MPC-PID Control of a Gas-Liquid Cylindrical Cyclone

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***Abstract*—Offshore oil production facilities exhibit nonlinear dynamic characteristics. With the existence of many flow regulating valves, these dynamics require to be linearized in order to achieve the performance criteria necessary for production of hydrocarbons. Consequently, the dynamic nature of these valves affect their production performance as regular tuning of process controllers are required due to changes in reservoir fluid flow and future constraints. To address this phenomenon, this paper proposes an MPC-PID control system strategy for offshore oil production platform. This strategy includes the use of model predictive controller providing the most economic and efficient set point for distributed PID controllers in the respective loops. The model predictive controller employs a strategy based on the process model to solve the optimal control problem. The proposed approach is further developed using a dynamic engineering design tools available in MATLAB/Simulink and implemented on Gas-Liquid Cylindrical Cyclone (GLCC) compact separator. The system is subjected to set point variation and process disturbances. The results indicate stable controller design and prove the ability of MPC controller to handle constraints and reject disturbances while reducing the energy required and hence overall reduction in production cost with maximum performance.**

***Index Terms*—controllers, design, dynamic characteristics, simulation.**

I. Introduction

An offshore oil platform can be described as a production platform that encompasses all the necessary facilities needed for processing hydrocarbon products by means of extraction and separation into a final component. When the production platform is close to the shore, connecting pipes are used to carry and transport the processed or separated oil and gas to the refinery for onward processing into marketable products. Basically, the extracted crude is processed and decomposed into various products such as oil, gas and water. An Oil exploration process although not a new technology, it continues to gain technological advancement in design and implementation [2, 3].

Offshore oil exploration activities are becoming the most vibrant oil mining technique which is on the increase due to improve technology and ease in reaching the reservoir. Search for discovering offshore exploration point is also on the increase notwithstanding the high risk associated with it. In view of this, offshore exploration activities require fast, efficient and sustainable technological approaches to meet the needed demand [2, 3].

In any process involving several stages which are dynamically changing such as hydrocarbon production processes, the design and implementation of a control system must be such that the strategy adopted should be able to complement any future disturbances that are likely to surface. Over the years, offshore oil production control systems have had several revolutions, and performances are questionable due to the complexity and the dynamic behaviour of the numerous control valves involved. This poses many challenges to operators during the production process. In the event of failure, large capital is at stake since experts are to be imported to the platform in order to diagnose and rectify the problem. Hence there is need to develop a sustainable control system in order to predict the future process behaviour and take prudent action before failure occurs. Such a system should provide safe operation and increase production while eliminating waste of energy.

The main objective of advanced process control is to provide and ensure sustainable process operations, monitoring and constantly evaluating control parameter in the presence of constraints and disturbances. Process control can be improved by the use of advanced techniques such as improved conventional controllers or more advanced methods such as model based predictive controllers. Industrial establishments aim at maximizing profit with optimal operation while taking into consideration, operational safety, equipment limitations and minimizing environmental impact.

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This study is limited to a resilient controller design for GLCC separator with a multi-phase (Gas and oil water) flow system. However, since on offshore oil production platforms there are many control loops available and this advanced control system could be developed for any of these systems such as three-phase separators after studying their dynamic characteristics. The resilient control system is designed and modelled using MATLAB/Simulink to study the performance of the controller with respect to various flow conditions which are representational of real time systems. The nonlinear behaviour could be linearized as show in Fig. 1, further linear feedback control algorithm using compact separator invested with feedback control approaches developed in PI model [12]. The algorithm proposed monitored and predict the state characteristic to minimize the transient effect of the plant [11].

II. METHODOLOGY

The GLCC system has a lot of valves which are controlled by a PID controller. A mathematical model of the GLCC control was developed using MATLAB/Simulink. The PID Simulink block was constructed and various parameters were entered into the program to simulate controller equations. In this way there was no need to handle physical calculations. The parameters evaluated using the mathematical model and its simulation using MATLAB/Simulink served as a reference point for tuning the controller. The dynamic nature of the process makes the PID controller to go out of tune frequently. Any time the controller goes out of tune it needs the services of an expert to re-tune the process. This is not cost effective because of frequent interruption of production and downtime could be very high due to the rigorous tuning process. An MPC controller was therefore designed to control the PID controller. In this way, any time the parameters of the process changes, the MPC controller can automatically re-adjust the process without affecting the PID controller. This makes the system resilient in nature and hence requires no frequent tuning in presence of process disturbances. The advanced controller was also designed using MATLAB/Simulink

A. Mathematical Modeling

The objectives of modelling the system are to develop model for:

(i) the GLCC based on gas and liquid pressure mass balance and equation for both the liquid leg and gas leg

(ii) the PID Control system based on the flow behavior of various phases in the GLCC to investigate the performance

(iii) an MPC control to make the system resilient

The geometry was based on existing design which corresponds to certain operational characteristics as shown by [10]. The separator consists of two phase inlet flow and single phase outlet flow of liquid and gas. Sensors were incorporated for the purpose of measuring the inflow and outflow parameters. The signal obtained from the level sensors are fed to the controller for actuating the liquid and gas control valves [10].

In modelling the GLCC, dynamics such as pressure and gas mass balance condition were considered to derive the dynamic equations based on the liquid and gas legs. We start by considering the liquid pressure drops.

$$P - P_{Lout} = \frac{C_L P_L q_{Lout}^2 - P_L g h}{gc} + \Delta P_L CV \qquad (1)$$

where C_L defines the overall coefficient of the liquid leg and is obtain by

$$C_L = \sum_{i=1}^{n} \frac{8 f_{Li} L_{Li}}{d_{Li}^5 \pi^2} + \sum_{j=1}^{m} \frac{8 K_{Li}}{d_{Li}^5 \pi^2} \qquad (2)$$

From eq. (1) is the $\Delta P_L CV$ pressure drop across the liquid control valve and it can be obtained by evaluating the liquid control flow rate [4].

$$q_{Lout} = (0.002228) CV \sqrt{\frac{\Delta P_L CV}{\delta_L}} \qquad (3)$$

$$\Delta P_L CV = \frac{q_{Lout}^2 \delta_L}{(0.002228)^2 C_V^2} \qquad (4)$$

By substituting eq. (4) into eq. (3.1) yield an expression for the total pressure drop across the liquid leg of the GLCC.

$$P - P_{gout} = \frac{C_L P_L q_{Lout}^2}{gc} - \frac{P_L g h + q_{Lout}^2 \delta_L}{(0.002228)^2 C_V^2} \qquad (5)$$

By differentiating eq. (5) with respect to time yielded the discharge flow rate.

$$\boldsymbol{\frac{dp}{dt} = \frac{C_L P_L (2 q_{Lout}) \frac{d q_{Lout} - P_L g \frac{dh}{dt}}{dt}}{gc} + \frac{\left(2 q_{Lout} \delta_L \frac{d q_{Lout}}{dt}\right)(0.002228)^2 C_V^2 - 2(0.002228^2) C_V q_{Lout}^2 \frac{d C_V}{dt}}{(0.002228^2 C_V^2)^2}} \qquad (6)$$

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Considering gas leg pressure drop the gas leg pressure drop is given by

$$P - P_{gout} = \frac{C_g P_g q_{gout}^2 - P_g g h}{gc} + \Delta P_g CV \qquad (7)$$

where C_g is the overall flow coefficient of gas leg and is obtain as

$$C_L = \sum_{i=1}^{n} \frac{8 f_{gi} L_{gi}}{d_{gi}^5 \pi^2} + \sum_{j=1}^{m} \frac{8 K_{gi}}{d_{gi}^5 \pi^2} \qquad (8)$$

From eq. (1) is the $\Delta P_g CV$ pressure drop across the gas leg of the GLCC and it can be obtained by evaluating as flow rate [4].

$$Q_{gout} = \frac{14.7}{3600} \sqrt{\frac{T}{(520)\delta g}}\, C_g sin \left[\frac{3417}{C_1}\right] \left[\frac{\Delta P_g CV}{P}\right] \qquad (9)$$

From eq. (9) we obtain $\Delta P_g CV$ as follows

$$\Delta P_g CV = \left[\frac{C_L}{3417}\right]^2 P\left[arc\ sin\left\{\frac{(3600)q_{gout}}{(14.7)C_g P}\sqrt{\frac{(520)\delta g}{T}}\right\}\right] \quad (10)$$

By substituting eq. (10) into eq. (7) above yielded the total pressure drop across the gas leg of the GLCC

$$P - P_{gout} = \frac{C_g P_g q_{gout}^2 - P_g gh}{gc} + \left[\frac{C_L}{3417}\right]^2 P\left[arc\ sin\left\{\frac{(3600)Q_{gout}}{(14.7)C_g P}\sqrt{\frac{(520)\delta g}{T}}\right\}\right] \quad (11)$$

Again by taking the derivative of eq. (11) with respect to time assuming a constant liquid discharge pressure P_{gout} and operating temperature T will give expression for the change in gas control valve (GCV).

$$\frac{dp}{dt} = \left(\frac{C_g q_{gout}^2 - gh}{gc}\right)\frac{dPg}{dt} + \frac{Pg}{gc}\left(2Cgq_{gout}\delta_g\frac{dq_{gout}}{dt} - g\frac{dh}{dt}\right) + \left[\frac{C_L}{3417}\right]^2\left[arc\ sin\left\{\frac{(3600)Q_{gout}}{(14.7)C_g P}\sqrt{\frac{(520)\delta g}{T}}\right\}\right]\frac{dP}{dt} + \left[\frac{C_L}{3417}\right]^2 P\left[\frac{1}{\sqrt{1-\left\{\frac{(3600)q_{gout}}{(14.7)C_g P}\sqrt{\frac{(520)\delta g}{T}}\right\}^2}}\right]\left(\frac{(3600)q_{gout}}{(14.7)C_g}\sqrt{\frac{(520)\delta g}{T}}\right)\left[\frac{\frac{dq_{gout}}{dt}C_g P - Q_{gout}P\frac{dC_g}{dt} + C_g\frac{dP}{dt}}{P^2 C_g^2}\right] \quad (12)$$

Gas density can be obtained from the equation of state given by

$$P_g = \frac{PM_g}{ZRT} \quad (13)$$

We obtain the density rate of change by differentiating eq. (13)

$$\frac{dP_g}{dt} = \frac{M_g}{ZRT}\frac{dP}{dt} \quad (14)$$

Liquid mass balance

Considering the liquid phase, the mass balance for the GLCC rate of liquid level is given by

$$\frac{dH}{dt} = \frac{4(dV_L)}{\pi d^2(dt)} \quad (15)$$

Also the rate of change of liquid volume is given by

$$\frac{dV_L}{dt} = q_{Lin} - q_{Lout} \quad (16)$$

We obtain the gas mass balance equation as follows:

Mass balance equation for GLCC gas phase rate of change is given by

$$\frac{dn_g}{dt} = (q_{gin} - q_{gout})\frac{P_g}{M_g} \quad (17)$$

When we obtain the derivate state equation ($PV_g = n_g ZRT$) with respect to time we obtain the rate of change of GLCC pressure in mole. Hence rate change gas volume is given by.

$$V_g\frac{dP}{dt} = ZRT\frac{dn_g}{dt} - P\frac{dV_g}{dt} \quad (18)$$

With the constant volume of GLCC, the rate of change of gas and liquid volumes are related as follows:

$$\frac{dV_g}{dt} = -\frac{dV_L}{dt} \quad (19)$$

By substituting equations (16, 17 and 19) into equation (18) will give the rate of change GLCC gas and liquid pressure rate to volume calculated.

$$V_g\frac{dP}{dt} = ZRT\frac{P_g}{M_g}(q_{gin} - q_{gout}) + P(q_{Lin} + q_{Lout}) \quad (20)$$

Here the gas volume is given by $V_g = (h_{GLCC} - h)\frac{\pi}{4}d^2$

The controller operates on the error signal e(t) which is the difference between the liquid level actuator variable and set point value to produce the control signal of u(t) that drives the actuator.

In the design, we proposed using PIDs as a distributed controller at various control loops and MPC controller to provide reference signal which drive the PIDs. Here we shall consider the design for PID controller using the system parameters with the controller equation.

$$\Delta u = Kc\left(e(t) + \frac{1}{t_i}\int edt + \frac{de}{dt}\right) \quad (21)$$

Δu - is the controller output variable data sign indicate the change in controller variable between initial and actual output. If the transducer signal is based on 4mA and 20mA, which corresponds to the variable u_{min} *and* u_{max}, then the error associated with the controller can be given by equations (20 and 24)

$$e = e_s - e_r \quad (22)$$

$$e_s = 4 + 16\left(\frac{u_s - u_{min}}{u_{max} - u_{min}}\right) \quad (23)$$

$$e_r = 4 + 16\left(\frac{u - u_{min}}{u_{max} - u_{min}}\right) \quad (24)$$

When we substitute equations (23) and (24) into equation (22) we obtain

$$e = G_T(u_s - u) \quad (25)$$

$$G_T = \left(\frac{20-4}{u_{max} - u_{min}}\right) \quad (26)$$

G_T is the transmitter gain and if we again substitute equation (25) into equation (21), we will establish a relationship between controller output and liquid level control or pressure level control [10].

$$\Delta u = KcG_T(u_s - u) + \frac{1}{t_i}\int(u_s - u)dt - \frac{d}{dt}(u_s - u) \quad (27)$$

B. Pneumatic Line and Actuator Delay

Since the controller output is either current or voltage signal which need to be converted to the right parameter of liquid using the scaling factor of 4mA-20mA current loop against the minimum and maximum pressure.

$$P_c = P_{vmin} + P_{vmin} - P_{vmax}\left(\frac{e_c - 4}{20-4}\right) \quad (28)$$

Where;

P_c *controller output pressure and* $P_{vmin,}, P_{vmax}$ are lower and upper limit of the pneumatic pressure required to actuate the valve. And if we define initial control valve pressure as P_i then pneumatic pressure (P_n) receive can be calculated as

$$P_n = P_c + (P_i - P_c)e^{-t/\tau_1} \tag{29}$$

C. Pneumatic Control Value

The pneumatic control modelling is based on first order model equation for open loop control system as

$$\frac{dx}{dt} = P_{vmax} - P_{vmin} - \left(\frac{(P_{vmax} - P_{vmin})}{100}\right)\frac{100}{(P_{vmax} - P_{vmin})\tau_2} \quad . \tag{30}$$

But

$$\tau_2 = \frac{t}{In\left(\frac{100}{100-x}\right)} \tag{31}$$

D. Liquid Control Loop

The dynamic model for the liquid loop is obtained by using equation (27). When we replace the controlled variable u with the liquid height h, this will yield an expression for the liquid control loop dynamic model based on the valve characteristics [10].

$$C_v = K_L x \tag{32}$$

Since we are using rate of flow, we need to take the derivative of equation (32). Hence, this yields the following expression.

$$\frac{dC_v}{dt} = K_L\left\{15 - P_{vL}\frac{12}{100}\left(\frac{C_v}{K_L}\right)\right\}\frac{100}{12\tau_{2L}} \tag{33}$$

K_L is the constant of liquid control valve and we assume pressure rang of 3-15 psi. P_{vL} is calculated using the expression below [10].

$$P_{vL} = 3 + 12\left\{\frac{e_{0L} + K_{cL}K_{TL}\left(\Delta h + \frac{1}{t_i}\int \Delta h dt - t_{dL}\frac{dh}{dt}\right) - 4}{16}\right\} +$$

$$\left\{P_{wL}\left[3 + 12\frac{e_{0L} + K_{cL}K_{TL}\left(\Delta h + \frac{1}{t_i}\int \Delta h dt - t_{dL}\frac{dh}{dt} - 4\right)}{16}\right]\right\} e^{-t/\tau 2L} \tag{34}$$

But; $\Delta h = h_s - h$

E. Gas Control Loop

In the gas control loop system there are three configurations that can be used for the modelling. Here we can control the GLCC pressure, liquid level and or liquid position depending on the control objective what parameter we want to obtain. Assuming we want to control the pressure then our general expression may be narrow down on the pressure parameter as follows;

$$P_{vg} = 3 + 12\left\{\frac{e_{0g} + K_{cg}K_{Tg}\left(\Delta P + \frac{1}{t_i}\int \Delta P dt - t_{dL}\frac{dP}{dt}\right) - 4}{16}\right\} +$$

$$\left\{P_{wg}\left[3 + 12\frac{e_{0g} + K_{cg}K_{Tg}\left(\Delta P + \frac{1}{t_i}\int \Delta P dt - t_{dL}\frac{dP}{dt}\right) - 4}{16}\right]\right\} e^{-t/\tau 2g} \quad . \tag{35}$$

But $\Delta P = P_s - P$

If we want to use it to control level, we just have to replace the g with L or for displacement replace g by x. Similarly, $\Delta L = L_s - L$ or $\Delta x = x_s - x$

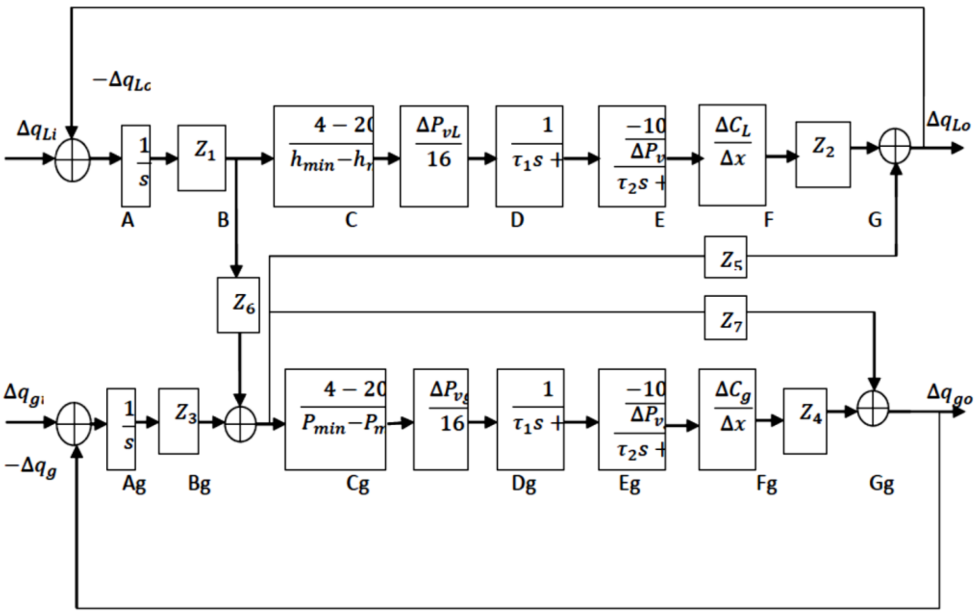

Figure 1. Linear model of integrated liquid level and pressure control of GLCC [8, 10]

F. State Equation of LCV Control Loop

$$\begin{vmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{vmatrix} = \begin{vmatrix}-5 & 0 & 5\\ -0.0415 & 0 & 5\\ 0 & 122.232 & -5\end{vmatrix}\begin{vmatrix}x_1\\ x_2\\ x_3\end{vmatrix} + \begin{vmatrix}0\\ 1\\ 0\end{vmatrix} u \quad (36)$$

$$y = \begin{vmatrix}0.0415 & 0 & 0\end{vmatrix}\begin{vmatrix}x_1(t)\\ x_2(t)\\ x_3(t)\end{vmatrix} + |0|\, u \quad (37)$$

System transfer function is given by;

$$G(s) = \frac{-4.441e^{-014}s - 2.753e^{-014}s + 25.36}{s^3 + 5.5s^2 + 2.5s + 25.36} \quad (38)$$

State space expression obtained from the dynamic simulation of GCV without the effect of controller is

$$\begin{vmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{vmatrix} = \begin{vmatrix}-5 & 0 & 5\\ -0.0581 & 0 & 0\\ 0 & 750 & -5\end{vmatrix}\begin{vmatrix}x_1\\ x_2\\ x_3\end{vmatrix} + \begin{vmatrix}0\\ 1\\ 0\end{vmatrix} u \quad (39)$$

$$y = \begin{vmatrix}0.0581 & 0 & 0\end{vmatrix}\begin{vmatrix}x_1(t)\\ x_2(t)\\ x_3(t)\end{vmatrix} + |0|\, u \quad (40)$$

The transfer function obtained was as followed;

$$G(s) = \frac{3.553e^{-015}s - 3.197e^{-014}s + 209.2}{s^3 + 5.5s^2 + 2.5s + 209.2} \quad (41)$$

State space parameter extracted from the simulation and the corresponding transfer functions are as follows;

$$\begin{vmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\\ \dot{x_4}\\ \dot{x_5}\\ x_6\end{vmatrix}\begin{vmatrix}-0.5 & 0 & 0 & 0 & 5 & 0\\ 0.2528 & -121.8 & 0.0581 & 0 & 0 & 0\\ 0 & 0 & -0.5 & 0 & 0 & 0\\ 0.04531 & -1.834 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -122.2 & -5 & 0\\ 1.631 & -786 & 0 & 0 & 0 & -5\end{vmatrix}\begin{vmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\\ x_6\end{vmatrix} + \begin{vmatrix}0 & 0\\ 0 & 1\\ 0 & 0\\ 1 & 0\\ 0 & 0\\ 0 & 0\end{vmatrix} u1, u2 \quad (42)$$

$$\begin{vmatrix}y_1\\ y_2\end{vmatrix}\begin{vmatrix}-0.04531 & 1.834 & 0 & 0 & 0 & 0\\ -0.2528 & 121.8 & -0.0581 & 0 & 0 & 0\end{vmatrix}\begin{vmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\\ x_6\end{vmatrix} + \begin{vmatrix}0 & 0\\ 0 & 0\end{vmatrix} u1, u2 \quad (43)$$

G. Transfer Function

$$G1(s) = \frac{1.421e^{-013}s^5 + 1.819e^{-012}s^4 + 27.695s^3 + 3242s^2 + 1.706e^{004}s + 1.352e^{004}}{s^6 + 132.85s^5 + 1375s^4 + 4578s^3 + 7855s^2 + 1.84e^{004}s + 1.352e^{004}} \quad (44)$$

$$G2(s) = \frac{1.99e^{-013}s^5 + 1.819e^{-012}s^4 + 154.5s^3 + 849.8s^2 + 675.8s - 2.547e^{-004}}{s^6 + 132.85s^5 + 1375s^4 + 4578s^3 + 7855s^2 + 1.84e^{004}s + 1.352e^{004}} \quad (45)$$

III. RESULTS AND DISCUSSION

TABLE I. PID TUNING PARAMETERS

Controller	Estimated Parameter 1	Auto-Tuned Parameter1	Tuned Parameter 1	Estimated Parameter 2	Tuned Parameter 2
Kp	20.283	0.159	0.42195	$5.15X10^{-6}$	1.1×10^{-5}
Ti	2.65	0.00095	0.04106	3.955	8.15×10^{-10}
Td	0.6625	0.320	0.3475	0.98875	2.4×10^{-5}

TABLE II. INTEGRATED PID TUNING PARAMETERS

Controller	LCV Control Loop		GCV Control Loop	
	Estimate Parameter	Tuned Parameter	Estimate Parameter	Tuned Parameter
Kp	4.03989	4.378	0.104377	0.07710
Ti	0.17705	1.197	0.025625	0.0210
Td	0.0442625	3.979	$6{,}40625\text{x } 10^{-3}$	0.0707

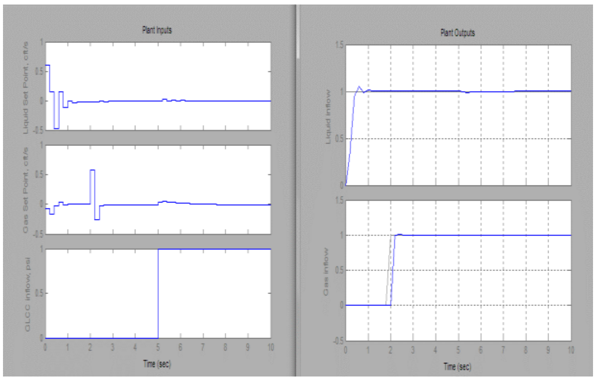

Figure 2. MPC Controller Design without Input/Output Constraint with Step Response

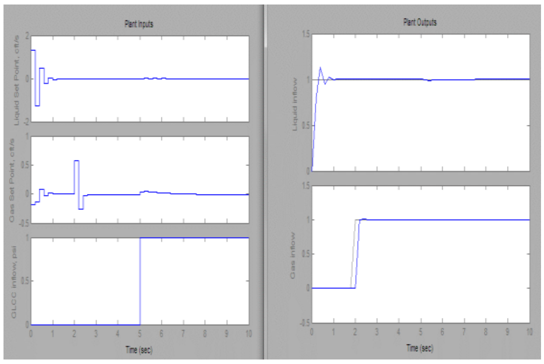

Figure 3. MPC Controller Design for GLCC Pressure and Level Control with Input Constraint

A MATLAB code was developed to examine the overall output of the liquid loop of the GLCC using the MPC command available in the MATLAB tool. We set the set point to 0.6, prediction horizon P to 30, control horizon Nc to 5 using sample time of 0.2. The MPC function was used to estimate the future trajectory and cost function. After a few tuning of the weighting matrix we obtained a response time of less than 1s and a good settling time less than 5s (Fig. 2).

The above systems are perfect however, it does not allow for comprehensive analysis of the system in terms of the measured pressure level and liquid level in the GLCC. This could be partly due to limitations in the MPC code. To provide complete evaluation of the system and visualized how the MPC calculate the economic set point so that it will improved the energy required by the controller to produce effective output response we use Simulink model. Two approaches were implemented, that is system MPC design without input constraint and system MPC design with input constraint (Fig. 3).

The system parameters obtained were control horizon 5, prediction horizon 20 with sampling time 0.2 and weighting matrix 0.84. From the MPC design the output followed the input signal as indicated in the diagram. After a small overshoot, the response settled down in about 1.2 seconds which was pretty good. Since the two reference points were programmed to change between 2 seconds, the second out also corresponded to this effect.

Once the controller design showed the expected performance, it was exported to MATLAB workspace used to simulate the Simulink block. With the gas and liquid set points at 0.6cft/s, the liquid outflow rate was initially high, about 0.029cft/s, but dropped drastically to 0.005cft/s and settled down at this value. The inrush was due to the delay in opening the control valve which enabled the pressure build across the valve. The valve opening was observed to be in accordance with the valve lift settings. It was also observed that the GLCC liquid level shot up after 20sec and dropped the gas pressure from 98psi to approximately 0.2psi. The pressure outflow also was high at 3.1cft/s with valve opening of 60%. However, it dropped to 0.6cft/s to follow the set point value with valve opening also dropping to 40%.

The designed controller met all the necessary specification and therefore was exported to the workspace. It was observed that this design did not differ much from Fig 3. The controller design revealed how rigorously the MPC controller performed in spite of the delay in opening the value when system was first put in operation.

IV. Conclusion

An advanced control for offshore oil production platform was realized by introducing an MPC controller on top of the PID controller for the GLCC separator to provide the most economic and efficient set point for the distributed control loops. The design was implemented using a GLCC separator with multi-phase inflow and multi-phase outflow using MATLAB/Simulink.

The complete system was evaluated in by varying the set points and introducing process disturbances. The result observed indicated stability of the controller since process output remains stable in the presence varying these two signals. It was also observed that the effect of gas overflow and liquid underflow and vice versa was eliminated after the MPC solved the optimization problem. The only drawback observed was initial delay in opening the valves.

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