Rule-Based Controller Design for Water Level Control of Fore Bay Fed by an Open Channel

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Abstract—The key problem addressed by this study is that how to regulate the water level of a very small fore bay fed by an open channel while it supplies large and varying demands of flow. From the initial simulation investigations of the physical system concerned the strong dependence of water level regulation of the fore bay on the flow control of the open channel was established and the primary importance of fast channel flow control capabilities were identified. Predictive flow controllers based on Smith predictor structure were designed using simple PI architecture and coefficient diagram (CDM) techniques for the first and second order linear models derived from the data generated from the channel simulator. The inefficiencies of linear modeling of the nonlinear system and variable nature of dead time of the system set limitations on the tuning above controllers in achieving fast response. Hence a novel rule-based flow controller was designed based on the basic mechanism (predictor plus complementary feedback controller) of the Smith predictor which resulted in speeding up the channel flow response and thus improving the fore bay water level regulation. It is further shown that if the disturbances of the prescheduled generator switching ON are known and fed into the control systems the fore bay water level can be regulated better.

I. INTRODUCTION

There are many hydraulic engineering systems with reservoirs or fore bays that are used to store water temporary and to feed various water demands of other systems like hydropower houses, water treatment plants and irrigation canal systems. These reservoirs or fore bays are often fed by free surface flow canals like natural streams or artificially built canals. Controls of water level and water flow in open channels have been addressed in numerous literatures having their emphasis on various aspects of the physical systems concerned. References [5], [8] have described the head controls and [2], [9] have dealt with flow control aspects of open channels. An overview of exiting applications and new research trends in open channel flow control are given in [7].

The control problem studied in this paper is to regulate the water level of a fore bay supplying water to a mini-hydro scheme, a water treatment plant and for irrigation as shown in Fig. 1. The system considered here nearly represents the Nillambe mini hydropower scheme in Sri Lanka. To feed the fore bay an open channel is used to transport water from a reservoir located 2.4 km away from the fore bay. The mini-hydro scheme has two turbines; each of them draws an almost constant flow rate of 1.6 m$^3$/s. The water treatment plant draws a flow of 0.15 m$^3$/s in few hourly spans daily. The irrigation supply of 0.25 m$^3$/s is made through an orifice in the bottom of the fore bay. The critical fore bay level control problem arises when one of the turbines starts or stops operating. An increment of flow demand caused by a generator switching ON can empty the small fore bay unless outflow rate from the channel is increased within a short time. On the other hand a decrement of flow caused by a sudden generator tripping OFF can lead to waste of water by overflowing the fore bay of limited capacity, unless outflow rate of the channel is decreased within a short period. To control the outflow rate of the channel, a controller can manipulate only the inflow rate to the channel at the reservoir end. Then the open channel becomes a process with a large variable time delay. Therefore in this study fast open channel flow control techniques are sought to compensate disturbances caused by the turbine flow demand variations. During the study no means were available to perform any tests on the real system.
other than to acquire some operational data. Therefore the only option was to carry out a comprehensive simulation study.

II. SYSTEM SIMULATOR

A ‘reservoir-open channel-fore bay’ simulator was developed to carry out the investigations. The simple case of non-interacting situations between the three systems considered. The shallow water equations (St. Venant equations [1]) are used to model open channel dynamics. A relatively new algorithm called Double Order algorithm, which has been applied to solve St. Venant equations with unconditional stability with respect to Courant – Friedrichs – Lewy condition [4], was used to implement the channel simulator. For the purpose of this investigation we have also assumed that the cross section of the bay is linearly varying with the depth giving a trapezoidal vertical cross section. Reservoir sluice gate system was lumped into a rate constraint of flow change.

III. CHANNEL FLOW CONTROL AND FORE BAY LEVEL CONTROL

In this particular problem, open channel flow control arises from the water level regulation of the fore bay. In order to maintain the fore bay water level within certain limits, it is necessary to adjust the flow rate of the down stream end of the channel to supply the flow rate expenditure of the fore bay. Therefore the ultimate task of the control system is to produce the magnitude of the varying flow rate expenditure of the fore bay at the down stream of the channel by manipulating the inflow rate to the channel at the upstream end. One of the critical problems, when manipulating inflow rate to the channel to control the flow rate at the down stream, is the large variable time dead time. The difference between the out flow rate of the channel and the flow rate expenditure causes accumulation leading to the water level variation. Thus the storage capacity within the level limits of the fore bay is the governing factor of how much of regulation error by the control system is allowed. The time integral of the difference between the out flow rate of the channel and the flow rate expenditure is the volume of water accumulated in a given period. In this particular system the time integral of the flow difference sometimes can be larger than the total capacity of the fore bay. Therefore objective of the control strategies is to keep this time integral of flow difference below the active capacity of the fore bay. It is thus clear that fast flow control capability is essentially important to the solution. Therefore our main investigation is directed towards speeding up the closed loop performance of the open channel control system.

IV. LINEAR FLOW CONTROLLER DESIGNS

A. Smith Predictor Based PI Controller Design

A simple Smith predictor design was investigated as used in [2] for river flow control. A linear model of the channel flow response at the downstream end derived from the data generated from the channel simulator for a nominal operating inflow was considered for the design. It is observed that when the flow controller is tuned to get faster responses, the performance of the system deteriorates due to non-linearity of the channel that has not been captured into the linearized model of the channel flow. This fact has been observed and recorded in [11].

B. Controller Design Using CDM

The coefficient diagram method (CDM) is a very powerful design technique to achieve simplest and robust Smith predictor controllers under practical limitations for any plant [3]. The study clearly shows that the controller designed using CDM suffers from the same problem of model mismatch, as this too uses the Smith Predictor structure.
The investigations so far show that linear controller designs based on linear models fail to work satisfactorily in this case mainly due to the variable dead time, model mismatches and the presence of the large disturbances operations. Hence a novel rule-based controller, which accommodates the non-linearity and the variable dead time indirectly, is proposed in the next section.

V. NOVEL RULE-BASED CONTROLLER DESIGN

An important finding from the extensive study on the channel flow dynamics is that the channel flow can be changed from one state ($Q_1$) to another ($Q_2$) very effectively (rapid settling and low overshoot) by a particular pattern of inflow as shown in Fig. 2. $Te$ is the only parameter of the pattern for a given pair of $Q_1$ and $Q_2$. A set of test runs on the channel simulator is used to obtain $Te$ values for different pairs of $Q_1$ and $Q_2$. The surface of $Te$ can be drawn upon the plane $Q_1Q_2$, as shown in the Fig. 3. This rule base can now be used to determine the similar flow rate pattern for a given two initial and final steady flow rates and is used to formulate a rule-based predictor to switch the open channel between two steady flow rates. To compensate external disturbances and to make minor corrections to the predictor actions, a PI compensator is coupled with the rule-based predictor (Fig. 5). The operation of the proposed rule-based controller is described by the flow chart shown in Fig 7 where $Q_r$ is the reference input to the rule-based controller.

A. Assumptions

The design of the rule-based controller is viable on the assumption that set point changes and disturbances to the flow controller can well be modeled by long-lasting steps.

B. Rule-Based Inference (RBI) Module

To deal with setpoint changes from the level control loop that can occur before reaching the new steady state, we need to dynamically decide the inflow patterns. This is done by Rule-Based Inference (RBI) module which dynamically predicts the new 'equivalent' steady state $Q_{state}$. The $Te$ surface in Fig. 3 is used for the calculations. Given the time elapsed from $t_1$ with the initial state $Q_i$, the present equivalent state $Q_{state}$ at time $t$ can be found by an interpolation on the curve shown in Fig. 4.

C. Moving Average (MA) Module

When the PI controller is active, it influences the inflow pattern and once again it is necessary to decide on equivalent steady state. This is done by the Moving Average (MA) Module where the moving average of the inflow to the channel over a specified time window (40 minutes in this particular case) is computed.

D. PI Compensator Design

The PI compensator design cannot be done considering the true plant model due to its dead time. For the problem a trial an error procedure was employed to determine the upper limits of the proportional coefficient $K_p$ and the integral coefficient $K_i$ values for a stable closed loop system. A very simple gain scheduling technique was found to work very effectively. $K_{p, max}$ was set by considering the highest value of $Q_{state}$ (4 m$^3$/s). Then the gain values were conditioned by using (1) for the other $Q_{state}$ values.
\[ K_p = K_{\text{pmax}} \left( \frac{Q_{\text{state}}}{\text{max}(Q_{\text{state}})} \right)^2 \]  

(1)

where \( K_{\text{pmax}} \) is the value of \( K_p \) conditioned to maximum value of \( Q_{\text{state}} \) and was found to be 4.0 and \( K_i \) can be kept constant at 0.0125.

E. Absorption of Integral of PI compensator to RBI Module

As the integral component of the PI controller computes the correction needed for the final steady state of the inflow pattern, the integral control output is absorbed to the RBI module and the integrator is reset periodically (Here period is 20 min; approximated average dead time of channel).

F. Initialization

The system is initialized by making the channel to operate in any steady state \( Q_{\text{in}} \) and by setting \( Q_{\text{state}} \), \( U_p \) and all the elements of the array in MA module equal to \( Q_{\text{in}} \) and \( M = 0 \). The parameter \( A \) is used to define the threshold in error within which the PI compensator is active and is determined by trials. \( A \) mainly depends on the accuracy of \( T_e \)-surface (\( A = 0.25 \text{ m}^3/\text{s} \) used for the particular case).

G. Level Controller Architecture.

To regulate fore bay water level within the operation limits the configuration shown in Fig. 8 is used around the channel flow control system. In addition, a disturbance estimator, which estimates the flow disturbance, is used to handle the demand of the generator operations. The disturbance estimator is based on the volume balance equation for the fore bay, and is given by (2) and (3).

\[ Q_{\text{dist}} = Q_{\text{out}} - Q_{\text{irr}} = A(L_{\text{out}}) \frac{dL_{\text{out}}}{dt} \]  

(2)

\[ Q_{\text{irr}} = 0.153 \sqrt{L_{\text{out}}} \]  

(3)

where \( Q_{\text{irr}} \), \( A \) and \( Q_{\text{dist}} \) are the supply for irrigation, water surface area of fore bay and the estimated flow disturbance.

H. Feed Forwarding Disturbance in Advance

Since the turning ON and OFF of generators are often known before hand (prescheduled), a feedforward signal can be used in advance to compensate for the future disturbance thus dealing with the time delay. The scheduled disturbance is feed forwarded 28 minutes in advance to the reference input signal of the flow controller. The period of 28 minutes was found to be reasonably good, by some trials.

VI. RESULTS

The rule-based controller is applied to the open channel as a flow controller. Initially the system operates in the steady state of 0.25 m\(^3\)/s. When the system is given a setpoint change +1.6 m\(^3\)/s, the predictor commands the sluice to operate in its saturation level for some time and brings it back to the final flow rate (Fig. 6). Then PI controller starts operating simultaneously and makes corrections to predictor actions and rejects disturbances of small magnitudes.

The rule-based flow controller is now cascaded with the disturbance estimator and is tested for a test sequence of generator 1 ON, generator 2 ON followed by a generator trip (Fig. 7). It is clear that any feed back controller cannot break the dead time barrier and compensate large flow disturbances outright thus it leads water level to sink to bottom and overflow.

However it can be shown that if the disturbances of the prescheduled generator switching ON are known and fed into the control systems they can regulate the fore bay water level better. The performance of these different
Fig 8. Rule-Based Level-Controller with Feedforward Mechanism

Fig 9. Flow Diagram of Rule-Based Controller Operation
controllers under the same test sequence of generator 1 ON, generator 2 ON followed by a generator trips are investigated and are shown in Fig. 10, 11 and 12 for simple PI Smith predictor, CDM designs and rule-based respectively with feed forwarded generator switching ON. The rule-based controller shows a superior capability, in regulation in generator switching ON cases and in reduction of overflow period compared to the other two controllers.

**VII. CONCLUSION**

In this study, a simulator for the open channel flow plus the fore bay was developed and was used to investigate flow and level control scenario. However, simulator developed hitherto is confined to the non-interactive open channel plus for bay system. The initial study indicated that to attain satisfactory performance in the fore bay water level control, the control loop for the open channel flow must have fast dynamics in the full operating region. Initial investigation with the conventional approach of Smith predictor based on linear controllers show poor performance due to non-linearities and variable dead time. Hence we have finally developed a novel controller for flow control, which is founded on a rule-based predictor and a complementary PI controller. This concept is similar to the predictor and the feedback compensator combination in the well-known Smith Predictor. The proposed rule-based controller gave satisfactory performance in speeding up the open channel flow. Finally the open channel control system combined with a disturbance estimator has been used to improve the performance of the fore bay water level control to operate within the specified operation conditions.

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