

## **Distributed Control Algorithm for Optimum Hybrid Nuclear and Hydrogen Production Plants**

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### **1. Introduction**

Hydrogen production using CANDU reactors has been an area of interest in the past few years due to the use of hydrogen as an alternate energy source [1]. Although the process design in this field has made rapid growth, the optimal control design has been neglected. The focus of this paper will be to develop a control design framework to optimize the hydrogen production using waste heat and steam from CANDU reactors. The proposed approach is based on a multi-objective genetic algorithm (MOGA) to study the dependence among different CANDU parameters. The dependent parameters are grouped together into distributed controllers for optimum performance. It is shown that separate controllers can be designed for each parameter groupings. The implementation of these controllers using distributed control systems (DCS) will enhance the modularity and optimization of the target integrated CANDU-Hydrogen process. A novel DCS setup is proposed with each of these controllers assigned to different nodes to ensure flexible implementation in nuclear power plants. Finally, a control design analysis is done through simulations to analyze the performance of the PID control implementation for the valve facilitating the flow of steam from the CANDU reactor to the hydrogen production plant.

### **2. Proposed Generalized Controller for the Hybrid Plant**

In this section, we propose a centralized system to control both the CANDU reactor and the hydrogen Production Plant as shown in figure 1. Our proposed design is based on the assumption that the electricity demand and the hydrogen demand are always met. For a setup such as this, an alternate mode is generally used as the preferred mode of operation for a CANDU reactor. However, it is also possible to meet the requirements of such setup using normal mode of operation as long as the output electrical power meets the demands of the grid. In case the steam and heat supply from the CANDU reactor is short, the Hydrogen production is reduced. If the produced amount of hydrogen does not meet the hydrogen demand, the use of an external electricity source and water supply to produce steam is proposed. It is recommended that the external electricity source must not be dependent on the CANDU electricity supply to ensure stable operation.

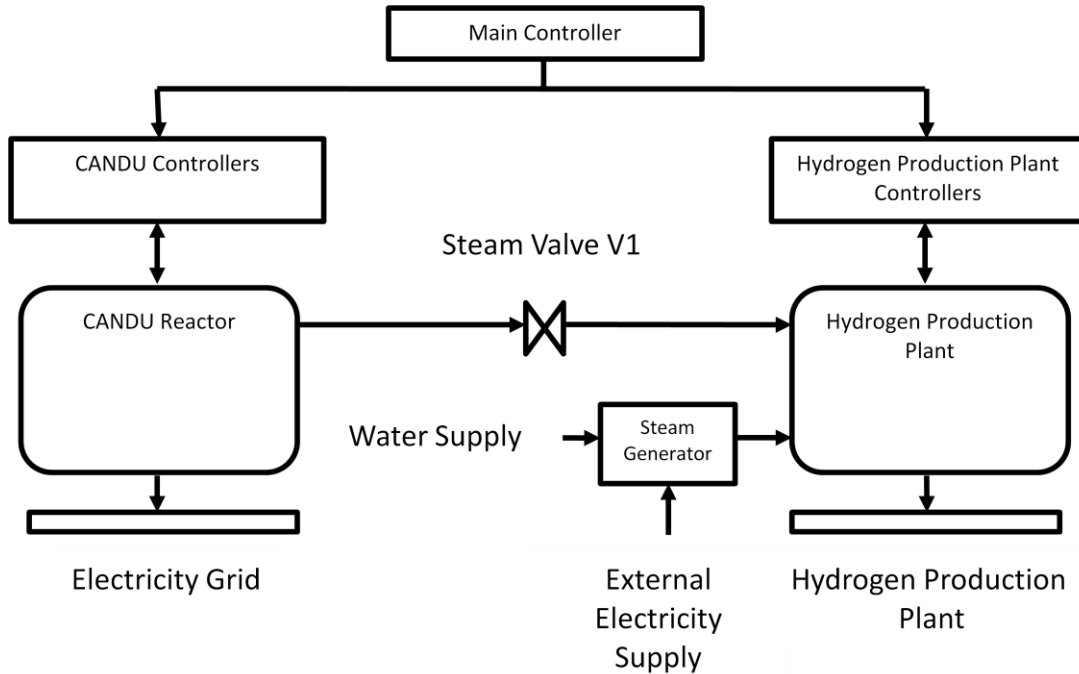


Figure 1: Overall plant control structure

### 3. Proposed Design of Distributed Control for CANDU and Hydrogen Production Plant

Using Multi-objective Genetic Algorithm (MOGA), we study the dependence among different CANDU and hydrogen plant parameters. The dependent parameters are grouped together. These groups are analyzed to establish which processes these parameters correspond to. It is important to note that there can be multiple processes that are dependent on each other and hence, parameters from all these processes can be found within the same group. Separate controllers are assigned to each of the processes that are described by the parameters within the group. Finally, the process controllers within each group are assigned a single main controller to facilitate the coordination among the controllers within each parameter grouping. These controllers are implemented on a DCS for optimal performance. The schematic of the proposed DCS setup is shown in figure 2.

We propose the following steps for a successful design of a distributed control system for the hybrid power plant:

#### 3.1 Process Data Acquisition

Real process data for both the CANDU reactor and the hydrogen production plant will be required. In case the real process data is not available, simulated data can be used for initial analysis. Due to simulation errors, the use of real plant data is recommended. CANDU 9 simulator can be used to acquire power plant data. To our knowledge, no data simulator is available yet for the hydrogen production plant.

#### 3.2 Parameter Grouping

Two methods can be used for parameter grouping: 1) Dynamic decoupling algorithm 2) Multi-Objective Genetic Algorithm [2]. For the application of dynamic decoupling algorithm, a regression analysis on the plant process data is first required to build a mathematical model for each plant parameter.

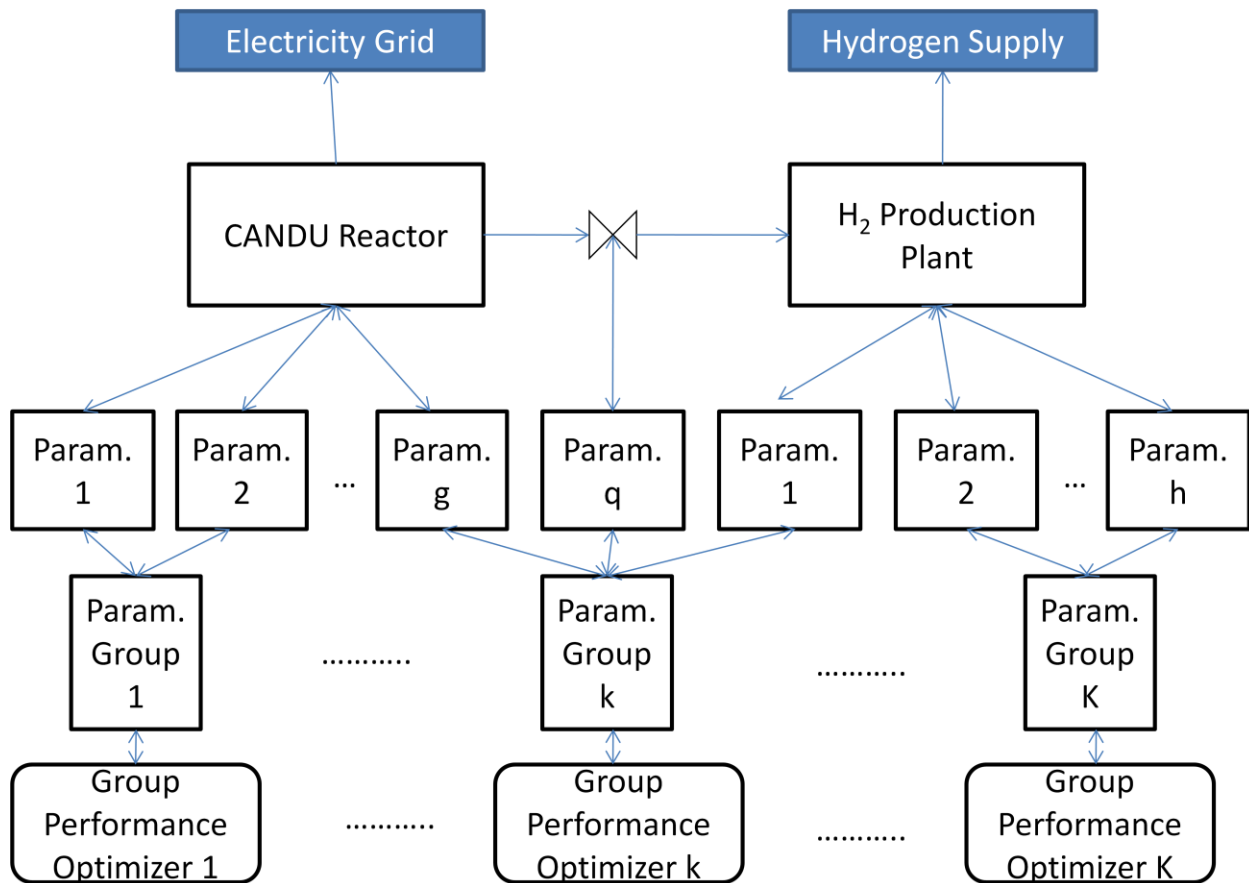


Figure 2: The Distributed Control Concept

The dynamic decoupling algorithm can then be applied to these mathematical models to form groups of decoupled input signals. Note however that the regression model is obtained using a curve of best fit and hence, is approximate.

On the other hand, the multi-objective genetic algorithm does not require a regression analysis. The design frame in this case is explained in [2] and is summarized here: given a group of  $n$ -signals, one can form  $M$  different groups of signals such that certain criteria are met. For design simplicity, we can assign  $n$ -bits to each group of signals. The bit value is one when if the signal is in the group and 0 if it not, as shown in figure 3.

Bit 1	Bit 2	Bit 3	.....	Bit n
0	1	0	.....	1

Figure 3: Bit allocation for a generic  $m^{\text{th}}$  group of signals

As explained in [2], our target is to achieve a set of highly diversified groups of signals with high correlation among the signals in each group. Hence, our objective is two-fold: 1) Form groups of signals,

say  $M$  in total, in such a way that the diversity among the groups is maximized. 2) The correlation among signals in each group is maximized. To apply the Multi-objective Genetic Algorithm, we need to first model these two objectives in a mathematical form. To compute the diversity among different group, we use the concept of Hamming distance [3; 4]. To compute the pair-wise diversity among two groups  $p$  and  $q$ , we first calculate the number of different,  $diff_{p,q}$ , and common signals,  $comm_{p,q}$ , between the two groups using the following relations:

$$diff_{p,q} = \sum_{i=1}^n |s_i^p - s_i^q|$$

$$comm_{p,q} = \sum_{i=1}^n \delta_{p,q}(i)$$

where  $s_i^r$  is one if the  $i^{\text{th}}$  signal is included in the  $r^{\text{th}}$  group and zero if it is not.  $\delta_{p,q}(i)$  is one if both  $p$  and  $q$  contain the  $i^{\text{th}}$  signal and zero if they do not.

The pair-wise diversity between the two groups is calculated using the following relations:

$$div_{p,q} = \frac{diff_{p,q}}{m_p + m_q - comm_{p,q}}$$

where  $m_r$  is the number of signals in the  $r^{\text{th}}$  group.

Note that the calculated diversity is zero if the two groups contain exactly the same signals (i.e.  $diff_{p,q}=0$ ) and is one if the groups have no signals in common.

Finally, the group diversity between the  $m^{\text{th}}$  group and the rest of the groups is finally computed as the average pair-wise diversity and is used as the objective function for the genetic algorithm [2]:

$$d_m = \frac{1}{M-1} \sum_{\substack{j=1 \\ j \neq m}}^M div_{m,j}$$

To compute the correlation among different signals within a group, we make use of the general mathematical formula [2]:

$$corr_{u,v} = \frac{1}{n-1} \sum_{t=1}^n \left( \frac{f_u(t) - \bar{f}_u}{s_{f_u}} \right) \left( \frac{f_v(t) - \bar{f}_v}{s_{f_v}} \right)$$

where  $f_r(t)$  is the signal measurements of  $r^{\text{th}}$  signal with respect to time,  $\bar{f}_r$  is the mean value and  $s_{f_r}$  is the standard deviation of the signal measurements of the  $r^{\text{th}}$  signal.

The values of correlation range between -1 and 1. If the signals  $v$  and  $u$  both increase or decrease with time,  $corr_{u,v}$  is positive and if they both are related inversely,  $corr_{u,v}$  takes a negative value. A correlation value of zero means that the signals are independent of each other.

We then compute the mean of absolute values of correlation for each signal assuming there are  $m$  signals in one group:

$$\langle corr_v \rangle = \frac{1}{m-1} \sum_{\substack{j=1 \\ j \neq v}}^m |corr_{u,v}|$$

Finally, the group correlation,  $r_m$ , is taken as the second objective function for the generic algorithm:

$$r_k = \sqrt{\prod_{p=1}^m \langle corr_p \rangle}$$

The above multi-objective optimization produces a set of  $M$  highly correlated and diverse groups of signals.

### 3.3 Block Diagram of the Control System through Group Analysis

We analyze each group and figure out which process or equipment (i.e. valve, pump etc) is described by these parameters. We establish which parameters are inputs and which of them are outputs to each process in the group. Note that multiple processes can be dependent on each other and hence, can be in the same group. We draw a block diagram of the control system for each of these processes. The dynamical model of each process is obtained through the use of extensive literature available on heat transfer, fluid dynamics, electronics etc based on the type of process/equipment under consideration.

### 3.4 Individual Controller Design

The dynamic model achieved through process analysis can then be either represented in a transfer function form or a state space form and traditional control techniques like Proportional-Integral-Derivative (PID) control, Model Predictive Control (MPC) and feedback control can be applied to stabilize the plant.

### 3.5 Control Design Analysis:

Different stability analysis tools are used to establish the effectiveness of the final control designs. These include Bode plots, Nyquist plots, Routh array etc. Robustness of the control design is also tested by introducing a random disturbance signal to observe if the controller has disturbance rejection capabilities.

### 3.6 Control Design Optimization

Since the parameters are divided into groups with maximum diversity between groups, we can optimize the control design by using a genetic algorithm to achieve better plant performance. The objective of the optimization can be the settling time minimization and satisfactory transient performance of the plant parameters in terms of overshoot/undershoot.

Please see figure 2 for a schematic of the overall distributed control system achieved by following these steps.

#### 4. Case Study

As a hypothetical case study, we focus on the control of the valve that assists the steam flow between the CANDU and the hydrogen plant. Figure 4 shows a schematic of the process under consideration. We follow each step from the previous section to build a distributed control structure.

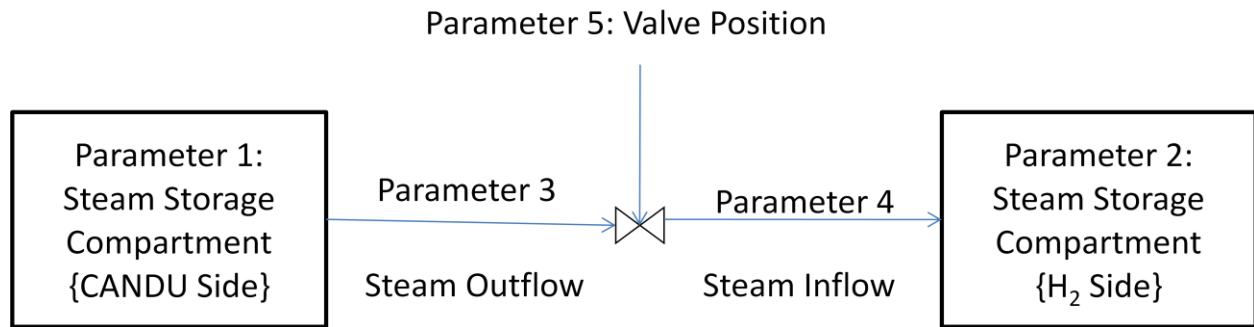


Figure 4: The correlated process parameters in  $k^{\text{th}}$  group

#### 4.1 Plant parameter data acquisition:

For the purposes of this case study, we assume that there is process data available for the hybrid nuclear and hydrogen production plant either through a simulator or through the sensors used in the real plant.

#### 4.2 Parameter Grouping through MOGA:

Due to the unavailability of real process data, we cannot actually complete this step in the case-study. However, it is fair to assume that, after the application of MOGA, we may end up with a  $k^{\text{th}}$  group that contains the steam outflow of the CANDU, steam inflow of hydrogen plant and the valve (V1) position as the parameters because they are all correlated. More specifically,

*$k^{\text{th}}$  group*

*[Steam inflow to H2, Valve position, Steam outflow from CANDU, Steam Pressure {CANDU side}, Steam Pressure {H2 side}, ...]*

Please see figure 4 for a detailed schematic diagram of the process involving the parameters in the  $k^{\text{th}}$  group.

#### 4.3 Block Diagram of the Control System through Group Analysis

The main equipment under control is the valve V1. We first identify the input and output parameters to the valve. In this case, the input parameter is the steam outflow from the CANDU and the output parameter is the steam inflow to the hydrogen production plant. The block diagram of the control structure is given in figure 5.

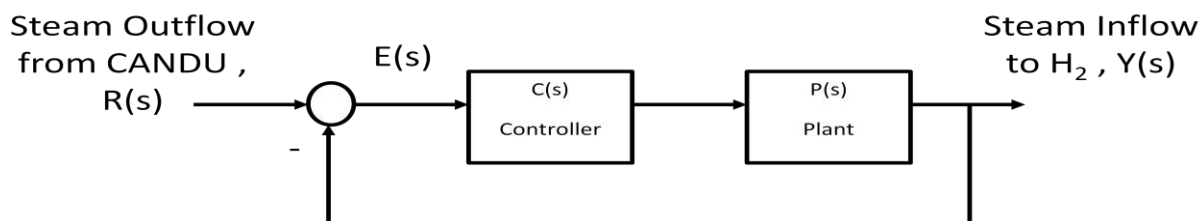


Figure 5: Schematic of the General Control System

Where  $R(s)$  is the desired set-point and  $Y(s)$  is the actual output. The target of the control system is to make the output  $Y(s)$  match the input  $R(s)$  by driving the error  $E(s)$  to zero.

The criterion for controller performance is iterated blow:

- 1) Small Settling time.
- 2) Minimal Overshoot.

#### 4.3.1 Steam Flow Control Modeling and Design

For simulation purposes, we assume that the valve V1 between the CANDU and the hydrogen plant, as shown in figure 2, is hydraulic actuated.

The schematic diagram of the hydraulic actuated valve is given in figure 6.

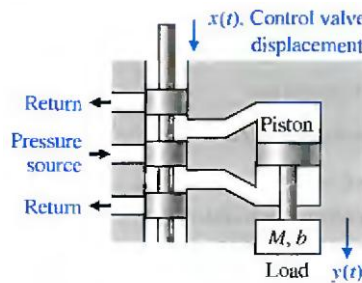


Figure 6: Hydraulic actuated Valve [5]

The dynamics of the hydraulic actuated value are given by the following equation [5]:

$$A(t)P = M\dot{y} + b\dot{y} \quad (1)$$

Where  $A(t)$  is the area of the piston,  $P$  is the pressure and  $M$  is the mass of the load as shown in figure.

Also, the mass flow rate is given by [5]:

$$\dot{m}(t) = \rho A\dot{y} \quad (2)$$

Where  $\rho$  is the weight density of fluid and  $V$  is the velocity of the fluid.

Also, from [5],

$$Q = \left( \frac{\partial g}{\partial x} \right)_{x_0, P_0} x + \left( \frac{\partial g}{\partial P} \right)_{x_0, P_0} P = k_x x - k_p P \quad (3)$$

$$Q = A \frac{dy}{dt} \quad (4)$$

Substituting (3) in (1) and combining with (4), we get

$$\frac{Ak_x}{k_p}x = M\frac{d^2y}{dt^2} + \left(b + \frac{A^2}{k_p}\right)\frac{dy}{dt} \quad (5)$$

Multiplying both sides of equation (5) by  $\rho A$ , we get

$$\frac{\rho A^2 k_x}{k_p}x = \rho A M \ddot{y} + \rho A \left(b + \frac{A^2}{k_p}\right) \dot{y} \quad (6)$$

Substituting (2) in (6), we get

$$\frac{\rho A^2 k_x}{k_p}x = M \ddot{m} + \left(b + \frac{A^2}{k_p}\right) \dot{m} \quad (7)$$

Taking the Laplace transform of equation (7) assuming all initial conditions to be zero, we get

$$\frac{\rho A^2 k_x}{k_p}X(s) = s^2 M m(s) + s \left(b + \frac{A^2}{k_p}\right) m(s) \quad (8)$$

$$G(s)_{valve} = \frac{m(s)}{X(s)} = \frac{\frac{\rho A^2 k_x}{k_p}}{s^2 M + s \left(b + \frac{A^2}{k_p}\right)} \quad (9)$$

Equation (9) represents the transfer function of our plant for the valve where  $m(s)$  is the mass flow of the steam to be controlled that passes through the valve and  $X(s)$  is the valve position.

For simplicity, we will make the following assumptions:

$$M = 1 \text{ kg}; k_p = k_x = b = 1; A = 1 \text{ m}^2; \rho = 1 \text{ N/m}^3$$

Hence, the simplified transfer function used in the proceeding sections of this paper is given by:

$$G(s)_{valve} = \frac{m(s)}{X(s)} = \frac{1}{s(s+2)} \quad (9)$$

#### 4.4 Individual Controller Design

The following schematic shows our controller and plant configuration:

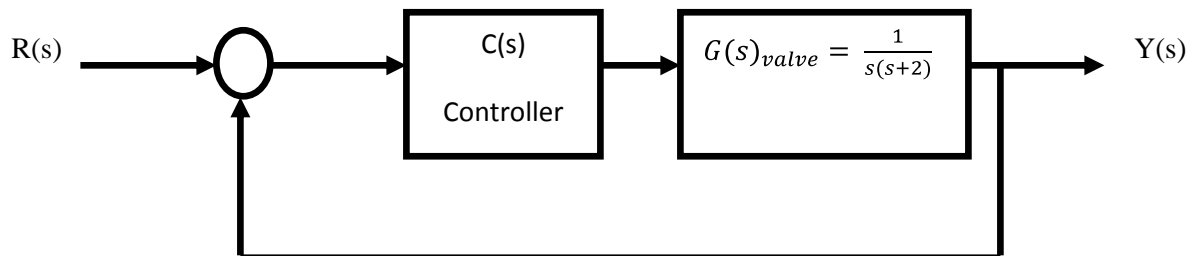


Figure 7: controller and plant configuration

#### 4.4.1 Controller Simulation

##### 4.4.1.1 Uncontrolled open-loop plant simulation

The open loop plant is excited with a step input and the results are shown in figure 8.

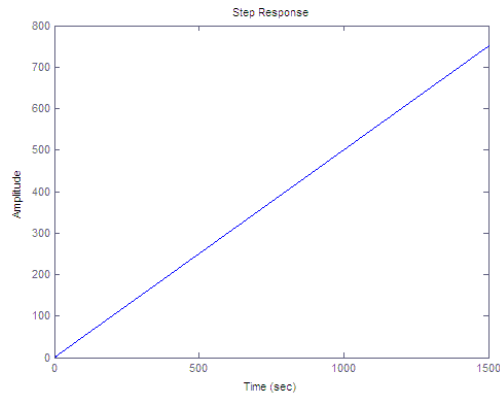


Figure 8: Uncontrolled Open Loop Plant Simulation

As the system does not converge to a certain value, it is inherently unstable.

##### 4.4.1.2 Proportional + Integral + Derivative Controller for V1

The PID controller transfer function is given by:

$$C(s) = K_p + K_I/s + K_D s$$

MATLAB code is used to simulate the plant with the above controller and the results are given below:

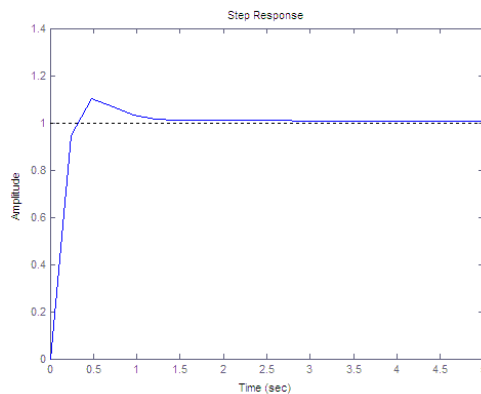


Figure 9: Plant simulation with PID Controller for  $K_p = 40$ ,  $K_I = 7$  and  $K_D = 7$

As seen in figure 9, the settling time is considerably high (i.e.,  $T_{\text{settling}} = 5\text{s}$ ) using the PID controller. Also, there is an overshoot of about 15%.

##### 4.4.1.3 PID Control Tuning

After some control tuning, we end up with the following step response:

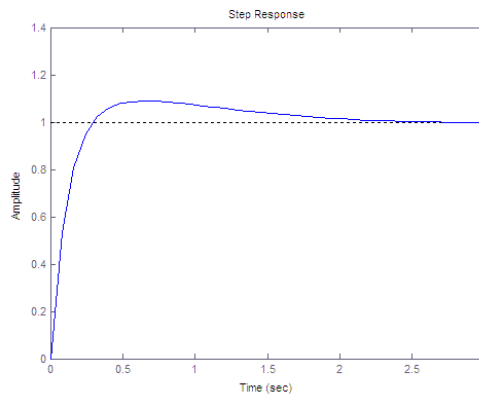


Figure 10: Plant simulation with PID Controller for  $K_p = 25$ ,  $K_I = 25$  and  $K_D = 9$

As seen in figure 10, the settling time is has decreased significantly (i.e,  $T_{\text{settling}} = 2.5\text{s}$ ) using the PID controller. Also, there is an overshoot of less than 10%.

The PID controller seems to be a logical choice for V1 as it is used extensively in the controls industry and the results show that it exhibits small overshoot and reasonably fast settling time.

#### 4.5 Control Design Analysis

Different stability analysis tools are used to establish the effectiveness of the final control design. The results of the analysis are given in the proceeding steps.

##### 4.5.1 Bode Plot of the PID Controlled System

The Bode plot for the PID controlled system is given below:

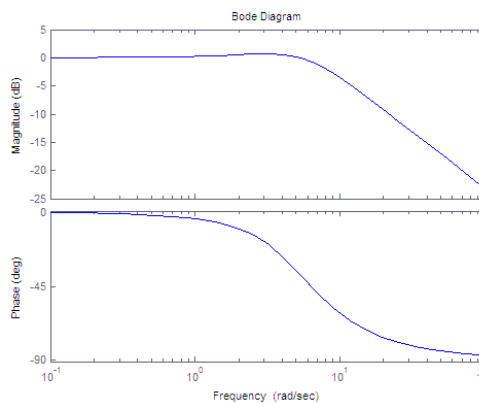


Figure 11: The Bode plot of the PID controlled system

The gain and phase margins are calculated using MATLAB and are given below:

$$\text{Gain Margin} = G_m = \text{infinity}$$

$$\text{Phase Margin} = P_m = 153.2452^\circ$$

Hence, the bode plot indicates that the system is stable with infinite gain margin.

#### 4.5.2 Root-Locus of the PID Controlled System

The root locus of the closed loop system for positive value of gain  $K$  is drawn using MATLAB and the plot is shown below:

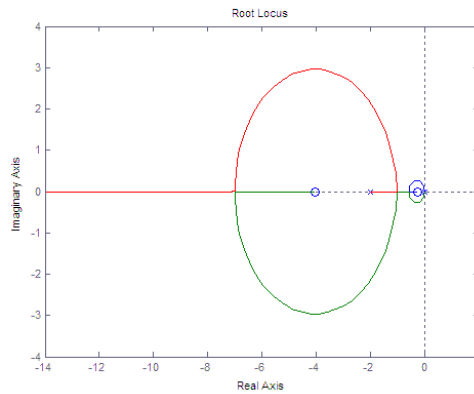


Figure 12: The Root locus of the PID controlled system

It is clear from figure 12 that the system is stable for all positive values of gain  $K$  as the root locus never crosses the  $j\omega$ -axis, i.e, no part of the root-locus is in the right half of the complex plane. Hence, the poles of the PID controlled closed loop system would never enter the right half plane and in turn, the system would never de-stabilize for positive values of  $K$ . Please refer to the Routh Array section as it verifies this result.

#### 4.5.3 Nyquist Plot of the PID Controlled System

The Nyquist diagram of the closed loop system with PID controller is drawn using MATLAB and the plot is shown below:

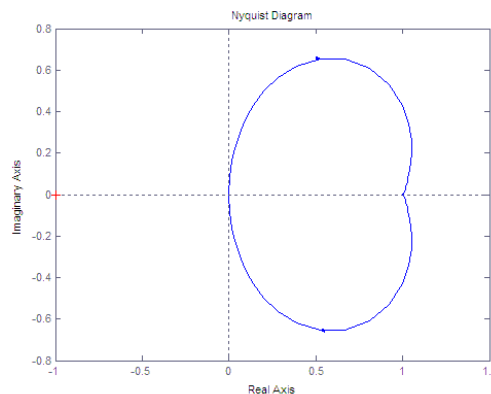


Figure 13: The Nyquist Plot of the PID controlled system

It is clear from the above plot that the system is stable as the Nyquist plot never encircles the  $(-1, 0)$  point in the complex plane.

#### 4.5.4 Routh Array for the tuned V1 (with PID Controller)

The characteristic equation of the closed loop negative feedback system is given by:

$$1+GH = 0$$

$$1 + K \frac{7s^2 + 30s + 7}{s^2(s + 2)} = 0$$

$$s^2(s + 2) + K(7s^2 + 30s + 7) = 0$$

$$s^3 + (2 + 7K)s^2 + 30Ks + 7K = 0$$

$s^3$	1	30K	0
$s^2$	2+7K	7K	0
$s$	$\frac{210K^2 + 53K}{2 + 7K}$	0	0
1	7K	0	0

Therefore,  $210K^2 + 53K > 0$  implies  $K > 0$  or  $K > -0.252$

$2 + 7K > 0$  implies  $K > -0.286$

$7K > 0$  implies  $K > 0$

Hence, System is stable for all values of  $K > 0$ . This result can also be seen in the Root Locus plot.

#### 4.6 Optimized Control Structure

Similar to the control design of V1, one can design control systems for other equipments within the group and use a main controller to optimize the overall performance of the group parameters. The following flowchart explains the optimization process:

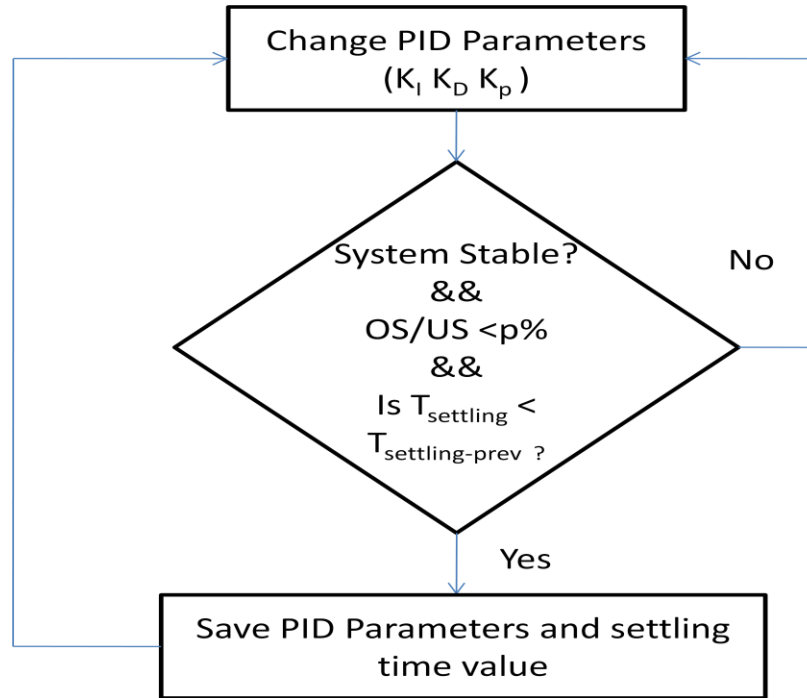


Figure 14: Optimizing the PID Parameters

The above process provides us with optimized PID parameters for the control system.

## 5. Conclusion

In conclusion, the paper provides an overview of the control structure for a hybrid nuclear and hydrogen power plant. It also explains the steps required to design a control system for the hybrid plant. Multi-objective genetic algorithm [2] explained in the paper can be employed to group signals with same trends. Although genetic algorithms are slow to converge to the solution, they are thorough and precise in results if sufficient time is allowed for simulations. In our application, the use of a genetic algorithm is justified since we want to achieve design optimization. A case study is presented on the control of the steam valve between the CANDU and the hydrogen production plant. It is assumed that the valve is hydraulic-actuated. PID controller is used for control design and its performance is analyzed in terms of settling time and peak overshoot.

## References

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