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Formulation of H_2 Norm-Based Power Deficiency Estimation for Isolated Power Systems

Mohd Saifuzam Jamri, Muhammad Nizam Kamarudin

Centre for Robotics and Industrial Automation (CeRIA), Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka
Email: saifuzam@utem.edu.my

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Abstract

An isolated power system was described as a local electrical network consisting of a transformer and isolation generator with branch circuits intended for specific uses. In an isolated power system, the essential primary source is the local generator. Unbalanced power and serious frequency deviation issues might result from the system's extreme sensitivity to abruptly high equilibrium conditions of electrical load demand. Therefore, the primary goal of this study is to use frequency observation to estimate the power deficit for isolated power systems. In order to create a power deficit estimator, the state-space model equations were added to the structure of H_2 norm filtering problems. Then, from the error system after decomposition, the feasibility of Linear Matrix Inequality (LMI) was verified and guaranteed the stable H_2 filter to estimate the power deficit. The formulation of H_2 filter under the uncertain inertia constant parameter was covered in this paper to investigate the robustness performance. At the last section, the proposed estimator result was compared with the conventional initial slope method. The results show the under-estimation, but it guarantees the stable estimation process under the trade-off of the H_2 norm optimization.

Keywords

Power Deficit, Isolated Power System, Dynamical Frequency Observation, Condition Monitoring

1. Introduction

Total power deficit is defined as a magnitude of power difference between load demand and generation supply. Particularly, an isolated small electrical system operating in island conditions is very sensitive to unbalanced power which may lead to severe frequency deviation problems. This is due to the disconnection of electricity from the main utility supply. This system is called micro-grid and mostly relying on the local generator to generate and supply electricity to the connected load [1]-[5]. In order to prevent local generator damage and complete load black-out during island mode operation, it is imperative to monitor the power deficiency before taking network safety measures. The works done by [6]-[9] proved that the generator system's inertia may have an impact on the power deficiency and, consequently, affect the frequency dynamic. The power deficit estimation approach has also been implemented in load shedding strategy where the first command for the load shed depends on size of total power deficiency [10]-[14]. However, these approaches are only based on experiences and might not be reliable for different severity conditions.

Conventionally, the method to determine the power deficit in the system is by observing the initial slope of the frequency drop and utilizing the general swing equation [15]-[18]. However, this method requires to know the exact value of system inertia which may vary depending on the loading size [19]. An isolated power system with mixed generation sources such as renewable energy and dispatchable generator may be faced with inertia deviation. This is because renewable energy is category as non-dispatchable due to highly depending on a natural source [20]-[22]. Thus, the inertia in the dispatchable generator system may affect and perturb the dynamical frequency behavior.

Therefore, another way to obtain accurate power shortage information is to formulate an estimator using an optimization technique. In this study, an island-mode generator model that was coupled to loads was used. For the formulation of the estimator model, an optimal H_2 norm filtering issue was selected. A fundamental component of contemporary control theory and signal processing is the H_2 norm filtering. It is primarily used to design filters that minimize the "energy" of the error signal when a system is subjected to known statistical noise profile [23]-[26]. The work procedure is referred to as the work done by [27] [28] related to a linear time-invariant continuous time system. However, the process in formulating a filter by minimizing the H_2 norm of transfer function is not straightforward due to subjected of unstable pole location in the system matrix representation. For instance, decomposition techniques were introduced by cancelling the zero eigenvalue and formulating the LMI solution based on reduced order form.

The seventh Sustainable Development Goal—Affordable and Clean Energy—is supported by this subject. Particularly in remote or off-grid locations where continuous energy access is essential, the effort advances the development of clever and affordable methods for improving the dependability and efficiency of local power generation.

2. Formulation Method

The work involved the derivation of power system model and augmented with an estimator. The estimator was formulated using H_2 norm filtering objective function in the sense of Lyapunov identity associated with LMI to optimize the upper bound of estimation performance.

2.1. Isolated Power System Model

The behaviour of a dynamically isolated power system for a dispatchable generator system connected with a load can be described by the state space averaging of all conceivable states [29] [30]. A system's state is described as a variable that is reliant on time. The time derivative is then represented in terms of the system's inputs and state variables. On the other hand, a system's output is its response to any changes in its state variable. The following is an expression for the time invariant state space equation:

$$\begin{aligned} \dot{\boldsymbol{\rho}} &= a\boldsymbol{\rho} + b\boldsymbol{u}_d \\ \boldsymbol{y} &= c\boldsymbol{\rho} \end{aligned} \tag{1}$$

$\boldsymbol{\rho} \in R^n$ state vectors consisting of frequency deviations ω_e, mechanical power P_m and governor power P_{gv}; $\boldsymbol{y} \in R^r$ r measured output; $\boldsymbol{u}_d \in R^m$ input vector (Load demand). The mathematical state space equation which explains the governor, turbine, and frequency output behaviour can be written as in equation (2). The prime mover model relates changes in steam position ΔP_{gv} to variations in mechanical power output ΔP_m. The most basic prime mover model, which may be roughly represented by a single time constant T_{ch}, was employed in this study.

$$\begin{aligned} a &= \begin{bmatrix} 0 & 1/2H & 0 \\ 0 & -1/T_{ch} & 1/T_{ch} \\ -1/RT_{gv} & 0 & -1/T_{gv} \end{bmatrix} \\ b &= \begin{bmatrix} -1/2H \\ 0 \\ 0 \end{bmatrix} \\ c &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \end{aligned} \tag{2}$$

H = the inertia constant; T_{ch} = the turbine time constant; T_{gv} = governor time constant; R = governor speed regulation. Note that, for the simplification purpose, the initial condition of system is assumed zero and all the corresponding vectors are measured in per unit.

2.2. Power Deficit Estimation Approach

It should be emphasized that rather than the state variable, the power deficit in the isolated power system model given in Equation (2) is related to the change in electrical demand that can be achieved from the input state. For the linear estimator solution to be useful, the power deficit related to the input state needs to be converted into a state variable. Figure 1 displays a block diagram used to formulate the estimator design problem. The power deficit input condition was changed into a variable state using the low-pass filter, h, without affecting the observability of the frequency dynamic. The generator model was then added to this state. Additionally, the loop's augmentation of h serves to guarantee an appropriate estimator transfer function.

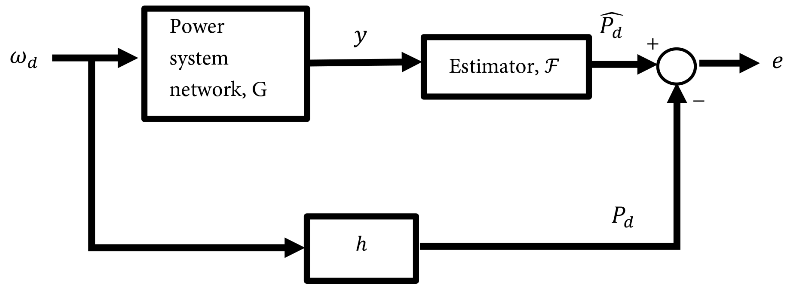

Figure 1. Block configuration for an estimator design.

With h in the feedforward loop, the full state-space realizations can be written as follows

$$\begin{aligned} \dot{\boldsymbol{x}}_N &= A_N \boldsymbol{x}_N + B_N \boldsymbol{\omega}_d \\ \boldsymbol{y}_N &= C_N \boldsymbol{x}_N + D_N \boldsymbol{\omega}_d \\ \boldsymbol{P}_d &= C_g \boldsymbol{x}_N \end{aligned} \tag{3}$$

The matrix size changes and becomes a fourth-order system with $\boldsymbol{x}_N = [\boldsymbol{x} \quad \boldsymbol{x}_h]^{\mathrm{T}}$, while the matrices $A_N \in R^{n\times n}$, $B_N \in R^{n\times m}$, $C_N \in R^{k\times n}$ and $C_g \in R^{k\times n}$ are defined as

$$\begin{aligned} A_N &= \begin{bmatrix} 0 & 1/2H & 0 & 0 \\ 0 & -1/\tau_T & 1/\tau_T & 0 \\ -1/RT_{gv} & 0 & -1/T_{gv} & 0 \\ 0 & 0 & 0 & -1/T_h \end{bmatrix} \\ B_N &= \begin{bmatrix} -1/2H \\ 0 \\ 0 \\ B_h \end{bmatrix} \\ C_N &= \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \\ C_g &= \begin{bmatrix} 0 & 0 & 0 & C_h \end{bmatrix} \end{aligned} \tag{4}$$

Note that the state vector is a separate system and is not dependent on the other state vectors. Hence, the fourth row in the matrix can be neglected during the verification of the observability system. Furthermore, an additional noise denoted as D_N is neglected in this work. The primary goal is to create an estimator to estimate $\hat{\boldsymbol{P}}_d$ of $\boldsymbol{P}_d$, which is provided by $\hat{\boldsymbol{P}}_d = \mathcal{F}\cdot \boldsymbol{y}$, where $\mathcal{F}$ is a member of a linear estimator with state space realization in the form of

$$\begin{aligned} \dot{\hat{\boldsymbol{x}}}_N &= A_f \hat{\boldsymbol{x}}_N + B_f \left(C_N \boldsymbol{x}_N + D_N \boldsymbol{\omega}_d\right) \\ &= A_f \hat{\boldsymbol{x}}_N + B_f C_N \boldsymbol{x}_N + B_f D_N \boldsymbol{\omega}_d \\ \hat{\boldsymbol{P}}_d &= C_f \hat{\boldsymbol{x}}_N \end{aligned} \tag{5}$$

Matrices $A_f \in R^{n_f \times n_f}$, $B_f \in R^{n_f \times n_r}$ and $C_f \in R^{s\times n_f}$ are to be determined and $\hat{x}_N = [\hat{x} \quad \hat{x}_h]^T$. Establishing a connection between Equation (5) and Equation (3) yields a network model for the entire system x_n and estimator model $\hat{x}_n$ as depicted in Equation (6)

$$\begin{bmatrix} \dot{x}_N \\ \dot{\hat{x}}_N \end{bmatrix} = \begin{bmatrix} A_N & 0 \\ B_f C_N & A_f \end{bmatrix} \begin{bmatrix} x_N \\ \hat{x}_N \end{bmatrix} + \begin{bmatrix} B_N \\ B_f D_N \end{bmatrix} \omega_d \tag{6}$$

Hence, $T_M(s) := \tilde{C}(sI - \tilde{A})^{-1} \tilde{B} = GE - h$ is the transfer function that relates the disturbance input ω_d to the estimate error $\tilde{z}$. The matrices $\tilde{A}, \tilde{B}$ and $\tilde{C}$ of compatible dimensions are given by

$$\begin{aligned} \tilde{A} &= \begin{bmatrix} A_N & 0 \\ B_f C_N & A_f \end{bmatrix} \\ \tilde{B} &= \begin{bmatrix} B_N \\ B_f D_N \end{bmatrix} \\ \tilde{C} &= \begin{bmatrix} -C_g & C_f \end{bmatrix} \end{aligned} \tag{7}$$

2.3. The Implementation of H_2 Norm Filtering Structure

The suggested setup to calculate the power deficit is depicted in Figure 2. It should

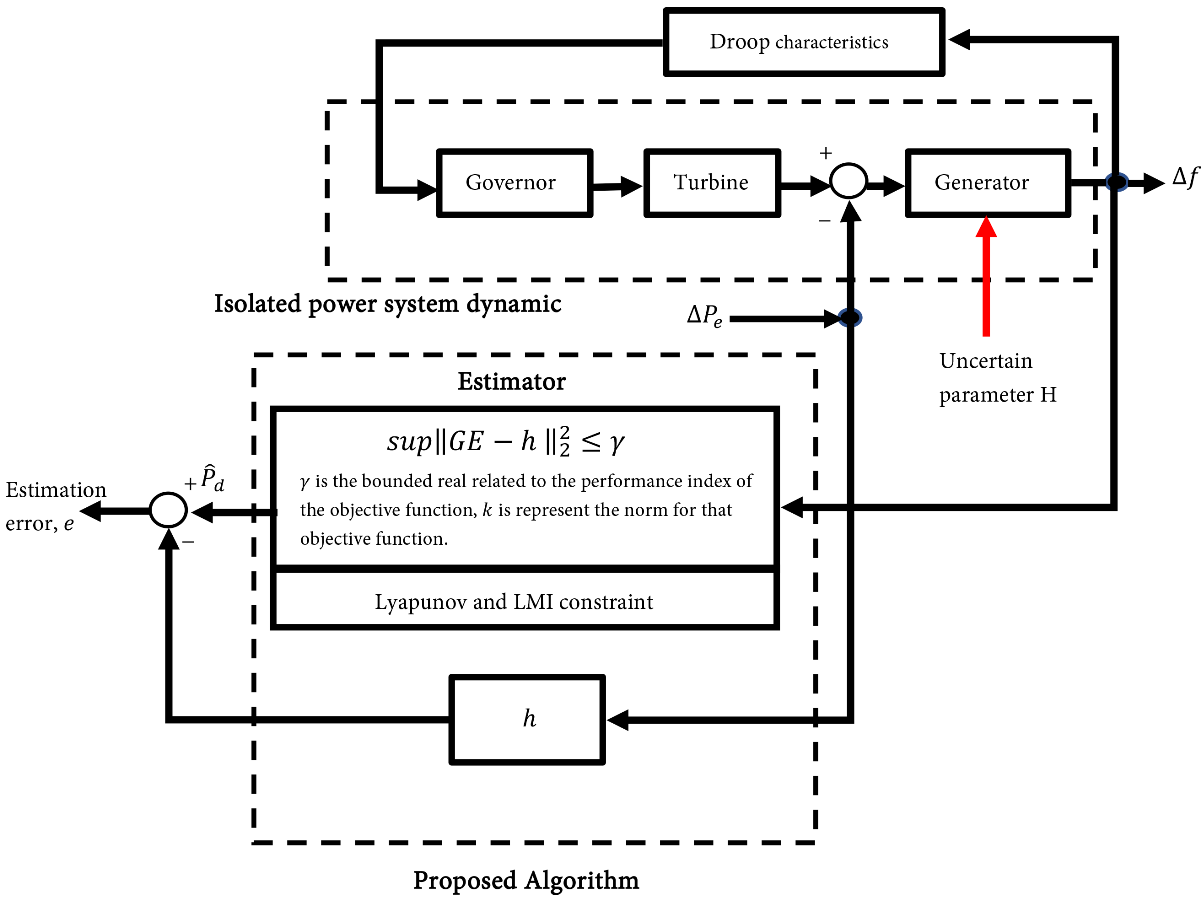

Figure 2. The proposed configuration to estimate the power deficit.

be noted that this configuration's primary objective is to determine the power deficit with minimal estimation inaccuracy. The isolated power system dynamic produced the frequency dynamic variations Δf after receiving the electrical power demand deviations ΔP_e. After feeding this Δf output to the estimator transfer function's input, the feasible objective function over the bounded real γ that satisfies the Lyapunov and LMI constraints yields the estimated power deficit $\hat{\boldsymbol{P}}_d$.

The purpose of the H_2 estimation issue is to establish a guaranteed estimation performance index γ that provides a realistic upper bound over the estimator state-space realisation in Equation (5) is produced by $\|GE-h\|_2^2 \le \gamma$. The Lyapunov equation solution in Schur complement form, as shown in Equation (8), can be used to solve this H_2 norm.

$$\begin{aligned} &\gamma := \min \operatorname{trace}[W] \\ &\text{Subject to} \\ &\begin{bmatrix} \tilde{P} & \tilde{P}\tilde{C}' \\ \blacksquare' & W \end{bmatrix} > 0; \begin{bmatrix} \tilde{A}\tilde{P}+\tilde{P}\tilde{A}' & \tilde{B} \\ \blacksquare' & -I \end{bmatrix} < 0 \end{aligned} \tag{8}$$

The power deficit estimator was designed to adapt with two isolated power system conditions which are nominal parameter and uncertain parameter.

Design for Uncertain Parameter Condition Case

The isolated power system model is thought to be tainted by parameter uncertainty in a robust instance. The inertia constant H is the uncertain quantity that has been taken into account in this instance. This is the sole factor that has a substantial impact on both the power deficit estimation performance and the slope of dynamical frequency. The inertia constant H parameter dependence can be clearly seen at the first row of matrix A_N and B_N in Equation (4). In this research, the parameter uncertainty is confined to a given polytope satisfying $m = \sum_{i=1}^{v} \lambda_i m_i$ for some $\lambda_i > 0$ such that $\sum_{i=1}^{v} \lambda_i = 1$ and m belongs to the state matrix in Equation (4). Since the uncertain inertia value denoted by H_i is the only parameter that is considered as uncertainty, every point of uncertain inertia value is confined between two vertices.

For the H_2 estimation problem, Equation (9) produces a viable estimator that minimizes γ over the estimator state-space realization, resulting in guaranteed estimation performance that matches the objective function such that $\|GE-h\|_2^2 \le \gamma$. As in Equation (9), the Schur complement matrix for the H_2 norm in the sense of Lyapunov stability given in Equation (8) can be expressed as an uncertain state matrix.

$$\begin{aligned} &\begin{bmatrix} \tilde{P} & \tilde{P}\tilde{C}' \\ \blacksquare' & W \end{bmatrix} > 0; \\ &\begin{bmatrix} \tilde{A}_i\tilde{P}+\tilde{P}\tilde{A}_i' & \tilde{B}_i \\ \blacksquare' & -I \end{bmatrix} < 0; \\ &i = 1, 2 \end{aligned} \tag{9}$$

Equation (9) shows that the uncertain inertia constant H_i only influences the state and input matrix. However, this inequality equation is not considered as a form of LMI due to the multiplication of multiple variables. conversion is required in order for the filter design to become a convex that can be solved extremely effectively by the numerical processes. The non-LMI equation can be decomposed by partitioning the matrix $\tilde{P} := \begin{bmatrix} X & U \\ \blacksquare' & \hat{X} \end{bmatrix}$, satisfying the inequality Equation (9) and multiplying to the left by $j' := \text{diag}\left[\tilde{j}', I\right]$ and to the right by j and $\tilde{j}� = \begin{bmatrix} X^{-1} & Y \\ 0 & V' \end{bmatrix}$. Then, introduce the new variable as described in [28], the inequalities are equivalent to Equation (10).

$$\begin{bmatrix} Y & C_g' \\ \blacksquare' & W \end{bmatrix} > 0; \begin{bmatrix} Z & Z \\ \blacksquare' & Y \end{bmatrix} > 0$$

$$\begin{bmatrix} ZA_{N_i} + A_{N_i}' Z & ZA_{N_i} + A_{N_i}' Y + C_N' F' + Q' & ZB_{N_i} \\ \blacksquare' & YA_{N_i} + FC_N + A_{N_i}' Y + C_N' F' & YB_{N_i} + FD_N \\ \blacksquare' & \blacksquare' & -I \end{bmatrix} < 0 \quad (10)$$

$$i = 1, 2$$

As a result, the estimator design problem is equivalent to the following programming problem on the determination of variable positive definite matrices $W = W'$, $Z = Z'$ and $Y = Y'$, as well as matrices Q, and F, given in terms of the LMI in Equation (10). The estimator matrices are defined by $A_f = -Y^{-1}Q\left(I - Y^{-1}Z\right)^{-1}$; $B_f = -Y^{-1}F$; $C_f = C_g$. Hence, the transfer function of H_2 Norm estimator can be written as $T_f(s) := C_f\left(sI - A_f\right)^{-1} B_f$.

2.4. Simulation Setup

The simulation is divided into two situations which are the variation of load demand and the response under different inertia constant parameter values. In addition to that, the isolated power system network model does not involve load frequency management via Automatic Generation Control (AGC) which allowing the influence of frequency droop response to be readily recognized. The dynamical frequency is the vital state to be observed as it will be the input for the designed estimator. Table 1 shows the list of parameters to set up the simulation.

Table 1. Isolated power system network model parameters setup.

Parameters	Value
Speed regulation, R	0.05
Inertia constant, H	5
Governor time constant, τ_{gv}	0.2 s
Turbine time constant, τ_T	0.5 s

The feasible solution for H_2 norm estimator is guaranteed by utilizing the LMI constraint in Equation (10) for robust case. The parameter settings for the isolated power system network model are shown in Table 1. Figure 3 illustrates a 15-second simulation with a sudden electrical load demand change of 0.2 per unit at 3 seconds. In addition, the H_2 norm estimation performance was analyzed through the Integral Absolute Error (IAE), Integral Square Error (ISE) and Root Means Square Error (RMSE) data collections. The IAE and ISE performances were identified to analyse the size of the estimation error over time, while the performance analysis through RMSE on the other hand, was identified to know the size of the data distribution over time.

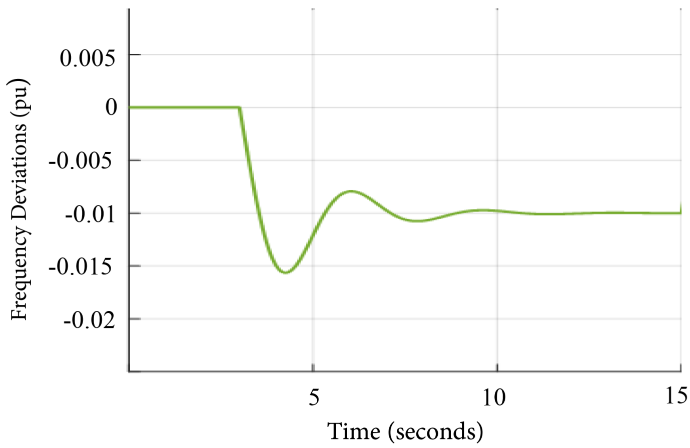

Figure 3. Frequency dynamical response in per unit towards the variation of load demand.

3. Results and Discussion

3.1. Estimation in Uncertain Parameter Case

The value of the inertia constant is supposed to be known, although it has uncertain minimum and maximum values ranging from 4.5 to 5.5, assuming the generator's inertia varies as the load size changes. The resilience H_2 estimation was ensured in accordance with the target function $\sup\|GE-h\|_2^2 \le \gamma$ under the 0.2 per-unit rapid electrical load demand shift at time 3 seconds. The LMI constraint in Equation (10) was feasible, resulting in an upper bound $\gamma = 159.17$. Table 2 displays the error performance at steady state response using the IAE, ISE, and RMSE. The data shows that the estimation distributions over time are under-conservative

Table 2. The estimation error performance at steady-state utilizing the H_2 norm approach under the uncertain inertia parameter condition.

Inertia Constant Value, H	Integral Absolute Error (IAE)	Integral Square Error (ISE)	Root Means Square Error (RMSE)	Estimated Total Power Deficit (pu)
4.5	2.9274	0.1714	0.0585	
5.0	2.9292	0.1716	0.0586	0.1413
5.5	2.9321	0.1719	0.0586	

for each inertia constant value. Compared to the reference of 0.2 per-unit, the steady-state estimated power deficit has a significant inaccuracy of roughly 29% at 0.1413 per-unit as shown in Figure 4. This value is the trade-off of the H_2 norm optimization.

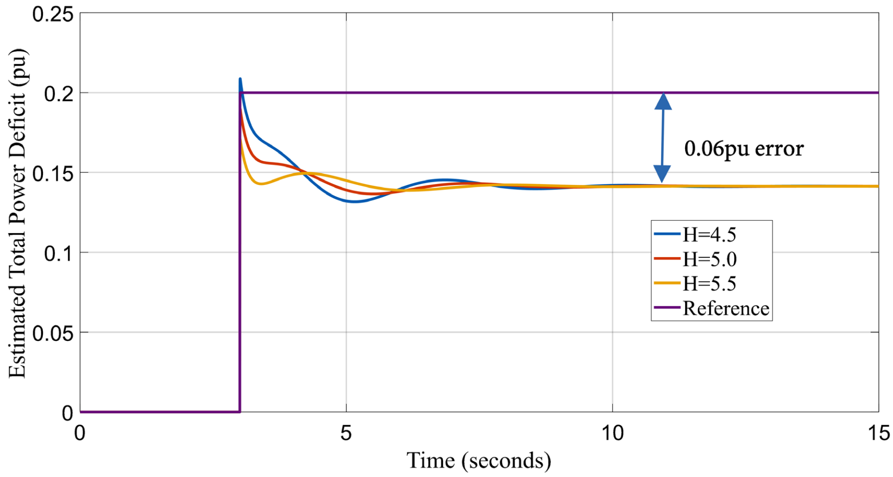

Figure 4. Estimated power deficit using H_2 norm with 0.2 per-unit rapid electrical load demand variation and uncertain inertia constant values.

3.2. The Comparison between H_2 Estimation towards Conventional Method in Uncertain Parameter Case

In a conventional way, the power deficit was estimated by observing the initial slope of the frequency drop upon the disturbance. The approach utilized the swing equation as depicted in Equation (1). Table 3 shows the analysis of steady-state estimation performance through the IAE, ISE and RMSE.

Table 3. The error performance of power deficit steady-state estimation using the initial slope approach with H = 5.0 and 0.2 per-unit load demand as reference.

Inertia constant value, H	Integral Absolute Error (IAE)	Integral Square Error (ISE)	Root Means Square Error (RMSE)	Estimated Power Deficit (pu)
4.5	3.604	0.0866	0.024	0.1760
5.0	0.6711	0.003	0.0045	0.1955
5.5	2.2617	0.0341	0.0151	0.2151

The result shows that when the inertia constant value deviates from the reference, the estimation error is larger. The IAE, ISE, and RMSE results are the error performance index that proved the weaknesses of the initial slope method. The estimation error becomes worse when the inertia constant changes larger and away from reference. Figures 5(a)-(c) shows the illustration of the error performance data.

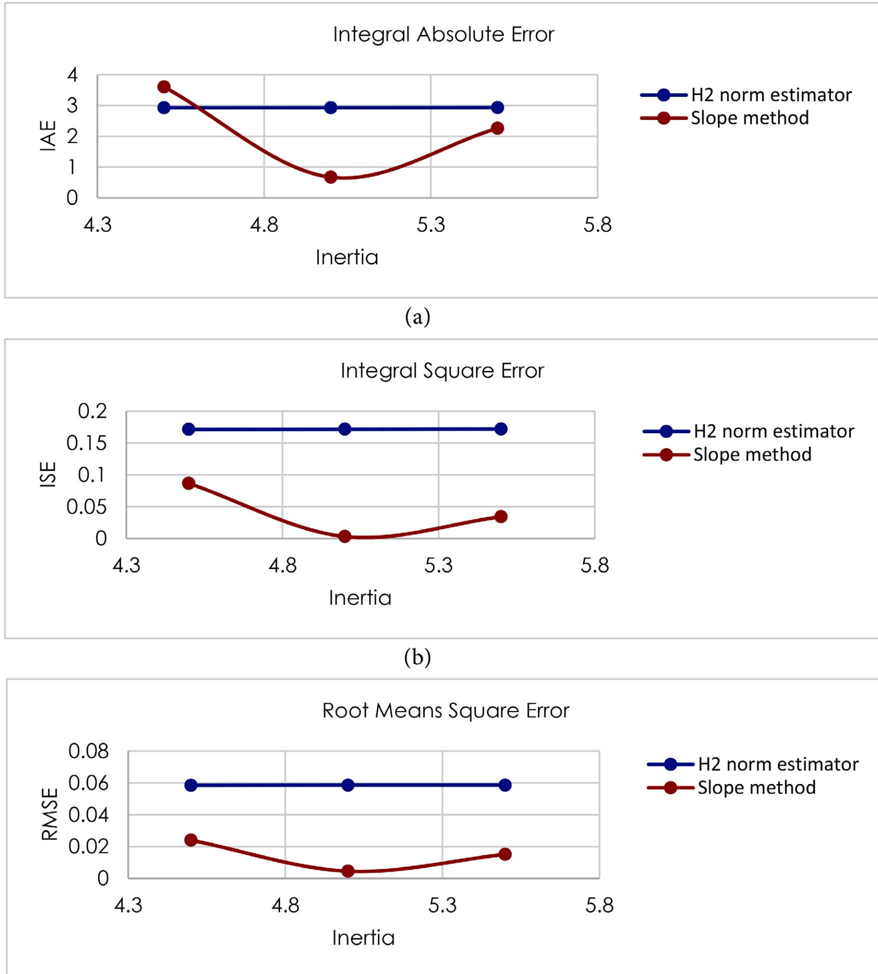

Figure 5. The comparison of error performance between H_2 Norm estimator and slope method under uncertain inertia parameter value.

3.3. Estimation in Nominal Case

In the nominal scenario, the isolated power system model parameters are assumed to be exactly known. The objective function in Equation (8) results in a slight norm below the optimal $\gamma = 0$. Choosing $H = 5.0$ as a known inertia parameter, the LMI constraint in Equation (10) was feasible and conformed with the estimation performance index γ, resulting in $\sup\|GE-h\|_2^2 \le \gamma$ for an upper bound of $\gamma = 12.64$. Table 4 displays tabulated statistics on the estimation error performance at steady-state response using the (IAE), (ISE), and (RMSE). The results

Table 4. The estimation error performance at steady-state using H_2 norm method under nominal case.

Inertia Constant Value, H	Integral Absolute Error (IAE)	Integral Square Error (ISE)	Root Means Square Error (RMSE)
5.0	8.65E−06	3.20E−12	2.61E−07

show that the estimation error is modest. Hence, the anticipated power shortfall is accurate.

4. Conclusion

The automatic generation control was not considered when developing the state space mathematical model for isolated electrical systems with a single generator. The whole system is now a third-order system due to the addition of all the models, which include rotating mass, prime mover, speed governor, and load. To assist the investigation, frequency deviation was chosen as the state variable to be examined on fluctuations in load demand per unit. However, to estimate the total power deficit, one additional function has been added without sacrificing the observability of the frequency dynamic. Simulation findings confirmed the estimation performance of the total power deficit using the H_2 norm. The under-estimation under the parameter uncertainty case is an inherent trade-off of the H_2 norm optimization which results in upper bound $\gamma = 159.17$. When the parameter uncertainty is introduced, the robust estimator prioritizes boundedness with 0.1413 pu estimated power deficit and system stability over strict nominal tracking. Compared to the slope method, the estimated power deficit is varying in accordance to the changes of inertia value. Control and power system engineers, as well as researchers establishing the methodology for the power condition estimator in isolated power systems, can considerably benefit from this foundational study. Monitoring the generator loading state also requires assessing the overall power deficit. Therefore, the method that uses the H_2 norm in conjunction with the optimization process via LMI is a good substitute, and the method's primary input is the frequency behaviour of the generator. However, additional changes to the current configuration could increase the accuracy of estimation towards an uncertain generator's parameters.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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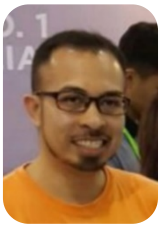
Biographies of Authors

Mohd Saifuzam Jamri was born in October 1984. He earned a Bachelor Degree in Electrical Engineering (Power Electronics & Drives) from Universiti Teknikal Malaysia Melaka, Malaysia in 2007 and a Master Degree in Electrical Power Engineering from Universiti Teknologi Malaysia in 2009. In 2024, he obtained his Doctor of Philosophy in Electrical Engineering from Universiti Teknikal Malaysia Melaka. He is a senior lecturer at Universiti Teknikal Malaysia Melaka (UTeM) and a member of the Centre for Robotics and Industrial Automation CeRIA group. He is interested in studying power systems, microgrids, load frequency control (LFC), and renewable energy integration. He can be contacted at email: saifuzam@utem.edu.my



Muhammad Nizam Kamarudin was born in Selangor, Malaysia. He received the B.Eng (Hons.) Electrical from the Universiti Teknologi MARA, Malaysian in 2002, and M.Sc in Automation and Control from the University of Newcastle Upon Tyne, United Kingdom in 2007. He received the Doctor of Philosophy in Electrical Engineering from the Universiti Teknologi Malaysia in 2015. He is currently with the Universiti Teknikal Malaysia Melaka (UTeM). He is the member of the Board of Engineers, Malaysia and Institute of Engineers, Malaysia. His research interests include nonlinear controls and robust control systems. Before joining UTeM, he worked as a Technical Engineer at the magnetron department of Samsung Electronics Malaysia. He can be contacted at email: nizamkamarudin@utem.edu.my