Seminar R&D Nuklear Malaysia 2012

DEVELOPMENT OF AUTOMATED CONTROLLER SYSTEM FOR CONTROLLING REACTIVITY BY USING FPGA IN RESEARCH REACTOR APPLICATION

Pembangunan Sistem Kawalan Automatik Bagi Mengawal Reaktiviti Dengan Menggunakan FPGA untuk Aplikasi Reaktor Penyelidikan

MOHD SABRI MINHAT (Nuklear Malaysia), Izhar Abu Hussin (Nuklear Malaysia), Mohd Idris Taib (Nuklear Malaysia), Mohd Khairulezwan Abd Manan (Nuklear Malaysia), Nurfarhana Ayuni Joha (Nuklear Malaysia), Mohd Zaid Mohamed (Nuklear Malaysia), Harzawardi Hasim (Nuklear Malaysia), Mohamad Hairie Rabir (Nuklear Malaysia), Ridzuan Abdul Mutalib (Nuklear Malaysia), Dr. Zainal Alam Haron (UTHM)

Electronic, Instrumentation and Control Section (RIC), Power Nuclear Division (BKN), Malaysian Nuclear Agency, Bangi, 43000 KAJANG, MALAYSIA

Abstract

The scope for this research paper is to produce a detail design for Development of Automated Controller System for Controlling Reactivity by using FPGA in Research Reactor Application for high safety nuclear operation. The development of this project including design, purchasing, fabrication, installation, testing and validation & verification for one prototype automated controller system for controlling reactivity in industry local technology for human capacity and capability development towards the first Nuclear Power Programme (NPP) in Malaysia.

*The specific objectives of this research paper are to Development of Automated Controller System for Controlling Reactivity (*ACSCR*) in Research Reactor Application (PUSPATI TRIGA Reactor) by using simultaneous movement method; To design, fabricate and produce the accuracy of Control Rods Drive Mechanism to 0.1 mm resolution using a stepper motor as an actuator; To design, install and produce the system response to be more faster by using Field Programmable Gate Array (FPGA) and High Speed Computer; and to improve the Safety Level of the Research Reactor in high safety nuclear operation condition.*

Katakunci/keywords : FPGA, Automated Controller System, Reactivity, Control Rod Drive Mechanism, LabVIEW

RESEARCH BACKGROUND

The Reactor TRIGA PUSPATI (RTP) was installed in the year 1982. The control rod mechanism is very important in reactor operation meaning to control reactivity or neutron production in the reactor. It has four (4) control rods, one (1) air follower control by pneumatic drive mechanism and three (3) fuel follower controlled by electromagnetic drive mechanism. The fuel follower type control rods movement are by sequential means one control rod is move at one time and manually. Due to aging, analog based technology, slow response and unstability affect the reactor safety.

Automated Controller System for Controlling Reactivity (ACSCR) is develop to control the movement of the control rods simultaneously (new algorithm movement method) by using high speed computer, Field Programmable Gate Array (FPGA) or Real Time Controller together with reconfigurable chassis (shown in Figure 1), programming using software LabVIEW, software LabVIEW FPGA, software LabVIEW Real-Time, software LabVIEW SoftMotion, I/O modules, PC Based Redundant Measurement System, Laser Displacement Sensor, Control Rod Drive Mechanism (CDRM) using stepper motors with encoder and rack and pinion system.

One simulation program for reactor reactivity will be develop using high speed computer and programming using LabVIEW, PC Based Redundant Measurement System and Laser Displacement Sensor. One control program for control movement of the control rods will be develop using high speed and programming using LabVIEW and software LabVIEW SoftMotion. Processing unit (controller) will be setup and install by using FPGA or Real-Time Controller together with reconfigurable chassis, programming using software LabVIEW Real-Time and I/O modules. Control rod drive mechanism will be design and fabricate by using stepper motors with encoder, rack and pinion system.

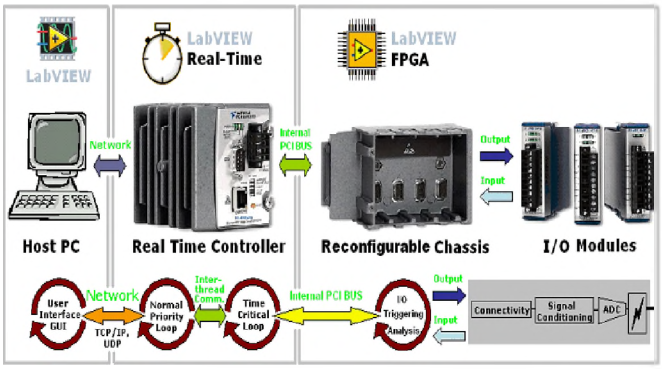

Figure 1: Hardware and Software requirements for Project Development

The whole components will be integrate to produce one prototype automated controller system. The prototype will produce a fast response, accuracy, high realiablity and safe operation of the reactor. After completing the research project within two years, the prototpe will be verify and validate by Atomic Enegy Licencing Board, Malaysia and/or International Atomic Energy Agency (IAEA). The prototype will be installed at Research TRIGA PUSPATI after being approved by the above institutes. In case this project receive strict regulation, this prototype will use and expand the scope for the development project of simulation I&C and the standard of this project will be enhance higher for application of big research reactor and nuclear power plant at Nuclear Malaysia in future.

MAIN OBJECTIVE

To develop a prototype Automated Controller System for Controlling Reactivity by using FPGA in Research Reactor and Radiation Facility in high safety nuclear operation. The development of this project including design, purchasing, fabrication, installation, testing and validation & verification for one prototype automated controller system for controlling reactivity in industry local technology for human capacity and capability development towards the first Nuclear Power Programme (NPP) in Malaysia.

SPECIFIC OBJECTIVE

1) To develop a Automated Controller System for Controlling Reactivity in Research Reactor Applications and Radiation Facilities by using simultaneous movement method. 2) To design, fabricate and produce the accuracy of Control Rods Drive Mechanism to 0.1 mm resolution using a stepper motor as an actuator. 3) To design, install and produce the system response to be more faster by using Field Programmable Gate Array (FPGA) and High Speed Computer. 4) To improve the Safety Level of the Reactor and Radiation Facilities in high safety nuclear operation condition.

RESEARCH METHODOLOGY

-Literature review and collection of technical specification equipments and software, scientific papers and history parameters data in the reactor (baseline data).
-Design the drive mechanism to control the movement of control rods (mechanical structure), design the processing unit (controller) using FPGA.
-Purchasing of software, tools and equipments involves.
-Fabricate the system (drive mechanism).
-Software development (Computer Program using LabVIEW, LabVIEW FPGA, LabVIEW Real-Time, LabVIEW SoftMotion).
-Installation prototype by Integrate hardware and software.
-Performance test of covering fail-safe, reliable, fast acting and accuracy.
-Validation and verification to evaluate the prototype from regulatory body (AELB), IAEA and establish nuclear application institute (Oversea).
-Establishment the manual of the prototype, industrial working procedure and final report.

THEORETICAL AND LITERATURE REVIEW

Control Rod Materials

Rods of neutron-absorbing material are installed in most reactors to provide precise, adjustable control of reactivity. These rods are able to be moved into or out of the reactor core and typically contain elements such as silver, indium, cadmium, boron, or hafnium. The RTP used **boron** as neutron absorbing material or material used for control rods.

The material used for the control rods varies depending on reactor design. Generally, the material selected should have a good absorption cross section for neutrons and have a long lifetime as an absorber (not burn out rapidly). The ability of a control rod to absorb neutrons can be adjusted during manufacture. A control rod that is referred to as a "black" absorber absorbs essentially all incident neutrons. A "grey" absorber absorbs only a part of them. While it takes more grey rods than black rods for a given reactivity effect, the grey rods are often preferred because they cause smaller depressions in the neutron flux and power in the vicinity of the rod. This leads to a flatter neutron flux profile and more even power distribution in the core.

If grey rods are desired, the amount of material with a high absorption cross section that is loaded in the rod is limited. Material with a very high absorption cross section may not be desired for use in a control rod, because it will burn out rapidly due to its high absorption cross section. The same amount of reactivity worth can be achieved by manufacturing the control rod from material with a slightly lower cross section and by loading more of the material. This also results in a rod that does not burn out as rapidly.

Another factor in control rod material selection is that materials that resonantly absorb neutrons are often preferred to those that merely have high thermal neutron absorption cross sections. Resonance neutron absorbers absorb neutrons in the epithermal energy range. The path length traveled by the epithermal neutrons in a reactor is greater than the path length traveled by thermal neutrons. Therefore, a resonance absorber absorbs neutrons that have their last collision farther (on the average) from the control rod than a thermal absorber. This has the effect of making the area of influence around a resonance absorber larger than around a thermal absorber and is useful in maintaining a flatter flux profile.

Types of Control Rods

There are several ways to classify the types of control rods. One classification method is by the purpose of the control rods. Three purposes of control rods are; Shim rods - used for coarse control and/or to remove reactivity in relatively large amounts. Regulating rods - used for fine adjustments and to maintain desired power or temperature. Safety rods - provide a means for very fast shutdown in the event of an unsafe condition. Addition of a large amount of negative reactivity by rapidly inserting the safety rods is referred to as a "scram" or "trip".

Not all reactors have different control rods to serve the purposes mentioned above. Depending upon the type of reactor and the controls necessary, it is possible to use dual-purpose or even triple-purpose rods. For example, consider a set of control rods that can insert enough reactivity to be used as shim rods. If the same rods can be operated at slow speeds, they will function as regulating rods. Additionally, these same rods can be designed for rapid insertion, or scram. These rods serve a triple function yet meet other specifications such as precise control, range of control, and efficiency.

Control Rod Effectiveness

The effectiveness of a control rod depends largely upon the value of the ratio of the neutron flux at the location of the rod to the average neutron flux in the reactor. The control rod has maximum effect (inserts the most negative reactivity) if it is placed in the reactor where the flux is maximum. If a reactor has only one control rod, the rod should be placed in the center of the reactor core. The effect of such a rod on the flux is illustrated in Figure 2.

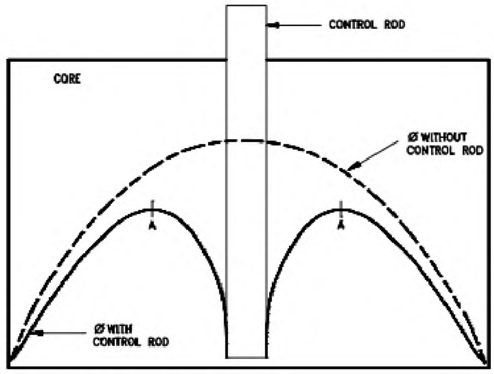

Figure 2: Effect of Control Rod on Radial Flux Distribution

If additional rods are added to this simple reactor, the most effective location is where the flux is maximum, that is, at point A. Numerous control rods are required for a reactor that has a large amount of excess reactivity (that amount of reactivity in excess of that needed to be critical). The exact amount of reactivity that each control rod inserts depends upon the reactor design. The change in reactivity caused by control rod motion is referred to as control rod worth.

Integral and Differential Control Rod Worth

The exact effect of control rods on reactivity can be determined experimentally. For example, a control rod can be withdrawn in small increments, such as 0.5 inch, and the change in reactivity can be determined following each increment of withdrawal. By plotting the resulting reactivity versus the rod position, a graph similar to Figure 3 is obtained. The graph depicts integral control rod worth over the full range of withdrawal. The invidual reactivity worth of the rods on RTP have shown on the right Figure 3. The integral control rod worth is the total reactivity worth of the rod at that particular degree of withdrawal and is usually defined to be the greatest when the rod is fully withdrawn. In this case, the highest reactivity worth control rod on RTP is Regulating rod.

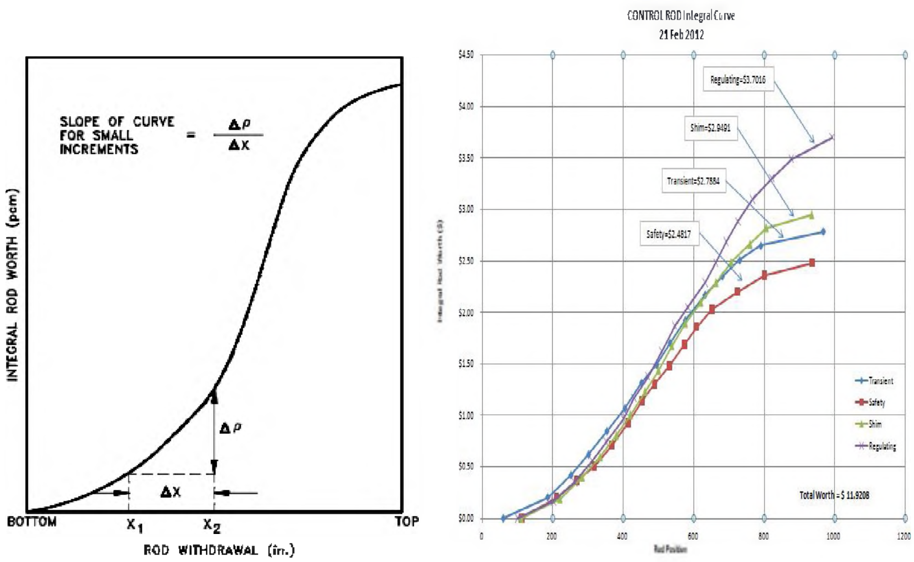

Figure 3: Integral Control Rod Worth

The slope of the curve ($\Delta\rho/\Delta x$), and therefore the amount of reactivity inserted per unit of withdrawal, is greatest when the control rod is midway out of the core. This occurs because the area of greatest neutron flux is near the center of the core; therefore, the amount of change in neutron absorption is greatest in this area. If the slope of the curve for integral rod worth in Figure 3 is taken, the result is a value for rate of change of control rod worth as a function of control rod position. A plot of the slope of the integral rod worth curve, also called the differential control rod worth, is shown in Figure 4. At the bottom of the core, where there are few neutrons, rod movement has little effect so the change in rod worth per inch varies little. As the rod approaches the center of the core its effect becomes greater, and the change in rod worth per inch is greater. At the center of the core the differential rod worth is greatest and varies little with rod motion. From the center of the core to the top, the rod worth per inch is basically the inverse of the rod worth per inch from the center to the bottom. The invidual differential control rod worth of the rods on RTP have shown on the right Figure 4.

Differential control rod worth is the reactivity change per unit movement of a rod and is normally expressed as ρ/inch, Δk/k per inch, or pcm/inch. The integral rod worth at a given withdrawal is merely the summation of all the differential rod worths up to that point of withdrawal. It is also the area under the differential rod worth curve at any given withdrawal position.

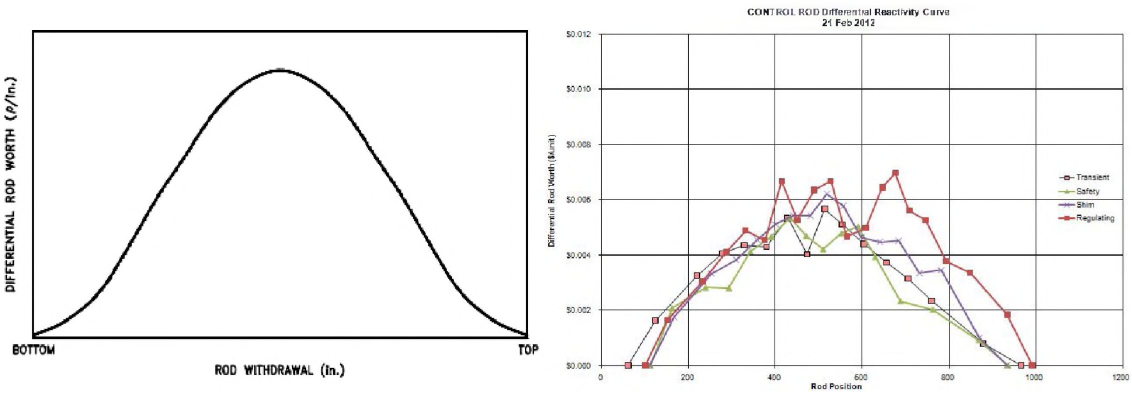

Figure 4: Differential Control Rod Worth

Rod Control Mechanisms

The control rod insertion rates on a scram are designed to be sufficient to protect the reactor against damage in all transients that are expected to occur during the life of the reactor. During normal rod motion, the control rods must be able to move rapidly enough to compensate for the most rapid rate at which positive reactivity is expected to build within the reactor in order to provide positive control. The transient that is normally considered when setting this minimum rod speed is the burnout of maximum peak xenon while at full power. Xenon burnout is usually the most rapid, non-accident transient expected. The maximum rod speed is normally limited in order to reduce the severity of an accident involving the continuous withdrawal of control rods.

DISCUSSION AND RESULTS

Table 1 presents the results obtained from experimental the relationship between control rod position (Regulating rod = REG, Safety rod = SF, Shim rod = SH, Transient rod = TR), rod worth ($), reactivity loss ∑Δρ ($) and power (kW). To determine core reactivity is differential between total worth ($11.92) and rod worth data. To deterimine differential control rod Δρ ($) is differential between current rod worth and previous rod worth data. The value of the reactivity introduced, and the final power level, at which the power rise ends, provided the data for determining, the power coefficient of reactivity (αP) in the power interval involved, shown in last column of the table 2. Figure 5 shows the power coefficient of reactivity, αP, and the associated reactivity loss to achieve a given power level. The experimental data were fitted in a 2nd degree polynomial where y in the equation is the reactivity loss and x is the reactor power. Because of the prompt negative temperature coefficient, a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at higher power levels in steady state operation. In order to keep the reactor power constant at a desired level, the reactivity loss is compensated by withdrawing the control rods. The power defect, which is the change in reactivity taking place between zero power and 850 kW is ~ $ 2.19. The curve of the reactivity loss is almost linear, and gives a power coefficient of reactivity of about -0.26 ¢/kW (-1.81x10-5/kW). The Δρ accuracy is limited mainly by the accuracy of the power calibration, which is estimated in 2.0%.

Table 1: Results obtained from experimental

P (kW)	REG	$	SF	$	SH	$	TR	$	rod worth	core reactivity	Δρ	ΣΔρ	ΣΔρ/100
1.50E-02	632	2.3407	450	1.1118	450	1.1735	968	2.7824	7.40840853	4.51E+00	0.0000	0.0000	0.0000
50	662	2.5127	450	1.1118	450	1.1735	968	2.7824	7.580419307	4.34E+00	17.2011	17.2011	0.1720
100	691	2.6736	450	1.1118	450	1.1735	968	2.7824	7.74136413	4.18E+00	16.0945	33.2956	0.3330
200	755	3.0035	450	1.1118	450	1.1735	968	2.7824	8.071202807	3.85E+00	32.9839	66.2794	0.6628
300	825	3.3101	450	1.1118	450	1.1735	968	2.7824	8.377810988	3.54E+00	30.6608	96.9402	0.9694
400	929	3.6211	450	1.1118	450	1.1735	968	2.7824	8.688862785	3.23E+00	31.1052	128.0454	1.2805
500	989	3.7006	465	1.1808	465	1.2544	968	2.7824	8.918281344	3.00E+00	22.9419	150.9873	1.5099
600	989	3.7006	488	1.2868	488	1.3796	968	2.7824	9.149464667	2.77E+00	23.1183	174.1056	1.7411
700	989	3.7006	510	1.3879	510	1.4999	968	2.7824	9.370867356	2.55E+00	22.1403	196.2459	1.9625
800	989	3.7006	526	1.4609	526	1.5873	968	2.7824	9.531297717	2.39E+00	16.0430	212.2889	2.1229
850	989	3.7006	533	1.4926	533	1.6255	968	2.7824	9.601182126	2.32E+00	6.9884	219.2774	2.1928

Table 2: Power coefficient for the power intervals measured

Power (kW)	Reactivity Changes Δρ (¢)	Reactivity Loss ΣΔρ (¢)	T (C°) IFE C12	T (C°) IFE F16	α_g C12 (¢/C°)	α_g F16 (¢/C°)	α_P (¢/kW)
15 W	0.0000	0.0000	30	30			
50	17.2011	17.2011	65	55	-0.4915	-0.6880	-0.3440
100	16.0945	33.2956	95	80	-0.5365	-0.6438	-0.3219
200	32.9839	66.2794	150	110	-0.5997	-1.0995	-0.3298
300	30.6608	96.9402	190	135	-0.7665	-1.2264	-0.3066
400	31.1052	128.0454	210	160	-1.5553	-1.2442	-0.3111
500	22.9419	150.9873	235	180	-0.9177	-1.1471	-0.2294
600	23.1183	174.1056	260	200	-0.9247	-1.1559	-0.2312
700	22.1403	196.2459	290	220	-0.7380	-1.1070	-0.2214
800	16.0430	212.2889	305	225	-1.0695	-3.2086	-0.1604
850	6.9884	219.2774	310	230	-1.3977	-1.3977	-0.1398

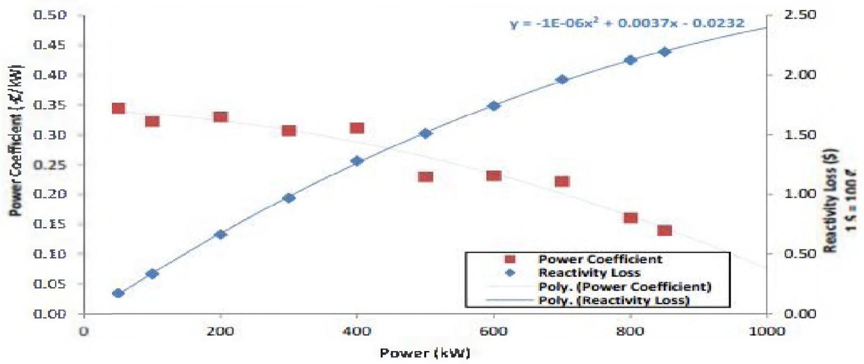

Figure 5: Power coefficient of reactivity and reactivity loss versus reactor power level

ACSCR

Automated Controller System for Controlling Reactivity (ACSCR) is a development system that aims to control the number of neutron flux production or the number of neutrons in the Reactor TRIGA PUSPATI (RTP) in high safety nuclear operation. The method to control the reactivity in the reactor, neutron absorbing material are required to control the number of neutrons that are directly proportional to reactivity. In the RTP, the neutron absorbing also known as control rods which the control rods using Boron Carbide as neutron-absorbing agents in reactor core.

The proposal to develop a prototype ACSCR has the capacity and ability to control the neutrons production, reactivity, flux, power and temperature can be quickly, accurate and safely. To ensure that this systems can be developed, controller system need to be upgraded from the old analogue system to a advance system of digital systems (FPGA). Previous studies ever carried out by experts the ability of fuzzy logic to be adapted to the research reactor. Investigation and research findings that have been made, has resulted in fuzzy logic theory and concepts to be used as a guide for a reference to the development of this project.

ACSCR project will provide a system and method in controlling the reactivity of nuclear fission in a reactor. This system will develop a controller using FPGA technology that can advance control the application controllably movable control rods and computer program (Software development) for determining the controllably movable control rods.

Currently, the RTP can be operated in two modes of operation: MANUAL and AUTOMATIC mode. In MANUAL mode operation, for the power / specific flux reactor operators need to push the control rod position by pressing the UP button on the console based reactor control rods position of the reference readings that represent the power / flux in the reactors. To reduce the floatation in the manual mode where the reactor operator had to make adjustments to get the right power for every moment in the operation of the reactor operation. Therefore, to facilitate the reactor operator to change the manual mode to automatic mode.

In the handling of RTP operations in only three (3) control rods. Each of these control rods can be controlled UP or DOWN at a time. In the operation of automatic mode operation, the system can only adjust one control rod while the other two control rods will remain at their current position. Adjustment of the control rod reactivity depends on the value of two permanent control rods, either to be increased to increase the reactivity or otherwise. For example, when the reactor operated for a maximum power of 1MW in the operation of automatic mode operation. To get maximum power, all control rods should be increased to the full.

The system will take power readings when taking into account the position of all the control rods at the time. Then, the system will provide signals on a control rod (Regulating), which will make adjustments and change the position of the other two control rods will remain at their current position. Each time the movement of a control rod (Regulating) as well as the account of the other two control rods will give the reactivity compared to the reactivity desired value (maximum power). If still not getting the desired reactivity, adjusting a control rod (Regulating) is to be done again.

As a result the control rods (Regulating) will be raised in full due to still achieve the maximum power (maximum reactivity) required. The system will provide signals to control a second rod (Shim) to make adjustments and change its position while the control rods (Safety) and the control rods (Regulate) the fully raised position will remain at the current position. Every time a motion for a new position of control rod (Shim) will give the reactivity that discriminate.

As a result the control rods (Shim) will be raised in full due to still achieve maximum power. The last adjustment will be made, where the system will give signals to the third control rod (Safety) who will make adjusting the control rods. Finally, the control rods (Safety) to find the position of maximum power (maximum reactivity) by raising the control rods at full value.

From this statement of the problem of development projects that will develop controller ACSCR to ensure that control rods can move simulataneously method compared to a single movement at a time in the past (mean the new algorithm movement similar previous movement method, the different are every control rods (3 rods) act like regulating). The advantages of this ACSCR, automatic control system will be a simulation computer program to control movement in and out of position all the control rods in a high speed computer specifications. From the computer program will send a signal to the controller for controlling the control rod drive mechanism to absorb the neutrons by means of controlling the control rod position.

Advantages of this system does not need to make adjustments and depending on a control rod for a time and wait for a signal from the controller again to move the other control rods for adjusting the power / flux / desired reactivity. Therefore, the guard will run and guide the movement of three control rods in simultaneous movement and not a single motion sequence for a control rod. Movement for the three control rods simultaneously means that each control rod will move in the position set by the computer program with a fast response rate.

The measurement reading of the each control rods get from displacement sensor (act like fission chamber detector). Each position control rod represent reactivity and to proportional the power level. However, the position of each specified of control rods will be monitored by a computer program and reactivity controller by taking readings (from displacement sensor) at all times to ensure the desired reactivity was right to reduce the modification occurs too often and the system of protection safety purposes. Further advantage of the ACSCR is to improve the accuracy of neutron absorbing and reactivity control mechanism from 0.3mm to 0.1mm resolution using a stepper motor as an actuator. Every reading 0.1mm will give different figures reactivity or flux in the reactor core. This is very important in giving the exact reactivity by narrowing the resolution of each motor movement. The feedback of stepper motor is from the potentiometer or encoder to make sure the movement of the actual is equal to the signal data from FPGA. The detail design for control drive mechanicm can refer the same author researh paper 'Study of Control Rod Withdrawal Rate by Using Stepper Motor Application in Reactor TRIGA PUSPATI'.

ACSCR project will also develop a system that has a very fast response, make good decisions and effective communications systems. Rapid response system is due to adaptation FPGA application with the High Speed Computer acting as a console in a reactor. At the end of ACSCR results is aimed to achieve zero defects condition in the control reactivity and to ensure safety of operation in the reactor operating at high levels.

Conceptual Design

At the figure 6 below, author come out with the conceptual design for Automated Controller System for Controlling Reactivity, ACSCR.

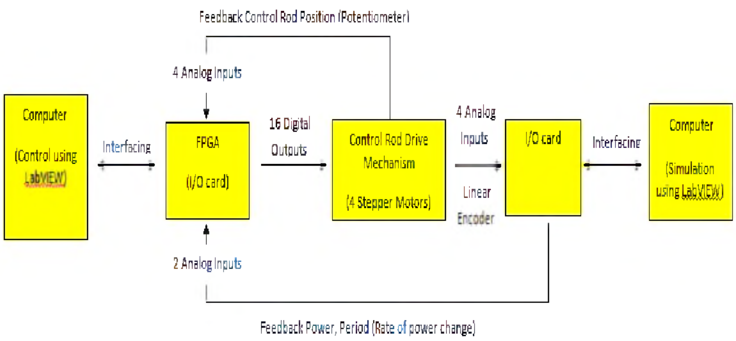

Figure 6: Conceptual Design for ACSCR

Detail Design

Figure 7 and 8 shown the detail design of ACSCR with complete setup. The specification component for this project, the author plan to use technology National Instrument (NI) products. Rather than spending a lots of money and many months of development to design a custom FPGA/DSP board, our team was able to develop this ACSCR system quickly and economically using NI CompactRIO, high-speed FPGA technology, and easy-to-use NI LabVIEW software. Hopefully, this project could be completed so quickly and efficiently.

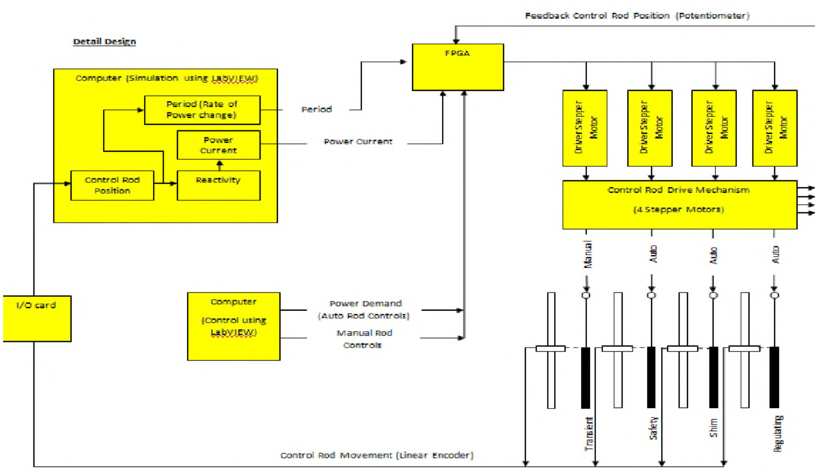

Figure 7: Detail Design for ACSCR

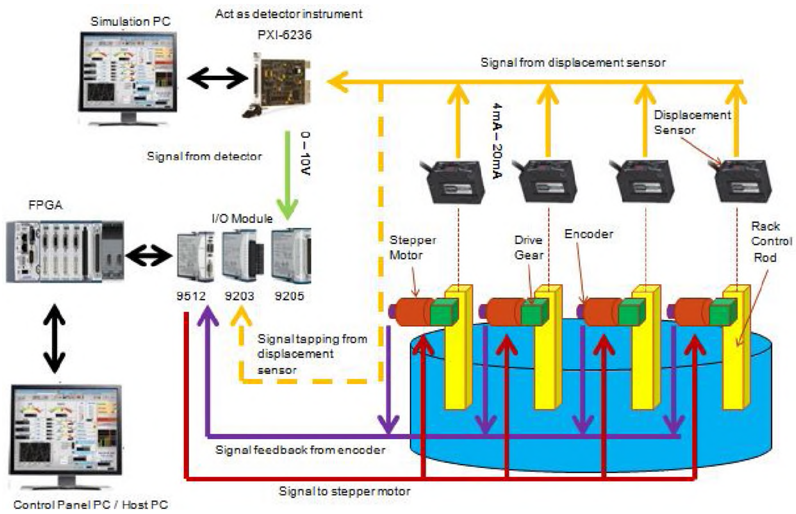

Figure 8: Detail Design of ACSCR with Complete Setup

SUMMARY

In conclusion, the study of detailed design for project development of automated controller system for controlling reactivity in research reactor application has been discussed in this research paper to comeout with the detailed design, analyze the experimental data and demonstrates the final detail design of the project with complete setup. After come out with the detailed design, the next stage is to make procurement, installation, fabricate, testing and produce the prototype. Outputs expected from the project; To develop Automated Controller System for Controlling Reactivity (ACSCR) prototype, Improving the accuracy of Neutron Absorbing Control Mechanisms to 0.1 mm resolution and improve the system response to be more faster, To develop automatic controller system to ensure that control rods can move simultaneously method, New software development for computer program (LabVIEW), controller (LabVIEW FPGA & LabVIEW Real-Time) and drive mechanism (LabVIEW SoftMotion), Involve in human capital and expert development for application Master Degree, Involve in economic contributions of the project by cost saving, time saving, safety, and Involve in infrastructural contributions of the project by produce new equipment (ACSCR) and improved facility (RTP).

REFERENCES

FINAL YEAR PROJECT DOCTOR OF PHILOSOPHY: DR. NAHRUL KHAIR ALANG MD, RASHID, THE UNIVERSITY OF NEW MEXICO, Albuquerque, New Mexico USA (1992), Nuclear Reactor Control Using Tunable Fuzzy Logic Controllers

RMK-7, IRPA PROJECT: MOHD IDRIS BIN TAIB, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (1996-1998), Development of Expert System for On-Line Nuclear Process Control

SEMINAR PAPER: MOHD DZUL AIMAN, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (2010), Conceptual of Stepper Motor Replacing Servo Motor for Control Rod Controller

SEMINAR PAPER: MOHD SABRI BIN MINHAT, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (2011), RTP Control Rod Drive Mechanism using Stepper Motor

SEMINAR PAPER: MOHD SABRI BIN MINHAT, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (2012), Study Of Control Rod Withdrawal Rate by using Stepper Motor Application in Reactor TRIGA PUSPATI

SEMINAR PAPER: MOHAMAD HAIRIE RABIR, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (2012), Measurement of The Power and Temperature Reactivity Coefficients of the RTP TRIGA Reactor

CALIBRATION DATA: OPERATION AND MAINTENANCE, MALAYSIAN NUCLEAR AGENCY, Bangi, Malaysia (2012), Control Rod Calibration Summary