-1 reactor is focused on the reactor and neutron physics, dosimetry, nuclear safety, and control of nuclear installations.

The complete I&C of the VR-1 reactor was changed in subsequent steps [2]. The individual steps were the human-machine interface, the control rod drives and the safety circuits, the control system, the independent power protection system and the operational power measuring system renovation. Finally, the installation of the complete I&C was carried out into a new I&C room with up-to date cabinets and a much better access to the systems for the inspections and maintenance than it was possible in the previous I&C location.

The first calibration of the new I&C was done with respect to the old I&C setting. Later, it was decided to carry out a new calibration with the use of an independent power measuring
system based on a compensated neutron chamber that was developed at the Department of Nuclear Reactors.

2 REACTOR I&C STRUCTURE

This chapter explains the reactor I&C (control and safety system) structure. A block diagram of the reactor I&C is shown in Figure 1. The system structure has to meet the requirements of the Czech State Office for Nuclear Safety [1].

![Block diagram of I&C](image)

Figure 1: Block diagram of I&C

Firstly, the safety (protection) part of the system is described. This part of the I&C is the most important one for nuclear safety. Four operational power measuring channels (OPM) receive signals from wide range fission chambers (OPMCH), evaluate them, calculate the reactor power and the power rate, and send the values to the control system and to adjacent individual displays on the operator’s desk of the human-machine interface (HMI) located in the control room. The OPMs initiate a safety action (send a safety signal) if safety limits have been exceeded. Another four channels equipped with boron chambers (IPPCH) work as an independent power protection system (IPP). They also evaluate the power and the power rate, send data to the control system and to their displays, and initiate a safety action if safety limits have been exceeded.

The control system receives data from the OPM and IPP channels, checks received values with each other and against the safety limits. The control system calculates the average values of the reactor power and the power rate; next, it evaluates the deviation between the real power and the demanded power value set by the operator. The control system sends data to the HMI and receives commands from it. The control system also serves as an automatic power regulator system and controls the movement of the control rods to achieve the required reactor power. The control system also, independently of the OPM and IPP channels, checks the reactor power and the power rate for safety reasons; the deviation in data of single OPM channels, and system and technology status. If the safety limits are exceeded or any failure occurs, the control system sends a safety signal to initiate the reactor scram.

The vote logic of the reactor safety circuits receives the safety signals from the OPM, IPP channels and the control system. The vote logic evaluates the inputs from the OPM channels in the logic 2 out of 3, from the IPP channels independently 2 out of 3, and the safety signal from the control system is evaluated in the logic 1 out of 1. If the conditions for
the safety action request are met, the power supply (48V DC) to the control rods is cut off by the safety circuits, the rods fall down and stop the chain reaction (reactor scram).

The HMI enables the communication between the reactor I&C and the operator. It consists of a computer with liquid crystal displays (LCDs) and indicators showing the operational status of the reactor, as well as a keyboard and buttons to control the reactor.

3 REACTOR POWER MEASUREMENT

The VR-1 reactor power measurement is based on the neutron flux measurement. According to the I&C structure (see chapter 2), the I&C is equipped with 4 OPM channels that measure the reactor power (neutron flux measurement). These OPM channels use uncompensated fission chambers RJ-1300 that operate in the pulse (lower power) or current (higher power) regimes according to the reactor power. The OPM channels evaluate the signal from the chambers convert it to digital data and calculate the reactor power.

The power at the VR-1 reactor is measured in “special” units – pulses per second, no Watts, Kilowatts, etc. The reason is that there it is not possible to measure directly the thermal power of the VR-1 reactor (the maximum VR-1 reactor power about 5kW cannot measurably heat 17m³ of water in the tank). However, the VR-1 I&C measures the neutron flux. The VR-1 thermal power can be assessed by comparison with the LVR15 research reactor (10MW) in Nuclear Research Institute in Rez. The result is that the power of $10^8$ pulses/s corresponds to the approximately 1kW of thermal power at the VR-1 reactor.

In the next paragraph, the OPM channel structure is briefly mentioned. Later, its pulse, DC current and Campbell regimes are described in more detail.

3.1 OPM Channel Structure

The operational power protection (OPM) channel calculates from the signal of the OPM chamber the reactor power and power rate. It consists of an analog and a digital section. The analog section processes the neutron chamber signal either in pulse, Campbell or DC current ranges and provides signals proportional to the neutron flux reactor power. The block diagram of the analog section is shown in Figure 2. The digital section of the OPM channel is based on a high quality industrial PC with appropriate additional hardware – an input unit for reading data from analog section; a supervisory unit for the supervision of the OPM hardware and software; communication unit for the fibre optics based communication with the control
system, the control desk individual display and the service computer; a local display control unit for the OPM status presentation and a safety relay unit to control the safety circuits.

3.2 Pulse Regime of OPM Channel

The pulse regime is used for the lower power of the VR-1 reactor, typically up to power of $5 \times 10^4$ pulses/s. The pulse signal from the chamber is amplified and discriminated to separate the neutron pulses from the noise and gamma. The proper discrimination level is set by a digital/analog (D/A) converter. The value of the discrimination is stored in the FLASH memory of the OPM channel computer. The neutron pulses are then counted, and the number of pulses is sent every 0.1 second to the digital section of the OPM channels that calculates from it the reactor power. Appropriate statistical calculations are used to establish the reactor power.

3.3 DC Current Regime of OPM Channel

The current regime of the OPM channel is used for the power measurement in the range from $5 \times 10^4$ pulses/s to $5 \times 10^8$ pulses/s, with a safety reserve up to $5 \times 10^9$ pulses/s. The DC current system needs to cover about 5 decades of the current measurement. It is difficult to produce a linear electronic system with this range; the previous system used 2 DC current subsystems - one for the range from $5 \times 10^4$ pulses/s to $5 \times 10^7$ pulses/s and the other one for the range from $5 \times 10^7$ pulses/s to $5 \times 10^9$ pulses/s. Then, it was necessary to connect these two subsystems in a way that the measurement smoothly continues from one subsystem to the other one.

The new DC current subsystem uses a logarithmic amplifier to convert the current value to its logarithm. The analog logarithmic value (a voltage value corresponding to the current) is then converted into the corresponding frequency by a voltage/frequency (U/f) converter. This frequency is measured by a counter and every 0.1 second sent to the digital section of the OPM channel. The computer calculates firstly the DC current (Eq. 1) and then corresponding reactor power as extrapolation of the pulse range in units of pulses/s (Eq. 2).

$$I_{DC} = k_{R1} \cdot 10^{k_{F2} \cdot f_{DC}} \ \ [A]$$

$$N_{DC} = k_{DC} \cdot \frac{\sum_{i=0}^{9} I_{DC\_i}}{10} + o_{DC} \ \ [imp/s]$$

3.4 Campbell Regime of OPM Channel

The Campbell regime of the OPM channel is similarly to the DC current regime used for the power measurement in the range from $5 \times 10^4$ pulses/s to $5 \times 10^8$ pulses/s, with a safety reserve up to $5 \times 10^9$ pulses/s. The Campbell regime is based on the evaluation of current noise of the neutron chamber [3], [4]. The reactor power (neutron flux) is then proportional to the square of the root mean square (RMS) value of the current noise signal. Because of the quadratic dependence of the reactor power on the electronic signal (Eq. 3), there are no problems with the range of 5 decades.

$$N_{Camp} = k_{Camp} \cdot \frac{\sum_{i=0}^{9} (f_{Camp\_i} + o_{CampSq})^2}{10} + o_{CampLin} \ \ [imp/s]$$
The electronics amplifies the AC signal from the chamber. Next, an adjustable filter (low and high pass) selects the proper frequency range of the measured signal. Then, an analog RMS unit evaluates the RMS value of the signal, and finally, a voltage/frequency (U/f) converter converts this value into a corresponding frequency. This frequency is measured by a counter and sent again every 0.1 second into the digital section of the OPM channel computer. The computer calculates the appropriate reactor power (Eq. 3).

4 CALIBRATION OF REACTOR POWER MEASUREMENT

To calibrate the reactor power measurement, it is necessary to set proper parameters for the operation of the OPM channels in all pulses, DC current and Campbell regimes. The calibration parameters are stored in the FLASH memories of the OPM channel computers.

The software OPM Manager serves to handle the calibration parameters. It runs on an independent personal computer that is connected via an optical serial line to the service communication line of an individual OPM channel and can read, change and store the calibration parameters.

The first calibration of the OPM channels and hereby of the whole I&C power measurement after the I&C upgrade was done with respect to the previous I&C. Later, it was decided to carry out a new calibration with a use of an independent power (neutron flux) measuring system.

4.1 Independent Power Measuring System

The independent power (neutron flux) measuring system that was used for the I&C (OPM channels) calibration was developed at the Department of Nuclear Reactors [5]. The system is based on a compensated B-lined neutron chamber CC54B that operates in the current regime; the current signal from the chamber is evaluated by the Keithley 6517A electrometer. The electrometer is connected to a personal computer via an HPIB interface, and the computer can store data during the reactor power measurement. It is necessary to set a proper working and compensating voltage to the neutron chamber.

4.2 Data Acquisition during I&C Calibration

During the calibration, it was necessary to acquire data from the I&C. The OPM channels send data to the control system via optical based serial lines. The data from the serial lines were used for data acquisition during the calibration. There are 4 OPM channels in the I&C, so it was necessary to read simultaneously 4 serial lines during the carrying out of the calibration. Special connectors were produced to split the serial lines signal between the OPM channels and the control system to get data also to the personal computer used for the calibration. The OPM channels send to the control system not only the calculated reactor power but also the data from individual counters of pulse, DC current and Campbell systems (see chapters 3.2, 3.3 and 3.4) that are worthwhile for the calibration.

There is a special format of the sent data from the OPM channels to the control system. It was necessary to convert these data to ASCII format for their evaluation e.g. Microsoft Excel. The special program OPM_CONV was developed for this purpose.

New personal computers typically do not provide standard serial interfaces (COM ports). They are equipped with USB interfaces instead. The converters RS232 (COM serial ports) to the USB are available. To read 4 serial lines simultaneously, 4 RS232/USB converters and a USB Hub were used. There were certain problems with the drivers that connected the RS232/USB converters to the personal computer operating system COM ports.
(typically high numbers like COM14, 15, 18, 23 etc. were set) and only the not very convenient Microsoft HyperTerminal software could have operated these COM ports.

4.3 Power Measurement Calibration

The independent power measuring and data acquisition systems were ready, so it was possible to start the I&C (OPM channels) power measurement calibration. The calibration was divided into three parts – the pulse regime, the DC current regime and the Campbell regime calibration.

4.3.1 Pulse Regime Calibration

The only parameter for the pulse regime calibration is the discrimination level to separate neutrons from gamma and noise signal. The spectrum of the chamber signals for all OPM channels was evaluated and a proper discrimination levels were found. These parameters were set to FLASH memories of the OPM channel computers using the OPM Manager software (see beginning of the chapter 4) and the neutron flux measurement of all OPM channels was successfully compared with the independent power measuring system (see chapter 4.1).

4.3.2 DC Current Regime Calibration

The DC current regime calibration consisted of two steps. The first step was the calibration of the logarithmic current measurement (Eq. 1); the second step was the calibration of the power measurement according to the chamber current (Eq. 2).

The calibration of the logarithmic current measurement was based on a current generator. The Universal Source HP3245A that provides an enough accurate DC source in a suitable range for the DC current regime calibration was used as the current generator. The calibration measurements for the currents of \(10^{-8}\), \(10^{-7}\), \(10^{-6}\), \(10^{-5}\), \(10^{-4}\), \(10^{-3}\) and \(5\times10^{-3}\)A (the expected range of the chamber DC current) were done, and appropriate parameters for the current calculation from the logarithmic data were established.

The second step of the DC current regime calibration was to find parameters that convert the DC chamber current to the power. There were two parameters to be found – the proportional parameter between the current and power and the offset parameter (there is typically some residual DC current of the chamber without any neutron flux). Full range reactor power measurements together with the independent power measuring system (see chapter 4.1) were done, and the proportional and offset parameters of the DC current measurement for all OPM channels were established. These parameters were then set to all OPM channels and a new comparison measurement with the independent power measuring system was successfully carried out. Great attention was also paid to the smooth transition between the pulse and the DC current power measurement regimes.

4.3.3 Campbell Regime Calibration

The Campbell regime calibration measurements were done together with the second step of the DC current regime calibration (see chapter 4.3.2). The finding of proper parameters for the Campbell regime calibration and also a test of linearity of the Campbell regime measurement were carried out.

During the first measurements, a non-linearity for high power measurement was detected in the Campbell regime. The reason for this non-linearity was found in the too high amplification setting. The operational amplifiers used in the AC amplifier provide lower
bandwidth in the case of higher amplitude of output signal. It was necessary to set proper amplification to get a linear response of the Campbell regime in the case of high reactor power.

Next, it was necessary to set proper filtering of the AC noise signal frequency. The Campbell system is equipped with a filter that consists of a low pass and a high pass filter. It is possible to set 16 different frequency values of the low pass and also 16 values of the high pass filter. It was found that the low frequency filter setting does not have any influence on the Campbell power measurement. The high pass filter setting seemed more critical. Different settings were investigated, and the most appropriate option was selected.

Later, the Campbell system power measurement with the proper amplification and frequency filtration setting together with the independent power measuring system was carried out and proper parameters were calculated on the base of this comparative measurement. The parameters for the Campbell power calculation were set in FLASH memories of the OPM channel computers and the system was finally tested.

![Figure 3: Gamma discrimination test](image)

4.3.4 Campbell Regime and Gamma Discrimination

The reactor I&C uses uncompensated neutron fission chambers for the full range power measurement. These chambers are sensitive not only to neutrons but also to gamma radiation. The influence of gamma is very observable in the DC current regime in case the reactor power is very high, then the power is significantly decreased but the power range still remains in the DC current regime. Then the measured power is higher than the real power because of substantial gamma current addition. The Campbell regime provides because of its nature [3], [4] gamma discrimination even with uncompensated neutron chambers.

The gamma discrimination of the Campbell system was investigated. The reactor was operated for 30 minutes at the maximum power $5.10^8$ pulses/s (aprox. 5kW), then the reactor was scrammed and the pulse, DC current a Campbell power measurement was stored and evaluated. The course of all three power measurements is shown in Figure 3. At the beginning, the DC current a Campbell system provides the same power, the pulse regime is saturated. With the decreasing power, the Campbell regime offers lower power values then the DC current one because of gamma discrimination. Finally, under a power of about $2.10^5$ pulses/s the Campbell and pulse regimes gives very similar power values (pulse regime provides excellent gamma discrimination because of chamber signal discrimination) but the DC current regime values are much higher because of gamma influence.
5 CONCLUSION

The contribution describes the calibration of the power measurement at the VR-1 training reactor at the Czech Technical University in Prague. An independent power measuring system based on the compensated chamber was used for the calibration. The proper discrimination level for the pulse regime was established, the parameters for the DC current regime and the Campbell regime for the power calculation were found. The parameters were then stored in the FLASH memories of the OPM channels and are used now for the reactor operation. The OPM channels 1, 2, 3 that are by default operational still evaluate the power using the DC current regimes, the OPM channel 4 that serves by default as a back-up uses the Campbell regime. Finally, new human machine interface at VR-1 reactor stores all operational data in a history server that also enables storage of the data from counters of all OPM channels regimes. These data allow reconstruction of all power calculations either in DC current or Campbell regimes. The data are planned to be evaluated to support the change to the Campbell regime for all OPM channels.

The correct power measurement is very important for the safe and reliable operation of the VR-1 reactor because the reactor is intensively used for training of students and future NPP staff in the framework of the Czech CENEN program in nuclear education. We must not forget to mention the co-operation with the European universities like Fachhochschule in Aachen, Technical University in Vienna, and Royal University in Stockholm. The reactor is also involved in a number of international programs such as the IAEA technical cooperation program and training courses, the European program ENEN for the nuclear education, e.g., Eugene Wigner Training Courses [6].

ACKNOWLEDGMENTS

This research has been supported by the Czech Ministry for Education grant MSM6840770020 called “Nuclear Safety”.

REFERENCES


