Hindawi Publishing Corporation
Journal of Engineering
Volume 2013, Article ID 450161, 12 pages
http://dx.doi.org/10.1155/2013/450161

*Research Article*

# Analysis of Liquid Zone Control Valve Oscillation Problem in CANDU Reactors

**Elnara Nasimi and Hossam A. Gabbar**

*University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, ON, Canada L1H 7K4*

Correspondence should be addressed to Hossam A. Gabbar; hossam.gabbar@uoit.ca

Received 14 November 2012; Revised 15 March 2013; Accepted 2 April 2013

Academic Editor: Ibrahim Asi



This paper looks at the existing challenges with steady-state Liquid Zone control at some CANDU (CANada Deuterium Uranium) stations, where—contrary to expectations for equilibrium flow—Liquid Zone Control Valve oscillations have proven to be a chronic, unanticipated challenge. Currently, the exact causes of this behaviour are not fully understood, although it is confirmed that the Control Valve oscillations are not due to automatic power adjustment requests or zone level changes due to process leaks. This phenomenon was analysed based on a case study of one domestic nuclear power station to determine whether it could be attributed to inherent controller properties. Next, a proposal is made in an attempt to improve current performance with minimal changes to the existing system hardware and logic using conventional technologies. Finally, a proposal was made to consider Model Predictive Control-based technology to minimize the undesirable Control Valve oscillations at steady state based on the obtained simulation results and discussion of other available alternatives.

## 1. Introduction

In CANDU nuclear power plants, reactor neutron power is measured and calibrated to the thermal power being produced. Operation of reactivity control devices, such as Liquid Zone light water-filled compartments and mechanical control rods, is used to reduce/eliminate power error.

This paper describes efforts of a project that looked into a specific case of Liquid Zone (LZ) Control Valve (CV) problem where a controller performance resulted in undesirable CV oscillations leading to excessive wear and tear of the valve. In addition to equipment reliability, this impacts the overall flux control stability and presents challenges for operation, engineering, and maintenance at the plant. The focus of this project was to analyze the existing condition and propose alternatives to the existing control scheme in an attempt to resolve the existing condition and introduce a new intelligent controller based on modern advanced technologies.

*1.1. Literature Review.* One of the main obstacles for the introduction of intelligent digital control for nuclear power plants appears to be the historical assumption that the old analogue controllers are more reliable, safer, and easier to maintain than the new digital programmable controllers. There is a perception among both the plant personnel as well as general public that the old analogue and electromechanical systems should remain the preferred method for implementing reactor control.

This issue is quite prominent among certain specialists and hugely pronounced among general population. Some sources mention that despite the fact that the new sophisticated intelligent control systems are more suitable for the demands of today's industry, the challenge of convincing all stakeholders that they can provide the required degree of reliability, validation, and verification still remains [1].

Studies done as early as 1989 [2] show that for nuclear reactors and steam generators where operating parameters change randomly, a development of synthesis methods rather than standard PID-controllers (Proportional-Integral-Derivative) is needed, which can be easily accomplished by using intelligent control systems built on the basis of fuzzy logic and artificial neural networks with genetic algorithms. Other studies [3] showed that there has already been a significant effort made in the area of automatic and fault-tolerant control research and development that can be applied for operating power plants.

Intelligent control systems with fault diagnostic capabilities have been deployed in other safety-critical industries and applications, such as aerospace, chemical, process and medical industries for quite some time now. Novel approaches for fault diagnosis and control reconfiguration for complex systems as well as trends and perspectives of intelligent control in manufacturing systems are widely discussed [4–6]. The use of fuzzy logic and neural network approach to intelligent reactor controller design appears to be the overall trend in the industry today, regardless of the type of the reactor design or country of origin. The 2003 Oak Ridge National Laboratory report for the US Department of Energy [7] states that the main focus in the control community is to integrate functions of intelligent systems, such as fuzzy logic, neural networks, genetic algorithms, and knowledge-based systems with the conventional control systems to perform complex tasks more easily. Other studies identify a WWPR-type (Water-Water Power Reactor) reactor core using a multi-nonlinear autoregressive with exogenous inputs (NARX) structure that makes use of neural networks with different time steps and a heuristic compound learning method with off- and online batch learning [8–11]. Results of these studies show that the proposed controller is very well able to control the reactor core during load following operations, using optimum control rod group manoeuvre and variable overlapping strategy. Power control stability of the Belgian Reactor 1 (BR1) at the Research Centre for the Applications of Nuclear Energy (SCK-CEN) was improved by using a fuzzy logic control scheme [12] and showed good potential compared with human control room operators. For Generation-3 CANDU-based plants, requirements for use of control computers in shutdown and other safety systems were identified as early as 1980s [13], but in most operating units only minimal changes have been implemented to date.

## 2. Liquid Zone Control (LZC) System

*2.1. Project Methodology.* This paper describes efforts of a preliminary study where a specific case of a known Liquid Zone Control Valve problem was looked at. First, historical plant data and troubleshooting results were obtained and analysed to define the problem and develop a project methodology. It is important to point out that although this condition has been experienced at several reactor units at some time, engineering analysis and troubleshooting activities have not produced conclusive findings identifying the root causes of this phenomenon. Furthermore, since this condition appears intermittent in nature and affects different units at various times, no comprehensive in-depth study has been conducted to review this issue from multidiscipline point of view. This project set out to conduct some preliminary analysis and set up a framework for a detailed research study that may be beneficial for this case. In order to comply with allocated time and scope constraints, it was necessary to make some simplification and use assumptions for unknown parameters.

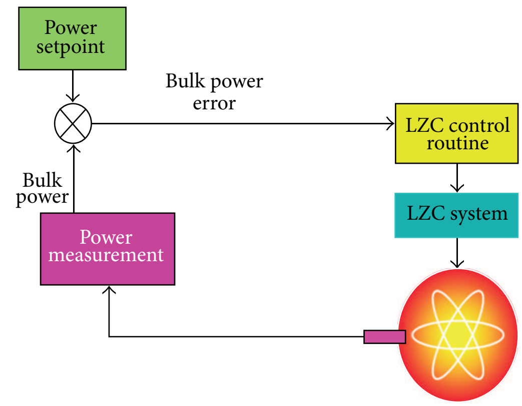


Figure 1: Simplified reactor control scheme in CANDU, where Liquid Zone Control system is shown as a means for fine reactivity control and reduction of power error.

First, the existing LZ control system design was analysed, and a simplified model was set up in MatLab Simulink 7.7 R2008 [14].

Next, step response simulation was conducted to determine whether the modeled system response matches historic plant data. This step was important to ensure that simplifications and assumptions made during initiation of the project are acceptable and do not have a significant impact on the model accuracy.

Next, an attempt was made to look at how the model performance can be improved with minimal changes to the existing components and using only conventional PI controller technology that is already available at the plant in question.

Lastly, other available technologies and methods based on modern intelligent control techniques were looked at to evaluate their potential for the selected case study, for example, fuzzy logic and neural network-based control schemes. The main emphasis was made on evaluating Model Predictive Control-based (MPC) controller integration with the original system model. Although further and more detailed studies are required to produce comprehensive results, some preliminary tests were done to check the proposed modified system response with the same step input disturbance.

Finally, project conclusions, feasibility of the proposed changes and proposals for future work are shown in the last section of this paper. These steps are shown in Figure 2 as a project task breakdown structure diagram.

*2.2. Liquid Zone Control System Description.* In a typical CANDU reactor, Liquid Zone system is comprised of 14 light-water filled compartments distributed throughout the reactor core. Light water in the LZ compartments acts as a neutron absorber, and thus Reactor Regulating System (RRS) automatically modulates zone levels by adjusting inflows for bulk and spatial neutron flux control. Individual zone power is measured using both neutronic and thermal power measurements and compared to the setpoint. A simplified reactor control scheme in CANDU is shown in Figure 1. Zone

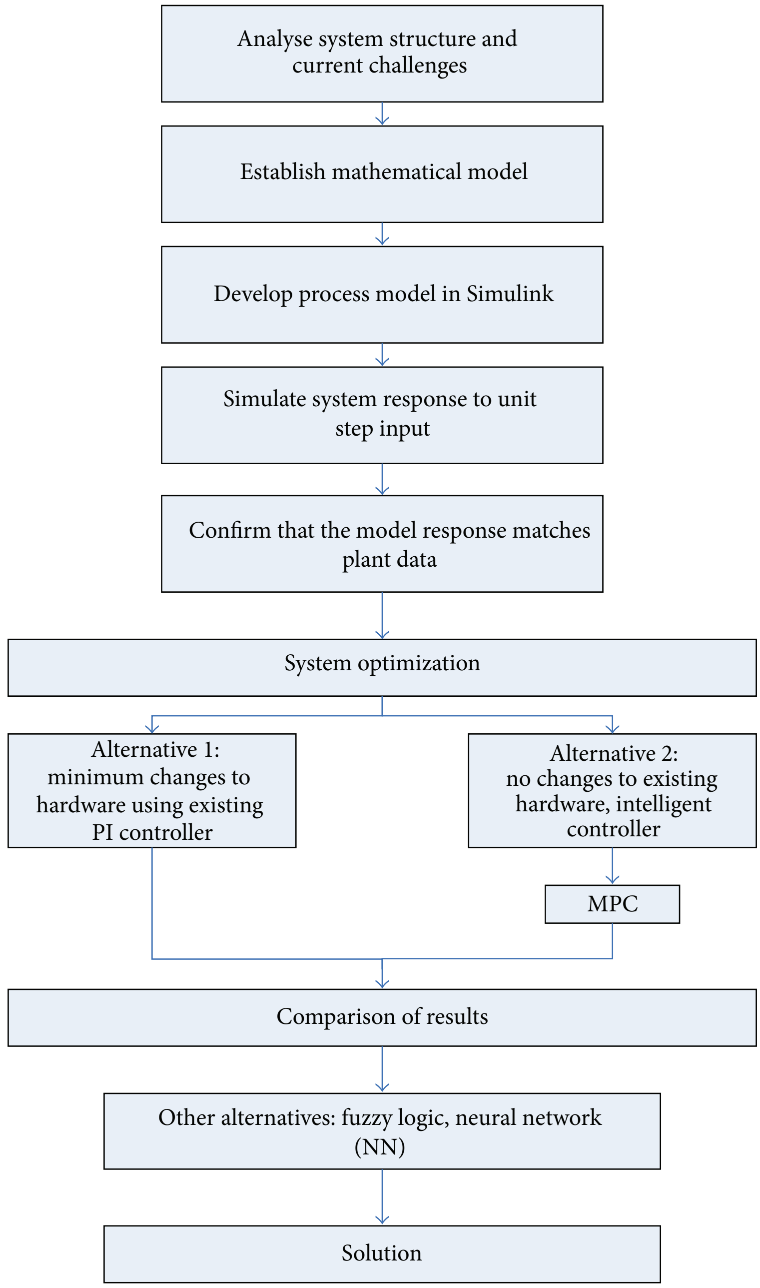


FIGURE 2: Project task breakdown structure.

levels are adjusted individually to minimize the power error and to ensure that each zone is producing the same power, and ideally during steady-state operation with no power maneuvers Liquid Zone levels are expected to remain steady with no RRS control demand.

*2.3. Performance Requirements.* A simplified block diagram of Liquid zone control is shown in Figure 3. Circulation of light water through all 14 Liquid Zone compartments is achieved by continuous water flow through the zones to ensure cooling to the zone control compartments. Water levels are adjusted by RRS by adjusting inlet Control Valves (CVs) so that a constant $\Delta P$ is maintained across the zones. In this case study, only one (1) valve will be considered in order to simplify the analysis. According to the original design documentation reviewed during early stages of this study, the CV in question will be assumed to be a linear diaphragm valve as shown in Figure 4.

The valve is assumed to have a flow restriction of 0.91 L/s maximum with a 0.05 sec deadband, with a natural frequency of 1 Hz and a damping ratio of 1.

Since the focus of this study is the controller itself, no parametrical studies were conducted on valve design or properties.

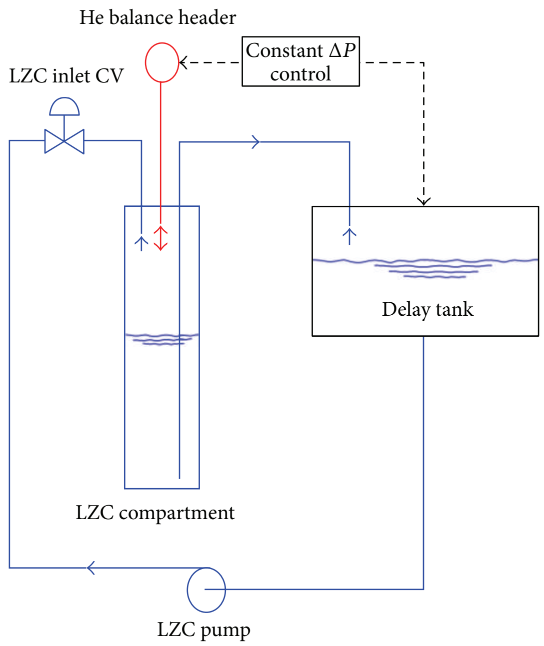


FIGURE 3: Simplified block diagram of LZ control; only 1 of 14 light-water compartments is shown.

*2.4. Existing System Principle of Operation.* During steady-state operation with no RRS power adjustment demand and no zone level changes, there should be equilibrium between inflow and outflow to the zones. For cases where the controller responds to either real or indicated power error, LIFT term is calculated using (1). For steady-state operation with no rate term (DLIF = 0), this can be expressed as

$$\text{LIFT} = \text{BIAS} \pm \text{BLIF}, \quad (1)$$

where BIAS: lift which causes inflow = outflow, RLIF: relative lift = BLIF + DLIF, BLIF: bulk lift = bulk power control term, and DLIF: differential lift = spatial control term for flux tilts.

In this case, the value of BLIF will depend on the effective power error Ep as shown below:

$$\begin{gathered} \text{BLIF} = \text{Kp} * \text{Ep (Power Error)}, \\ \text{Ep} = \text{KB}\,(\text{PLOG} - \text{PDLOG}) + \text{KR}\,(\text{RI} - \text{RD}), \end{gathered} \quad (2)$$

where Ep: effective power error, PLOG: measured reactor power, PDLOG: demand power setpoint, KB: normalized flux loop control gain (=1 at >25% FP), KR: flux loop derivative gain (=0.5), RI: indicated log rate, median ion chamber log rate signal, and RD: demanded reactor power maneuvering rate.

Since the focus of this study is on unanticipated steady-state oscillations at full power, the following assumptions can be made: RP > 25% so KB = 1.0, RD = 0.0, steady state, no power maneuvering, (PLOG-PDLOG) = 0, system at setpoint,

$$\text{Ep} = +\text{KR (RI)} = 0.5\ \text{(RI)}. \quad (3)$$

Since BIAS in (3) is a constant value, this is similar to proportional-only mode, where

$$\text{output} = \text{gain} * (\text{measured variable} - \text{setpoint}). \quad (4)$$

Thus, for the purpose of this study, the existing steady-state LZ controller will be considered to be proportional-only, no adjustments for flux tilts or zone level tilts, and no antiflood/antidrain restrictions, as shown in Figure 5.

*2.5. Current Challenges.* Based on the system design and performance requirements, the following assumptions should be true for steady state with no flux or zone level tilts:

$$\begin{gathered} \text{BLIF} = \text{DLIF} = 0, \\ \text{LIFT} = \text{BIAS} = \text{Const}\ \ (= 0.455). \end{gathered} \quad (5)$$

Therefore, at steady state with no RRS demand for zone adjustments, the zones should remain in a state where inflow is equal to outflow, which is achieved by a constant value of the BIAS term (set to 0.455 in this case).

In practice, as was seen in this case study, it is common to see steady-state LZC CV oscillations. This behaviour was confirmed by running simulation on the LZ Controller and Valve model shown in Figure 6.

The controller response to a unit step change results in a high degree of oscillation exceeding ±15%, which is consistent with the field observations of cases where the zone oscillations of up to a total of 20% (±10%) have been noted in worst case scenarios. This condition appears to be intermittent in nature with random occurrence where exact causes are not fully understood, despite engineering analysis and troubleshooting efforts conducted at the plant. It has been confirmed that the CV oscillations are not due to RRS power adjustment requests or zone level changes due to process leaks. Some of these transients are attributed to level transmitter (LT) drifts, signal noise, or impulse line moisture build-up. The lack of understanding the exact cause of this behaviour adversely affects operators' confidence in the field instrumentation (as a potential source of erroneous readings). Similar to control valves, design and performance of LZ level transmitters will not be considered other than as a component adding to the overall noise (disturbance) that the controller must mitigate while maintaining robustness and speed of response.

*2.6. The Need for Intelligent Control.* There are several key challenges that spurious zone oscillation during steady state is present. First, this raises concerns about RRS capability to respond to real changes when CV manipulation is required for power manoeuvres. Hardware-wise, the unanticipated CV oscillation accelerates wear and tear of the mechanical components and increases their rate of failure, thus resulting in increased demands on maintenance resources and costs. Additional unscheduled calibrations and drift checks for all components of RRS/LZ control circuits add to maintenance burden and increase risk of inadvertent system upsets and potential emergency shutdowns during reactor operation.

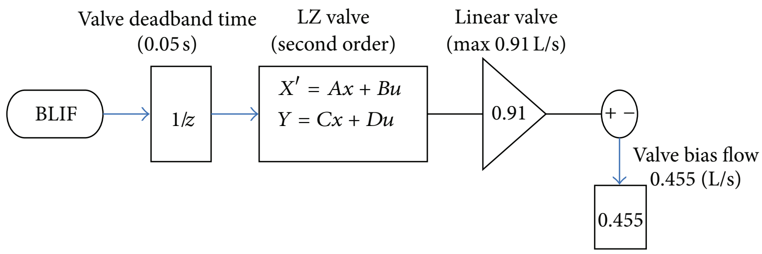


Figure 4: Simplified LZ Control Valve set-up.

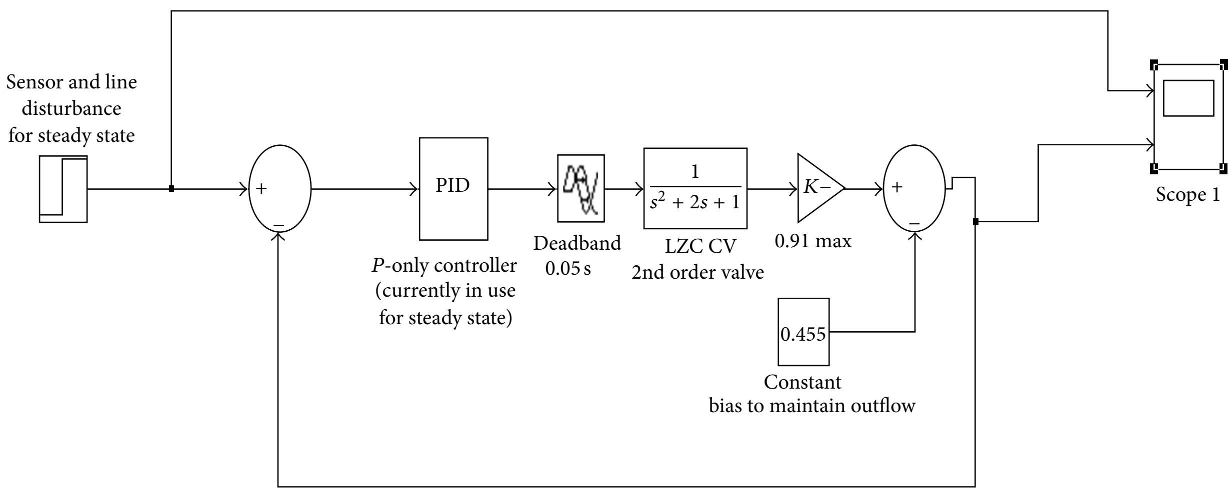


Figure 5: Existing LZ Controller and Valve set-up in Simulink.

In addition to these equipment reliability issues, steady-state zone level transients challenge overall reactor flux control and stability, which presents significant burden to operators, engineering, and maintenance as it sets ground for questioning the overall RRS/LZ control scheme and accuracy of system design and behaviour model.

In this study, an initial attempt was made to look into potential changes to the existing system that would require only most minimal changes to the existing hardware and control logic. A set up for the optimized LZ controller is shown in Figure 7 and controller response is shown in Figure 8. Saturation control and rate limiter were added to the model so that the first derivative of the signal is passing through it to ensure that the output changes not faster than the specified limit and the controller output never reaches the actuator limits.

The proposed improved controller set-up was tested against the same unit of disturbance as in the first case.

The results of this experiment showed that these modifications resulted in conservative bounds and some improvement in controller performance. Noticeably, the magnitude of oscillations (up to ±2%) has improved but did not entirely eliminate the undesirable valve cycling, thus failing to satisfy the criteria for required improvements.

More importantly, the original LZ Fisher & Porter 3000 controllers used at a facility selected for a case study are obsolete and are no longer supported by vendors, and thus implementation of these changes is unlikely to be beneficial in terms of cost savings. The recently installed replacement ABB 5000-series controllers were also analysed as an alternative solution for the obsolescence problem but have shown to have an unusual failure mode (memory failure following Class-II power and battery failure) that had not been fully analysed or understood prior to installation. Additionally, ABB 5000 series is near obsolete and is not going to present a viable long-term solution for the future; thus, the initial proposal is not recommended for further detailed study and a different approach, based on a modern technology, is required.

This study proceeded to look at feasibility of implementation of such controller based on Model Predictive Control (MPC) [15] principles. Several other control methods, such as fuzzy logic and neural network-based controllers [16], were examined to determine whether they can provide suitable alternatives as well. This is described in more detail in the subsequent sections.

## 3. Proposed Controller with MPC

In order to address the needs for a sustainable, long-term solution to the existing LZ control challenges, several alternative technologies were considered. Model-Predictive-Control- (MPC-) based model was designed and tested first in order to see whether intelligent control algorithm can present a suitable solution. This is described in the following sections.

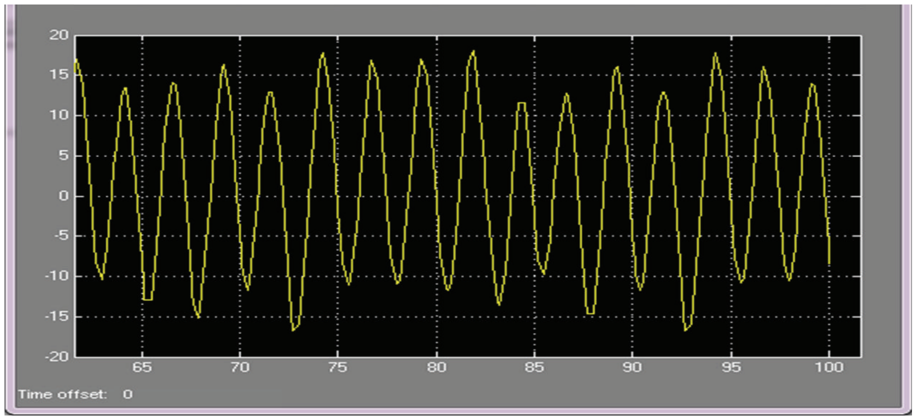


FIGURE 6: Existing LZ CV response to unit step change; the magnitude of controller response is shown over 100 sec interval.

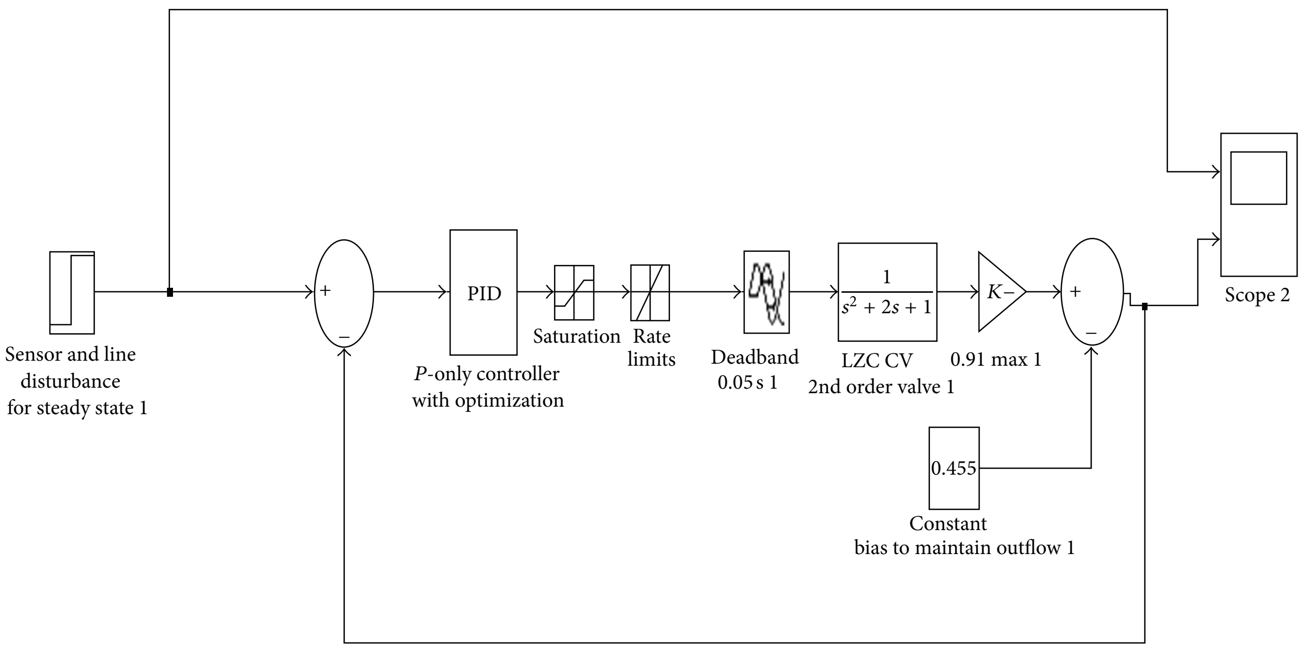


FIGURE 7: Optimized LZ controller set-up in Simulink.

As discussed earlier, the main driver for implementation changes to the existing LZ steady-state control was to minimize or eliminate the undesirable CV oscillations. There are, however, other general performance requirements that the new controller must satisfy in order to present an acceptable alternative to the existing system. These are summarized as follows:

(i) *Closed-Loop Stability*. The new MPC controller must maintain the system output bounded to avoid reaching actuator limits and saturation and minimize overshot.

(ii) *Fast Response*. The new MPC controller must suppress or reject changes in the reference disturbances in the loop.

(iii) *Robustness*. The new MPC controller must have sufficient margin to allow for modeling errors or variations in system dynamics.

*3.1. Control Design.* Principles of Model Predictive Control were used to develop the new LZC control algorithm and set up a model. MPC control algorithm is based on iterative prediction of future plant states based on the presently measured information, for example, Level Transmitter indication at time interval $k$ as well as known measured disturbances. Based on known constrains and control objectives, the alternative future states or the so-called trajectories are calculated. The next step would be to develop an optimization cost function $J$ over the receding prediction horizon:

$$J = \sum_{i=1}^{N} w_{xi}(r_i - x_i)^2 + \sum_{i=1}^{N} w_{ui}\Delta u_i^2, \tag{6}$$

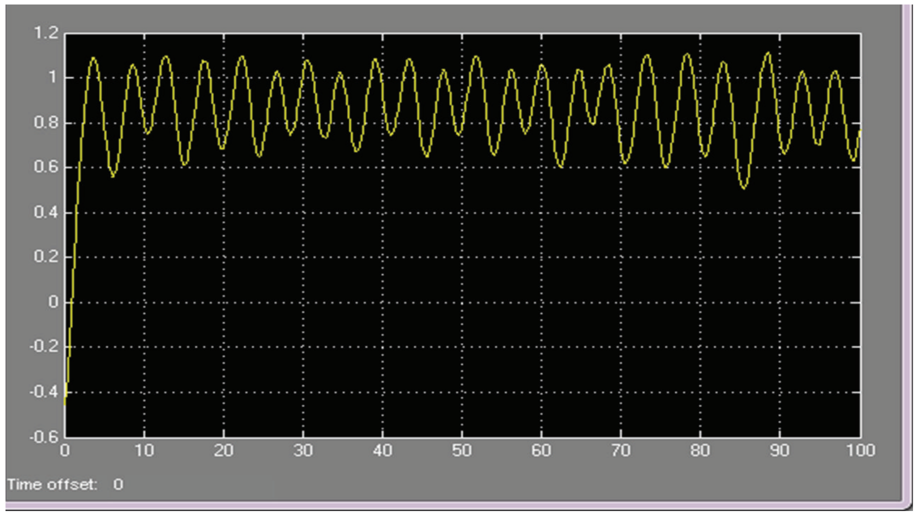


Figure 8: Response of the optimized LZ controller to a unit disturbance; the magnitude of controller response is shown over 100 sec interval.

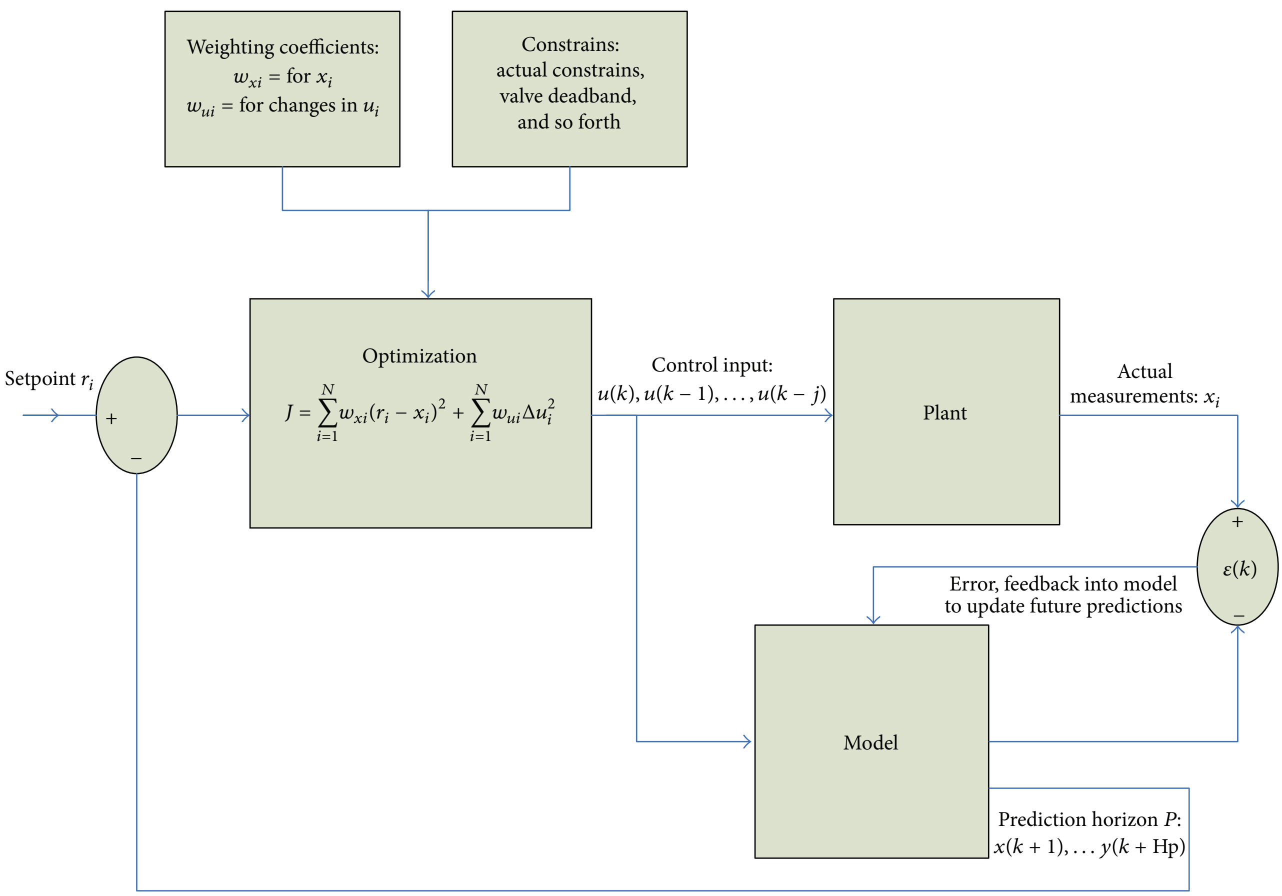


Figure 9: MPC block diagram.

where $x_i$ = controlled variable, for example, LZ level, $r_i$ = reference variable, for example, BIAS (0.455), $u_i$ = manipulated variable (e.g., control valve CV), $w_{xi}$ = weighting coefficient for $x_i$, $w_{ui}$ = weighting coefficient for changes in $u_i$.

Block diagram for this process is shown in Figure 9.

Error $\varepsilon(k)$ represents discrepancy between the physical plant and its model and is used as feedback for the MPC controller to adjust future predictions.

The MPC process is iterative; that is, once a selected control scheme is applied, new measured values for plant

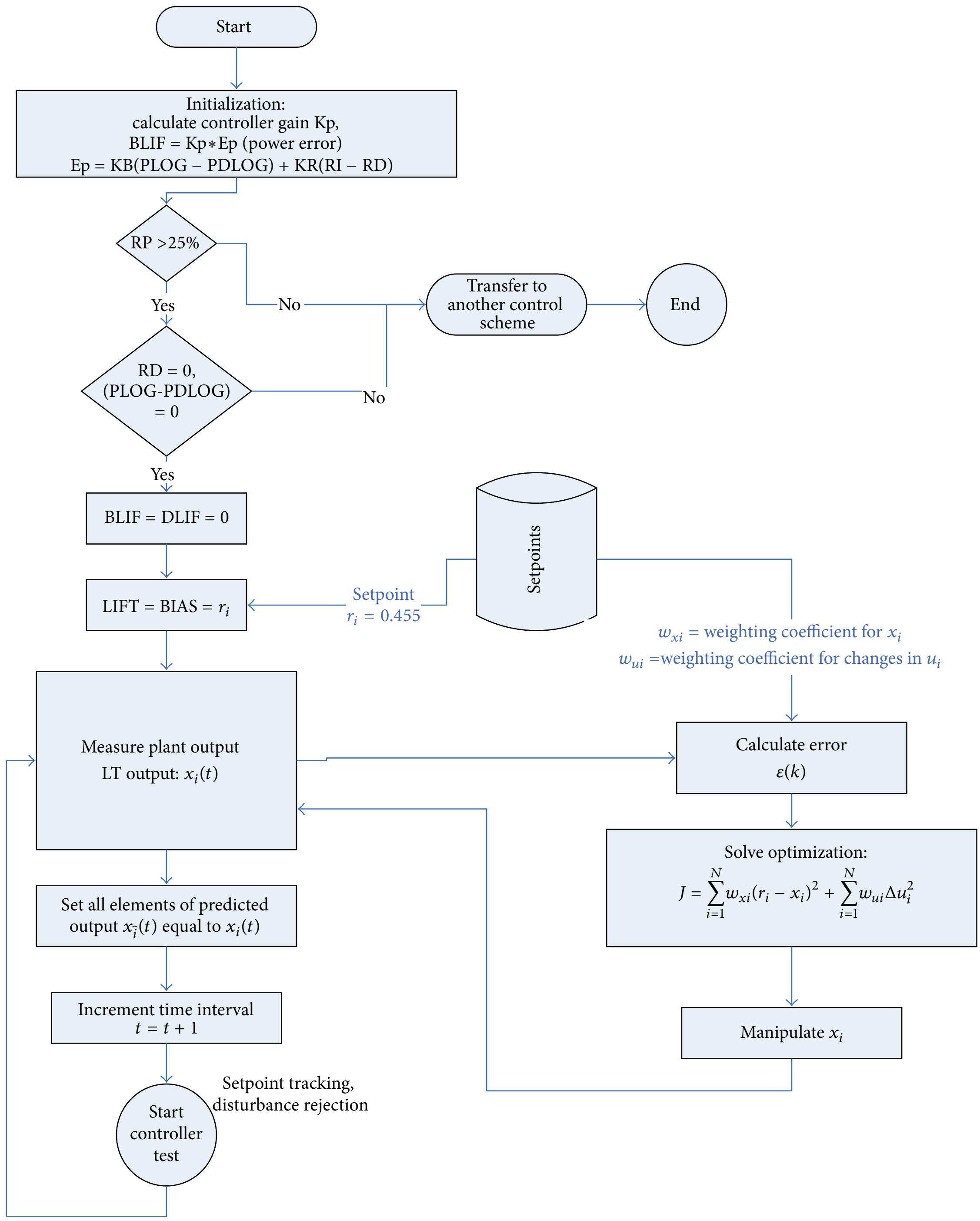


Figure 10: Proposed control design algorithm.

response become available. These measurements become new inputs into the control algorithm calculation, and the process is repeated for the next time interval; that is, $k = k + 1$. The flowchart in Figure 10 illustrates a step-by-step control scheme for the proposed controller.

Next, the proposed MPC-based controller was integrated into the previously created LZ CV system model in Simulink (MatLab Simulink 7.7 R2008 [14] on a standard student Windows PC computer) so that MPC controller would assume all of the performance functions of the existing PID controller. The subsequent modifications to the system, with saturation and rate limiter, were removed with the expectation that the new controller would be able to maintain the required saturation control. This model is shown in Figure 11.

Controller parameters, listed below, were arbitrarily selected to represent:

(i) prediction and control horizons;

(ii) hard and soft constraints on manipulated variables and output variables;

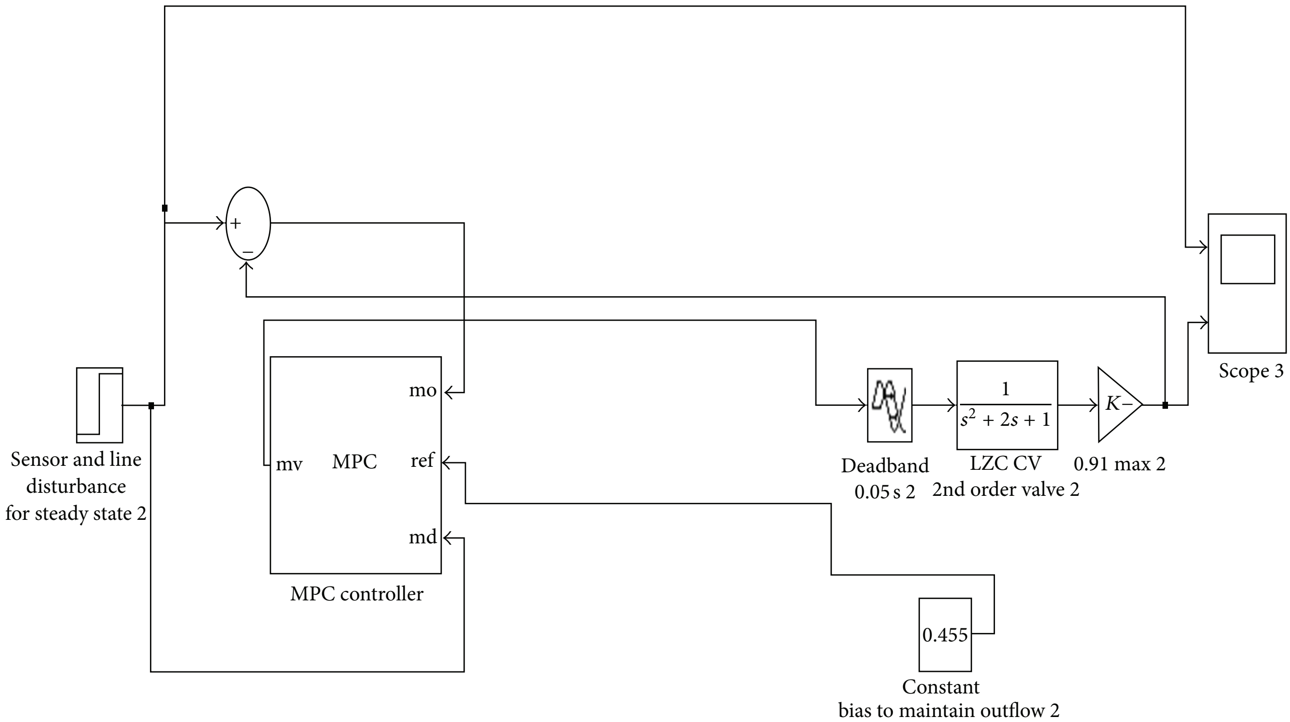


Figure 11: MPC for LZ controller set-up in Simulink.

(iii) weights on manipulated variables and output variables;

(iv) model for measurement noise and for unmeasured input and output disturbances.

Once the model was finalized, the new controller performance was tested by simulating closed-loop system response. The output characteristics were tested to check if performance can be tuned to achieve the desirable balance between controller robustness versus speed of response. Since the scope of this study was to confirm feasibility of this approach, no detailed parametric experiments were conducted until more research is conducted for this proposal.

## 4. Discussion of Results

*4.1. Run Time Adjustment.* One of the main advantages of MPC controllers is that controller performance can be improved by manipulating controller parameters such as weights and constraints and simulating closed-loop system response. This method was used in an iterative process so that the new controller performance can be tested against by running closed-loop simulations the linear plant model. Run time adjustment of output characteristics was performed to demonstrate that the controller is able to achieve the desirable balance between robustness versus speed of response. Shown in Figure 12 are the results for three scenarios where the ratio of speed of response versus robustness is arbitrarily chosen to be 1.0, 0.5, and 0.3 and response of MPC vs. nonlinear proportional only and optimized proportional-only controller is shown in Figure 13.

This confirmed that various options are available and controller's performance can be tuned based on the system performance requirements. Next, the MPC controller performance was compared to the nonlinear proportional-only PID controller described earlier. In all cases, the MPC controller rejected disturbance and attempted to return plant output to the desired setpoint while remaining within the preset constrains. It can be seen that when a higher speed of response was chosen, the controller recovered in the least time but with a higher overshot. In the third case, where a higher degree of robustness was required, the controller overshot was the smallest. This, however, was achieved at the expense of longer recovery time.

*4.2. Proposed Implementation.* Based on the results obtained during this study, MPC-based controller appears to be a strong alternative to the existing obsolete PID controllers, especially for older Nuclear power units, and is recommended for consideration for future generations of CANDU nuclear power plants Implementation of hardware set-up for the proposed model predictive control system on a PC-compatible hardware using Simulink Coder is shown in Figure 14.

Comprehensive further work will be required to develop and verify optimal cost and control sequence at each computation step and to extend the control scheme to encompass the entire range of LZ operation, for example, integral control required during power manoeuvres.

Next, "C" code from Simulink blocks can be used to deploy a supported target system for prototype testing to determine if the proposed controller will have enough computational speed to address performance requirements for

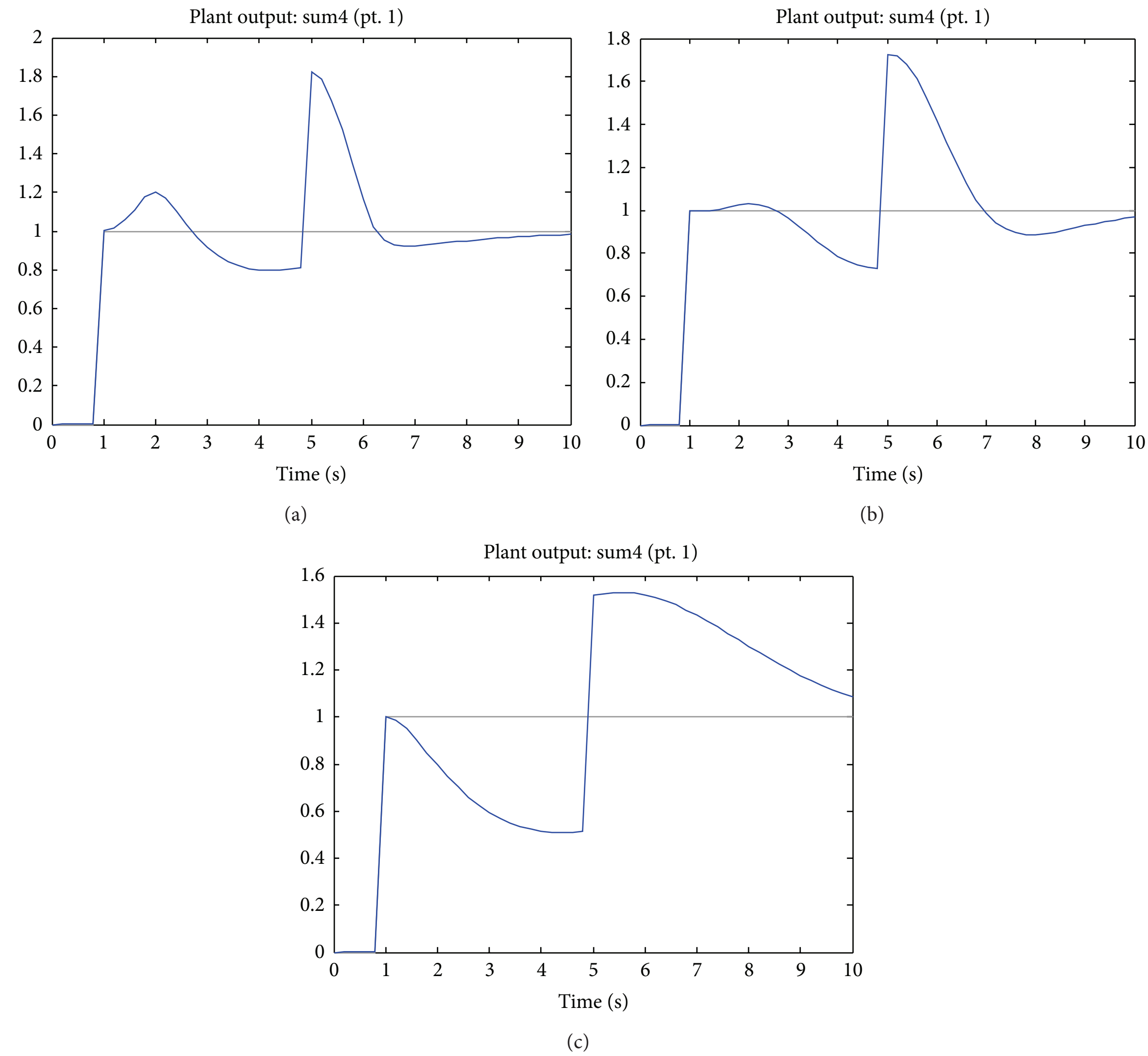


Figure 12: MPC controller performance is shown for three cases where the ratio of speed of response versus robustness of the MPC controller is adjusted to 1.0 (a), 0.5 (b), and 0.3 (c). Plant output is shown in blue versus the reference setpoint in grey.

a larger, more complex plant model. One of the foreseeable challenges that the current LZ control scheme set-up may represent for MPC-based controller deployment could be the need for synchronization of the individual systems. As mentioned earlier, a typical CANDU LZ control is comprised of 14 light water compartments, each with its own associated Control Valve. Bulk and special level adjustment is calculated by Reactor Regulating System (RRS) residing on the Digital Control Computers (DCCs). It is critical to ensure that the new controller is able to maintain process variables at setpoint in a MPC-DCC set-up.

Additionally, field installation of the proposed MPC controller will require extensive design verification by an independent third party to ensure compliance with all applicable codes and standards and will require approval from the Canadian Nuclear Safety Commission.

*4.3. Comparative Analysis of Other Alternative Technologies.* Fuzzy logic-based control methods were considered for this project as an alternative means to enhance the currently obsolete LZ controllers at nuclear power stations. Typically fuzzy logic is used in applications for complex system or behaviours where relationships are unknown or unclear. This alternative was rejected since the system model is known and understood. Also, negative feedback, received from the current operations staff at a selected nuclear facility on the use of "fuzzy logic" term, highlighted additional challenges that will need to be overcome in order to implement this approach, especially at older utilities. It became apparent that a large number of control room operators and some maintenance personnel are not familiar with recent developments in control technology. The use of "fuzzy" term in fuzzy-logic methods was perceived to be equal to "unclear" or "confusing" and is, therefore, not readily accepted as "appropriate" to the critical control and safety applications in nuclear power plants. Therefore, should this method be selected in future work, specifically for older plants, the researches must consider the required changes to

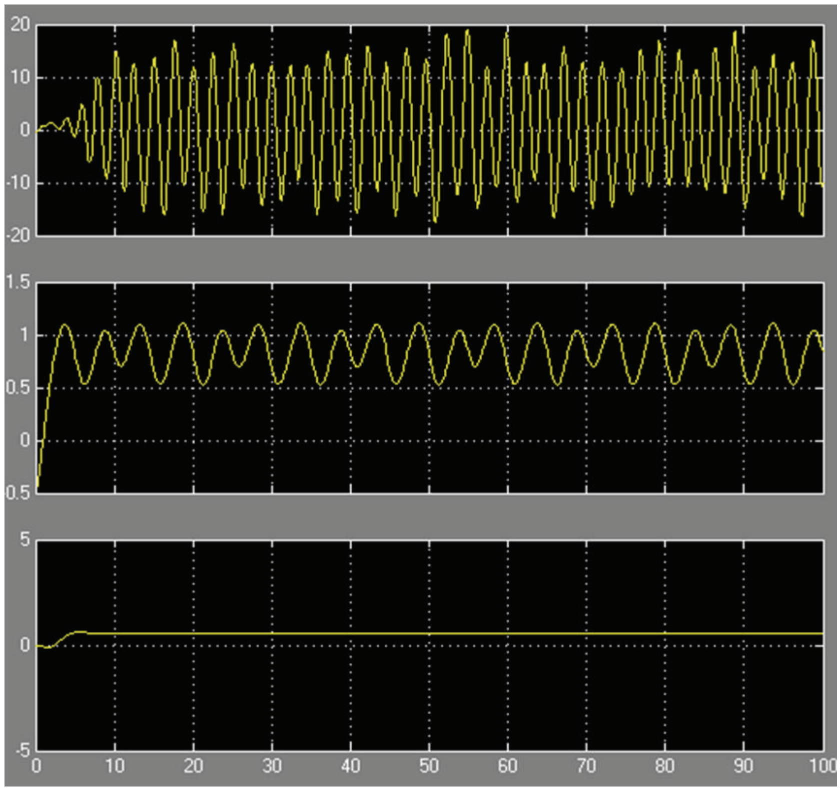


FIGURE 13: MPC controller (bottom graph) is shown against the nonlinear proportional-only controller (topmost) and optimized proportional-only controller (middle); the magnitude of controller response is shown over 100 sec interval.

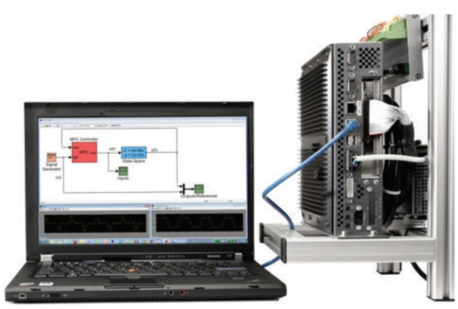

FIGURE 14: Hardware setup for rapid prototyping of a model predictive controller on PC-compatible hardware using Simulink Coder and xPC Target [14].

the existing operations and maintenance training programs and include provisions for education and familiarization of personnel with this technology in order to eliminate cultural barrier.

Another alternative considered in this project for future consideration was Neural-Network- (NN-) based controller. It was also rejected since the NN methods are most suitable for applications where formal analysis is difficult or impossible due to complexity of pattern recognition and system identification and control. In the case of LZ controllers, where patterns and identification are simple and formal analysis can be readily conducted, this technology does not seem to provide the best fit, especially as it may require high computational resources. Also, from the cultural perspective, the main principle of NN methods was perceived by certain operators as overcomplicated and "not technological enough" due to association with biological organisms, based on a preconceived notions of "human factors = human error." This feedback was consistent with earlier findings in the literature review [1] where public acceptance is identified as one of the main "soft" criteria for nuclear industry.

## 5. Conclusions

It has become clear that the old obsolete F&P 3000 controllers and the newly installed ABB 5000 series controllers cannot provide a sustainable long-term solution for LZ control at existing CANDU nuclear power plants and will have to be replaced with a modern technology for the next generation of CANDU reactors. This project was conducted as a preliminary feasibility study to evaluate the existing challenges and consider suitable alternatives. The existing proportional-only steady-state control scheme was examined based on performance history at a selected operating facility. An optimized proportional controller was considered, and early tests showed a significant improvement in the magnitude of steady-state error. Despite the advantages of minimal changes to the existing equipment and circuitry and ease of implementation, this approach was not able to eliminate the undesired oscillation of CV valves that was the main focus of this study. Furthermore, this controller would still be based on the obsolete hardware and technology currently in service at production facilities and is not going to present a long-term solution for the next generation of CANDU plants.

An alternative MPC-based control scheme was implemented in Matlab Simulink and tested against the same disturbance to emulate simplified plant conditions leading to CV oscillations. The MPC-based controller showed a significant improvement both in terms of rejecting the disturbance and returning plant output to the desired reference point, as well as minimizing oscillations on the CV valves. This highlighted an important benefit of application of MPC controller technology for operating power plants where prescribed plant constrains can be addressed. For example, actuator constraints and controller's performance can be tuned in terms of speed of response, magnitude of error, or robustness, based on specific plant requirements.

Two other alternatives, namely, fuzzy logic and neural network-based control schemes, were investigated to determine whether they could provide another suitable option for future study. These alternatives were rejected for various reasons, such as complexity, required computational power, and cultural perceptions.

Based on these results, it is proposed to consider further detailed study for application of MPC-based controller for Liquid Zone control in CANDU reactors with model and prototype development and testing using historical plant data. Based on results of these studies, field implementation and in-service tests can be conducted at one of the existing facilities, so that lessons learned could be incorporated into the future generation of CANDU reactor design as a sustainable long-term solution based on widely available and supported modern technology [17–20]. It is anticipated that this project will involve high levels of financial costs and multidisciplinary resources, and thus future work will depend on industry interest in advancing this proposal.

## References

[1] J. G. Williams and W. C. Jouse, "Intelligent control in safety systems: criteria for acceptance in the nuclear power industry," *IEEE Transactions on Nuclear Science*, vol. 40, no. 6, pp. 2040–2044, 1993.

[2] D. E. Goldberg, *Genetic Algorithms in Search Optimizations and Machine Learning*, Addison-Wesley, Reading, Mass, USA, 1989.

[3] Y. Zhang and J. Jiang, "Bibliographical review on reconfigurable fault-tolerant control systems," *Annual Reviews in Control*, vol. 32, no. 2, pp. 229–252, 2008.

[4] H. E. Rauch, "Intelligent fault diagnosis and control reconfiguration," *IEEE Control Systems*, vol. 14, no. 3, pp. 6–12, 1994.

[5] M. Bruccoleri, M. Amico, and G. Perrone, "Distributed intelligent control of exceptions in reconfigurable manufacturing systems," *International Journal of Production Research*, vol. 41, no. 7, pp. 1393–1412, 2003.

[6] M. G. Mehrabi, A. G. Ulsoy, Y. Koren, and P. Heytler, "Trends and perspectives in flexible and reconfigurable manufacturing systems," *Journal of Intelligent Manufacturing*, vol. 13, no. 2, pp. 135–146, 2002.

[7] "INL—Idaho National Laboratory," https://inlportal.inl.gov/portal/server.pt/community/instrumentation,_control_and_intelligent_systems/315/dcnf.

[8] M. Boroushakia, M. B. Ghofrania, C. Lucasb, and M. J. Yazdanpanahb, "An intelligent nuclear reactor core controller for load following operations, using recurrent neural networks and fuzzy systems," *Annals of Nuclear Energy*, vol. 30, no. 1, pp. 63–80, 2003.

[9] M. Boroushakia, M. B. Ghofrania, C. Lucasb, M. J. Yazdanpanahb, and N. Sadatic, "Axial offset control of PWR nuclear reactor core using intelligent techniques," *Nuclear Engineering and Design*, vol. 227, no. 3, pp. 285–300, 2004.

[10] S. S. Khorramabadi, M. Boroushaki, and C. Lucas, "Emotional learning based intelligent controller for a PWR nuclear reactor core during load following operation," *Annals of Nuclear Energy*, vol. 35, no. 11, pp. 2051–2058, 2008.

[11] M. Boroushaki, M. B. Ghofrani, C. Lucas, and M. J. Yazdanpanah, "Identification and control of a nuclear reactor core (VVER) using recurrent neural networks and fuzzy systems," *IEEE Transactions on Nuclear Science*, vol. 50, no. 2, pp. 159–174, 2003.

[12] D. Ruan, "Intelligent systems in nuclear applications," *International Journal of Intelligent Systems*, vol. 13, pp. 115–125, 1998.

[13] R. S. Gilbert, "Control and safety computers in CANDU power stations," in *Nuclear Power and Electronics*, IAEA Bulletin, 1985, http://www.iaea.org/Publications/Magazines/Bulletin/Bull273/27302390712.pdf.

[14] http://www.mathworks.com/.

[15] http://en.wikipedia.org/wiki/Model_predictive_control.

[16] S. J. Qina and T. A. Badgwell, "Survey of industrial model predictive control technology," *Control Engineering Practice*, vol. 11, pp. 733–764, 2003, http://www.elsevier.com/.

[17] K. Hu and J. Yuan, "Multi-model predictive control method for nuclear steam generator water level," *Energy Conversion and Management*, vol. 49, no. 5, pp. 1167–1174, 2008, http://www.sciencedirect.com/.

[18] M. G. Na, "Auto-tuned PID controller using a model predictive control method for the steam generator water level," *IEEE Transactions on Nuclear Science*, vol. 48, no. 5, pp. 1664–11671, 2001.

[19] G. Xia, J. Su, and W. Zhang, "Multivariable integrated model predictive control of nuclear power plant," in *Proceedings of the 2nd International Conference on Future Generation Communication and Networking Symposia (FGCNS '08)*, pp. 8–11, December 2008.

[20] M. G. Na and I. J. Hwang, "Design of a PWR power controller using model predictive control optimized by a genetic algorithm," *Nuclear Engineering and Technology*, vol. 38, no. 1, 2006, http://www.kns.org/jknsfile/v38/JK0380081.pdf.