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On the Innovation of Level Control of an Offshore Three-Phase Separator

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***Abstract*—The innovation of level control of an offshore three-phase separator is discussed. The control objective is to smooth down the water outflow-rate as much as possible, subject to keeping the water level inside the separator within a permissible range. Based on the current control system (PI control) which seems developed as a level servo control system, a number of new control coefficients are developed using three different cost-effective tuning methods, namely trial-and-error method, butterworth filter design method and IMC method. The simulation results show that all these developments can significantly improve the system performance compared with the current control system. The potential to use some new control structures and advanced control methods are also discussed.**

***Index Terms*—Process control, PID tuning, butterworth filter, IMC**

I. INTRODUCTION

In order to protect our global environment, there is no doubt that more and more renewable and green energy will be used in the future. However, this does not mean that all conventional energy, such as fossil-fuels, oil and natural gas, will vanish immediately from our daily life. For a long while the global energy system will be some kind of combination of renewable energy with some portion of conventional energy [3], [4]. Therefore, how to improve the efficiency of acquisition and usage of conventional energy, especially for these industrial systems developed many decades ago, becomes more and more challenging and urgent now.

This work focuses on the conventional oil and gas production. More specific, we will investigate the potential improvement of a (water) level control system of an offshore high-pressure three-phase separator, named V-3440 separator. The V-3440 separator is located on a platform in North Sea, and it is used as the first processor for treating the multiple-phase well fluid transported from nearby wellhead platforms. The V-3440 separator is a typical horizontal gravity separator. Due to the gravity influence, as shown in Fig.1, the well fluid inside the separator are separated as gaseous, oil and water fluids and afterwards they flow out separately for further processing. As a typical process control system, the liquid level control of this separator also faces the *surge problem* [8], [9]. The well fluid produced in one nearby platform is sent to the separator through an 11 km three-phase pipeline and a riser at the production platform without any processing before entering the separator. The long pipeline transportation and rising head of the well fluid can cause large oscillations of these liquid levels and gas pressure inside the separator [8].

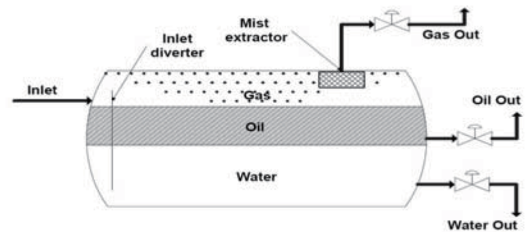

Fig. 1. A Schematic Configuration of a three-phase gravity separator [9]

The liquid levels (and gas pressure as well) in the multi-phase separator need to be controlled in order to keep a safe operation and handle the potential surge problem. In general, level controls can be classified into two categories [10], [11]: The first category is those conventional level control systems in which the level is controlled for its own sake, e.g., the servo level control in nuclear reactor systems [6]. The other category is those control systems where the exact level is not important, as long as the level is kept within some permissible range, so that the potential surge input can be damped by allowing the level to rise and fall within permissible range [11]. From the technical point of view, the level control of V-3440 belongs to the second category. However, it is not clear that whether the current control systems in V-3440, which were initially developed along with the platform several decades ago, had taken this damping functionality into consideration or not. Often, some large fluctuations in the gas, oil and water outflows can be observed in the current daily operation. Thereby, our task is to investigate some cost-effective methods to improve current level control systems in V-3440, especially the water level control systems. The objective is to smooth down the water outflow as much as

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possible, subject to the water level inside the separator is kept within a permissible range.

The focus on the water level control has a very important practical concern. As the amount of oil and gas in the field reservoir declines, more and more water need to be used now. Thereby the water treatment and circulation becomes vitally important in terms of operating efficiency and environmental influence. Another benefit of smooth outflow operation is that it reduces the worn-out of equipments, thereby diminishing maintenance and operation costs. Furthermore, a smooth outflow operation could also lead to a better energy-usage efficiency.

An extensive research and work can be found regarding surge tank/system control [6], [9], [10], [11]. For instance, a two-degree-of-freedom level control is proposed in [11], where the surge tank system is modeled as a simple integrator system, and a P-controller is proposed along with a load estimation gain. These two gains are properly assigned according to a cost function which balances the maximum rate of change in outflow and maximum peak height. The method is limited to simple dynamic (integrator) systems, while [9] gave a detail dynamic model of a thee-phase separator. A water level control in the steam generator of a nuclear power plant is investigated in [6]. The system's characteristics of nonlinearities, nonminimum-phase and constraints are considered in a linear parameter varying system model, a sophisticated Model Predictive Control (MPC) method is proposed as the level control solution.

With the concern of future implementation and current financial limits, our investigation starts with some simple modification/extensions of the current systems, i.e., some improved PID-type of controllers at this beginning stage. We leave the investigation of advanced and sophisticated solutions, such as MPC solution or H_∞/μ control, as the task for our next step. In the following, three kinds of PI tuning methods, namely trial-and-error method, PI design using butterworth filter design and IMC method, and their consequent results are reported. The simulation study shows that system performances, in terms of smooth outflow-rates and satisfactory water level controls, are significantly improved by all three kinds of developments. This indicates a huge potential to improve the current control system by some simple innovations (only update control coefficients).

The rest of the paper is organized as the following: Section II introduces the considered V-3440 separator system; Section III discusses modeling and parameter identification; Section IV illustrates three kinds of control developments and their consequent results; finally we conclude the paper in Section V.

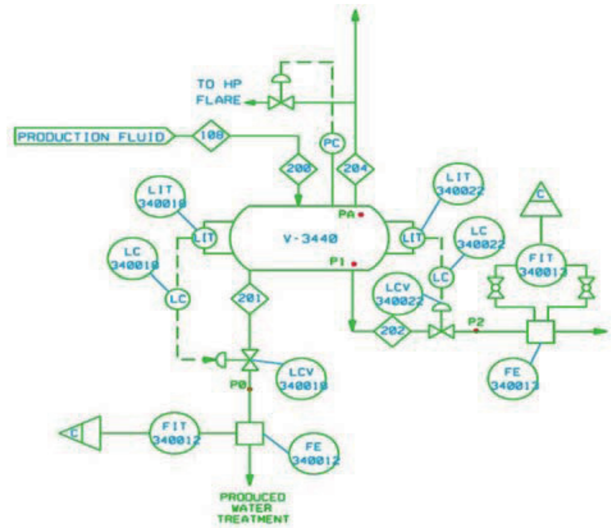

Fig. 2. P& I diagram of relevant control loops of V-3440 System

II. CONSIDERED SYSTEM

A. Physical Configuration

The water and oil levels and the gas pressure inside the separator are controlled by a number of separate control systems as shown in Fig.2. If we focus on the water level control loop, it can be observed that a level indicator transmitter, tagged LIT-340018, is employed to measure the water level inside the separator. The measured level signal is sent to a level controller, tagged LC-340018. The level controller runs a PI-type of algorithm and sends the control signal to a level control valve, tagged LCV-340018. The LCV-340018 regulates the water outflow in order to control the water level inside the separator. It can be noticed that a flow indicator transmitter, named FIT-340012, is used to measure the water outflow-rate for some other purpose. This measurement is not used by the current level controller. Nevertheless, this measurement is essential to estimate the inlet (water) flow-rate and thereby validate a new controller in simulation.

B. Current System Performance

Some operating data for the water and oil outflow-rates are illustrated in Fig.3. There are obvious fluctuations of water outflow-rate. The water and oil levels inside the separator are illustrated in Fig.4. It can be observed the fluctuations of water level are in a much smaller scale (percentage) compared with fluctuations of water outflow-rate as shown in Fig.3, especially after the first 1000 sec.. Some surge problem can also be observed by analyzing these data. For instance, during the period of 3900 sec. to 4100 sec., from Fig.4, the water level is slightly lower than the average, while from Fig.3 it is obvious that the water outflow-rate is increased. Meanwhile, the oil outflow-rate is quite low and the oil level is decreasing during this period. All these observations

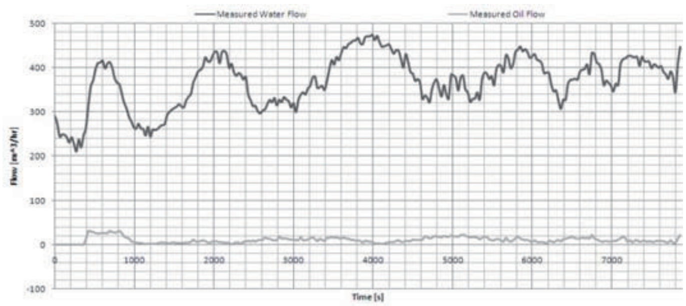

Fig. 3. Measured water and oil outflow-rates over a time interval

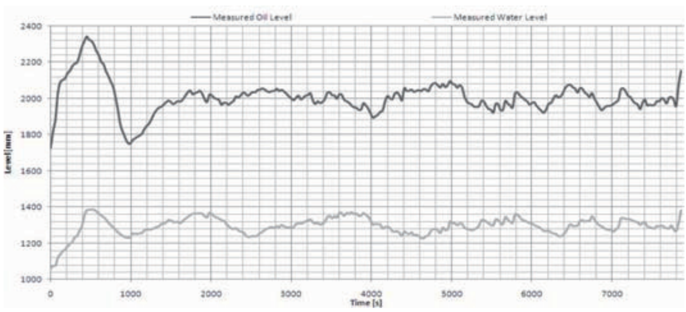

Fig. 4. Measured water and oil levels over a time interval

conclude that large water or gas surges happened during this period.

III. MODELING AND IDENTIFICATION

TABLE I
SYSTEM VARIABLES AND PARAMETERS

Notation	Description	Unit
$h(t)$	Level of water inside separator	m
$Q_{in}(t)$	water inflow-rate	m^3/h
$Q_{out}(t)$	water outflow-rate	m^3/h
r	separator cross-section radius	m
L	length of water section	m
$h_o(t)$	level of oil inside the separator	m
$P_g(t)$	gas pressure inside the separator	Pa
C_v	outlet valve discharge coefficient	-
$u(t)$	percentage of the valve openness	-
ρ_w	water density at the operating temp.	kg/m^3
ρ_o	oil density at the operating temp.	kg/m^3
P_w	valve downstream pressure	Pa
U_{max}	maximal opening area of control valve	m^2
ΔP_{out}	Pressure drop over control valve	Pa

A. Separator Modeling

System parameters and variables used in the following are listed in Table 1 According to the geometry of the separator, the volume of water inside the separator is a function of the water level h and has the specific relationship as:

$$V(h) = (r^2 cos^{-1}(\frac{r-h}{r}) - (r-h)\sqrt{2rh-h^2})L. \quad (1)$$

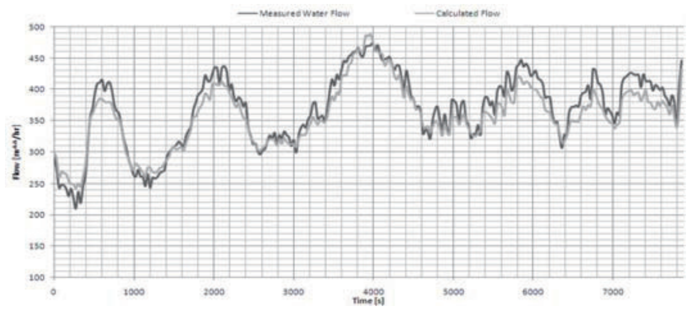

Fig. 5. Model Validation: Measured and Predicted Outflow-rates

Since the normal operation requires the water level between the Level Alarm High (LAH) and Level Alarm Low (LAL), thereby the relationship (1) can be simplified as a linear relationship during this interval, i.e., $V(h) = ALh(t)$, where $A \approx \pi r^2$.

The water volume dynamic inside the separator follows the mass balance principle [8], i.e., there is:

$$\frac{dV(t)}{dt} \approx AL\frac{dh(t)}{dt} = Q_{in}(t) - Q_{out}(t). \quad (2)$$

According to the flow dynamic theory, the water outflow-rate over valve LCV-340018 can be determined as

$$Q_{out} = C_v f(u)\sqrt{\frac{\triangle P_{out}}{\rho_w}}, \quad (3)$$

where $f(u)$ represents the valve's characteristics of the openness area related to the openness percentage u. For this specific linear valve LCV-340018, the linear relationship is well observed. Thereby, there is $f(u) = uU_{max}$. The differential pressure over the valve, denoted as $\triangle P_{out}$, can be estimated as:

$$\triangle P_{out}(t) = P_g(t) + \rho_o g h_o(t) + \rho_w g h(t) - P_w(t). \quad (4)$$

B. Parameter Identification

Valve coefficient C_v in (3) is estimated using least square method based on recorded data of the water outflow-rate, water and oil levels inside the separator, gas pressure inside the separator and downstream water pressure. Under the assumption that the water density is constant, the C_v value will be the solution of:

$$\min_{C_v} \Sigma_i |Q_{out}(i) - C_v u(i) U_{max}\sqrt{\frac{\triangle P_{out}(i)}{\rho_w}}|^2.$$

A validation of the obtained system model is shown in Fig.5. In general, the prediction error is limited within 10%.

C. Linearized Model

Under the assumption that the gas pressure, water valve downstream pressure and oil level inside the separator are constants or their deviations from the average values are

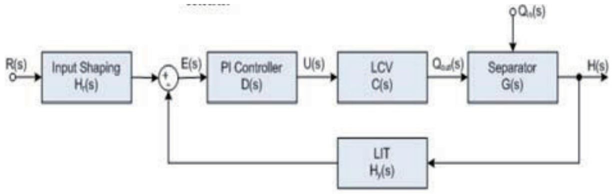

Fig. 6. Block Diagram of Current PI Level Control System

ignorable, the nonlinear system model is linearized at a normal operating condition. By inserting specific system parameters, the linearized model leads to the form:

$$47.55\frac{d\Delta h(t)}{dt} = Q_{in}(t) - 1.81\Delta h(t) - 10.82\Delta u(t), \quad (5)$$

where $\Delta h(t)$ ($\Delta u(t)$) represents the deviations of the water level (valve position) to the equilibrium. Thereby, two transfer functions representing the relationships from unknown disturbance $Q_{in}(t)$ and control input $\Delta u(t)$ to output $\Delta h(t)$, respectively, can be defined as:

$$\begin{aligned} G_1(s) &\hat{=} \frac{H(s)}{Q_{in}(s)} = \frac{1}{47.55s+1.81}, \\ G_2(s) &\hat{=} \frac{H(s)}{U(s)} = -\frac{10.82}{47.55s+1.81}. \end{aligned} \quad (6)$$

It should be noticed that the linearized separator model is a first-order system instead of a simple integrator which is used in [11]. The reason is that we consider the water outflow-rate is as level dependent as stated in (3). This feature also leads to the following control design to be focused on PI-type of controller instead of P-controller.

IV. CONTROL DEVELOPMENT

Our control development starts from the analysis of current control system. Then, a set of new PI control coefficients are obtained by trial-and-error tuning. Afterwards, the PI control development using the butterworth filter design is proposed. Finally, a PI controller using the IMC method is developed. Comparisons and analysis of system performances and system features are carried out along with each development.

A. Current Control System

The current level control system is a PI controller as shown in Fig.6. The closed-loop transfer function from the reference input $R(s)$ to the water level $H(s)$ is:

$$G_{HR}(s) = \frac{243.5s + 4382}{47.55s^2 + 245.3s + 4382}.$$

It can be noticed that the closed loop system has a bandwidth of 2.49 Hz, and the existing zero causes a large overshoot during the transient period, e.g., the overshoot is up to 48% for the unit step input. This indicates that the current controller seems a level control system for its own sake.

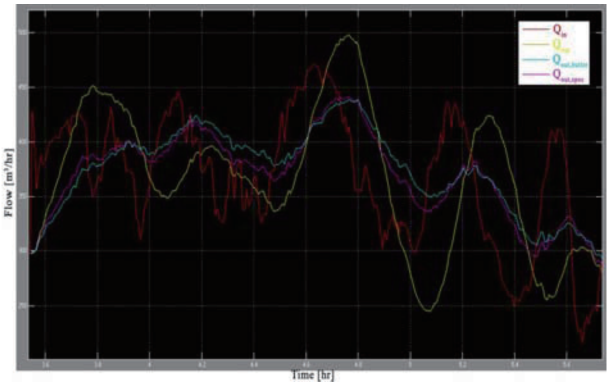

Fig. 7. Comparison of Water flow-rates - Q_{in}:input; Q_{out}: current control; $Q_{out,spec}$: Trial-control; $Q_{out,butter}$: Butterworth method

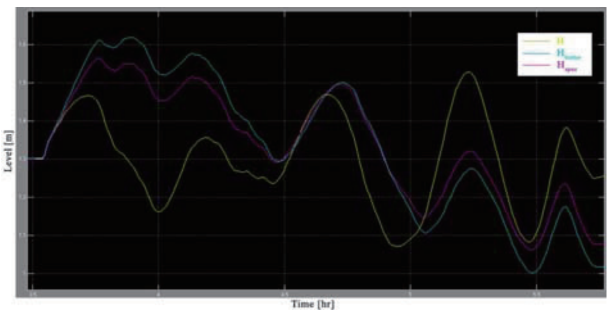

Fig. 8. Comparison of Water levels - H: current control; H_{spec}: trial-control; H_{butter}: Butterworth method

B. PI Tuning by Trial-and-Error Method

A set of new PI coefficients $K_p = -1.05,_I = -1.76$ are obtained by the trial-and-error tuning [1]. The bandwidth of this obtained closed-loop system is reduced to 1.2 Hz. The overshoot corresponding to unit step response is now down to about 14%. It is clear that the new PI controller is more gentle compared with the current controller. This can be observed from simulations shown in Fig.7 and Fig.8, respectively.

C. PI Design Using Butterworth Filter Design

In the following, we still focus on the PI controller, but wish to use a systematic tuning method. Inspired by the sensitivity/robust analysis [7], [10], we construct a block diagram as shown in Fig.9. The total four transfer functions are:

$$\begin{aligned} G_{HR}(s) &= \frac{W_1(s)G_1(s)C(s)}{1+G_1(s)C(s)}, \ G_{HQ_{in}}(s) = \frac{W_1(s)G_2(s)C(s)}{1+G_1(s)C(s)}, \\ G_{UR}(s) &= \frac{W_2(s)C(s)}{1+G_1(s)C(s)}, \ G_{UQ_{in}}(s) = -\frac{W_2(s)G_2(s)C(s)}{1+G_1(s)C(s)}. \end{aligned} \quad (7)$$

Assume both weighting functions $W_1(s)$ and $W_2(s)$ are unity. From (6), it is known that transfer function $G_{HR}(s)$ ($G_2(s)$) and $G_{UQ_{in}}(s)$ ($G_1(s)$) have same dynamic features except different DC-gains. This observation gives a consistent indication in helping us handle two objectives: smoothing the outflow-rate and controlling the level in a gentle way. The

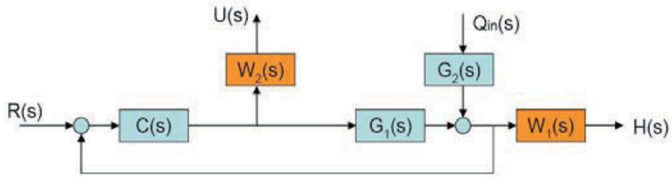

Fig. 9. Block Diagram of Sensitivity Analysis of the Considered System

first objective requires that the control signal $U(s)$ should be insensitive to disturbance $Q_{in}(s)$ for some high-frequency range. The second objective means that we need to control the level for some low-frequency range. Regarding the high frequency disturbance, we can let the separator dampen them. All these turns out that we need to develop a controlled system $G_{HR}(s)$ (or $G_{UQ_{in}}(s)$) acting as a type of low-pass filter with a maximally flat magnitude in the pass-band. Thereby, the butterworth filter design [2] is employed here for tuning the PI controller. The further benefit of this idea is that the two-degree-of-freedom tuning of PI control reduces to only tune the cutoff frequency of a butterworth filter which order is predetermined according to the closed-loop system order.

Denote the PI control transfer function as $C(s) = K_p + \frac{K_I}{s}$, and the transfer function $G_2(s)$ as $G_2(s) = \frac{\beta}{\alpha_1 s + \alpha_2}$, where all coefficients are defined in (6). Then the closed loop transfer function $G_{HR}(s)$ is:

$$G_{HR}(s) = \frac{\frac{\beta}{\alpha_1}(K_p s + K_I)}{s^2 + \frac{\alpha_2 + \beta K_p}{\alpha_1} s + \frac{\beta}{\alpha_1} K_I}. \quad (8)$$

Correspondingly, a second-order butterworth filter, denoted as $H_{but}(s)$, is constructed, and it has the characteristics [2]:

$$|H_{but}(j\Omega)|^2 = H_{but}(j\Omega)H_{but}(-j\Omega) = \frac{1}{1 + \Omega^4/\Omega_c^4}.$$

A butterworth filter has the transfer function as:

$$H(s) = \frac{p_1 p_2}{(s - p_1)(s - p_2)}, \quad (9)$$

where $p_1,\ p_2$ are two stable poles of $H_{but}(s)H_{but}(-s)$, i.e.,

$$p_{1,2} = -\frac{\sqrt{2}\Omega_c}{2} \pm \frac{\sqrt{2}\Omega_c}{2} j.$$

The cutoff frequency Ω_c can be selected according to the demanded system response speed and the potential surge disturbance frequency. Contrast with standard control design problem, here we don't expect the level control loop has some fast response, because it will increase the sensitivity of the level control valve to disturbance, so that the smoothness of outflow-rate will be a problem. From the primary data (surge) analysis, the cutoff frequency is selected as 0.5 Hz in our concern.

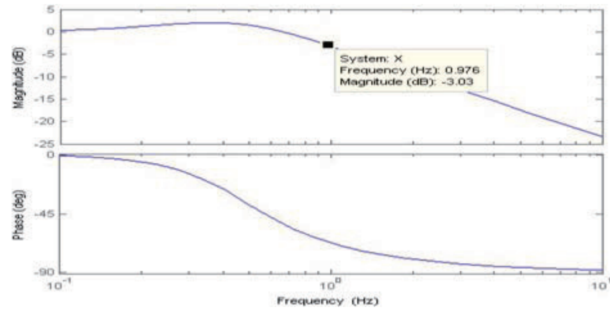

Fig. 10. Frequency feature of the controlled system $G_{HR}(s)$

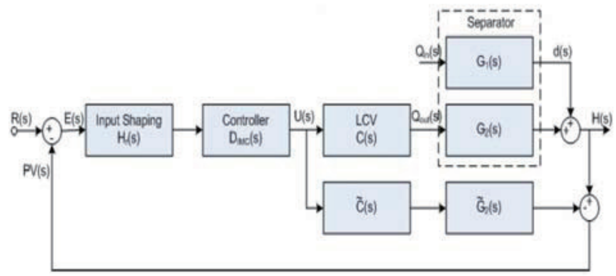

Fig. 11. Block Diagram of Controlled System Using IMC Method

By assigning denominators in (8) and (9) equal, the two control coefficients $K_p,\ K_I$ can be determined simultaneously. For instance, one set of PI coefficients for $\Omega_c = 0.5Hz$ are determined as $K_p = -0.7391,\ K_I = -1.5820$. The frequency feature of $G_{HR(s)}$ is shown in Fig.10. It can be observed that the system bandwidth is increased up to 0.97 Hz, instead of expected 0.5 Hz. The reason is due to the existing zero's effect, and this zero can be seen in (8). The simulated system outflow-rate and controlled level are compared with the other two designs as shown in Fig.7 and Fig.8, respectively. It is obvious that this design leads to a better system performance compared with the existing control and the previous trial-and-error design. In order to handle potential trouble concerned to the zero effect, the IMC method is investigated in the following.

D. Control Design Using IMC Method

We refer to [5], [8] for a general explanation of the IMC method. The control system using the IMC method is shown in Fig.11, where the open loop system's model ($\tilde{C}_1(s)\tilde{G}_2(s)$) is used in the controller structure (LCV model $\tilde{C}(s)$ is assumed simply as a gain in our concern). The cascaded controller $D_{IMC}(s)$ consists of two serial parts: The stable inverse model of $\tilde{C}_1(s)G_2(s)$ and a low-pass first-order filter, i.e.,

$$D_{IMC}(s) = -\frac{47.55s + 1.81}{270.5} \frac{1}{\tau s + 1}. \quad (10)$$

The selection of time constant τ of the low-pass filter can follow the same principle as we discussed in previous sub-

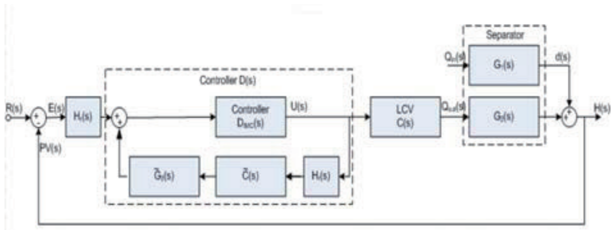

Fig. 12. Implementation Diagram of IMC Controller

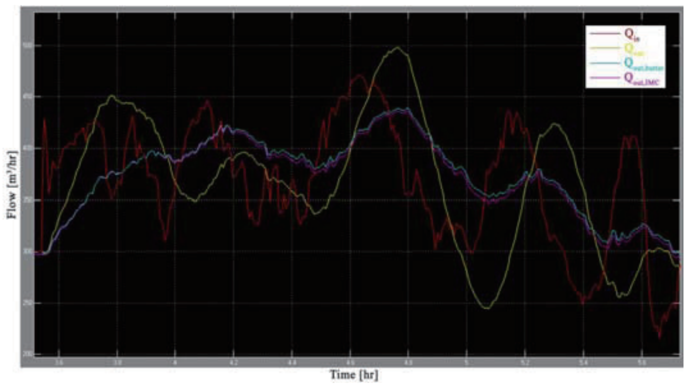

Fig. 13. Comparisons of Outflow-rates Under Different Control Methods

section for determining the cutoff frequency of a butterworth filter [5]. For instance $\tau = 0.17$ is chosen for our concern, and it corresponds to $\Omega_c = 0.92Hz$.

The designed IMC controller as shown in Fig.11 can be converted into an equivalent structure as shown in Fig.12 for implementation purpose. The controller $D(s)$ has a PI formulation as

$$D(s) = \frac{1}{\tilde{C}_1(s)G_2(s)H_r(s)\tau s} = -\frac{47.55s + 1.81}{270.5}\frac{1}{\tau s}. \quad (11)$$

Thereby the developed IMC controller can be easily implemented in the current system with coefficient $K_p = -0.7031$, $K_I = -1.405$. The controlled system performances and comparisons with the other designs are illustrated in Fig.13 and Fig.14, respectively. It can be observed that the IMC control leads to slightly better system performances than the butterworth filter design. Furthermore, there is no frequency distortion due to the existing zero.

E. Discussion and Future Work

In general, the innovation objective leads to a non-standard servo control problem if the development is limited to only modify the current control coefficients. As shown in Fig.2, an outflow transmitter (FIT-340012) has been deployed in the current system. If the control innovation can also use this signal for control purpose, we believe the system performance can have a significant improvement. Furthermore, some advanced control method, such as MPC [12] and H_∞/μ robust control [8], can also be naturally employed. The investigation

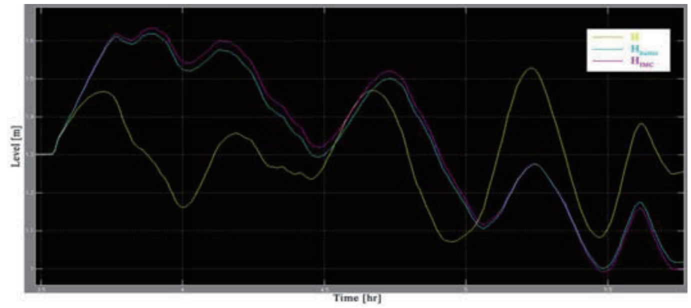

Fig. 14. Comparisons of Water Levels Under Different Control Methods

of these concerns are undergoing and we wish to report new results in the near future.

V. CONCLUSION

The improvement of the level control of a three-phase separator on an offshore platform is discussed. A number of PI-type controllers are developed according to different tuning methods, namely trial-and-error method; butterworth filer design method and IMC method. All developments lead to significant improvements of the current control system in terms of more smooth water outflow-rate with a satisfactory level control. The implementation of these developments in the real system and the investigation of using the outflow-rate measurement for feedback control are part of our future work.

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