Adaptive Variable Structure Observer for System States and Disturbances Estimation with Application to Building Climate Control System in a Smart Grid

Mohamed, Mokhtar; Ahmed, Hafiz; Yan, Xing-Gang ; Pierce, Iestyn

Energy Reports

DOI:
https://doi.org/10.1016/j.egyr.2022.10.100

E-pub ahead of print: 01/11/2022

Publisher's PDF, also known as Version of record

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):
Mohamed, M., Ahmed, H., Yan, X-G., & Pierce, I. (2022). Adaptive Variable Structure Observer for System States and Disturbances Estimation with Application to Building Climate Control System in a Smart Grid. *Energy Reports*, *8*(supplement 15), 549-556. https://doi.org/10.1016/j.egyr.2022.10.100

Available online at www.sciencedirect.com
ScienceDirect

Energy Reports 8 (2022) 549–556

www.elsevier.com/locate/egyr

2022 The 5th International Conference on Renewable Energy and Environment Engineering (REEE 2022), 24–26 August, 2022, Brest, France

Adaptive variable structure observer for system states and disturbances estimation with application to building climate control system in a smart grid

Mokhtar Mohamed[a,*], Hafiz Ahmed[a], Xing-Gang Yan[b], Iestyn Pierce[a]

[a] *School of Computer Science and Electronic Engineering, Bangor University, Bangor, LL57 1UT, UK*
[b] *School of Engineering, University of Kent, Canterbury, CT2 7NT, UK*

Received 5 October 2022; accepted 6 October 2022
Available online xxxx

Abstract

In order to reach the ambitious net-zero emission target by 2050, various technological solutions need to be developed to ensure efficient utilisation of energy. Commercial and residential buildings are a big source of greenhouse gas emissions, where efficient utilisation of energy can play a major role towards decarbonisation of the buildings sector. Heat pumps have recently emerged as an effective solution for space heating applications in buildings. Energy-efficient operation of heat pumps will make a significant contribution toward making buildings energy-efficient. In this context, heat pump control systems have a major role. Some of the existing literature on the heat pump control systems assume that various system states are available to measure. This may not always be true and/or economical to measure all the states. Moreover, the system is subject to various disturbances which cannot be directly measured. To reduce the number of sensors in heat pump control systems, an adaptive observer is developed in this paper to estimate inaccessible system states and disturbances simultaneously. An advantage of the proposed approach is that it does not require any bound on the disturbance itself, however, only assumes that the rate of change of disturbance is bounded. This is always the case in practice. In the developed method, adaptive control techniques and variable structure control techniques are combined to implement the proposed observer. In order to estimate the unknown disturbance, an augmented systems model is considered. Globally uniformly ultimately bounded property of the error dynamical systems is established by suitably designing the adaptive laws. The developed method is applied to a model of the heat dynamics of a house floor heating system connected to a ground source-based heat pump. Different disturbance signals formats and amplitudes are considered to show the effectiveness of the proposed technique. Simulation results are given to demonstrate the suitability of the proposed method.

Peer-review under responsibility of the scientific committee of the 5th International Conference on Renewable Energy and Environment Engineering, REEE, 2022.

Keywords: Variable structure observer; Adaptive control techniques; Adaptive disturbance observer; Globally uniformly ultimately bounded; Building climate control system in a smart grid

---

* Corresponding author.
E-mail address: m.mohamed@bangor.ac.uk (M. Mohamed).

https://doi.org/10.1016/j.egyr.2022.10.100

Peer-review under responsibility of the scientific committee of the 5th International Conference on Renewable Energy and Environment Engineering, REEE, 2022.

1. Introduction

In 2019, the United Kingdom (UK) government had made it legally-binding to achieve net-zero emission by 2050 [1]. To address this challenging target, significant alteration of the current energy mix will be needed, which is still heavily relying on the fossil fuels. The recent energy crisis and the subsequent price hike of fossil fuels has further exacerbated the effect of fossil fuels on the environment and economy. The UK government has already pledged to achieve 100% power generation from renewable energy sources by 2035 [2]. The decarbonisation of power generation will be a great step towards the ambitious net-zero target. In addition to the power generation decarbonisation, the energy consumption will also need to be decarbonised. Efficient utilisation of the energy is one such step that will be necessary for the net-zero target. Commercial and residential buildings are a big user of energy. Ensuring efficient utilisation of energy in building is therefor a topic of great interest for the sustainable environment.

Modern buildings consume energy to provide various services such as thermal comfort (heating or cooling), ventilation, hot water for cooking and other usage, electric appliances (TV, fridge, washing machine etc.). According to the United Nations Environment Programme (UNEP), buildings are the biggest consumers of electricity, roughly 60% of the total electricity production [3]. This also makes buildings the biggest contributor to greenhouse gas emissions. As such, there is huge potential of emission savings in buildings through efficient utilisation of the energy. In colder climate, e.g., Europe, space heating accounts for the majority of energy consumption in buildings. Various national and international organisations have promoted heat pumps as an effective indoor heating solution. Heat pump is powered by electricity and can provide more than three times equivalent heat than the consumed electric energy. As heat pumps are typically grid-connected, they can be used to mitigate the effects of uncertainties that arise from connecting variable renewable energy (VRE) sources to the grid. If heat pumps are connected to district heating systems, heat pumps then can provide wider flexibility of shifting the electric load in daily or weekly cycle. This can further accelerate the adoption of VRE sources into the grid. Production uncertainties are a big concern for large-scale adoption of VRE sources. District heating system connected heat pumps can be effectively considered as a large-scale thermal battery energy storage system which is capable of absorbing the uncertainties of VRE.

Different heat pump controller design schemes have considered in literature to meet the desired performance [4–7]. In much of this work, however, it is assumed that all the system state variables are available for use by the controller. However, in real world, this assumption can limit practical application as usually only a subset of state variables may be measurable. Therefore, it becomes of interest to establish observers to estimate the system states and then use the estimated states to replace the true system states in order to implement state feedback decentralised controllers [8,9]. In addition, disturbances effect is a very important issue in real physical systems and need to be considered in any control problem. Hence, disturbances estimation is very useful in designing robust control system schemes [10]. The concept of the observer was first introduced by Luenberger in 1964 where the observation error between the output of the actual plant and the output of the observer converges to zero when time goes to infinity. Subsequently, many approaches have been developed to design observers for different systems to estimate system states [11–14]. However, the problem becomes more challenging when the system is subject to parametric uncertainties various disturbances. Therefore, adaptive techniques are utilised to estimate online unknown time varying parameters and/or disturbances [15–18]. When variable structure control techniques is applied to systems to obtain and maintain the desired performance, the system becomes a variable structure system. One of the main approaches in control field that using variable structure control techniques is so-called sliding mode control [19]. 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 distribution matrix). 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 around sliding surface may result in chattering phenomenon that might limit the practicability of the technique in some systems such as mechanical systems ([20] and references therein). However, no sliding motion is required in the methods that only use variable structure control techniques as no need to design sliding surfaces, and hence, the chattering issue is avoidable [8,9].

An adaptive observer, which is one of the effective methods to handle the system uncertainties, is designed for many different kind of systems to estimate the disturbances in order to be taken into account in control system design schemes to improve the robustness and efficiency [21–23]. However, in much of this work, it is assumed that the disturbances are bounded. Unbounded disturbances are considered in Guerrero [24] and Xiao et al. [25], Yu et al.

[26] where adaptive disturbance observers are developed for specific purposes and particular applications, and all system states assumed to be measurable. In this paper, the advantages of adaptive techniques and variable structure techniques are combined to develop a robust adaptive observer to estimate the system states and disturbances simultaneously. It is not required that the disturbances to be bounded, but the time derivative of the disturbances need to be bounded. A dynamical system is proposed and then, the error systems between the original system and the designed dynamical system are analysed. The Lyapunov direct method is used to analysis the stability of designed system and it is not required to solve the so-called constrained Lyapunov problem. 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. The developed method is applied to a model of the heat dynamics of a house floor heating system connected to a ground source-based heat pump. Different disturbance signals formats and amplitudes are considered to show the effectiveness of the proposed technique. Simulation results are given to demonstrate the suitability of the proposed method.

2. System description and preliminaries

Consider a nonlinear system described as follows:

$$\dot{x} = Ax + Hf(x) + Bu + E\theta(t) \tag{1}$$

$$y = Cx \tag{2}$$

where $x \in R^n, u \in R^m$ and $y \in R$ are the state variables, input and output, respectively. The function $f(x)$ is known continuous, and $\theta(t)$ represents the disturbances. The matrices A, B, H, E and C are constant with appropriate dimensions, and C is of full rank.

Assumption 1. The matrix pair (A, C) is detectable.

From Assumption 1, there exist matrix L such that $A - LC$ is Hurwitz stable. This implies that, for any positive-definite matrix $Q \in R^{n\times n}$ the Lyapunov equation

$$(A - LC)^T P + P(A - LC) = -Q \tag{3}$$

has unique positive-definite solution $P \in R^{n\times n}$.

Assumption 2. The disturbances $\theta(t)$ satisfy

$$\left|\dot{\theta}(t)\right| \le \mu \tag{4}$$

Remark 1. Assumption 2 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. Appropriate adaptive laws are to be designed to identify it.

Assumption 3. The nonlinear term $f(x)$ satisfy the Lipschitz condition with respect to $x \in R^n$ and uniformly for $u \in R^m$, that is, there exist nonnegative function ℓ such that

$$\left\| f(x) - f(\hat{x})\right\| \le \ell \left\|x - \hat{x}\right\| \tag{5}$$

3. Adaptive variable structure observer with disturbances estimation

In this section, adaptive variable structure observer (AVSO) is proposed to estimate system states and disturbance. For system (1)–(2), construct dynamical systems

$$\widehat{\dot{x}} = A\hat{x} + Hf(\hat{x}) + Bu + L(y - \hat{y}) + E\hat{\theta}(t) + \phi(\hat{y}, y) \tag{6}$$

$$\hat{y} = C\hat{x} \tag{7}$$

where

$$\phi(\hat{y}, y) = \alpha P^{-1} C^T (y - \hat{y})^T sgn(y - \hat{y}) \tag{8}$$

and $P\&C$ satisfies the Lyapunov equation (3), with adaptive laws

$$\begin{aligned} \hat{\theta}(t) &= \Gamma + \rho\, y \\ \dot{\Gamma} &= -\rho\, \dot{\hat{y}} \end{aligned} \tag{9}$$

where α and ρ are positive constants.

Let $e_x = x - \hat{x}$, $e_y = y - \hat{y}$, and $e_\theta = \theta(t) - \hat{\theta}(t)$. Then from (1)–(2) and (6)–(7), the error dynamics are described by

$$\dot{e}_x = (A - LC)e_x + H[f(x) - f(\hat{x})] + E[\theta(t) - \hat{\theta}(t)] - \phi(\cdot) \tag{10}$$

From (9),

$$\begin{aligned} \dot{e}_\theta &= \dot{\theta}(t) - \widehat{\dot{\theta}}(t) \\ &= \dot{\theta}(t) - [\dot{\Gamma} + \rho\, \dot{y}] \\ &= \dot{\theta}(t) - [-\rho\ \dot{\hat{y}} + \rho\, \dot{y}] \\ &= \dot{\theta}(t) - [-\rho\, C\, \dot{\hat{x}} + \rho\, C\, \dot{x}] \\ &= \dot{\theta}(t) - \rho\, C\, \dot{e}_x \\ &= \dot{\theta}(t) - \rho\, C\{(A - L\,C)e_x + \mathrm{H}[f(\cdot) - f(\hat{\cdot})] + E[\theta(t) - \hat{\theta}(t)] - \phi(\cdot)\} \\ &= \dot{\theta}(t) - \rho\, C(A - L\,C)e_x - \rho\, C\, \mathrm{H}[f(\cdot) - f(\hat{\cdot})] - \rho\, C\, E[\theta(t) - \hat{\theta}(t)] + \rho\, C\, \phi(\cdot) \end{aligned} \tag{11}$$

4. Stability of the error dynamical systems

The following result is ready to be presented:

Theorem 1. *Under Assumptions 1–3, the error dynamical systems (10) with adaptive law (9) are globally uniformly ultimately bounded if the matrix* $W^T + W$ *is positive definite, where*

$$W = \begin{pmatrix} w^a & w^b \\ w^c & w^d \end{pmatrix} \tag{12}$$

and

$$\begin{aligned} w^a &= [\lambda_{\min}(Q) - 2\,\ell\ \|P\|\ \ \|\mathrm{H}\| + 2\alpha\ \|C\|^2], \\ w^b &= w^c = -[\|P\|\ \ \|E\| - \rho\ \ \|C\|\ \ \|A - L\,C\| - \rho\,\ell\ \ \|C\|\ \ \|\mathrm{H}\| + \rho\,\alpha\ \|C\|\ \ \left\|P^{-1}\right\|\ \|C\|^2], \\ w^d &= 2\rho\ \ \|C\|\ \ \|E\| \end{aligned}$$

Proof. For systems (10) and (11), consider the candidate Lyapunov function

$$V = e_x^T P e_x + e_\theta^T e_\theta \tag{13}$$

The time derivative of $V(\cdot)$ along the trajectories of systems (10) and (11) is given by

$$\begin{aligned} \dot{V} = &\left\{e_x^T[(A - L\,C)^T P + P(A - LC)]e_x + 2e_x^T P\, \mathrm{H}[f(\cdot) - f(\hat{\cdot})] + 2e_x^T\ P\ E\ e_\theta^T - 2e_x^T\ P\ \phi(\cdot)\right\} \\ &+ \left\{\dot{e}_\theta^T\ e_\theta + e_\theta^T\ \dot{e}_\theta\right\} \end{aligned} \tag{14}$$

From (3), (5), (8) and (11), it follows that

$$\begin{aligned} \dot{V} &\le -e_x^T\ Q\, e_x + 2\,\ell\, e_x^T\ P\, \mathrm{H}\, e_x + 2e_x^T\ P\ E\, e_\theta - 2e_x^T\ P\, \phi(\cdot) + 2e_\theta^T\ \dot{e}_\theta \\ &\le -e_x^T\ Q\, e_x + 2\,\ell\ P\, \mathrm{H}\, e_x^2 + 2e_x^T\ P\ E\ e_\theta - 2\alpha e_x^T\ C^T(y - \hat{y})^T\ \mathrm{sgn}(y - \hat{y}) \\ &\quad +2e_\theta^T \dot{\theta}(t) - \rho\, C(A - L\,C)e_x \\ &\quad -\rho\, C\, \mathrm{H}[f(\cdot) - f(\hat{\cdot})] - \rho\, C\ E[\theta(t) - \hat{\theta}(t)] + \rho\, C\, \phi(\cdot) \end{aligned} \tag{15}$$

From the inequality $\|X\| \le X^T sgn(X)$

$$\begin{aligned} \dot{V} \le &-e_x^T\ Q\, e_x + 2\,\ell\, e_x^T\ P\, \mathrm{H}\, e_x + 2e_x^T\ P\ E\, e_\theta - 2\alpha\, e_x^T\ C^T\ \left\|y - \hat{y}\right\| - 2\rho\, C\, e_\theta^T(A - LC)e_x \\ &-2\rho\,\ell\, C\, \mathrm{H}\, e_\theta^T\ e_x - 2\rho\, C\ E\ e_\theta^T\ e_\theta + 2\rho\,\alpha\, C\ e_\theta^T\ P^{-1}C^T\ \ \left\|y - \hat{y}\right\| + 2e_\theta^T\ \dot{\theta}(t) \end{aligned} \tag{16}$$

From Assumption 2 in (4), it follows that

$$\begin{aligned}\dot{V} &\le -\lambda_{\min}(Q)\|e_x\|^2 + 2\ell\ \|P\|\ \|\mathrm{H}\|\ \|e_x\|^2 + 2\|P\|\ \|E\|\ \|e_x\|\ \|e_\theta\| - 2\alpha\ \|C\|^2\|e_x\|^2 \\ &\quad -2\rho\ \|C\|\ \|A-LC\|\ \|e_x\|\ \|e_\theta\| \\ &\quad -2\rho\ell\ \|C\|\ \|\mathrm{H}\|\ \|e_x\|\ \|e_\theta\| - 2\rho\ \|C\|\ \|E\|\ \|e_\theta\|^2 + 2\rho\alpha\ \|C\|\ \left\|P^{-1}\right\|\|C\|^2\|e_x\|\ \|e_\theta\| + 2\mu\ \|e_\theta\| \\ &\le [-\lambda_{\min}(Q) + 2\ell\ \|P\|\ \|\mathrm{H}\| - 2\alpha\ \|C\|^2]\|e_x\|^2 + [2\|P\|\ \|E\| - 2\rho\ \|C\|\ \|A-LC\| - 2\rho\ell\ \|C\|\ \|\mathrm{H}\| \\ &\quad +2\rho\alpha\ \|C\|\ \left\|P^{-1}\right\|\|C\|^2]\|e_x\|\ \|e_\theta\| - 2\rho\ \|C\|\ \|E\|\ \|e_\theta\|^2 + 2\mu\ \|e_\theta\| \\ &\le -\{[\lambda_{\min}(Q) - 2\ell\ \|P\|\ \|\mathrm{H}\| + 2\alpha\ \|C\|^2]\|e_x\|^2 - 2[\|P\|\ \|E\| - \rho\ \|C\|\ \|A-LC\| - \rho\ell\ \|C\|\ \|\mathrm{H}\| \\ &\quad +\rho\ \alpha\ \|C\|\ \left\|P^{-1}\right\|\|C\|^2]\|e_x\|\ \|e_\theta\| + 2\rho\ \|C\|\ \|E\|\ \|e_\theta\|^2\} + 2\mu\ \|e_\theta\|\end{aligned} \tag{17}$$

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

$$\begin{aligned}\dot{V} &\le -\tfrac{1}{2}\mathrm{X}^T\ \left[W^T + W\right]\ \mathrm{X} + \beta\ \|\mathrm{X}\| \\ &\le -\left(\tfrac{1}{2}\lambda_{\min}\ \left(W^T + W\right)\ \|\mathrm{X}\| - \beta\right)\ \|\mathrm{X}\|\end{aligned} \tag{18}$$

where $\beta = 2\mu$ and $X = [e_x, e_\theta]^T$. Therefore, from the condition that $W^T + W$ is positive definite, system (10) is globally uniformly ultimately bounded.

5. Simulation studies

In this section, the developed method in this paper is applied to a model of the heat dynamics of a house floor heating system connected to a ground source based heat pump. The matrices (A, B, C) in (1)–(2) that described in Halvgaard [27] are used in this paper to develop AVSO. The system parameters used in this simulation example can be found in Table II in Halvgaard [27]. The system states are $x = [T_r T_f T_w]^T$, where T_r is a room air temperature, T_f is a floor temperature, and T_w is a water temperature in floor heating pipes. The disturbances considered in this paper $\theta(t)$ is the sun radiation. The system matrices (A, B, C, E) are

$$A = \begin{pmatrix} -0.7358 & 0.7704 & 0 \\ 0.1882 & 0.1798 & 0.0084 \\ 0 & 0.0335 & -0.0335 \end{pmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0.0036 \end{bmatrix}$$

$$C = [100], E = \begin{bmatrix} 0.0011 \\ 0.00003 \\ 0 \end{bmatrix}$$

Choose $L = [0.01050.48090.4846]$ and $Q = I$. Then, the Lyapunov equation (3) has unique solution:

$$P = \begin{pmatrix} 6.7689 & 5.9083 & -7.2926 \\ 5.9083 & 6.9965 & -3.3811 \\ -7.2926 & -3.3811 & 117.0517 \end{pmatrix}$$

For simulation purposes, the controllers are chosen as $u = -k_u x$ where $k_u = 1 \times 10^5[2.37162.42910.0095]$. By direct computation, it follows that the matrix $W^T + W$ is positive definite, where W is

$$W = \begin{pmatrix} 3 & 0.0457 \\ 0.0457 & 0.0051 \end{pmatrix}$$

Thus, all the conditions of Theorem 1 are satisfied.

Simulation results in Fig. 1 show the system state variables and their estimations in the presence of disturbances. Figs. 2, 3 and 4 show the disturbances estimation at different signal formats and amplitudes ($\theta(t) = \sin(t)$, $\theta(t) = 5\sin(t)$ and when $\theta(t)$ is a square wave signal, respectively). The estimation error between the states of the system and the states of the observer converges to zero globally ultimately bounded.

6. Conclusion

An adaptive variable structure observer has been proposed based on Lyapunov direct method to estimate the system states and disturbances simultaneously. Variable structure technique is combined adaptive techniques to

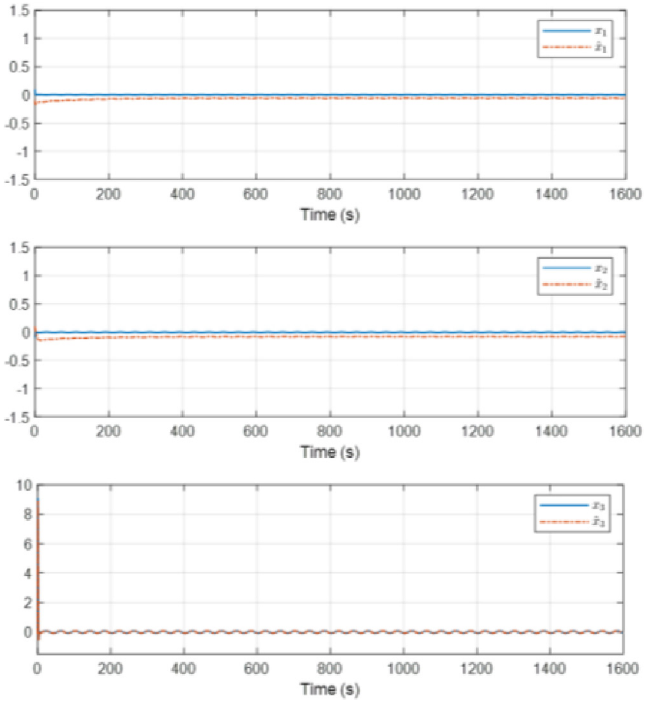

Fig. 1. System states estimation.

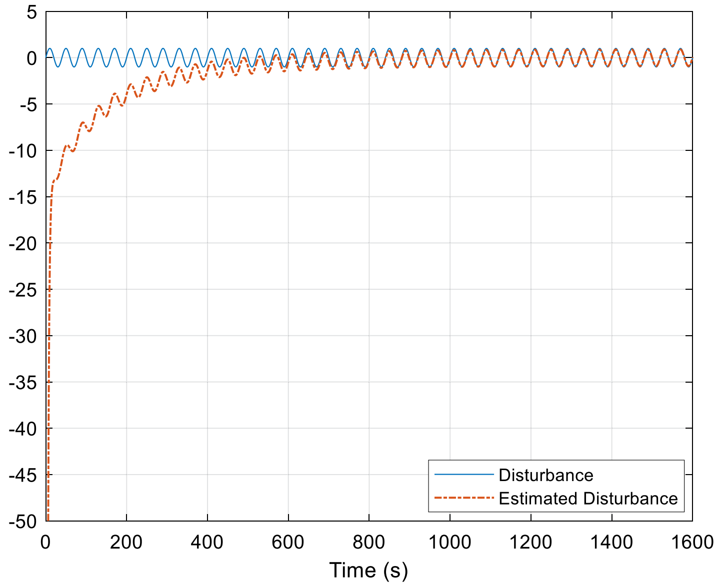

Fig. 2. Disturbance estimation $\theta(t) = \sin(t)$.

guarantee the ultimate boundedness of the estimation error of the designed observer. No bound is considered on the disturbances, but the rate of change of the disturbances should be bounded. Case study on model of the heat dynamics of a house floor heating system connected to a ground source based heat pump shows the practicability of the developed observer. Disturbances at different amplitudes are considered to show the reliability of the proposed technique.

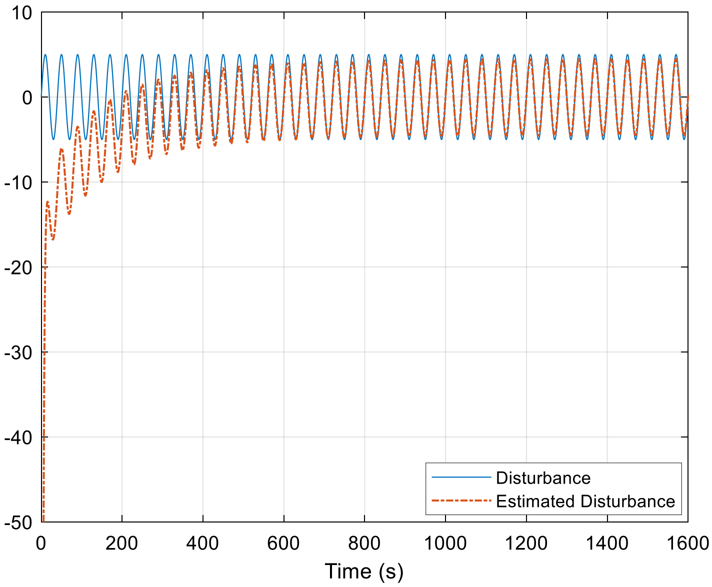

Fig. 3. Disturbance estimation $\theta(t) = 5\sin(t)$.

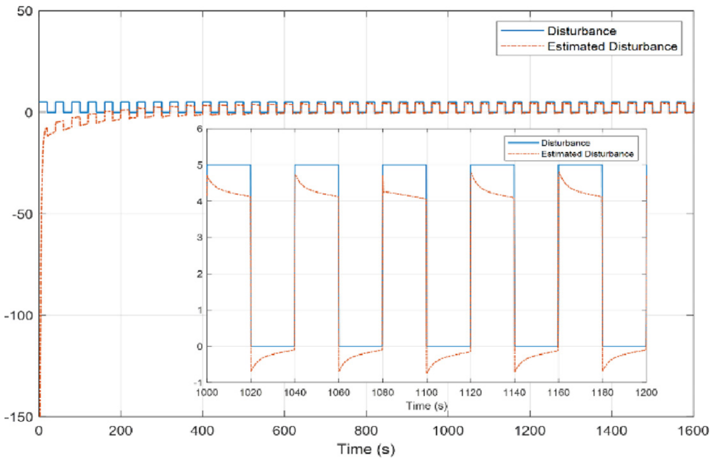

Fig. 4. Disturbance estimation when $\theta(t)$ is a square signal with amplitude 5.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported by Smart Efficient Energy Centre (SEEC) at Bangor University, United Kingdom, part-funded by the European Regional Development Fund (ERDF), administered by the Welsh Government. The work of H. Ahmed is funded through the Sêr Cymru II 80761-BU-103 project by Welsh European Funding Office (WEFO) under the European Regional Development Fund (ERDF).

References

[1] Gudde PO. The role of UK local government in delivering on net zero carbon commitments: You've declared a climate emergency, so what's the plan? Energy Policy - Elsevier 2021;112245.

[2] Vella H. Ten steps to net zero [energy decarbonisation]. Eng Technol 2021;20–4.

[3] Agency IE. Global status report for buildings and construction. Paris, France: IEA; 2019.

[4] Candanedo JA. Predictive control of radiant floor heating and solar-source heat pump operation in a solar house. Hvac R Res 2011;235–56.

[5] Ma ZX. Recent advances and development in optimal design and control of ground source heat pump systems. Renew Sustain Energy Rev 2020;131:110001.

[6] Péan TQ, Salom J, Costa-Castelló R. Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings. J Process Control 2019;35–49.

[7] Vering CW. Towards an integrated design of heat pump systems: Application of process intensification using two-stage optimization. Energy Convers Manage 2021;114888.

[8] Mohamed M, Yan XG, Spurgeon SK, Mao Z. Robust variable structure observer design for non-linear large-scale systems with non-linear interconnections. IMA J Math Control Inform 2018a;535–53.

[9] Mohamed M, Yan XG, Spurgeon SK, Mao Z. Variable structure observers for nonlinear interconnected systems. In: Advances in variable structure systems and sliding mode control—theory and applications. Cham: Springer; 2018b, p. 195–221.

[10] Pawlowski AG. Application of time-series methods to disturbance estimation in predictive control problems. In: IEEE international symposium on industrial electronics. 2010, p. 409–14.

[11] Liu WJ. Decentralized observer design for a class of nonlinear uncertain large scale systems with lumped perturbations. Asian J Control 2016;2037–46.

[12] Mohamed M, Yan XG, Spurgeon SK, Jiang B. Robust sliding mode observers for large scale systems with application to a multimachine power system. IET Control Theory Appl 2017;1307–15.

[13] Nguyen CM, Pathirana PN, Trinh H. Robust observer and observer-based control designs for discrete one-sided Lipschitz systems subject to uncertainties and disturbances. Appl Math Comput 2019;42–53.

[14] Wang C, Zuo Z, Qi Z, Ding Z. Predictor-based extended-state-observer design for consensus of MASs with delays and disturbances. IEEE Trans Cybern 2018;1259–69.

[15] Efimov DC. Enhancement of adaptive observer robustness applying sliding mode techniques. Automatica 2016;53–6.

[16] Han J, H Z. Anti-disturbance control for nonlinear system via adaptive disturbance observer. Internat J Robust Nonlinear Control 2017;2121–44.

[17] Mohamed M, Yan XG, Mao Z, Jiang B. Adaptive observer design for nonlinear interconnected systems by the application of LaSalle's theorem. Internat J Adapt Control Signal Process 2020;1559–71.

[18] Yan XG, Edwards C. Adaptive sliding-mode-observer-based fault reconstruction for nonlinear systems with parametric uncertainties. IEEE Trans Ind Electron 2008;4029–36.

[19] Yan XG, Spurgeon SK, Edwards C. Variable structure control of complex systems. Springer; 2017.

[20] Utkin V, Guldner J, Shi J. Sliding mode control in electro-mechanical systems. CRC Press; 2009.

[21] Hu XW. Adaptive disturbance estimation and cancelation for ships under thruster saturation. Internat J Robust Nonlinear Control 2020;5004–20.

[22] Liu W, Li P. Disturbance observer-based fault-tolerant adaptive control for nonlinearly parameterized systems. IEEE Trans Ind Electron 2019;8681–91.

[23] Muramatsu H, Katsura S. An adaptive periodic-disturbance observer for periodic-disturbance suppression. IEEE Trans Ind Inf 2018;4446–56.

[24] Guerrero JT. Adaptive disturbance observer for trajectory tracking control of underwater vehicles. Ocean Eng 2020;107080.

[25] Xiao D, Nalakath S, Sun Y, Wiseman J, Emadi A. Complex-coefficient adaptive disturbance observer for position estimation of IPMSMs with robustness to DC errors. IEEE Trans Ind Electron 2019;5924–35.

[26] Yu Z, Zhang Y, Jiang B, Fu J, Jin Y, Chai T. Composite adaptive disturbance observer-based decentralized fractional-order fault-tolerant control of networked UAVs. IEEE Trans Syst Man Cybern Syst 2022;79:9–813.

[27] Halvgaard RP. Economic model predictive control for building climate control in a smart grid. In: 2012 IEEE PES innovative smart grid technologies. ISGT, IEEE; 2012.