

Isolated Local Generator Condition Monitoring Using State-Observer Method

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Abstract

This project was focused on the generator condition monitoring for an isolated power system using state observer method. An isolated power system is a system that is normally located in low voltage side and basically does not connect to the main grid or utility supply. The power capacity is much lower than the main grid capacity and commonly used as a backup system for the critical load. Without connecting to the main grid, the isolated power system generator may be disturbed by the sudden contingencies problem. These problems have basically occurred due to the sudden demand change during isolation. Without a proper monitoring approach, the generator might be unintentionally operating over the limitation. Hence, this project purposely introduces an approach to monitor the operating condition of a generator in isolated power system. The proposed approach is to apply a state observer model into the isolated power system model. The input for the state observer is the network's dynamical frequency behaviour. Then, an estimated generator's state such as governor state and turbine state was determined. The estimation process was verified through multifarious load demand changes, and the result shows the effectiveness of the state observer in application towards the generator's state behaviour.

Keywords

Transient Respond, State Observer, Isolated Power System, State-Space Model, Frequency Deviations

1. Introduction

An isolated power system is a system that can operate independently without being connected to the main power grid. In isolated power systems, it has limited generation capacity that led to the low level of fault [1] [2]. The system may suffer

from a blackout when a huge contingency occurs, which makes a protective relay remove the generator from the network [3]-[5]. The load demand and supply in an isolated power network must be balanced to ensure the stable behavior of dynamical frequency network. To make the system less affected by any contingencies, it needs some of the control loops in the system to be integrated. Thus, secondary frequency control also known as Load Frequency Control (LFC) is utilized. Furthermore, these control loops can ensure that the frequency will keep under desirable level after a disturbance [6]-[9]. Another definition related to an isolated power system is an islanded micro-grid. This system is commonly integrated with non-dispatchable distributed generators such as photovoltaic system and wind turbine system which is composed into a small-scale distributed energy resource. They are completely limited due to relying on a natural source [10]-[12]. These integrations may affect the system's inertia. Consequently, the low inertia phenomenon may directly affect the local dispatchable generator performance [13] [14]. Hence, a virtual synchronous generator was introduced to create a virtual inertia to mitigate the low inertia effect during contingency [15]-[19]. The other approach to sustain the stability of a system during isolated operation is by triggering an Under Frequency Load Shedding (UFLS) as a last resort tool [20]-[22]. From UFLS approach, the total power deficiency in the system was reduced by shutting down a few uncritical loads when the dynamic frequency of the system drops over the determinate threshold value. However, this approach can be considered as a heuristic because the size of the load to be shed was determined through experience.

In 1964, David G. Luenberger delivered a Luenberger observer to figure out the problem related to the state estimation of linear system which is modelled by Ordinary Differential Equations (ODEs). This observer cannot be used instantaneously to some physical processes, such as thermal diffusion process, fluid heat exchange and chemical engineering [23]. Around 1960, Rudolf E. Kalman suggested Kalman filter to estimate the values of state variable of a dynamic system that has a present of disturbances and noise. On the other hand, an observer is one of the options to represent Kalman filter. This is because the structure in the observer mimics the Kalman filter. However, an observer consists of a specified estimator error dynamic that needs to be calculated. The total disturbances of a system can be compensated by cooperating a controller into the state observer such as by utilizing a sliding mode controller with the back stepping technique to force the state variables of the closed-loop system converge to the reference state [24]. Another type of observer is referring to the unknown input observer which is used to estimate unmeasured input to the dynamic system. The estimation will only use the available measurement of input and output. This method is applicable in fault detection and diagnosis either linear or non-linear system [25]-[27].

The isolated power system condition shows that the generator performance may be affected due to the integration of other resources and variations of demand. In a real situation, the generator's performance is relying on its prime mover and governor system state behaviour. These systems need to be monitored

to ensure their operating point is always within the permissible level. Hence, an approach to estimate the system state is needed. In a conventional way, the prime mover and governor system behaviour was described through the transfer function, which translated as an input and output of the system's responses. However, this approach does not emphasize the estimation error, making the accuracy of the estimated value become unreliable. Furthermore, the conventional governor and turbine monitoring was relied on direct measurement through sensors which require extensive instrumentation and are susceptible to sensor degradation. Thus, this project proposed a model-based state-observer approach that utilizes the generator's dynamic frequency response. The behaviour of the generator system was described using a mathematical equation which is written in state space averaging representation. Then, the state observer model was augmented to become an overall observer system where the dynamic frequency behaviour of the generator is observed and used as an input.

This topic supports the Sustainable Development Goal 7 which is Affordable and Clean Energy. The work contributes to the development of intelligent and cost-effective techniques for enhancing the reliability and efficiency of local power generation, particularly in isolated or off-grid areas where uninterrupted energy access is critical.

2. Research Method

The behavior of a dynamically isolated power system can be described by the state space averaging consisting of all set of possible states. The state equation is a mathematical description in the standard form that explicit as a set of coupled first-order ordinary differential equations. The state of a system is defined as a variable by which dependently changed with respect to time. Then, the time derivative is expressed in terms of state variables and inputs for the system. While the output for a system is defined as the state that response to any changes of state variable. The time invariant state space equation can be written as follows:

$$\begin{aligned}\dot{x} &= Ax + B\omega_d \\ y &= C_1x + D\omega_d \\ z &= C_2x\end{aligned}\tag{1}$$

Figure 1 shows the illustration of the generator supplying isolated load to be studied. The network consists of one generator system and connected loads. The mathematical model that has been derived was divided into four main parts which are rotating mass, prime mover, speed governor and load. Each part was modeled separately and augmented all together to become a single model.

The generator system was modeled according to the basic acceleration swing equation. The mathematical state space equation was derived to describe the behavior of governor, turbine and frequency output as shown in Equation (2). The model for prime mover is related to the changes in mechanical power output ΔP_m to the changes in steam position ΔP_v . This work used the simplest prime mover model which can be approximated with a single time constant τ_T .

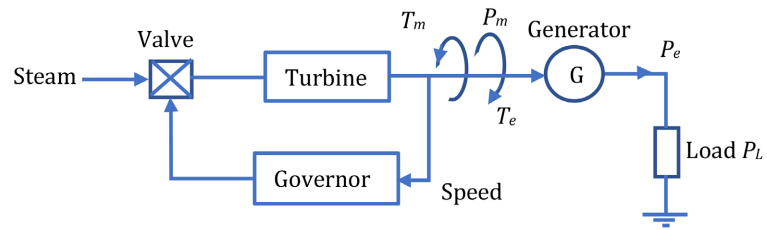


Figure 1. Generator supplying isolated load.

$$\begin{aligned}
 \frac{d\Delta\omega}{dt} &= \frac{1}{2H} [\Delta P_m - \Delta P_e] \\
 \frac{d\Delta P_m}{dt} &= \frac{1}{\tau_T} [\Delta P_v - \Delta P_m] \\
 \frac{d\Delta P_v}{dt} &= \frac{1}{\tau_g} \left[-\frac{\Delta\omega}{R} - \Delta P_v \right]
 \end{aligned}
 \tag{2}$$

Hence, connecting Equation (2) into Equation (1), the differential equation can be written into state space representation as shown in Equation (3). Note that the state space model system is considered as third-order system.

$$\begin{aligned}
 \frac{d}{dt} \begin{bmatrix} \Delta\omega \\ \Delta P_m \\ \Delta P_v \end{bmatrix} &= \begin{bmatrix} 0 & \frac{1}{2H} & 0 \\ 0 & -\frac{1}{\tau_T} & \frac{1}{\tau_T} \\ -\frac{1}{\tau_g R} & 0 & \frac{1}{\tau_g} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta P_m \\ \Delta P_v \end{bmatrix} + \begin{bmatrix} -\frac{1}{2H} \\ 0 \\ 0 \end{bmatrix} \Delta P_e \\
 y &= [1 \quad 0 \quad 0] \begin{bmatrix} \Delta\omega \\ \Delta P_m \\ \Delta P_v \end{bmatrix}
 \end{aligned}
 \tag{3}$$

where the $\Delta\omega$ represent as a frequency, ΔP_m as a mechanical power and ΔP_v as a governor power are the state vectors respectively. While for input signal, ΔP_e represent as an electrical power. Note that the symbol Δ was denoted as the deviation of the state while Δ/dt is the deviation of the state with respect to time. The observer model mimics the state space averaging structure which is written as in Equation (4)

$$\begin{aligned}
 \dot{\hat{x}} &= (A - LC_1)\hat{x} + Ly + B\omega_d \\
 \hat{y} &= C_1\hat{x} \\
 \hat{z} &= C_2\hat{x}
 \end{aligned}
 \tag{4}$$

Note that the observer model is stable if only if it satisfies the estimation error $\tilde{z} = z - \hat{z}$ converges to zero. The observer gain L is determined through the heuristic pole-placement method so that the matrix $A - LC_1$ has all eigenvalues inside the stable region. Figure 2 shows the conceptual block diagram of augmented isolated power system model depicted in Equation (3) and observer model depicted in Equation (4) respectively. The matrix A and B were denoted in Equation (3) respectively. y is the output vector that represents the frequency

dynamic, while z is the output vector that is the expected state variable to be estimated. The gain L is a vital part to weight the dynamical frequency error $y - \hat{y}$ and provides a feasible solution for the observer state matrix $(A - LC_1)$ so that the system always stable with negative eigenvalues.

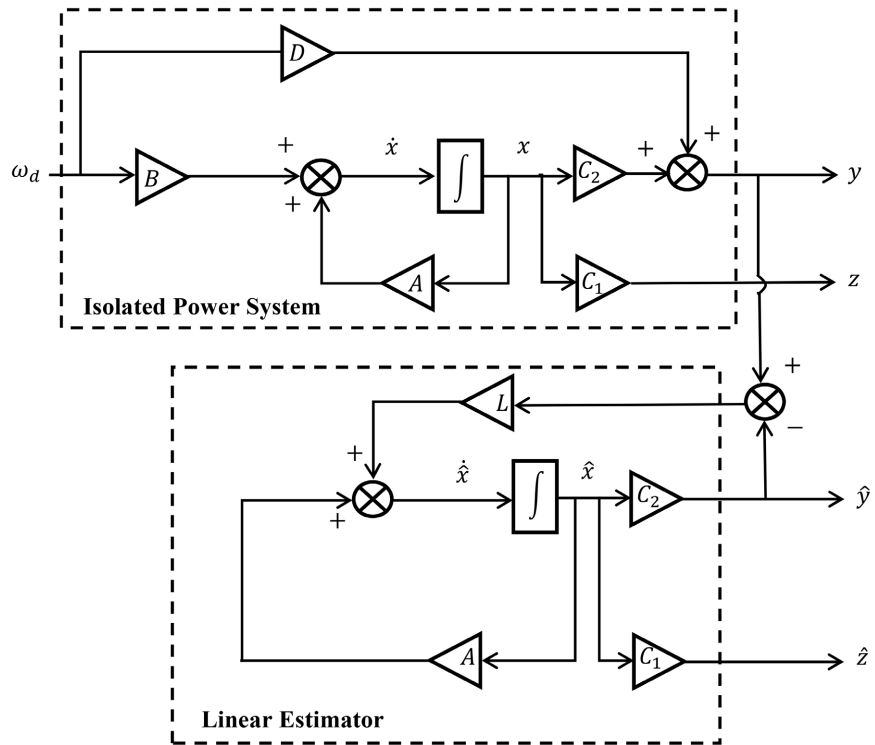


Figure 2. Conceptual block diagram of augmented isolated power system and observer system.

Simulation Setup

The parameters of the isolated power system model are shown in **Table 1**. Noted that all the parameter values are chosen based on the typical generator with non-reheat turbine system as considered in book chapter shown in [28]. The model was tested with sudden 0.15 pu and 0.2 pu of load deviation. Then the dynamical frequency responses were observed. The simulation was carried out using MATLAB/Simulink as shown in **Figure 3**.

Table 1. Parameters of isolated power system model.

Parameters	Value
Speed regulation, R	0.05
Frequency-sensitivity, D	0
Inertia constant, H	5
Governor time constant, τ_{gv}	0.2 s
Turbine time constant, τ_r	0.5 s

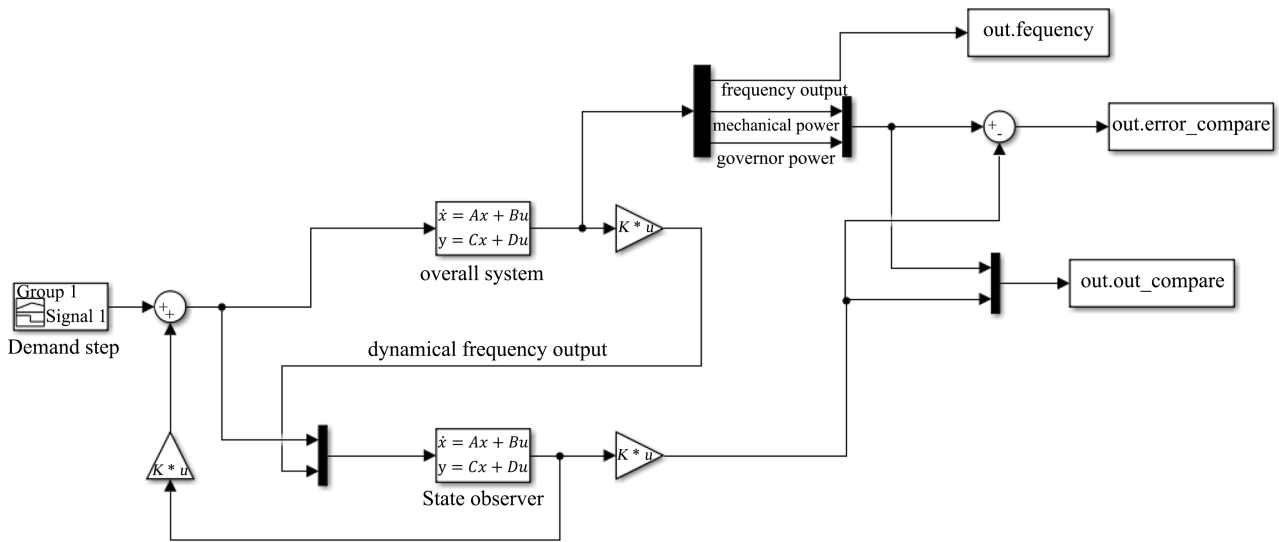


Figure 3. Simulink block for augmented isolated power system and state-observer model.

3. Results and Discussion

3.1. The Dynamical Frequency Performance

The main objective of this work is to estimate the generator’s governor power and mechanical turbine power through observing the dynamical frequency response towards the demand changes. The isolated power system was modeled which related to the general swing equation and augmented with the turbine and governor system. The turbine system was modeled as a non-reheat turbine type while the reference power in the governor system is always equal to zero so that the network model does not consider P_{ref} as required in AGC. Thus, the system will only experience the primary control in its load frequency control mechanism. The model was simulated for 30 seconds for two load variations, and the transient output response of the frequency is shown in Figure 4.

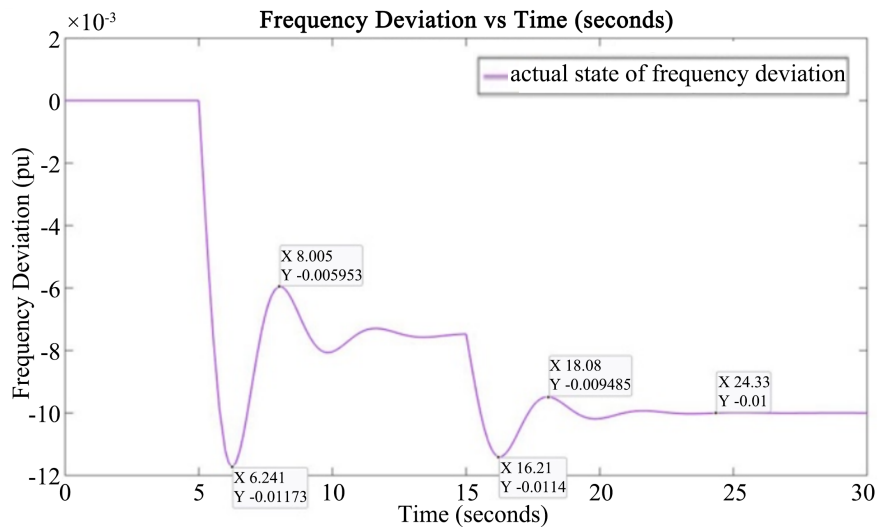


Figure 4. The dynamical frequency response towards the demand changed.

The frequency drop after the load demand changed portrays that the generator respond is very sensitive towards the load demand changed. The frequency drop is higher when the deviation of the load demand changed is higher. Hence, the dynamical frequency respond would oscillate when the load demand changed fluctuates. This relation can be clearly seen at the time 15 s where the droop is smaller after the load demand deviated with 0.05 pu compared to the first droop at time 5 s with 0.15 pu load demand deviation. This dynamical response verified that the mathematical model successfully described the generator's behaviour.

3.2. The Estimation Performance

The role of the governor system in a generator is to maintain the speed and frequency of the prime mover during operation. Hence, the generator can run with desired frequency and mechanical output power even under the variations of load demand. The dynamical behavior of the governor and mechanical power was successfully estimated as shown in **Figure 5**. The oscillation at the initial transient is due to the effect of the frequency oscillation upon the disturbance. It can be seen that the steady state respond has occurred at time around 12 s when the mechanical output power meets the load demand and hence, the power deficit is converged to zero value.

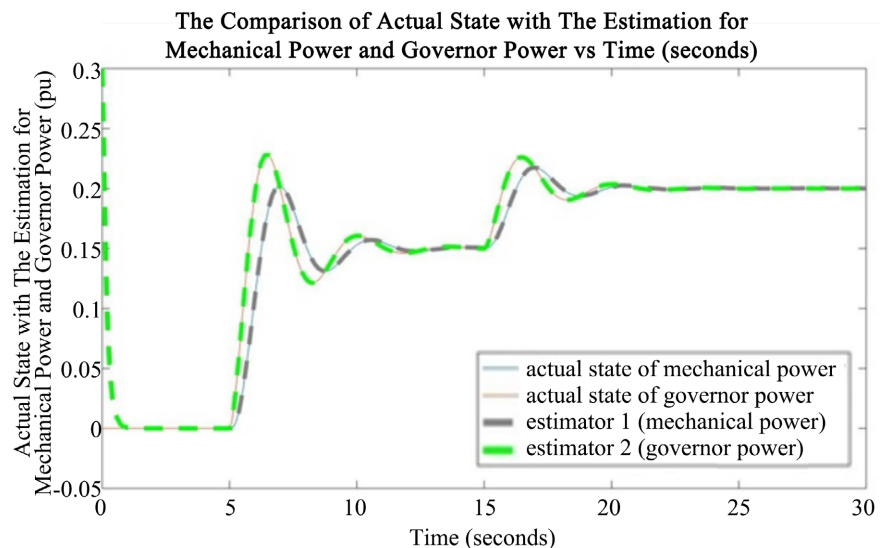


Figure 5. The estimated governor power and turbine mechanical power.

However, the estimated state variables may be affected when the observer gain is perturbed due to the pole placement changed. As mentioned in the previous section, the observer gain plays an important role in restructuring the observer state matrix and ensuring the negative eigenvalues of the new observer state matrix. **Table 2** shows the investigation of estimation percentage error when the pole placement is arbitrarily changed. The value of the pole placement matrix was determined according to the eigenvalues of the generator's state matrix. In this work, the observer gain was determined using the desired pole $[-25 \ -8 \ -6]$ which cor-

responds to the lowest estimation error. The percentage of estimation error was calculated using Equation (5).

$$\text{Percentage Error} = \left(\frac{\text{Estimated Value} - \text{Actual Value}}{|\text{Actual Value}|} \right) \times 100\% \quad (5)$$

Table 2. The influence of estimation performance towards the pole location.

Location of poles	Percentage estimation error (%)
[-25 -8 -6]	0.45
[-5 -4 -3]	26.72
[-23 -22 -20]	32.91

4. Conclusion

The state space mathematical model for an isolated electrical system with a single generator has been derived without considering the automatic generation control. The augmentation of all the models consisting of rotating mass, prime mover, speed governor and load has made the overall system become the third-order system. To facilitate the analysis, frequency deviation has been selected as the only state variable to be observed upon the deviations of load demand in per unit. During the estimation process, the observer gain plays a vital role to ensure a feasible stable estimation with low estimation error. Hence, investigation on the three-pole placement value was carried out to see the effect of estimation performance. From the simulation results, the estimation performance of generator's governor power and turbine mechanical power was verified. This fundamental study will bring significant information, knowledge and understanding to the control and power system engineers, as well as researchers in formulating the approach for the power condition estimator in an isolated power system. Furthermore, estimating the mechanical power and governor power of a generator in a real situation is crucial for monitoring the generator loading condition. Hence, the approach using the Luenberger observer is a good alternative and simple to implement as the approach only requires the generator's frequency behaviour as a main input. However, verification of robustness towards an uncertain generator's parameters is not covered in this paper and will be discussed in the future work.

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Conflicts of Interest

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

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