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Adopting Setpoint Weighting Strategy for WirelessHART Networked Control Systems Characterised by Stochastic Delay

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ABSTRACT In networked control system, such as WirelessHART that is characterized by stochastic delay, the use of proportional integral and differential (PID) controllers is inadequate. This is because PID performs poorly in handling time-delay processes. The main reason for this poor performance is the limitation in the range of stable gain of the controller. Time delay causes oscillatory response of the PID with large gain. Likewise, sluggish response is experienced with small gain of the PID. Also, dead time compensators like smith predictor and internal model controller are difficult to be implemented practically since they require exact model of the process to be controlled. Therefore, this paper proposes the application of setpoint weighting strategy to be used alongside PID controller in a WirelessHART network. This method extends significantly the range of the PID gain, while providing good set point tracking and load regulation. From the simulation and experimental results obtained, the capability of the approach to load regulation and tracking can be seen in its fast recovery from effect of disturbance with minimal overshoot. Thus, a two degree of freedom control is achieved. Results also showed that the method is robust to real-time random variable network delay and model mismatches.

INDEX TERMS Deadtime, PID controller, setpoint weighting, stochastic network delay, WirelessHART.

I. INTRODUCTION

Recently, the industry and academics have paid significant attention to wireless sensor network (WSN) technology, especially towards its application for industrial monitoring and control [1]–[9]. There are several reasons for this attention. For example, compared to the wired system, the advantages are need for fewer cabling, higher scalability, improved flexibility, and increased reliability. Other advantages are the reduction in the time for installation, reconfiguration, maintenance and the extension of wired networks capabilities to difficult areas [10].

Wireless Standards such as Bluetooth, Wi-Fi and ZigBee were however not designed to handle the stringent industrial requirement of security, reliability and device interoperability [1], [7], [8], [11]. For example, while Bluetooth was designed primarily for personal applications and can support up to 8 devices within the network, Wi-Fi and ZigBee are designed for office and home applications respectively. Thus, this led to the emergence of three industrial standards of WirelessHART, Wireless network for Industrial Automation-Process Automation (WIA-PA) and ISA100.11 Wireless [12]. This is in response to the increasing demand of the wireless technology for monitoring and control applications in the industry [13].

WirelessHART is an extension of the HART industry standard. The HART is popular due to its simplicity. Currently, there more than 30 million installed HART enabled devices world over. This puts the WirelessHART on the lead ahead of its WIA-PA and ISA100 Wireless counterparts [10]. Although the technology is designed to be used for both monitoring and control applications, at the moment it is limited to monitoring while effort is being made to extend it to control [2], [5], [6], [14]. However, applying wireless for control applications could lead to challenges such as stochastic network delays, packet drop-out and non-periodic measurement updates by wireless transmitters [6], [14], [15]. Therefore, employing adequate control strategy to curtail the effect of these challenges is of paramount importance. Specifically, the stochastic network delay is capable of degrading the network performance and could lead to packet drop-out.

PID controllers are the most widely used in the industry [16]. However, these type of controllers are inadequate in handling long time delays and uncertainties. Furthermore, the PID has a very limited stabilizing gain range. Thus, as the delay in the network increases, the gain range of the PID becomes inadequate. Also, if large gain is used for PID in delayed environment, the response becomes oscillatory and unstable. On the overhand, if small gain is used the response becomes highly sluggish [17], [18]. Another issue faced by PID is that setpoint is often changed in a stepwise manner, as such an abrupt change in the setpoint causes large change in control signal. This leads to large overshoot which adversely affects the actuator [19]. Thus, oscillations caused by delay could lead to faster degradation of the actuator. The main contribution of this paper are as follows:

1) establishment through experimentations, the existence of stochastic delay in WirelessHART control network;
2) development of setpoint weighting control strategy to achieve two degree of freedom to address the effect of stochastic network delay in a WirelessHART control environment;
3) performance evaluation of the proposed approach through experimentation with hardware in the loop simulator to demonstrate the technique's ability for setpoint tracking and its robustness to load disturbance and model mismatches.

The reminder of the paper is organised as follows: In Section II, brief review of related work is presented while Section III presents the methodology for delay measurement and the hardware in the loop simulation. In Section IV, the controller design is presented. Results and analysis are presented in Section V while the last section concludes the paper and gives suggestion for future works.

II. RELATED WORK

Several researchers have proposed improvement of PID controller to suit its application in time delay systems [20]–[22]. At the advanced level, techniques such as deadtime compensator (DTC), model based predictive controller (MPC) and generalized predictive controller (GPC) have been proposed for wired and wireless applications [14], [15]. A key and common drawback of these controllers is that of complexity, which makes them difficult to be practically implemented [18]. Another reason for the implementation issue is that some of these controllers require the exact model of the process to be controlled. This is impossible in reality [18].

Implementation of two degree of freedom (2-DoF) control through setpoint weighting technique for delayed systems has been attempted by many researchers [18], [20], [23]–[27]. Foremost, the strategies focus on avoiding the complexity of model based controllers while maintaining the simplicity of the PID controller. The next feature of these techniques is that they try to address the problem of gain range associated with PID when it is used in delayed environment. Furthermore, the implementation of some of the setpoint weighting structure can be achieved without altering the closed loop stability because the structure lies outside the loop.

On the 2-DoF control strategies for instance, the setpoint weighting strategy reported in [20] involves the use of flexible structure which treats separately the setpoint and the process output. This is achieved by incorporating two tunable gains in the proportional and derivative terms of the PID controller. The aim of this method is for the controller to be robust to setpoint changes and load disturbance. The drawback of this method is that, it does not solve the problem of gain limitation. This is because the proportional gain β introduced is still limited usually within the range of 0 and 1 (i.e. $0 \leq \beta \leq 1$). Furthermore, the gain associated with the derivative term is set to 0 to avoid transient due to setpoint changes. Another disadvantage of this method is that, part of the structure lies within the closed loop of the original PID. Thus using it may require some modification to the existing structure. The use of fuzzy logic has been proposed to tune setpoint weight of PID controller in both [28] and [29]. Here, while the weighting term associated with the proportional action of the controller (β) is tuned via fuzzy logic, the load regulation performance is achieved by preserving or improving on the Ziegler-Nichols formula. The drawback of this method is that it is based on the previous method in [20]. Thus, this method does not extend significantly the range of gain used for the controller. It should be noted that with this method, any gain above unity will cause large overshoots and oscillation. Another drawback of this method is that the use of fuzzy logic impose additional task of having to tune the fuzzy logic parameters. In [24] a setpoint weighted multi-variable PID controller was tuned using bilinear matrix inequalities (BMI) optimization. Again, this method is based on the method proposed in [20] thus, has the same limitation of gain range and structure. Attempt to increase the gain (i.e. $\beta > 1$) of weight associated with the proportional term of the PID controller is made in [23]. Here, the selection criteria for the proportional weight β depends on the design parameter T_c and the PI controller gain K_c. Although this method has allowed the use of $\beta > 1$, it has not significantly increased the gain range as maximum value of β achieved is limited to less than 3. In that case, the high gain increases the sluggishness of the response. An on-line dynamic setpoint weighting schemes using linear relation, fuzzy and sigmoid function to dynamically tune β were proposed in [25], [30] and [31] respectively. These methods still retain the limitation of restricting β to not more than unity. In [26] and [27], the use of a filter with the structure of first order plus deadtime (FOPDT) in a setpoint weighing arrangement to achieve 2-DoF control is reported. It should be noted that the complete structure is similar to the that reported in [18] with the exception that the entire setpoint weighting block configuration of the two are different.

In the structure, the setpoint weighting block is outside the closed loop control set-up. However, no attempt has been made to implement the 2-DoF control for the WirelessHART networked environment until when the structure reported in [18] was adopted for WirelessHART control and reported in our initial work in [32]. The structure, provides for flexibility in the gain range which the earlier methods earlier discussed did not.

This paper presents the adoption of setpoint weighting strategy to achieve a 2-DoF control for WirelessHART networked system characterized by random variable delay as reported in our earlier work [32] that was presented in I2MTC 2016. In addition to the earlier work, the design is extended to higher order systems. Robustness analysis of the proposed method is also provided. Further experiments and simulation using real-time measurement to demonstrate the effectiveness of the design have also been conducted. The followings are some merits of the proposed technique:

- Although model is required, there is no need for exact model of the system for implementation. In other words model mismatch is allowed. This is in contrast to DTCs;
- Estimate of the network delay and desired loop specifications are sufficient for design;
- Stable closed loop gain range of the PID is increased without compromising stability.
- Model Mismatch does not affect the robust performance of the system with the setpoint weighting structure;
- By having the setpoint weighting outside of the closed loop, the common structure of PID is retained.

The proposed approach is general, hence it is applicable to long range of processes characterised by delay including WirelessHART Networked Control Systems (WHNCs). With the approach, good tracking ability and good load regulation is guaranteed compared to both PID and DTCs like Smith Predictor.

III. WIRELESSHART NETWORK DELAY MEASUREMENT AND HARDWARE IN THE LOOP SIMULATION

This Section presents the procedure for measuring the WirelessHART network delay as well as the WirelessHART hardware in the loop simulation (WH-HILS). Two WirelessHART network development and evaluation kits developed by RF Monolithics (RFM) and Linear Technology are used for experimentation in this work. The RFM kit is used to ascertain the level of network induced delay in the system while the Linear Technology kit is used for the WH-HILS to verify the effectiveness of the proposed approach to real-time stochastic delay. A brief explanation on the two experiments is presented in the following sub-sections.

A. DELAY ESTIMATION

WirelessHART network development and evaluation kit developed by RFM is used in the experiment to measure the network induced delays. The experimental set-up of Fig. 1 consists of a computer which implements the network manager, a gateway (XG2510HE) and a field

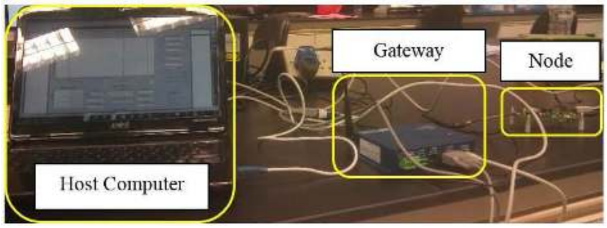

FIGURE 1. Experimental set up of Gateway, Network manager and Field devices.

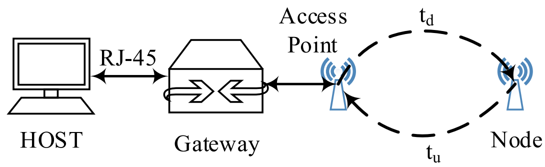

FIGURE 2. WirelessHART network measurement schematics.

node or mote (XDM2510H). Its schematics is presented in Fig. 2. As shown, RJ-45 cable is used to connect the host computer to the gateway while communication between the gateway and the mote is through wireless. The downstream delay t_u is the delay from gateway to the mote, while the upstream delay t_d is delay from mote to the gateway. In the gateway, the delays are obtained by specifying the MAC address of the mote in the command *exec getLatency MACaddress* [33]. To read this information in MATLAB from the gateway, Secure Shell (SSH2) software [34] is used to interface MATLAB and the gateway. The SSH2 command *ssh2_config ('gateway IP', 'admin', 'admin')* is used to get the required information. In the command, the first argument is the IP address of the gateway (192.168.99.100) while the second and last arguments are the respective username and password. Similar to the works reported in [35], [36], and [37] each of the t_u and t_d is obtained using timestamps on the communication messages. To achieve this, the difference between received timestamps generated at the gateway and the sent timestamps embedded on the arrival message is measured.

B. WIRELESSHART HARDWARE IN THE LOOP SIMULATOR (WH-HILS)

The WH-HILS is developed using the Linear Technology SmartMesh WirelessHART network development kit [38]. The block diagram of the WH-HIL simulation process which involves both MATLAB simulation and real-time experiment is shown in Fig 3. It should be noted that the experimental setup is similar to that of Fig. 1 with the exception that the WH-HIL simulation uses real-time variable delay in simulating the controller design. In order to access both upstream and downstream real-time delay information into the Simulink from the gateway, Python instructions are employed rather than the earlier used SSH2 commands. The fetched real-time delays are instantly used for the WH-HIL simulation. The WH-HILS is capable of being used to test and

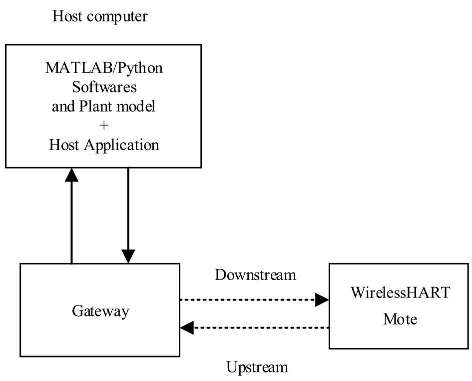

FIGURE 3. WirelessHART network measurement schematics.

diagnose new control strategies before being finally deployed. For recent examples of application of similar technique see [39] and [40]. As seen from block diagram, the gateway communicates with the computer running MATLAB software using LAN interface. Simulink is used to simulate virtual process plants given real-time network induced delays from the gateway. The delay information obtained from the gateway are fed into the variable time delay blocks of the Simulink to simulate upstream and downstream delays. To synchronise model simulation to real time clock, real-time sync block is used.

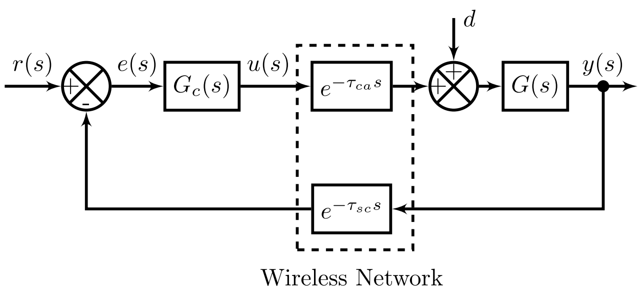

FIGURE 4. Network delay representation in a single loop wireless networked control system.

IV. CONTROLLER DESIGN

A. DELAY IN WIRELESSHART NETWORKED CONTROL SYSTEMS

Delay sources in a delayed networked control system (NCS) and by extension WHNCS can be broadly classified in to three: (a) process deadtime, (b) controller processing delay and (c) network induced delays which can be further summarized into (i) controller-to-actuator delay (τ_{CA}) and (ii) sensor-to-controller delay (τ_{SC}) (see Fig 4) . The second value which is the controller processing delay (τ_C) is usually negligible [38]. In this work, for the purpose of designing the controller, average values of t_u and t_d from the experimental set-up in Fig. 1 are used for the respective values of τ_{SC} and τ_{CA}. The robustness of the proposed method to the stochastic effect of these delays will be demonstrated through the WH-HIL simulation.

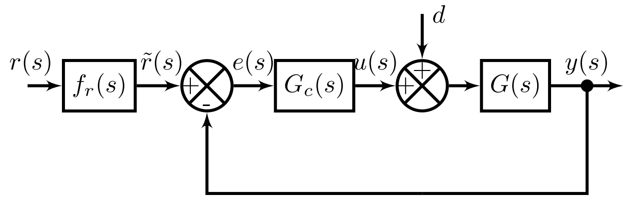

FIGURE 5. Simple setpoint weighting control scheme.

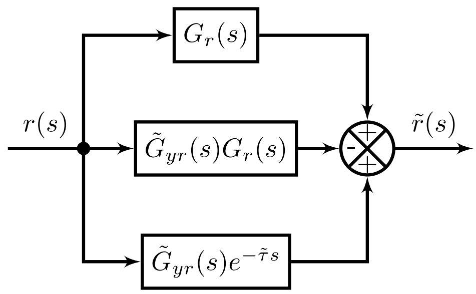

FIGURE 6. Setpoint weighted WirelessHART networked control structure.

B. SIMPLE SETPOINT WEIGHTING FUNCTION

Consider the setpoint weighting control structure of Fig. 5 with $G(s) = P(s)e^{-s\tau}$, assuming $f_r(s)$ is the simple setpoint weighting function given as

$$f_r(s) = \frac{\tilde{r}(s)}{r(s)} = 1 + \tilde{G}_{yr}(s)(e^{\tilde{\tau}s} - 1) \tag{1}$$

where the estimate of the dealy is $\tilde{\tau}$, the weighted reference is $\tilde{r}(s)$ and the desired closed loop response free from delay is $\tilde{G}_{yr}(s)$. Thus, the close-loop transfer function is

$$\frac{y(s)}{r(s)} = \frac{G_c(s)P(s)e^{-\tau s}}{1 + G_c(s)P(s)e^{-\tau s}}\left(1 + \tilde{G}_{yr}(s)(e^{\tilde{\tau}s} - 1)\right) \tag{2}$$

By defining $G_{yr}(s) = \frac{G_c(s)P(s)}{1+G_c(s)P(s)}$, then it can be established that (2) can be expressed as

$$\frac{y(s)}{r(s)} = \frac{G_{yr}(s)e^{-\tau s}\left(1 + \tilde{G}_{yr}(s)e^{\tilde{\tau}s} - \tilde{G}_{yr}(s)\right)}{1 + G_{yr}(s)e^{-\tau s} - G_{yr}(s)} \tag{3}$$

If $1 + G_{yr}(s)e^{-\tau s} - G_{yr}(s) = 0$, the denominator of (3) can be shown to have the same solution as $1 + G_c(s)P(s)e^{-\tau s} = 0$, which is the characteristic equation of Fig. 5 when $f_r(s) = 0$. It is also assumed that $\tilde{\tau} = \tau$ and $G_{yr}(s) = \tilde{G}_{yr}(s)$. Thus, if $G_c(s)$ is designed such that the characteristic equation of (3) has real negative parts only, pole-zero cancellation on (3) can be done. Thus, the transfer function from $r(s)$ to $y(s)$ in Fig. 5 is

$$\frac{y(s)}{r(s)} = G_{yr}(s)e^{-\tau s} \tag{4}$$

where $G_{yr}(s)$ is the closed loop transfer function without the delay. The relationship in (4) shows that the delay term $e^{-\tau s}$ is decoupled from the delay-free function $G_{yr}(s)$. This enables the design of $G_c(s)$ to be done with respect to the delay-free portion of the process $P(s)$. However, this approach still does not significantly extend the gain range of $G_c(s)$ for closed

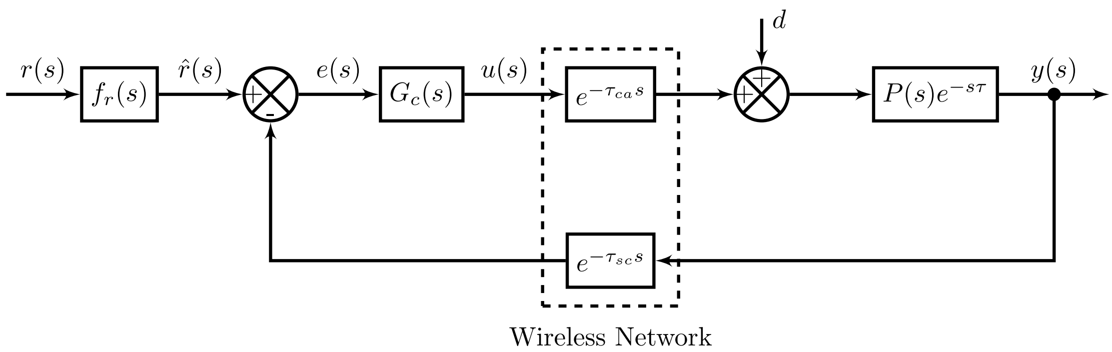

FIGURE 7. Setpoint weighted WirelessHART networked control structure.

loop stability. Therefore, a more general structure is needed to extend the gain range.

C. GENERAL SETPOINT WEIGHTING FUNCTION

To allow the use of a wider range of controller gain while still maintaining closed loop stability, a generic setpoint weighting function (5) was proposed in [18]. This structure (see Fig. 6) permits the 2-DoF ability of both good setpoint tracking and disturbance rejection of the controller.

$$f_r(s) = \frac{\tilde{r}(s)}{r(s)} = G_r(s) + \tilde{G}_{yr}(s)\big(e^{\tilde{\tau}s} - G_r(s)\big) \tag{5}$$

where $G_r(s)$ is the setpoint regulating feed-forward controller.

In a similar fashion to Section IV-B, after integrating $G_r(s)$, the transfer function of the closed loop is written the same way as

$$\frac{y(s)}{r(s)} = \frac{\hat{G}_{yr}(s)e^{-\tau s}\big(G_r(s) + \tilde{G}_{yr}(s)e^{\tilde{\tau}s} - G_r(s)\tilde{G}_{yr}(s)\big)}{G_r(s) + \hat{G}_{yr}(s)e^{-\tau s} - G_r(s)\hat{G}_{yr}(s)} \tag{6}$$

If $\hat{G}_{yr}(s) = \frac{G_r(s)G_c(s)P(s)}{1+G_r(s)G_c(s)P(s)}$ is the desired closed loop transfer function with the higher gain, $\tilde{\tau} = \tau$ and $\hat{G}_{yr}(s) = \tilde{G}_{yr}(s)$, and after pole-zero cancellation on (6). Hence the delay-free portion of the process $\hat{G}_{yr}(s)$ can be decoupled from the delay term $e^{-\tau s}$ as in (4). Such that the overall transfer function of the loop is written as

$$\frac{y(s)}{r(s)} = \hat{G}_{yr}(s)e^{-\tau s}. \tag{7}$$

D. SETPOINT WEIGHTING FUNCTION FOR WHNCS

The setpoint weighting controller design for WHNCS is done by analysing the diagram of Fig. 7 for closed loop control. The diagram is based on the structure discussed in [41]. The transfer function from $y(s)$ to $r(s)$ assuming commutativity of the terms is

$$\frac{y(s)}{r(s)} = \frac{G_c(s)P(s)e^{-(\tau_{CA}+\tau)s}}{1 + G_c(s)P(s)e^{-(\tau_{CA}+\tau_{SC}+\tau)s}} f_r(s) \tag{8}$$

Defining $\tau_1 = \tau_{CA} + \tau$ and $\tau_2 = \tau_{CA} + \tau_{SC} + \tau$, (8) can be written as

$$\frac{y(s)}{r(s)} = \frac{G_c(s)P(s)e^{-\tau_1 s}}{1 + G_c(s)P(s)e^{-\tau_2 s}} f_r(s) \tag{9}$$

In a similar way to what has been done in Sections IV-B and IV-C, the closed-loop transfer function of Fig. 7 is

$$\frac{y(s)}{r(s)} = \frac{\hat{G}_{yr}(s)e^{-\tau_1 s}\big(G_r(s) + \tilde{G}_{yr}(s)e^{\tilde{\tau}s} - G_r(s)\tilde{G}_{yr}(s)\big)}{G_r(s) + \hat{G}_{yr}(s)e^{-\tau_2 s} - G_r(s)\hat{G}_{yr}(s)} \tag{10}$$

where $\hat{G}_{yr}(s) = \frac{G_r(s)G_c(s)P(s)}{1+G_r(s)G_c(s)P(s)}$. Again if $\tilde{\tau} = \tau_2$ and $\hat{G}_{yr}(s) = \tilde{G}_{yr}(s)$ and pole-zero cancellation in (10), then

$$\frac{y(s)}{r(s)} = \hat{G}_{yr}(s)e^{-\tau_1 s} \tag{11}$$

Likewise, the decoupling of delay term $e^{-\tau_1 s}$ from the delay free term $\hat{G}_{yr}(s)$ is revealed in (11). Again, the design of the controller $G_c(s)$ can be done with respect to the portion of the process $P(s)$ that is free from the delay.

If $G_r(s) = K$ (i.e proportional controller). The delay free term of (11) can now be written as

$$\hat{G}_{yr}(s) = \frac{KG_c(s)P(s)}{1 + KG_c(s)P(s)} \tag{12}$$

Equation (12) is an indication that the use of setpoint weighting function $f_r(s)$ will enable 2-DoF of good setpoint tracking and load regulation can be achieved while still permitting the use of high stable gain K.

E. DESIGN PROCEDURES

There are two major phases of designing setpoint weighting function for WHNCS. The first phase is to design the PI controller $G_c(s)$. This controller is designed for good load regulation which takes care of the first DoF. The second phase takes care of the design of setpoint weighting function which handles the second DoF of good set point tracking. The PI controller $G_c(s)$ is given by

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right) \tag{13}$$

where the gain K_c and time constant T_i of the PI controller given in (14) and (15) are designed based on modification of the method proposed by Smith and Corripio [42]. The term

ΔL should be chosen between 5-20% of the total delay L.

$$K_c = \frac{T}{2K_p(L+\Delta L)} \tag{14}$$

$$T_i = T \tag{15}$$

The design ensures robustness to load disturbances while delivering around 5% overshoot. The design of $f_r(s)$ involves deigning two components $G_r(s)$ and $\hat{G}_{yr}(s)$. The first component $G_r(s)$ can be chosen simply as K if no much information on the process is available. However, if there is enough information of the process to be controlled, it can be designed as (16).

$$G_r(s) = \frac{KG_c(s)^{-1}P(s)^{-1}}{B_c(s)} \tag{16}$$

where $B_c(s)$ is the denominator of $G_c(s)$ when expressed as $\frac{A_c(s)}{B_c(s)}$. The desired closed loop transfer function is given as

$$\hat{G}_{yr}(s) = \frac{1}{B_c(s)/K+1} \tag{17}$$

$B_c(s) = T_i s$ if $G_c(s)$ is a PI or PID controller. Hence, (17) can be written as

$$\hat{G}_{yr}(s) = \frac{1}{T_i s/K+1} \tag{18}$$

where K is chosen such that the desired closed loop response is met.

It should be noted that the design for $G_r(s)$ in the case of second and higher order systems leads to a transfer function with more zeros than poles, this can be corrected by appending fast poles to the transfer function of $G_r(s)$. Usually, the design for second order system leads to one more zero and that for third order system leads to two more zeros than poles in the transfer function of $G_r(s)$. Thus appending poles should be added to counter the corresponding extra zeros. Alternatively, $G_r(s)$ can be designed simply as a gain K as explained above.

F. ROBUSTNESS ANALYSIS

Under acceptable conditions, the setpoint weighting for the wireless control system with the assumptions that $\tilde{\tau} = \tau_2$ and $\hat{G}_{yr}(s) = \tilde{G}_{yr}(s)$ will result in improved setpoint tracking performance of the system. It should be noted that since the setpoint weighting term $f_r(s)$ is outside the closed loop as shown in Fig. 5, it does not affect the stability and robustness of the system in as much as it does not add unstable pole to the system. This conforms to the robustness analysis presented in [43] and [18] for 2-DoF controllers. However, if the acceptable conditions are not met i.e. $\tilde{\tau} \neq \tau_2$ and $\hat{G}_{yr}(s) \neq \tilde{G}_{yr}(s)$, the robustness and setpoint tracking performance will be affected.

A general condition to maintain robust tracking performance for systems with long deadtime is presented in [18]. Thus, accordingly, we adopt and modify some of these conditions to suit the WirelessHART networked control environment. The tracking error of Fig. 7 is given by

$$e(s) = \tilde{r}(s) - y(s)e^{-\tau_{SC}s} \tag{19}$$

It follows from (11) that the output can be expressed as $y(s) = r(s)\hat{G}_{yr}(s)e^{-\tau_1 s}$ also from (1), $f_r(s) = \frac{\tilde{r}(s)}{r(s)}$. Thus, (19) can be written as

$$e(s) = \tilde{r}(s)\Big(f_r(s) - \frac{f_r(s)}{\hat{f}_r(s)}\hat{G}_{yr}(s)e^{-\tau_2 s}\Big) \tag{20}$$

where the setpoint weighing function under nominal condition $\tilde{\tau} = \tau_2$ and $\hat{G}_{yr}(s) = \tilde{G}_{yr}(s)$ is $\hat{f}_r(s) = G_r(s) + \hat{G}_{yr}(s)\big(e^{\tilde{\tau}s} - G_r(s)\big)$, thus if these nominal conditions hold, the setpoint term is expressed as $f_r(s) = \hat{f}_r(s)$ and the error in (20) becomes

$$e(s) = \tilde{r}(s)\Big(f_r(s) - \hat{G}_{yr}(s)e^{-\tau_2 s}\Big) \tag{21}$$

When there is deviation from nominal conditions, the deviation can be modeled as either an additive or multiplicative uncertainty [43].

The additive uncertainty in the frequency domain (i.e. when $s = i\omega$) is represented as $f_r(i\omega) = \hat{f}_r(i\omega) + l_a(i\omega)$. Hence, the sensitivity function derived from (20) should satisfy the following condition:

$$\left|\Big(\hat{f}_r(i\omega) + l_a(i\omega)\Big)\Big(1 - \frac{1}{\hat{f}_r(i\omega)}\hat{G}_{yr}(i\omega)e^{-\tau_2 i\omega}\Big)\alpha\right| < 1 \tag{22}$$

where α is the robust performance weight and l_a is the additive uncertainty term. Consequently, (22) can be written in the form

$$\Big(\big|\hat{f}_r(i\omega)\big| + \big|l_a(i\omega)\big|\Big)\left|\Big(1 - \frac{1}{\hat{f}_r(i\omega)}\hat{G}_{yr}(i\omega)e^{-\tau_2 i\omega}\Big)\alpha\right| < 1 \tag{23}$$

with $|l_a(i\omega)| \leq \bar{l}_a(\omega)$ being the bound on the uncertainty. Therefore, the setpoint weighting function should be designed to satisfy (23) for robust performance.

Similarly, when multiplicative uncertainty is considered, the deviation can be represented as $f_r(i\omega) = \hat{f}_r\big(i\omega)(1 + l_m(i\omega)\big)$. The uncertainty function also derived from (20) should satisfy the following for robust performance:

$$\big|\hat{f}_r(i\omega)\big|\Big(1 + \big|l_m(i\omega)\big|\Big)\left|\Big(1 - \frac{1}{\hat{f}_r(i\omega)}\hat{G}_{yr}(i\omega)e^{-\tau_2 i\omega}\Big)\alpha\right| < 1 \tag{24}$$

where l_m is the multiplicative uncertainty term. Hence, the multiplicative uncertainty bound condition is $|l_m(i\omega)| \leq \bar{l}_m(\omega)$. Likewise, the setpoint weighting function should be designed to satisfy (24) for robust performance if multiplicative uncertainty is considered.

V. RESULTS AND ANALYSIS

This section presents the results and analysis for the experiments, simulation and WH-HIL simulation conducted with the RFM and Linear technology WirelessHART network development and evaluation kits.

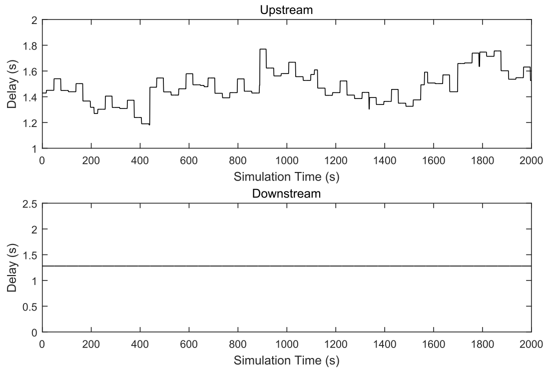

FIGURE 8. Upstream and downstream experimental real-time variable delays.

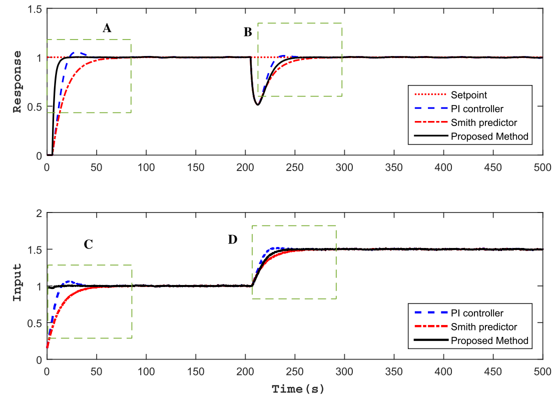

FIGURE 9. First order plant with load disturbance and noise.

TABLE 1. Key statistical delay information.

Delay Type	Statistics			
	Max	Min	Mean	Std. Dev.
Upstream (s)	1.770	1.181	2.145	0.1244
Downstream (s)	1.280	1.280	1.280	0.000

A. PLANT OVERVIEW

The first, second, third and fourth order plants with dead-time models in (25), (26), (27) and (28) are considered for both pure and WH-HIL simulations. The models can approximate adequately the dynamics of range of industrial processes [20].

$$G_1(s) = \frac{1}{2s+1}e^{-4s} \tag{25}$$

$$G_2(s) = \frac{1}{s^2+2s+1}e^{-4s} \tag{26}$$

$$G_3(s) = \frac{1}{(s+1)^3}e^{-5s} \tag{27}$$

$$G_4(s) = \frac{1}{(1+s)(1+0.5s)(1+0.25s)(1+0.125s)}e^{-5s} \tag{28}$$

B. MEASURED NETWORK DELAY WITH RFM KITS

The delay trend and statistical information of the upstream t_u and downstream delays t_d measured using the setup of Fig. 1 are shown Fig. 8 and Table 1. The average values of these delays are used for the controller design.

C. COMPARISON OF PLANTS CONTROL PERFORMANCE

The setpoint weighting and PI controller parameters for (25), (26), (27) and (28) are shown in Table 2. These parameters are used where necessary in the proposed method, the PI and the Smith predictor controllers. In the table, K_{C1} is the PI controller gain used in the setpoint weighting strategy whereas K_{C2} is PI controller gain according to the design in [42]. The T_i used for both designs is the same. To achieve faster recovery from the effect of disturbance offset without compromise to overshoot, the value of K_{C1} should be chosen between $85 - 95\%$ of the calculated value as recommended in [18]. To evaluate the performance of the proposed method, both the first order and the second order plants are simulated to a unit step signal. A disturbance signal of magnitude 0.5 with step time of 200s is injected at the input of all plants. The performance evaluation is based on the comparison of the integral absolute error (IAE), rise time (response speed), settling times and percentage overshoot. Furthermore, to test for the robustness of the design to model mismatch variable delay and changing setpoint, additional simulations are provided for the first order plant to that effect.

1) FIRST ORDER PLANT

By carefully observing Fig. 9 and Table 3, it can be easily seen that the time domain performance of proposed setpoint weighting controller with respect to setpoint tracking and disturbance rejection is better compared to the performance both PI and Smith predictor. The rise time of the plant with the proposed method at around 5s is almost three and six times faster than those of the PI and Smith predictor respectively. The settling time with the proposed method follows similar pattern to that of the response time. In terms of overshoot, the proposed method fares favourably compared to the other two methods. Smaller value integral absolute error (IAE) is recorded for the proposed method compared to those recorded for PI and Smith predictor methods. Furthermore, the proposed method recovered faster and without overshoot from the effect of the disturbance compared to the PI controller. Compared to the smith predictor, the recovery is still faster as seen from the figure.

The fast controller action of the proposed method to the step change can also be noticed from Fig. 9 as against the other two controllers. The zoomed-in view of regions of interest A, B, C and D in Fig. 9 is presented in Fig. 10. This further corroborate the effectiveness of the proposed setpoint weighting controller.

In Fig. 11, robustness of the setpoint weighting controller to parametric model mismatch is presented. For this purpose, parameters of the model (i.e. time constant and the gain) are varied 5% above and 5% below their nominal value while the controller parameters remain unchanged. Simulation results with these variations are compared to that of the original

TABLE 2. **Setpoint weighting and Smith predictor / PI parameters.**

Plant	Parameter				
	$G_r(s)$	$\hat{G}_{yr}(s)$	K_{C1}	K_{C2}	T_i
$P_1(s)$	8.199	$\frac{1}{2s+1}$	0.1188	0.1518	2
$P_2(s)$	$\frac{15.1(s+1)}{(1.3s+1)}$	$\frac{1}{1.3s+1}$	0.0988	0.0988	1.3
$P_3(s)$	$\frac{10(s+1)}{(2s+1)}$	$\frac{1}{2s+1}$	0.0954	0.1061	2
$P_4(s)$	$\frac{12.274(0.016s^4+0.234s^3+1.094s^2+1.87s^4+1)}{(1.5s^4+5.5s^3+7.5s^2+4.5s^4+1)}$	$\frac{1}{1.5s+1}$	0.0895	0.0942	1.5

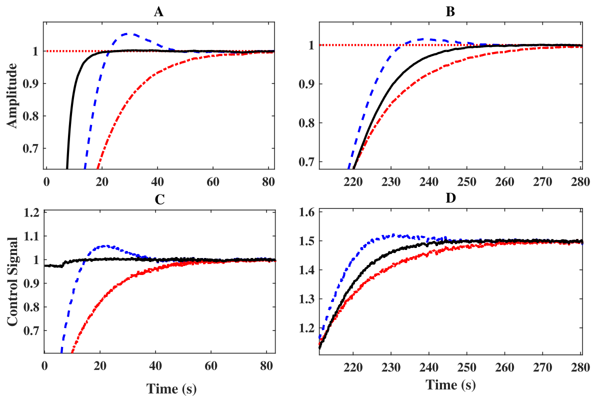

FIGURE 10. **Zoomed-in view of Fig. 9 for regions A, B, C and D.**

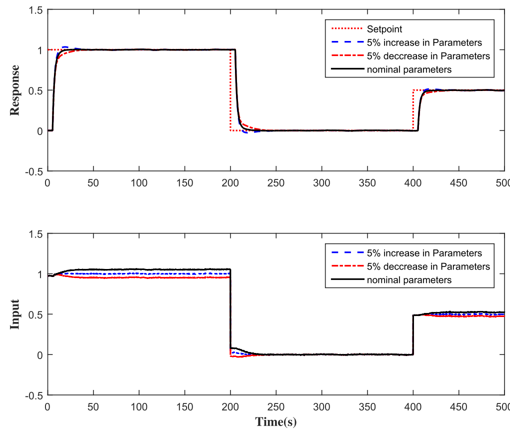

FIGURE 11. **Robustness of proposed method to model mismatch and variable delay, first order plant.**

TABLE 3. **Control performance of first order plant.**

Parameter	Proposed	PI controller	Smith predictor
Rise Time (s)	4.9021	12.1877	28.0783
Settling Time (s)	14.8910	40.6986	55.1527
Settling Time 2 (s)	242.0447	230.2543	256.6726
Overshoot (%)	0.6770	5.7198	0.5505
IAE	186.7814	229.4248	307.2321

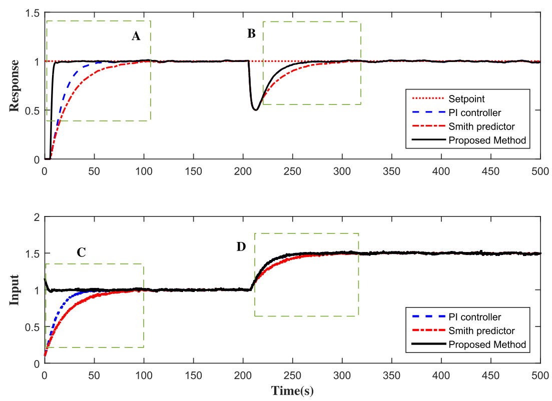

FIGURE 12. **Second order plant with load disturbance and noise.**

values. It can be clearly seen from these graphs that despite the variations, not significant change is observed in terms of the ability of the controller to track the change in setpoint. This clearly reaffirmed the assertion that the controller can be employed in an environment characterized by uncertainties. It also proves the assertion that exact model is necessary but not compulsory for the implementation.

2) SECOND ORDER PLANT

The simulation results for this plant are shown in Fig. 12 and the zoomed-in of the various regions of interest is given in Fig. 13. The information regarding these figures is reported numerically in Table 4. In consonant with the results obtain for the first order plant, similar trends are observed for the second order plant. The response with proposed method is almost ten times faster than that of PI controller and more than sixteen times that of Smith predictor at 2.75, 25.08 and 45.02s respectively. While the plant with the setpoint weighting controller settled at around 10s, the respective settling time with PI and smith predictor is around 49 and 84s. This indicates that the proposed approach settled much faster than the other controllers. It is observed that all controllers produce overshoots of less than 2% for this plant. The overshoot values for Smith predictor, PI and setpoint weighted controllers stand at 1.37, 1.92 and 1.94% respectively. However, the proposed setpoint weighting controller produced the least IAE of around 210 as against 324 and 431 of PI and Smith predictor respectively. The recovery from disturbance effect of the proposed method and that of PI are similar and faster than the smith predictor. This is because, the design of the PI controller within the setpoint weighting structure is similar to the PI controller compared.

If we observe the input signal or the controller action, the aggressiveness of the proposed approach can especially at the point of setpoint change and at the point of disturbance

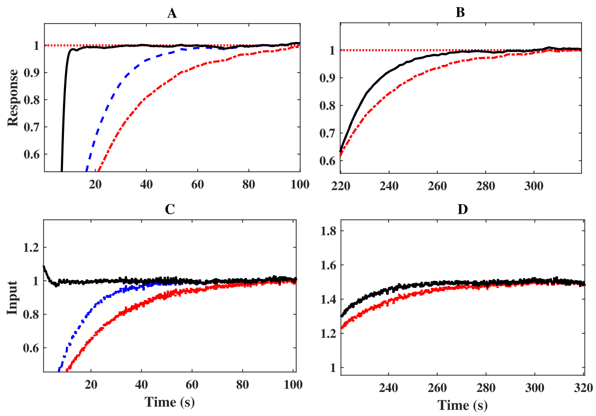

FIGURE 13. Zoomed-in view of Fig. 12 for regions A, B, C and D.

TABLE 4. Control performance of second order plant.

Parameter	Proposed	PI controller	Smith predictor
Rise Time (s)	2.7521	25.0820	45.0158
Settling Time (s)	9.7851	48.9987	84.0075
Settling Time 2 (s)	253.0675	253.0675	284.3269
Overshoot (%)	1.9356	1.9194	1.3698
IAE	210.0829	324.5484	431.0605

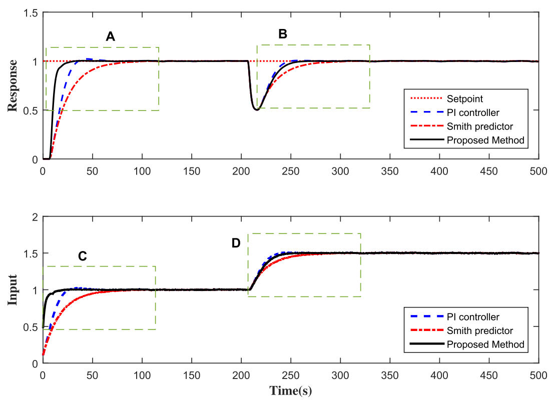

FIGURE 14. Third order plant with load disturbance and noise.

TABLE 5. Control performance of third order plant.

Parameter	Proposed	PI controller	Smith predictor
Rise Time (s)	6.8902	18.3065	37.8866
Settling Time (s)	22.4816	51.3941	74.7931
Settling Time 2 (s)	249.6206	243.0957	273.3782
Overshoot (%)	0.7712	2.6163	0.5992
IAE	239.4999	302.9715	404.2869

i.e. regions C and D. In region C, the setpoint weighting approach produce the most aggressive control signal followed by the PI and then the Smith predictor. However, in region D, both setpoint weighting and PI controllers produce similar and faster control actions compared to that produced by Smith predictor controller. This is because, the design of both PI within the setpoint weighting and the ordinary PI is the same. This design is targeted at good disturbance regulation.

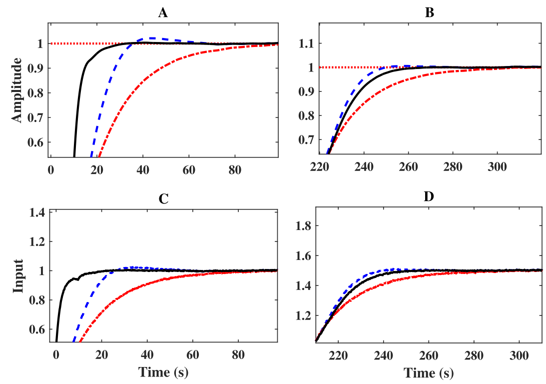

FIGURE 15. Zoomed-in view of Fig. 14 for regions A, B, C and D.

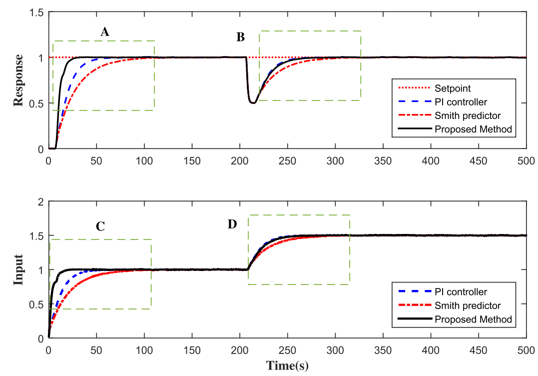

FIGURE 16. Fourth order plant with load disturbance and noise.

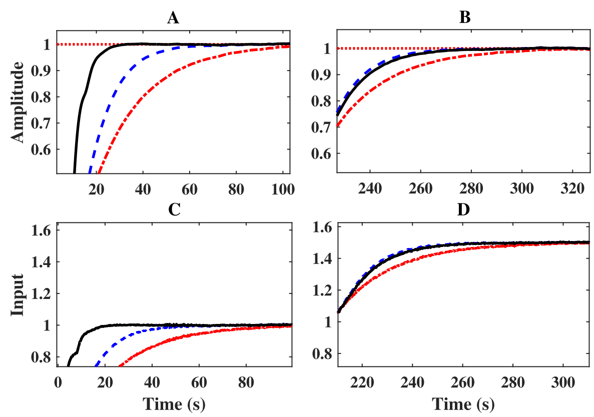

FIGURE 17. Zoomed-in view of Fig. 16 for regions A, B, C and D.

3) THIRD ORDER PLANT

Simulation results for the third order plant are shown in Fig. 14. The zoomed-in of regions of interest A, B, C and D in the figure is given in Fig. 15. In Table 5, numerical results of the two figures are given. The results here are conforms to the trend of results obtained for the first and second order plants. The response with proposed method is almost three times faster than that of PI controller and more than five times that of Smith predictor at 6.89, 18.31 and 37.89s respectively.The setpoint weighting controller settled at around 22.5s. This is less than halve the settling time of PI and around one third of the Smith predictor. This shows

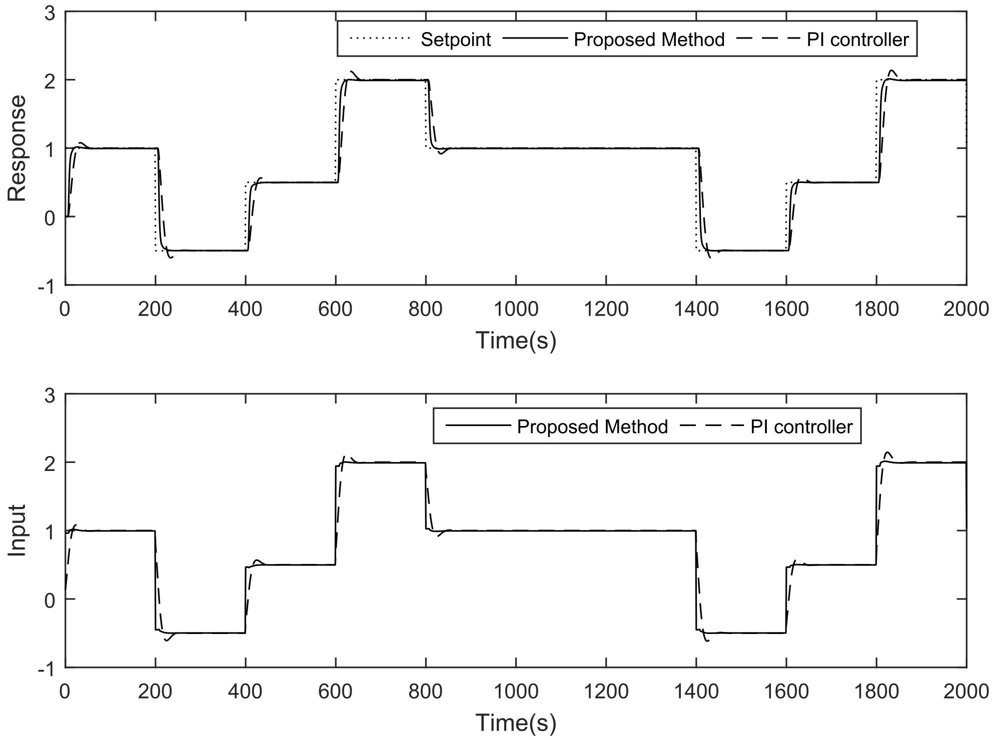

FIGURE 18. First order plant with changing setpoint and experimental real-time variable delay.

that the proposed approach settled much faster than the other controllers. While both the proposed controller and the smith predictor produce respective overshoots of 0.77 and 0.60%, the PI controller produce overshoot of 2.62%. The proposed setpoint weighting approach also produced the least IAE of around 240.50 as against 302.97 and 404.29 of PI and Smith predictor respectively. The recovery from disturbance effect of the proposed method is smooth without overshoot when compared to the little produced by the PI. Furthermore, the recovery of the proposed approach is faster than the recovery with smith predictor even though the latter did not produce overshoot.

Observing the various control signals, the proposed approach produce more aggressive signal than other controller during step change (see regions A and C of 15). An intermediate control signal between that of PI and Smith predictor is produced by the setpoint weighting controller at the point of disturbance to avoid overshoot while achieving fast recovery (see regions B and D of 15).

4) FOURTH ORDER PLANT

Fig. 16 shows the simulation results for the fourth order plant while Fig. 17 shows the zoomed-in of regions of interest A, B, C and D of the plots in Fig. 16. Numerical results of the two figures are given in Table 6. Here, results followed similar pattern to the three lower order plants considered earlier. The rise time of the plant with proposed approach is around 9.5s. This makes it more than two times faster than that with PI controller and almost than five times that of Smith predictor. The setpoint weighting controller settled at around 24s. This is less than halve the settling time of PI and around one fourth of the Smith predictor. This shows that the proposed approach settled much faster than the other controllers. The overshoots produced by all control approaches is in the range 0.51−0.67%. This shows that all controllers performed well for this plant. The proposed setpoint weighting approach also produced the least IAE of around 306.50 as against 383.90 and 511.90 of PI and Smith predictor respectively. The recovery from disturbance effect of the proposed method for the fourth order plant also followed similar pattern to the second order plant.

TABLE 6. Control performance of fourth order plant.

Parameter	Proposed	PI controller	Smith predictor
Rise Time (s)	9.4962	25.4462	45.5658
Settling Time (s)	24.0004	49.8581	86.1282
Settling Time 2 (s)	258.1088	254.1890	284.6645
Overshoot (%)	0.6604	0.6671	0.5114
IAE	306.4781	383.9040	511.8992

Observing the various control signals, the proposed approach produce more aggressive signal than other controller during step change (see regions A and C of Fig. 17). At the point of disturbance, a control signal similar to that of PI and more aggressive to that of Smith predictor is produced by the setpoint weighting controller (see regions B and D of Fig. 17).

5) WH-HIL SIMULATION OF FIRST ORDER PLANT WITH REAL-TIME VARIABLE DELAY

To verify the viability of the proposed method for application in real-time wireless environment, an experiment is conducted using WH-HIL simulator developed in our laboratory as explained in Section III-B The WH-HIL simulator enables for real-time delay to be used for online simulations. It is expected that the design should work in real-life as it works with the simulator.

Fig. 18 shows the response of the plant to the real-time delay. Within the figure, the controller action are also shown Compared to that of PI controller, the response of the proposed method with real-time variable delay performed remarkably better. It is clearly seen from Fig. 18 that, the proposed method has ability to track changing setpoint without overshoots under real wireless communication conditions.

6) SUMMARY

From both the pure simulation and WHILS results presented, the following can be observed on the performance of the compared controllers:

- For all four plants considered, the setpoint tracking ability of the proposed approach outperformed both the PI and Smith predictor controllers in terms of rise time, settling time and overshoot.
- The proposed approach recovers from the effect of disturbance with minimal overshoot for all the plants considered.
- The proposed approach is robust to model parameter mismatch and variation in network delay
- The proposed approach has enabled the use of high stable gain on the traditional PI structure while maintianing stability and improving the performance of the closed loop.

VI. CONCLUSION

This work has presented the adoption of setpoint weighting control strategy for WHNCS. It has been shown that through variation of the setpoint, the gain range of PID can be extended to permit its usage conveniently in delayed environments. Thus, this method can be used even in the presence of model mismatch and stochastic delay and noise. The structure of the setpoint weighing can be easily deployed in a plug and play manner without having to change the original process loop set up. This is because it lies outside the closed loop. Future work will focus on proposing an easy way to design the gain $G_r(s)$ and implementation on an actual plant. Adaptation of the technique to process and delay variation will also be attempted.

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