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System States and Disturbance Estimation Using Adaptive Integral Terminal Sliding Mode Observer for U-Tube Steam Generator Model in Nuclear Power Plant

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ABSTRACT

Designing water level control for a U-tube steam generator (UTSG) in nuclear power plants (NPP) remains a challenge, especially at low power demand due to unreliable steam flow measurements. This paper addresses the steam flow rate as a disturbance to the plant, treating it as an inaccessible variable. To estimate the disturbance (steam flow rate) and system states, an adaptive integral terminal sliding mode observer is developed. These estimated values can be utilized in the water level control design to enhance the reliability and performance of the control system. An adaptive observer is developed such that the augmented systems formed by the error dynamical systems and the designed adaptive laws are globally uniformly ultimately bounded. This technique is applied to a non-minimum phase system model representing the UTSG system to improve water level control and prevent possible serious consequences. Various disturbance signal forms with different amplitudes are simulated to demonstrate the reliability of the proposed technique. The simulation results show the effectiveness of the method proposed in this paper.

1 | Introduction

Nuclear power plant (NPP) uses the process of nuclear fission for the sake of producing a thermal energy to heat water in order to generate steam. Then, the produced steam is used to spin the steam turbine to generate electricity. According to the UK government, nearly 16% of Britain's electricity is generated by nuclear power from 13 reactors, and it is expected to be 25% by 2025 [1]. One of the major components in NPP is pressurized-water reactor (PWR) that consists of a number of equivalent inverted vertical U-tubes. The heat energy released by the fission reaction is transferred by pressurized water through tube wall to steam generator (SG) before exiting at the bottom of the U-tube steam generator (UTSG) in a closed loop [2–4]. Design a robust water level control system for SG is a challenging problem due to inherent high nonlinearity, nonminimum characteristics caused by the so called "swell and shrink" effect (this phenomenon is explained in [3]), and unreliable steam flow measurements at low power demand (less than 20% of the nominal power) [2, 3, 5]. It is reported in [6] that a quarter of all PWR shutdowns were as a result of poor water level control system of UTSG in particular during start-up phase and low power load. Therefore, developing a robust water level controller is required to maintain the water level of UTSG within a specific range to avoid any serious consequences such as damaging the turbine blades. The latter could happen by a wet steam if the water level is increased or reactor shutdowns due to the poor cooling system if the water level dropped lower than a preset value.

Many researchers have devoted themselves for developing water level controllers for SG. In early work, Irving et al. in [7] developed a model reference adaptive proportional integral derivative (PID) level controller based on a linear parameter varying model (LPV) for SG. The LPV model of SG developed by Irving et al. is used widely in the literature to design water level controllers such as in [8, 9]. PI controller is designed in [8] using Irving model to offset the inverse response behaviour of the SG due to swell and shrink effects. The Irving model is used by Choi et al. in [9] to develop a PI-like local stabilizing water level controller. However, the water level cannot be maintained properly with PI controllers in particular at low power operation [10]. Many advanced control approaches have been applied in the water level control of SG. Multi-model based robust model predictive control (MPC) algorithm for water level control of the SG is presented in [11] to deal with model uncertainties. MPC techniques have been applied in [3] to develop a framework for addressing the various issues in the SG level control problem. In [12], a switching control to LPV systems has been developed based on multiple parameter-dependent Lyapunov functions to control the water level of SG. Intelligent control systems based on neuro-network and fuzzy logic have been presented in many works (see, e.g., [13, 14]). Sliding-mode control (SMC) techniques have been used in [2] based on gain scheduling approach to design a controller applicable in the entire operating regime of the UTSG. An adaptive SMC is developed in [4] based on a nonlinear model for the level control problem of UTSG. In spite of aforementioned promising works and others, still the problem of designing effective water level controllers for SG is a huge challenge, and manual operations are still needed due to unreliability of steam flow measurements, in particular at low power operation [2–4, 10].

It is well-known that sliding-mode control techniques exhibit high robustness and insensitivity to the so-called matched uncertainty (uncertainties that lie in the range space of the input channel). However, it is sensitive to unmatched disturbances (uncertainties do not generally enter into the system via input channel). In addition, the discontinuity of the control law may result in chattering phenomenon that might limit the practicability of the technique in some systems such as mechanical systems [15] (and references therein). Moreover, conditions such as so-called matching condition and minimum phase condition (invariant zeroes of the system must be in the left half plane) are necessary and sufficient conditions for designing conventional sliding mode observers (SMO) [16–22]. There are a few attempts to relax these conditions either by using high-order sliding mode differentiator to build a new system that satisfies the matching condition [23–25], or by using multiple SMOs in cascade [26], or by employing high gain observers [27]. However, the systems still need to satisfy the minimum phase condition which might not be applicable for some of practical systems such as the application in this paper. Compared with the conventional SMC, the terminal SMC (TSMC) is finite-time convergent for the systems on the ideal sliding motion (The term “terminal” refers to the finite-time reachable equilibrium). However, a singularity and chattering issues are still major limitations in the TSMC systems. Therefore, integral action has been used in designing sliding surfaces to reduce the effect of chattering problem, and to avoid the singularity problem in the control law design of the TSMC systems [28–30].

Various control strategies have been developed to address the problem of disturbance estimation, such as super twisting disturbance observer-based sliding mode control and adaptive control techniques [31–38]. These methods, however, require disturbances to be bounded and/or assume that all system states are available and measurable, as discussed in [31, 33]. An extended state observer designed in [39] estimates disturbances but also requires the upper bound of the total disturbances. Adaptive extended state disturbance observer-based terminal sliding mode control is proposed in [40], though it may suffer from singularity issues. This issue is addressed in [41], but the assumption remains that system states are measurable.

Much fewer works considered estimation techniques in water level control design to estimate unknown system states and/or unknown time varying parameters to overcome the difficulty of incorrect steam flow measurements especially at low power operation. In [42], an adaptive estimator is proposed to estimate unmeasured states and unknown parameters in order to design the adaptive dynamic sliding mode controller for controlling the UTSG water level. Na and No in [5] designed an adaptive observer based controller to estimate parameters and state variables of the system simultaneously. However, perturbation signals were added to the inputs in order to explore all the dynamics of the SG to be able to estimate the unknown time varying parameters accurately which might not be possible in practice. On the same issue, Na in [43] has developed water level controller for UTSG by using the least square method to estimate flow errors, in particular at low power demand. In [44], the authors proposed a sliding mode observer for a reactor model without considering parametric uncertainties, which is designed using the Lyapunov approach. Subsequently, they developed an adaptive observer-based adaptive sliding mode controller to account for parametric uncertainties in the reactor model, updating the parameters using the Lyapunov approach. A high-gain observer was designed in [45] to simultaneously estimate the unmeasured average fuel temperature and unknown lumped disturbances. In [46], A variable structure control-based active disturbance rejection control approach, where no sliding motion occurs, is developed for an unstable non-minimum phase process with delay and for a UTSG level control system. However, the studies in [45–47] assume that the lumped disturbances and their first derivatives are bounded.

In this paper, due to unreliability steam flow measurements at low power load [2–5, 10, 43], the steam flow rate is assumed to be an unmeasurable state and it is considered as a disturbance to the plant [2, 3, 48]. Then, an adaptive integral terminal sliding mode observer (AITSMO) is developed to estimate disturbance (steam flow rate), and system states simultaneously. It is not required that the bound on disturbance is known, but the rate of change of unknown disturbance needs to be known. Sliding mode techniques and adaptive techniques are employed together to estimate system states in the presence of disturbances. Integral terminal sliding surface is proposed to reduce the effect of chattering problem. Furthermore, the minimum phase condition is relaxed to only requiring detectability. Sufficient conditions are developed such that the augmented systems formed by the error dynamical system and the designed adaptive laws, are globally uniformly ultimately bounded. *This method is developed to contribute positively in the well-known problem which is water level control design for UTSG in NPP, and simulation results for this application are presented to demonstrate the effectiveness of the developed results.*

The main contributions and advantages of the proposed observer in this paper can be summarised as follows:

- An adaptive integral terminal sliding mode observer (AITSMO) is proposed to estimate system states and disturbances simultaneously which does not require that the considered system satisfy the minimum phase condition.
- No non-singularity conditions are needed for the distribution matrix of the disturbance W.
- The matching condition is relaxed. It is only required that the matrices (A, B, W, C) to be known and constant satisfying $m \leq q \leq p \leq n$ where m, q, p and n are the dimensions of system input, disturbance, and system output, respectively, and n is the order of the system.

It should be noted that the observer to be proposed in the paper has a practical convergence. That means the estimation error is bounded instead of the convergence to zero.

The remainder of this paper is organized as follows: Section 2 provides a brief overview of the steam generator used in PWR. Section 3 describes the system and presents the preliminaries. The adaptive integral terminal SMO is proposed in Section 4. Section 5 develops the stability analysis of the error dynamical systems. The simulation results and the conclusion are presented in Sections 6 and 7, respectively.

2 | Brief Overview of Steam Generator Used in PWR

PWR is a popular method of generating electrical power using nuclear fission technology. An overview of a typical nuclear-powered PWR is given in Figure 1. PWR system constitutes of two circuits called a primary and secondary circuits. The primary circuit is responsible for generating the steam while the secondary circuit is responsible for power conversion using the generated steam. In this work, we are focusing on the primary circuit, that is, the steam supply system. Radiation safety critical aspects of the PWR system are actually part of the primary circuit. The nuclear reactor and associated cooling system together with the steam generator constitute the steam supply system. In a nuclear fission system, thermal energy is generated by the fission reaction of the nuclear fuel. Light water acts as the primary coolant for the PWR reactor. When the coolant is passed to the core at high pressure, the water gets heated by the thermal energy generated from the nuclear fission reaction. This high temperature pressurised water is then passed to the steam generator to generate the necessary steam for the turbine to produce electrical power through the generator. High pressure prevents the water to be vaporized at the reactor core, hence, the reactor is called PWR.

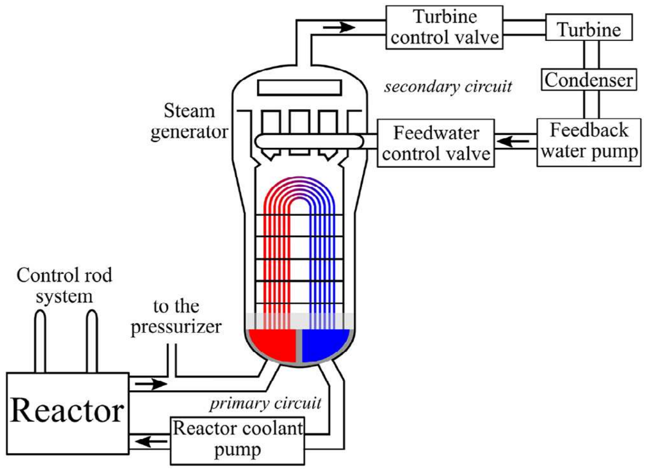


FIGURE 1 | Layout of a pressurized water reactor (PWR).

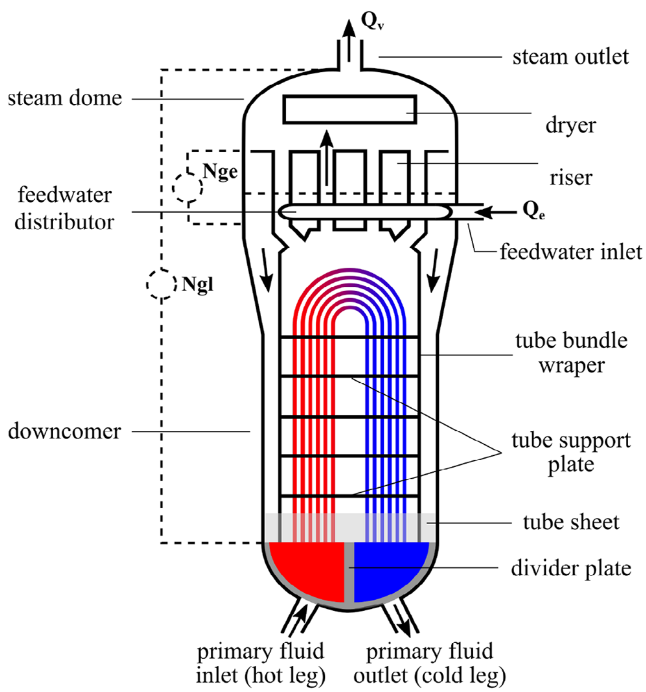


FIGURE 2 | Schematic of a steam generator, where Nge is narrow range steam generator water level, and Ngl is wide range steam generator water level.

Steam generator acts as the heat transfer medium between the primary and the secondary circuit of the PWR system. High pressure and heated primary coolant exchange the heat with low pressure secondary side coolant at the steam generator. This is typically done by vertical tubular evaporators which work under natural circulation. The evaporator has vertical U-shapes which gives rise to the name of U-tube steam generator. Overview of the UTSG is given in Figure 2. In this system, heated and pressurized water which is the primary coolant enters the tube at the primary side and then moves upward at the beginning and downwards before leaving the UTSG. In this process heat is transferred to the secondary side coolant through the tube wall. Since the secondary coolant is at lower pressure, heat will generate steam from the water which will in turn drive the turbine for electrical power generation. After driving the turbine, the remaining steam is condensed and used again as the feed water to the steam generator. So, by controlling the feed water flow rate through the inlet valve, the water level inside the UTSG can be regulated to ensure safe and reliable operation of nuclear power plant. This problem is known as the water level control problem in the nuclear power plant control literature.

Water level control problem of UTSG is inherently very challenging due to the following reasons:

i. Open-Loop Dynamics: The dynamics of UTSG in openloop is unstable.
ii. Nonlinear Behaviour: Dynamic behaviour of the plant has a strong relationship with the operating power which makes the system dynamics highly nonlinear. Moreover, swell and shrink effect, which is caused by the variations in the vapor–liquid ratio, is also very prominent at low power level which limits the control system's ability to regulate the power
iii. The available feed water is limited which results in constrained control action.

Much more discussion on water level control problem for UTSG can be found in [2–4, 49]. Therefore, in order to improve the water level control design in particular at low power demand where sensors become unreliable, estimation of system states and disturbance is required.

The next section will focus on designing observer for general form of systems that typical system of UTSG developed in [2]. Then, the result will be applied to UTSG system to estimate system states and disturbance where the system parameters have been taken at low power demand, particularly, the system is considered as nonminimum phase system.

3 | System Description and Preliminaries

Consider a dynamic system as follows:

$$\dot{x} = \bar{A}x(t) + \bar{B}u + \bar{W}\theta(t) \tag{1}$$

$$y = \bar{C}x \tag{2}$$

where $x \in R^n$, $u \in U \in R^m$ (U is the admissible control set), and $y \in R^p$ are the state variables, inputs, and outputs of the system, respectively. The $\theta(t)$ is a disturbance signal, and $\bar{W} \in R^q$. The matrices $(\bar{A}, \bar{B}, \bar{W}, \bar{C})$ are known and constant with appropriate dimensions where $m \le q \le p \le n$, and $\bar{C}$ is full row rank.

Since the C is full row rank, there exists nonsingular matrices T_c such that

$$A = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} := T_c \bar{A} T_c^{-1}, \qquad B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} := T_c \bar{B}, \tag{3}$$

$$W = \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} := T_c \bar{W}, \qquad C = \begin{bmatrix} 0 & I_p \end{bmatrix} := \bar{C} T_c^{-1} \tag{4}$$

where $A_1 \in R^{(n-p)\times(n-p)}$, $B_1 \in R^{(n-p)\times m}$ and $B_2 \in R^{p\times m}$. Thus in the new coordinates $(x_1 \;\; x_2) = T_c x$, the system can be written as

$$\dot{x}_1(t) = A_1 x_1(t) + A_2 x_2(t) + B_1 u(t) + W_1 \theta(t) \tag{5}$$

$$\dot{x}_2(t) = A_3 x_1(t) + A_4 x_2(t) + B_2 u(t) + W_2 \theta(t) \tag{6}$$

$$y(t) = x_2(t) \tag{7}$$

Assumption 1. The disturbances $\theta(t)$ satisfies

$$|\dot{\theta}(t)| \le \mu \tag{8}$$

where μ is known constant and $\mu > 0$.

Remark 1. Assumption 1 implies that there is a limitation to the unknown disturbance $\theta(t)$, which requires that the change rate of disturbance $\theta(t)$ is bounded. This can be satisfied in most cases in reality. It should be noted that in this paper, it is not required that the unknown disturbance $\theta(t)$ is bounded. An appropriate adaptive law is to be designed to identify it. Similar assumptions can be found in [50, 51]. Unlike the works in [52, 53] where both the disturbances and its time derivative are bounded or the time derivative of the disturbances dies away gradually or even equals to zero as in [54–56].

Assumption 2. The matrix pair (A, C) in (3) and (4) is detectable.

From Definition 3.5 and Theorem 3.4 in [57], the system is detectable if the matrix:

$$\text{rank} \begin{bmatrix} (\lambda_i I - A) \\ C \end{bmatrix} = n,$$

has full-column rank n for all eigenvalues $\lambda_i \in R \ge 0$.

Under Assumption 2, there exist matrix L, such that $A - LC$ is stable, and thus for any $Q > 0$ the Lyapunov equation

$$(A - LC)^T P + P(A - LC) = -Q \tag{9}$$

has an unique solution $P > 0$.

For further analysis, introduce partitions of P and Q which are conformable with the decomposition in (5)–(7) as follows.

$$P = \begin{bmatrix} P_1 & P_2 \\ P_2^T & P_3 \end{bmatrix}, \qquad Q = \begin{bmatrix} Q_1 & Q_2 \\ Q_3 & Q_4 \end{bmatrix} \tag{10}$$

Here, $P_1 \in R^{(n-p)\times(n-p)}$ and $Q_1 \in R^{(n-p)\times(n-p)}$. Then, from $P > 0$ and $Q > 0$, it follows that $P_1 > 0$, $P_3 > 0$, $Q_1 > 0$ and $Q_3 > 0$. The following result is required for further analysis.

Lemma 1. *The matrix $A_1 + KA_3$ is Hurwitz stable, where $K = P_1^{-1}P_2$, and P_1 & P_2 are defined in (10) and A_1 and A_3 are defined in (3), if the Lyapunov equation (9) is satisfied.*

Proof. See Lemma 2.1 in [58]. □

4 | Adaptive Integral Terminal Sliding Mode Observer Design

In this section, adaptive integral terminal SMO (AITSMO) is proposed to estimate system states and disturbance.

Consider the system in (5)–(7). Introduce a linear coordinate transformation

$$z = \underbrace{\begin{bmatrix} I_{n-p} & K \\ 0 & I_p \end{bmatrix}}_{T_c} x \tag{11}$$

where K is defined in Lemma 1. In the new coordinate system z,

$$\begin{aligned} \dot{z}_1 &= (A_1 + KA_3)z_1 + (A_2 - A_1K + K(A_4 - A_3K))z_2 \\ &\quad + B_1u + KB_2u + W_1\theta(t) + KW_2\theta(t) \end{aligned} \tag{12}$$

$$\dot{z}_2 = A_3z_1 + (A_4 - A_3K)z_2 + B_2u + W_2\theta(t) \tag{13}$$

$$y = z_2 \tag{14}$$

For system (12)–(14), consider a dynamical system

$$\begin{aligned} \dot{\hat{z}}_1 &= (A_1 + KA_3)\hat{z}_1 + (A_2 - A_1K + K(A_4 - A_3K))y + B_1u \\ &\quad + KB_2u + W_1\hat{\theta}(t) + KW_2\hat{\theta}(t) + H(y - \hat{y}) + \kappa\phi(\cdot) + \kappa I\eta \end{aligned} \tag{15}$$

$$\dot{\hat{z}}_2 = A_3\hat{z}_1 + (A_4 - A_3K)y + B_2u + W_2\hat{\theta}(t) + \phi(\cdot) + I\eta \tag{16}$$

$$\hat{y} = \hat{z}_2 \tag{17}$$

where κ is a matrix which has same dimensions with the matrix K in Lemma 1, and $I \in R^p$ is identity matrix. η is a constant to be defined later.

$$\phi(\cdot) = \beta(y - \hat{y})^r \mathrm{sgn}(y - \hat{y}) \tag{18}$$

and $\beta > 0$, and $0 < r < 1$ with adaptive laws

$$\dot{\Gamma} = -\dot{y} - \phi(\cdot) + \alpha(y - \hat{y}) - I\eta \tag{19}$$

$$\hat{\theta}(t) = K[\Gamma + \hat{y}] \tag{20}$$

As a direct result of Lemma 1 under Assumption 2, there exists a matrix κ such that $(\tilde{A}_1 + \kappa A_3)$ with $\tilde{A}_1 = A_1 + KA_3$ is the Hurwitz matrix, where K is defined in Lemma 1. Thus for any $\tilde{Q}_1 > 0$, the Lyapunov equation

$$(\tilde{A}_1 - \kappa A_3)^T\tilde{P}_1 + \tilde{P}_1(\tilde{A}_1 - \kappa A_3) = -\tilde{Q}_1 \tag{21}$$

has an unique solution $\tilde{P}_1 > 0$, and α need to be selected such that

$$||(\alpha - A_3\kappa)|| = 0 \tag{22}$$

The associate adaptive laws are employed to estimate the disturbance $\theta(t)$ which do not require a priori disturbance information. Studies on disturbances estimation to enhance control design schemes have received great attention (see, e.g.,[51, 59], and references therein).

Remark 2. It can be seen that the output signal from (19) is based mainly on the accessible/measurable signals from the system and the observer y and $\hat{y}$. It should be noted that the system (19) also needs the time derivative of y to implement the observer if $\dot{y}$ is measurable, which is an assumption that has been employed by many authors (see, e.g., [60, 61]). Furthermore, the exact differentiator proposed in [62] can be used to estimate the time derivative of the system output in finite time if $\dot{y}$ is not available.

If the state estimation errors are defined as $e_1 = z_1 - \hat{z}_1, e_y = z_2 - \hat{z}_2$ ($e_y = y - \hat{y}$), and $e_\theta = \theta(t) - \hat{\theta}(t)$ then from (12)–(14) and (15)–(17), the error dynamics can be described by

$$\dot{e}_1 = (A_1 + KA_3)e_1 + (W_1 + KW_2)e_\theta - He_y - \kappa\phi(\cdot) - \kappa I\eta \tag{23}$$

$$\dot{e}_y = A_3e_1 + W_2e_\theta - \phi(\cdot) - I\eta \tag{24}$$

From (19) and (20)

$$\begin{aligned} \dot{e}_\theta &= \dot{\theta}(t) - \dot{\hat{\theta}}(t) = \dot{\theta}(t) - K[\dot{\Gamma} + \dot{\hat{y}}] \\ &= \dot{\theta}(t) - K[(-\dot{y} - \phi(\cdot) + \alpha(y - \hat{y}) - I\eta) + \dot{\hat{y}}] \\ &= \dot{\theta}(t) + K\dot{y} + K\phi(\cdot) - K\alpha(y - \hat{y}) + KI\eta - K\dot{\hat{y}} \\ &= \dot{\theta}(t) + K\dot{e}_y + K\phi(\cdot) - K\alpha e_y + KI\eta \\ &= \dot{\theta}(t) + \left\{K[A_3e_1 + W_2e_\theta - \phi(\cdot) - I\eta]\right\} + K\phi(\cdot) - K\alpha e_y + KI\eta \\ &= \dot{\theta}(t) + KA_3e_1 + KW_2e_\theta - K\alpha e_y \end{aligned} \tag{25}$$

In (23), and for convenience, let $\tilde{A}_1 = A_1 + KA_3$. Then,

$$\dot{e}_1 = \tilde{A}_1e_1 + (W_1 + KW_2)e_\theta - He_y - \kappa\phi(\cdot) - \kappa I\eta \tag{26}$$

$$\dot{e}_y = A_3e_1 + W_2e_\theta - \phi(\cdot) - I\eta \tag{27}$$

Now, introducing a new coordinate transformation $\mathrm{col}(e_1, e_y) \rightarrow \mathrm{col}(e_s, e_y)$ with $e_s = e_1 - \kappa e_y$ (i.e., $e_1 = e_s + \kappa e_y$). Then, the error system in (26) and (27) becomes

$$\begin{aligned} \dot{e}_s &= \left\{\tilde{A}_1e_1 + (W_1 + KW_2)e_\theta - He_y - \kappa\phi(\cdot) - \kappa I\eta\right\} \\ &\quad -\kappa\left\{A_3e_1 + W_2e_\theta - \phi(\cdot) - I\eta\right\} \\ &= \left\{\tilde{A}_1(e_s + \kappa e_y) + (W_1 + KW_2)e_\theta - He_y - \kappa\phi(\cdot) - \kappa I\eta\right\} \\ &\quad -\kappa\left\{A_3(e_s + \kappa e_y) + W_2e_\theta - \phi(\cdot) - I\eta\right\} \\ &= (\tilde{A}_1 - \kappa A_3)e_s - [H - (\tilde{A}_1 - \kappa A_3)\kappa]e_y + (W_1 + (K - \kappa)W_2)e_\theta \end{aligned} \tag{28}$$

With the selection of $H = (\tilde{A}_1 - \kappa A_3)\kappa$, the system (28) becomes

$$\dot{e}_s = (\tilde{A}_1 - \kappa A_3)e_s + (W_1 + (K - \kappa)W_2)e_\theta \tag{29}$$

System in (27) under new coordinate transformation becomes

$$\begin{aligned}\dot{e}_y &= A_3 e_1 + W_2 e_\theta - \phi(\cdot) - I\eta \\ &= A_3(e_s + \kappa e_y) + W_2 e_\theta - \phi(\cdot) - I\eta \\ &= A_3 e_s + A_3\kappa e_y + W_2 e_\theta - \phi(\cdot) - I\eta \end{aligned} \tag{30}$$

System in (25) under new coordinate transformation becomes

$$\begin{aligned}\dot{e}_\theta &= \dot{\theta}(t) + KA_3 e_1 + KW_2 e_\theta - K\alpha e_y \\ &= \dot{\theta}(t) + KA_3(e_s + \kappa e_y) + KW_2 e_\theta - K\alpha e_y \\ &= \dot{\theta}(t) + KA_3 e_s + KA_3\kappa e_y + KW_2 e_\theta - K\alpha e_y \\ &= \dot{\theta}(t) + KA_3 e_s - K(\alpha - A_3\kappa)e_y + KW_2 e_\theta \end{aligned} \tag{31}$$

Select α such that $||(\alpha - A_3\kappa)|| = 0$, the system (31) becomes

$$\dot{e}_\theta = \dot{\theta}(t) + KA_3 e_s + KW_2 e_\theta \tag{32}$$

So system (23)–(25) becomes

$$\dot{e}_s = (\tilde{A}_1 - \kappa A_3)e_s + (W_1 + (K - \kappa)W_2)e_\theta \tag{33}$$

$$\dot{e}_y = A_3 e_s + A_3\kappa e_y + W_2 e_\theta - \phi(\cdot) - I\eta \tag{34}$$

$$\dot{e}_\theta = \dot{\theta}(t) + KA_3 e_s + KW_2 e_\theta \tag{35}$$

Remark 3. It is well-known that sliding mode is a reduced order system. In this paper, the sliding motion governs by the error dynamical system (33) with adaptive laws (19) and (20) while the error dynamical system (34) does not affect the sliding motion, which makes the obtained results less conservative.

5 | Stability of the Error Dynamical Systems

Theorem 1. *Under Assumptions 1–2, the error dynamical system (33) with adaptive laws (19)–(20) are globally uniformly ultimately bounded if the matrix $R^T + R$ is positive definite, where*

$$R = \begin{bmatrix} R_1 & R_2 \\ R_3 & R_4 \end{bmatrix} \tag{36}$$

and

$$\begin{aligned} R_1 &= \lambda_{\min}(\tilde{Q}_1) \\ R_2 &= R_3 = ||(W_1 + (K - \kappa)W_2)||||\tilde{P}_1|| + ||KA_3|| \\ R_4 &= 2||KW_2|| \end{aligned} \tag{37}$$

Proof. For systems (33) and (34), consider the candidate Lyapunov function

$$V = e_s^T \tilde{P}_1 e_s + e_\theta^T e_\theta \tag{38}$$

The time derivative of $V(\cdot)$ along the trajectories of system (33) and (34) is given by

$$\begin{aligned}\dot{V} &= \dot{e}_s^T \tilde{P}_1 e_s + e_s^T \tilde{P}_1 \dot{e}_s + \dot{e}_\theta^T e_\theta + e_\theta^T \dot{e}_\theta \\ &= \left\{[(\tilde{A}_1 - \kappa A_3)e_s + (W_1 + (K - \kappa)W_2)e_\theta]^T \tilde{P}_1 e_s \right. \\ &\quad \left. + e_s^T \tilde{P}_1[(\tilde{A}_1 - \kappa A_3)e_s + (W_1 + (K - \kappa)W_2)e_\theta]\right\} \\ &\quad + \left\{[KA_3 e_s + KW_2 e_\theta + \dot{\theta}(t)]^T e_\theta + e_\theta^T[KA_3 e_s + KW_2 e_\theta + \dot{\theta}(t)]\right\}\end{aligned}$$

From (21),

$$\begin{aligned}\dot{V} &\le -e_s \tilde{Q}_1 e_s + 2||(W_1 + (K - \kappa)W_2)||\, ||\tilde{P}_1||||e_s||\, ||e_\theta|| \\ &\quad + 2||KA_3||\, ||e_s||\, ||e_\theta|| + 2||KW_2||\, ||e_\theta||^2 + 2\mu||e_\theta|| \\ &\le -\lambda_{\min}(\tilde{Q}_1)||e_s||^2 + 2||(W_1 + (K - \kappa)W_2)||\, ||\tilde{P}_1||\, ||e_s||\, ||e_\theta|| \\ &\quad + 2||KA_3||\, ||e_s||\, ||e_\theta|| + 2||KW_2||\, ||e_\theta||^2 + 2\mu||e_\theta|| \\ &\le -\Big\{\left\{\lambda_{\min}(\tilde{Q}_1)\right\}||e_s||^2 - \left\{2(||(W_1 + (K - \kappa)W_2)||\, ||\tilde{P}_1|| \right. \\ &\quad \left. + ||KA_3||)\right\}||e_s||\, ||e_\theta|| - 2||KW_2||\, ||e_\theta||^2 - 2\mu\, ||e_\theta||\Big\} \\ &\le -\Big\{\left\{\lambda_{\min}(\tilde{Q}_1)\right\}||e_s||^2 - \left\{2(||(W_1 + (K - \kappa)W_2)||\, ||\tilde{P}_1|| \right. \\ &\quad \left. + ||KA_3||)\right\}||e_s||\, ||e_\theta|| - \left\{2||KW_2||\right\}||e_\theta||^2 - 2\mu||e_\theta||\Big\}\end{aligned} \tag{39}$$

Then, from the definition of the matrix R in Theorem 1 and the inequality above, it follows that

$$\begin{aligned}\dot{V} &\le -\frac{1}{2}X^T[R^T + R]X + \rho||X|| \\ &\le -\left\{\frac{1}{2}\lambda_{\min}(R^T + R) - \rho\right\}||X||\end{aligned} \tag{40}$$

where $\rho = 2\mu$ and $X = [||e_s||, ||e_\theta||]^T$. The constant ρ needs to be smaller than the value of $\frac{1}{2}\lambda_{\min}(R^T + R)$ to ensure that the right hand side of (40) is negative definite. From the definition of Lyapunov function in (38), it is straightforward to see that

$$\lambda_{\min}(\tilde{P}_1)||X||^2 \le V \le \lambda_{\max}(\tilde{P}_1)||X||^2 \tag{41}$$

□

Remark 4. From Theorem 1, it follows that e_s and e_θ are bounded and thus there exist constants $\beta_1 > 0$ and $\beta_2 > 0$ such that

$$||e_s|| \le \beta_1, \quad \text{and} \quad ||e_\theta|| \le \beta_2 \tag{42}$$

where β_1 can be estimated using the approach given in [58].

In this paper, the integral terminal sliding surface is considered as

$$S = e_y - \int_0^t (\alpha e_y - \beta(e_y)^r \mathrm{sgn}(e_y))d\tau \tag{43}$$

where α is defined in (31), and β & r are defined in (18).

Theorem 2. *Under Assumptions 1 and 2, system (33) and (34) is driven to the sliding surface (43) in finite time and remains on it thereafter if*

$$\eta \ge (||A_3||\, ||\beta_1|| + ||W_2||\, ||\beta_2||) \tag{44}$$

where A_3 and W_2 are given in (3) and (4).

Proof. Let the candidate Lyapunov function

$$V = \frac{1}{2}S^2 \tag{45}$$

The time derivative of $V(\cdot)$ in (45) is given by

$$\dot{V} = S\dot{S}$$

$$\begin{aligned}\dot{V} &= S[\dot{e}_y - \alpha e_y + \beta|e_y|^r \mathrm{sgn}(e_y)] \\ &= S\{[A_3 e_s + A_3\kappa e_y + W_2 e_\theta - \phi(\cdot) - I\eta] - \alpha e_y + \beta(e_y)^r \mathrm{sgn}(e_y)\} \\ &= S\{A_3 e_s - (\alpha - A_3\kappa)e_y + W_2 e_\theta - \phi(\cdot) + \beta(e_y)^r \mathrm{sgn}(e_y) - I\eta\}\end{aligned}$$

where α is defined in (31), and from (18),

$$\begin{aligned}\dot{V} &\le ||S||\{||A_3||\,||e_s|| + ||W_2||\,||e_\theta|| - ||I\eta||\} \\ &\le ||S||\{||A_3||\,||\beta_1|| + ||W_2||\,||\beta_2|| - ||I\eta||\} \\ &\le -||S||\{||I\eta|| - (||A_3||\,||\beta_1|| + ||W_2||\,||\beta_2||)\}\end{aligned} \tag{46}$$

By choosing η as in Theorem 2, it can be seen clearly that the inequality (46) becomes

$$S\dot{S} \le -\eta||S|| \tag{47}$$

This shows that the reachability condition is satisfied. After sliding motion occurs, $e_y = \dot{e}_y = 0$, and $e_s = e_1$. Thus

$$\lim_{t\to\infty} e_s = 0, \qquad \lim_{t\to\infty} e_1 = 0 \tag{48}$$

□

Remark 5. From sliding mode theory, Theorems 1 and 2 show that system (15)–(17) is an approximate observer for the system (12)–(14) and the estimation error enters a bounded domain in finite time.

Remark 6. From Theorem 1, it is observed that the matrix R depends on $W_1, W_2, K, \kappa, \tilde{Q}_1$ and $\tilde{P}_1$. The quantities W_1 and W_2 are determined by the given system, the terms K and κ can be found as explained in Lemma 1 and in the observer systems (15)–(22). While $\tilde{P}_1$ depends on $\tilde{Q}_1$ which can be designed freely. From (36), a sensible choice is one which minimises $\bar{\lambda}(\tilde{P}_1)/\underline{\lambda}(\tilde{Q}_1)$ which assists in making $R + R^T$ diagonally dominant and to have all positive diagonal elements. As argued by [63], an optimal choice is $\tilde{Q} = \varrho I_n$ for any positive scalar ϱ.

6 | Simulation Example

In this section, the developed method in this paper is applied to an UTSG system in NPPs where the input $u(t)$ represents the feed water flow rate, and the steam flow rate $\theta(t)$ is assumed an unmeasurable state at low power load where sensors become unreliable, and it is considered as a disturbance to the plant [2, 3, 48], and need to be estimated. The relationship between the feed water flow rate Q_e, and the steam flow rate Q_v presented in Figure 2 to the water level y (output), is given in details in [2, 64].

The matrices (A, B, C, W) in (1) and (2) are developed at low power demand (power level 5%) using the parameters values provided in Table 1 in [2]. It should be noted that matrix (A, W, C) of the system is a nonminimum phase system.

The system matrices (A, B, W, C) are

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -0.0207 & 0 & 0 \\ 0 & 0 & -0.0477 & 1 \\ 0 & 0 & -0.0033 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0.0580 \\ -0.1990 \\ 0.1810 \\ 0 \end{bmatrix}$$

$$W = \begin{bmatrix} -0.0580 \\ 0.1990 \\ 0 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 1 & 1 & 0 \end{bmatrix}$$

Choose $L = 1 \times 10^5[-0.0575 \;\; 0.5266 \;\; -4.0153 \;\; 3.4888]$ and $Q = 10I$. Then, the Lyapunov equation (9) has unique solution:

$$P = 1 \times 10^{10}\begin{bmatrix} 0.0002 & -0.0019 & 0.0147 & -0.0127 \\ -0.0019 & 0.0177 & -0.1342 & 0.1165 \\ 0.0147 & -0.1342 & 1.0231 & -0.8889 \\ -0.0127 & 0.1165 & -0.8889 & 0.7724 \end{bmatrix}$$

Therefore, under the transformation $x = (TT_c)^{-1}z$

$$T = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

and T_c is defined in (11) with $K = [-9.1252 \;\; 69.7247 \;\; -60.5995]$.

It should be noted that one of the eigenvalues of this system $\lambda = 0$. Then, from Assumption 2, the matrix pair (A, C) in (3) and (4) is detectable where the matrix:

$$\mathrm{rank}\begin{bmatrix} (\lambda_i I - A) \\ C \end{bmatrix} = 4 \tag{49}$$

Thus, the condition of detectability is satisfied.

The system can be described in z coordinates as follows.

$$\begin{aligned}\dot{z}_1 &= -9.1252z_1 - 82.8378z_{21} + 634.8z_{22} - 552.98z_{23} \\ &\quad - 19.0394u + 17.3877\theta(t)\end{aligned} \tag{50}$$

$$\dot{z}_{21} = z_1 + 9.0775z_{21} - 69.7247z_{22} + 60.6z_{23} + 0.181u \tag{51}$$

$$y_1 = z_{21} \tag{52}$$

$$\dot{z}_{22} = -0.0207z_{22} - 0.199u + 0.199\theta(t) \tag{53}$$

$$y_2 = z_{22} \tag{54}$$

$$\dot{z}_{23} = 0.058u - 0.058\theta(t) \tag{55}$$

$$y_3 = z_{23} \tag{56}$$

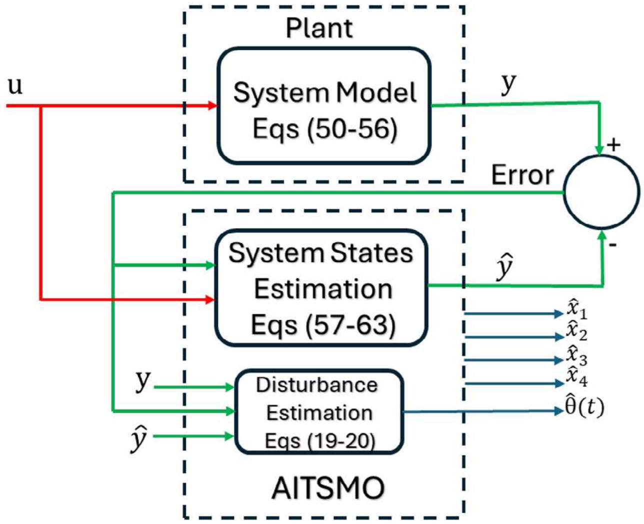


FIGURE 3 | Block diagram of system model and AITSMO.

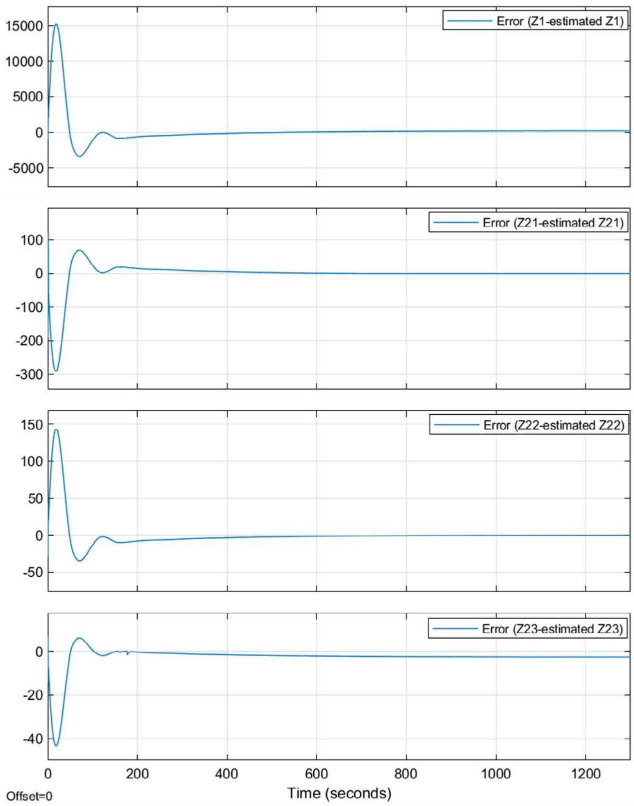
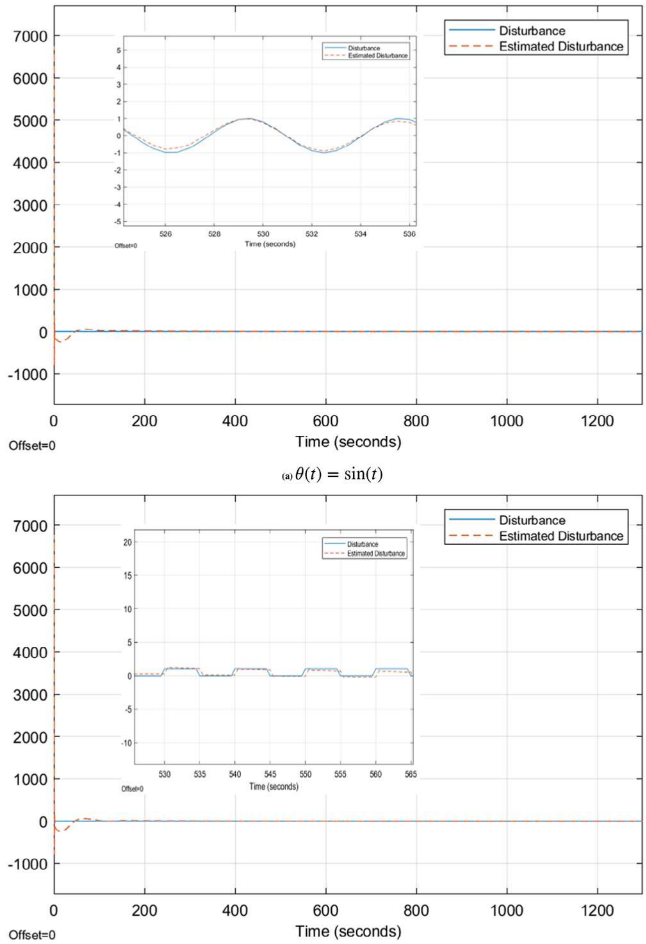


FIGURE 4 | The time response of system states error.

For simulation purposes, the controllers are chosen as $u = -k_u x$ where $k_u = 1 \times 10^5$ $[6.3390 \quad 0.1224 \quad 1.2070 \quad 3.7595]$. By direct computation, it follows that the matrix $R^T + R$ is positive definite. Thus, all the conditions of Theorem 1 are satisfied. Therefore the following dynamical system is an observer of the system (50)–(56).

$$\begin{aligned}\dot{\hat{z}}_1 &= -9.1252\hat{z}_1 - 82.8378y_1 + 634.8y_2 - 552.98y_3 \\ &\quad - 19.0394u + 17.3877\hat{\theta}(t) + H(y - \hat{y}) + \kappa\phi(\cdot) + \kappa I\eta \end{aligned} \tag{57}$$

$$\dot{\hat{z}}_{21} = \hat{z}_1 + 9.0775y_1 - 69.7247y_2 + 60.6y_3 + 0.181u + \phi_1(\cdot) + \eta \tag{58}$$



(a) $\theta(t) = \sin(t)$

(b) $\theta(t) =$ Pulse signal with amplitude $=1$

FIGURE 5 | The time response of disturbance and its estimated (a): $\theta(t) = \sin(t)$; (b): $\theta(t) =$ Pulse signal with amplitude $= 1$.

$$\hat{y}_1 = \hat{z}_{21} \tag{59}$$

$$\dot{\hat{z}}_{22} = -0.0207y_2 - 0.199u + 0.199\hat{\theta}(t) + \phi_2(\cdot) + \eta \tag{60}$$

$$y_2 = z_{22} \tag{61}$$

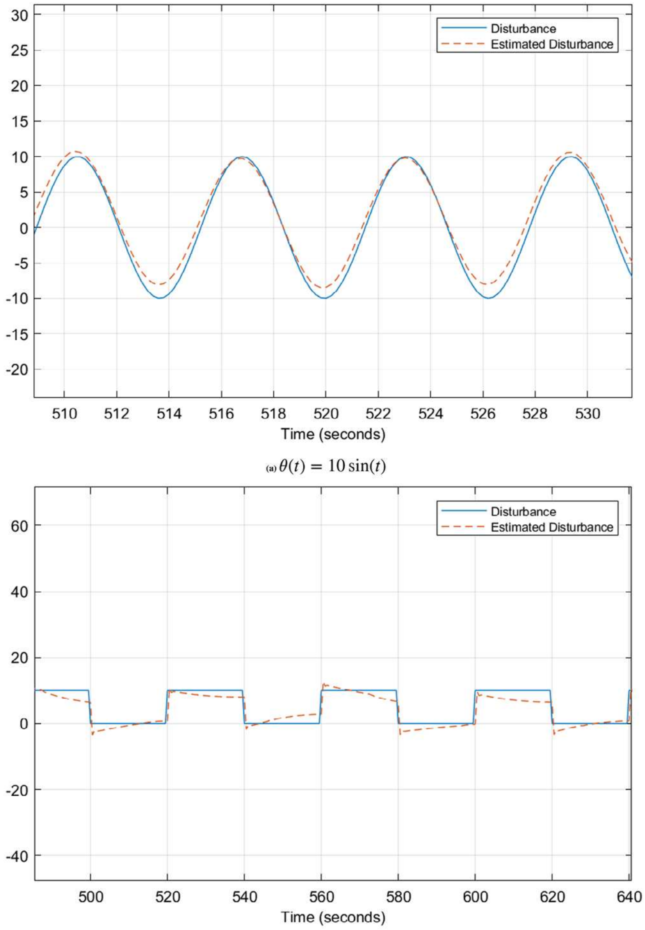
$$\dot{z}_{23} = 0.058u - 0.058\hat{\theta}(t) + \phi_3(\cdot) + \eta \tag{62}$$

$$y_3 = z_{23} \tag{63}$$

where

$$\begin{aligned}\phi_1(\cdot) &= \beta(y_1 - \hat{y}_1)^r \mathrm{sgn}(y_1 - \hat{y}_1) \\ \phi_2(\cdot) &= \beta(y_2 - \hat{y}_2)^r \mathrm{sgn}(y_2 - \hat{y}_2) \\ \phi_3(\cdot) &= \beta(y_3 - \hat{y}_3)^r \mathrm{sgn}(y_3 - \hat{y}_3)\end{aligned}$$

and the design parameters are chosen as $H = [-191.2524 \quad -286.8786 \quad 114.7515]$, $\kappa = [10 \quad 15 \quad -6]$, $\eta = 10$, $\beta = 8$, $r = 0.9$, $\tilde{Q}_1 = 8I$, $\tilde{P}_1 = 0.2091$, and $\hat{\theta}(t)$ can be found from adaptive laws



(a) $\theta(t) = 10\sin(t)$

(b) $\theta(t) =$ Pulse signal with amplitude $=10$

FIGURE 6 | The time response of disturbance and its estimated (a): $\theta(t) = 10\sin(t)$; (b): $\theta(t) =$ Pulse signal with amplitude $= 10$.

defined in (19) and (20), and

$$\alpha = \begin{bmatrix} 10 & 15 & -6 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Simulation results in Figure 4 shows the error system response that between system states and their estimation in presence of unbounded disturbances. Figures 5 and 6 show the estimation of both disturbance signals (sinusoidal signal and pulse signal) at different amplitudes: Case 1; $\theta(t) = \sin(t)$, and $\theta(t) =$ Pulse signal with amplitude $= 1$, Case 2; when their amplitudes are increased to 10. It can be seen in Figures 4–6 that the estimation error between the states of the system (50)–(56) and the states of the observer (57)–(63) converges to zero globally ultimately bounded. Figure 3 shows the block diagram of system model and AITSMO.

Remark 7. It is straightforward to see that the application considered in Section 6 is a nonminimum phase system. The results obtained in this paper show the effectiveness of using the advantages of the AITSMO technique to develop a robust observer to estimate system states and disturbances for a nonminimum phase system.

7 | Conclusion

An adaptive integral terminal sliding mode observer in the presence of disturbances has been proposed based on Lyapunov direct method. Although bound on disturbance is not required, the rate of change of the disturbance is bounded. The technique that used in this paper is combined of sliding mode techniques and adaptive techniques to guarantee the ultimate boundedness of the estimation error of the designed observer. In this paper, integral terminal sliding surface is considered to reduce the effect of chattering problem, and to avoid the singularity problem. The results have been applied on nonminimum phase system which is UTSG model with real physical parameters. Different disturbances signals with different amplitudes are used to show the reliability of the proposed technique. Simulation example has shown that the method is effective. As a future work, nonlinear models of U-tube steam generator need to be considered to develop a disturbance observer.

Author Contributions

Mokhtar Mohamed: conceptualization (lead), writing – original draft (lead), formal analysis (lead), methodology (lead), software (lead), review and editing (equal). **Iestyn Pierce:** funding acquisition (lead), project administration (lead), resources (lead), review and editing (equal). **Xing-Gang Yan:** formal analysis (equal), validation (lead), visualization (lead), review and editing (equal). **Hafiz Ahmed:** supervision (lead), visualization (equal), review and editing (equal).

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Conflicts of Interest

The authors confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. The authors declare no conflicts of interest to disclose.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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