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Minimum-Order Observers for hybrid Wind Turbine and Fuel cell

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Abstrak

Sumber energy yang terbarukan akan menjadi sumber energy yang mendatang, dan sumber energy tersebut telah tersedia. Bentuk-bentuk dari sumber energy ini bergantung pada input yang telah tersedia. Sebuah pengawasan yang berkelanjutan dari output yang juga bergantung pada variable keadaan dari sumber model sangat diperlukan. Hal tersebut kemudian mengharuskan penggabungan dari seorang pengamatan pada system yang telah ada, dimana pengamat tersebut menilai variable-variabel keadaan secara berkelanjutan. Makalah ini mengemukakan sebuah metode design baru pada tatanan pengamatan yang minimum untuk turbin angin. Pengamatan ini menilai variabel-variabel kondisi dari turbin angin dan membandingkannya dengan variable-variable kondisi dari model tanam yang ada. Hal ini kemudian menghasilkan control vector yang kemudian lebih jauh memberikan tindakan-tindakan kontorl yang diperlukan, sehingga output dari turbin angin secara optimis dapat diterima secara luas. Tiga sususan berbeda digunakan untuk simulasi. Model tanam dengan kontrol PI serangkaian dengan putaran terbuka dibawa, model tanam pada bentuk putaran tertutup dengan pengaruh negative dan pada akhirnya model tanam dengan design tatanan yang minim diterapkan. Hal tersebut telah diamati bahwa respon dari keseluruhan system meningkat dengan penerapan model tersebut, dan stabilitas keseluruhan system juga meningkat . Matlab/Simulink digunakan untuk mengesahkan ide yang dikemukakan.

Kata kunci: Minimum Order Observer, Renewable Energy Sources, Wind Turbine, State model, Response, Stability

Abstract

Renewable Energy Sources are the upcoming energy sources, for they are readily available. The performance of these sources depends upon the available input. A continuous monitoring of the output which is also dependent upon the state variables of the source model (state model) is necessary. It necessitates the incorporation of an observer in the existing system which estimates the state variables continuously. This paper proposes a novel method of design at the design of a minimum order observer for a wind turbine, which further feeds a PMSG. This observer estimates the state variables of the wind turbine and compares this with the state variables of the actual plant model. This in turn generates a control vector which further provides the necessary control actions so that the output of the wind turbine is optimized to an acceptable extent. Three different configurations are made use for the simulation. The plant model with a PI controller in series with it, under open loop, the plant model in its closed loop form with negative feedback and finally the plant with the designed minimum order observer are simulated. It has been observed that the response of the overall system is improved with the implementation of the observer and so does the stability of the overall system. Matlab/Simulink is used for validating the proposed idea.

Keywords: *Minimum Order Observer, Renewable Energy Sources, Wind Turbine, State model, Response, Stabili*ty

1. Introduction

In the recent days, dependency on electrical energy is more than ever, thus the importance of generating energy increases significantly. Because of economical and ecological problems of fossil fuel power plants, developing renewable energies for generating electrical power attracts many attentions.

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Renewable energy comes from the natural resources such as sunlight, wind, rain tides and geothermal heat which are naturally replenished.This replaces the conventional fuels in four distinct areas namely power generation, hot water or space heating, transport fuels and rural (off-grid) energy services.

Wind power is the power obtained by the conversion of wind energy into a useful form of energy such as using wind turbines to make electricity. Further, a wind turbine is a rotary device which extracts energy from the wind and converts it to electricity. Wind Energy Conversion System (WECS) is one of the most widely used systems for electric power generation.

Fuel cell is the other most widely used renewable energy source for electric power generation. It generates electricity from hydrogen by a chemical process and emits water. Fuel cells are used in the standalone purposes at homes, hospitals, industries and now are finding their use in numerous vehicles. Proton Exchange Membrane (PEM) is the most famous and commonly used Fuel Cell. In PEM, the electrochemical power is generated by passing gas of Hydrogen from anode and Oxygen from cathode. There is an electrolyte between anode and cathode that fasten the electric charge. For supporting high power and voltage, couple of cells must be connected in series. Because of this, a DC/DC converter is usually between the fuel cell and the load.

The operation of a wind turbine and Fuel Cell (or any other renewable energy source) connected power system is required to operate under optimal conditions. This, in other words, implies that the nominal values of them should always be ensured under the corresponding operating conditions, and for this proper energy management should be ensured. For a wind turbine system connected to a grid (or micro grid) via a generator, for a good energy management [1], should be operated under optimal conditions. Many papers have been proposed for energy storage for a WTS [2], [3] and [4] which helps for energy management. Various other problems associated by birds also with a WTS such as bird fatalities have been analysed thoroughly in [5], [6] and [7].

A combination of WECS and Fuel Cell may be employed for continuous supply of electricity and reliability. In doing so, the various parameters associated with them such as the displacement, the velocity kinetic energy of the air (for WECS) and the inverter current, inductor current etc., (for Fuel Cells) need to be monitored continuously. However, observing these and hence the necessary control of these quantities with the physical (actual) system is difficult. An easier way to tackle this problem is to make use of an observer. In practice, two types of observers, namely the full order observer and a minimum order observer are available.

This paper proposes the design of minimum order observers for hybrid wind turbine and a fuel cell.The state model of the WT is obtained by making use of the various variables associated with it and the FC based inverter system are directly taken from [8] and [9] respectively. After the design of observer, the transfer function of it and the system are connected in three different configurations as explained in the section 6.

The impulse response of the system should die out to zero, which implies that the designed system is then stable [10]. However the main aim is to check whether the impulse response of the WT (and FC) along with their observers, in the closed loop configuration should die out to zero. It is observed that this comes true which implies that the WT (and FC) with their designed observers is stable.

1.1 Block Diagram of the Proposed Method

The block diagram of the proposed method is shown in figure 1. The state model of the wind turbine and the fuel cell are obtained as discussed in the later sections. As we seen in the figure 1, the wind turbine's minimum order observer and the wind turbine itself are connected in series and to this combination a negative feedback is given. Finally, the state model of PMSG is connected in series with this. A similar procedure is adopted for the Proton Exchange Membrane Fuel Cell (PEMFC) combined with the DC/DC converter which is done. However, now the state model of the inverter is connected in series with the latter. The outputs of both these, i.e., PMSG and Inverter are then connected to the grid.

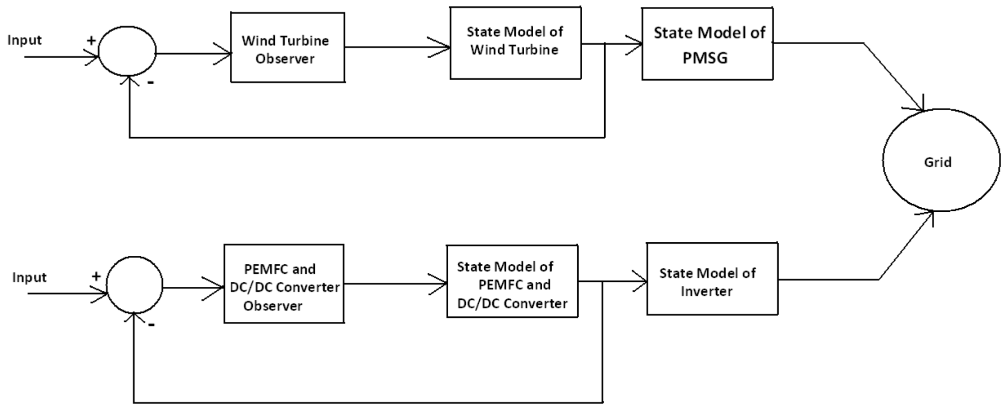

Figure 1. Grid integrated system with the implementation of minimum order observer.

The observer estimates the state variables of the wind turbine and fuel cell, and compares this with the actual state variables of the actual plant model. Thereby generates a control vector which provides the necessary control actions so that the output of the sources is optimized. This is actually equivalent to connect the observer in series with the plant. The concept is validated by testing the system with an impulse signal input. Obviously for the system to be stable, the response of the system for the impulse signal as the input should die down to zero.

1.2 State Model of Wind Turbine System

The state model of a wind turbine is obtained as follows. The parameters considered for the stated variables are displacement(x), velocity (v) and kinetic energy (E) of the air.
The state variables are defined as follows:

$x_1 = x$ (1)

$x'_1 = x_2 = v$ (2)

$x'_2 = x_3 = E$ (3)

$x'_3 = P = mx_2 + 193\,998u$ (4)

Using state variables above, the state model of wind turbine is obtained as follows,

$$\begin{bmatrix} x'_1 \\ x'_2 \\ x'_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 193998 \end{bmatrix} u \quad (5)$$

Where,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 0 \\ 193998 \end{bmatrix} \quad (6)$$

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

The parameters used for obtaining the state model are pitch angle (θ), power conversion co-efficient (C_p), displacement (x), Velocity (v) and kinetic energy (E). The wind turbine drives the permanent magnet synchronous generator (PMSG), for which its state model is obtained using its state equations

$V_d = R_s i_d + P\varphi_d - \omega_r \varphi_q$ (7)

$V_q = R_s i_q + P\varphi_q + \omega_r \varphi_d$ (8)

the state model of PMSG is

$$\begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} -338.23 & 314 \\ -314.15 & -338.23 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 24 \\ 10 \end{bmatrix} u \quad (9)$$

1.3 State model of fuel cell system

The state model of fuel cell based inverter system as obtained in [8] is made use of.

$$x = [x_1 \quad x_2 \quad x_3]^T = [i_L \quad V_c \quad V_{CFC}]^T \quad (10)$$

$$u = [u_1]^T = [d]^T \quad (11)$$

$$y = [y_1 \quad y_2]^T = [i_L \quad V_c]^T \quad (12)$$

The state variables are defined as follows:

$$i_L' = \frac{1}{L}(V_{CFC} - R_{ohm} i_L - V_c + V_c u_1) \quad (13)$$

$$V_C' = \frac{1}{c}\left(-\frac{V_c}{r_0} + \frac{2V_c}{r_0} u_1\right) \quad (14)$$

$$V_{CFC}' = \frac{1}{c}\left(i_L - \frac{V_C}{r_0}\right) \quad (15)$$

Here, the capacitor is assumed to be pre-charged so the equation (25) becomes,

$$V_{CFC}' = \frac{1}{c}\left(i_L + \frac{V_C}{r_0}\right) \quad (16)$$

Using the state variables above, the state model of fuel cell and DC/DC converter is obtained as follows,

The state equation is,

$$[i_L' \quad V_c' \quad V_{CFC}']^T = \begin{bmatrix} \frac{R_{ohm}}{L} & \frac{-1}{L} & \frac{1}{L} \\ 0 & \frac{-1}{cr_0} & 0 \\ \frac{1}{c} & 0 & \frac{1}{cr_0} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \\ V_{CFC} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{1}{L} \\ 0 & \frac{2}{cr_0} \\ 0 & 0 \end{bmatrix} u \quad (17)$$

On substituting values for the parameters in the matrix,

$$A = \begin{bmatrix} -499.14 & -13333 & 13333 \\ 0 & -1385.8 & 0 \\ 2564.1 & 0 & 1385.8 \end{bmatrix} \quad (18)$$

$$B = \begin{bmatrix} 13157.8 & 13157.8 \\ 0 & 2772 \\ 0 & 0 \end{bmatrix} \quad (19)$$

The output equation of the model is,

$$y = [1 \quad 1 \quad 0] \begin{bmatrix} i_L \\ V_c \\ V_{CFC} \end{bmatrix} \quad (20)$$

The regulated terminal voltage from the DC/DC converter is interfaced to the DC/AC inverters for residential or grid applications.

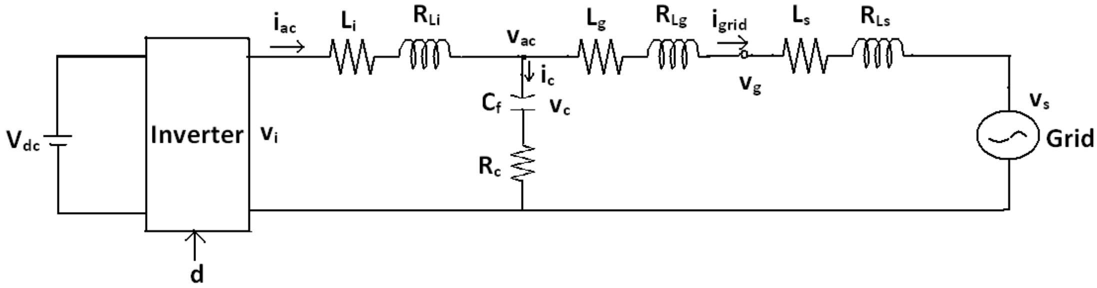

Figure 2. DC/AC inverter equivalent circuit

The state model of the DC/AC inverter, obtained from its equivalent circuit shown in figure 1 is,

$$\begin{bmatrix} L_i & 0 & R_c C_f \\ 0 & L_g + L_s & -R_c C_f \\ 0 & 0 & C_f \end{bmatrix} \begin{bmatrix} \frac{di_{ac}}{dt} \\ \frac{di_g}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} R_{Li} & 0 & -1 \\ 0 & -R_{Lg} - R_{Ls} & 1 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} i_{ac} \\ i_g \\ V_c \end{bmatrix} + \begin{bmatrix} V_{dc} & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} d \\ V_s \\ V_i \end{bmatrix} \quad (21)$$

Three state variables i_{ac} , i_g and V_c are the inverter-side inductor current, grid-side inductor current and capacitor voltage, respectively. The excitation signals *d,* the grid voltage V_s *and* V_i are the control inputs.

The state space model of DC/AC inverter then converted into its corresponding transfer function model using the following equation.

$$T(s) = C[sI - A]^{-1}B \quad (22)$$

The transfer function of the DC/AC inverter is

$$T(s) = \frac{7901.2}{-0.0816s - 9.9160}$$

2. Minimum order observer for wind turbine and fuel cell.

Let the closed loop poles be located at,

$$s_1 = -2 + j2\sqrt{3} \quad (23)$$

$$s_2 = -2 - j2\sqrt{3} \quad (24)$$

$$s_3 = -6 \quad (25)$$

Let the desired observer poles are located at,

S=-10, s= -10 (26)

The characteristic equation for minimum order observer is,

$$|sI - A_{bb} + K_e A_b| = (s - \mu_1)(s - \mu_2) \quad (25)$$

The Aukermann's formula is used to obtain the state observer gain matrix as follows

$$K_e = \varphi(A_{bb}) \begin{bmatrix} A_{ab} \\ A_{ab}A_{bb} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (27)$$

Where,

$$\varphi(A_{bb}) = A_{bb}{}^2 + \hat{\alpha_1} A_{bb} + \hat{\alpha_2} I = A_{bb}{}^2 + 20A_{bb} + 100I \quad (28)$$

$$K_e = \begin{bmatrix} 20 \\ 101 \end{bmatrix} \quad (29)$$

Where K_e is called as state observer gain matrix of wind turbine, using this K_e, transfer function equation

$$T(s) = C[sI - A]^{-1}B, \quad (30)$$

The transfer function of wind turbine is

$$T(s) = \frac{19.4s^2 + 19.4}{s^3 + s} \quad (31)$$

Its corresponding observer's transfer function is

$$T\,(obs) = \frac{0.9928s + 24}{s + 24.1} \quad (32)$$

$$K_{e1} = \begin{bmatrix} 0.0512 \\ 0.0527 \end{bmatrix} \quad (33)$$

Where K_{e1} is called as state observer gain matrix of fuel cell.
The transfer function of fuel cell is

$$T(s) = \frac{0.0032s + 6.2534}{0.0036s + 4.8335} \quad (34)$$

Its corresponding observer's transfer function is

$$T_{obs}(s) = \frac{0.034s + 3.7149}{-0.0024s + 1.3530} \quad (35)$$

3. Simulink circuits

The simulink circuits are shown and discussed as below.

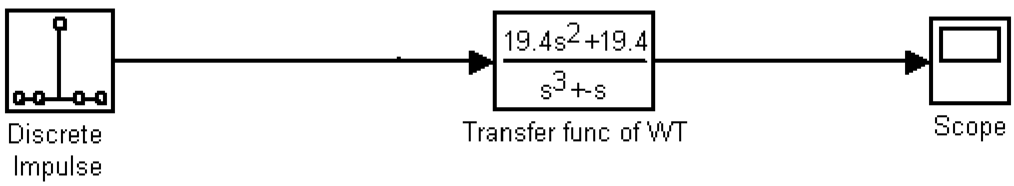

Figure 3. Wind Turbine in openloop configuration

The transfer function of wind turbine obtained as before is the plant model, which discrete impulse signal is given as input and its response is obtained.

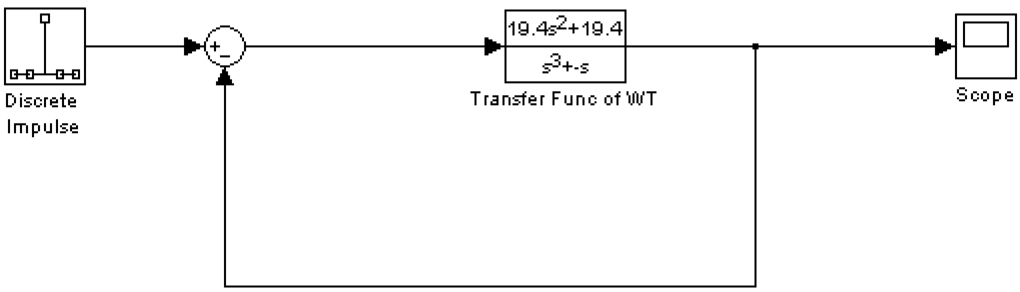

Figure 4. Wind Turbine in closed loop configuration.

The transfer function of wind turbine obtained as before is the plant model, which discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

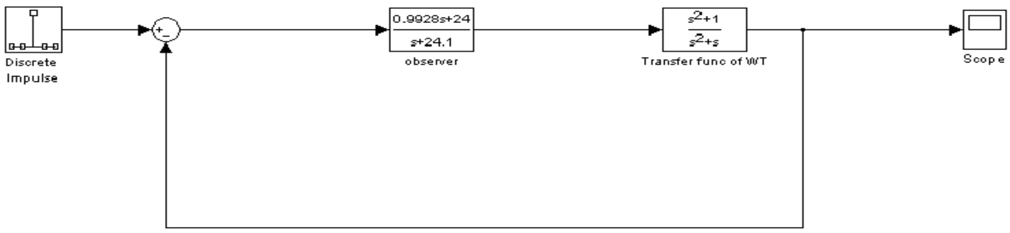

Figure 5. Closed loop configuration of the Wind Turbine with observer.

The transfer function of wind turbine obtained as before is the plant model, which is connected in series with an observer. This observer estimates the state variables of the wind turbine and compares with the actual state variables of the actual model, thereby generates a control vector which provides the necessary control actions so that the output of the source is optimized. Discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

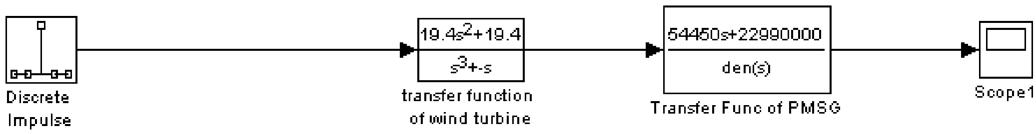

Figure 6. Wind Turbine driven PMSG in open loop configuration

The transfer function of wind turbine obtained as before is the plant model is connected in series with the PMSG, which discrete impulse signal is given as input and its response is obtained.

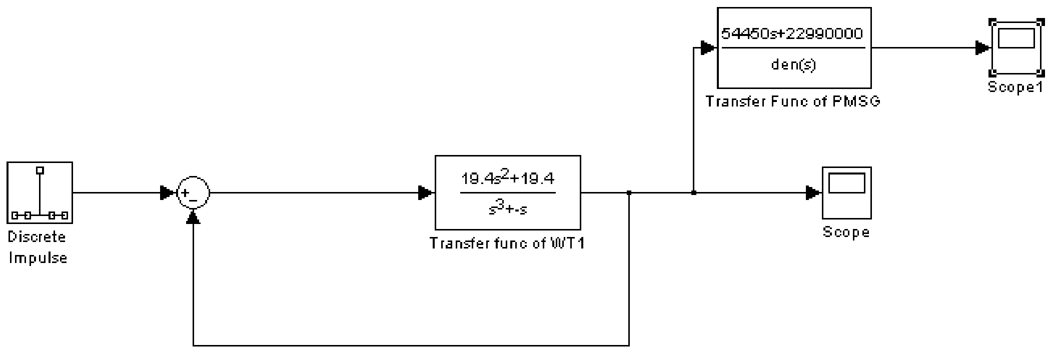

Figure 7. Wind Turbine driven PMSG in closed loop configuration.

The transfer function of wind turbine obtained as before is the plant model is connected in series with the PMSG, which discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

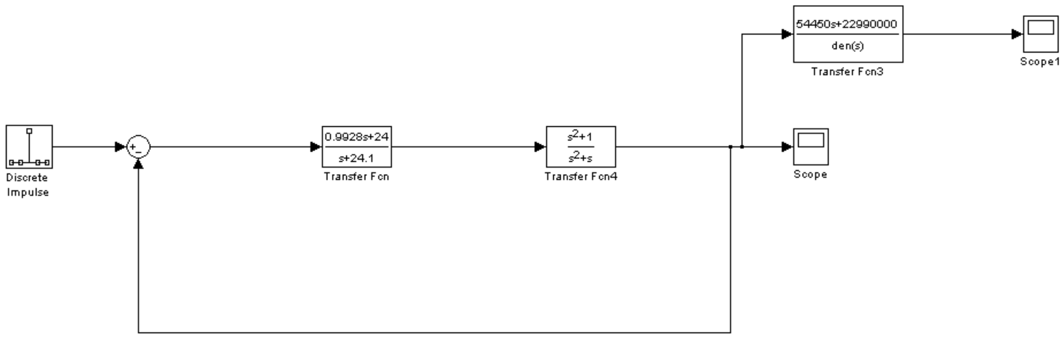

Figure 8. Wind Turbine driven PMSG in closed loop configuration with minimum order observer

The transfer function of wind turbine obtained as before is the plant model, which is connected in series with PMSG and an observer. This observer estimates the state variables of the wind turbine and compares this with the actual state variables of the actual model, thereby generates a control vector which provides the necessary control actions so that the output of the source is optimized. Discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

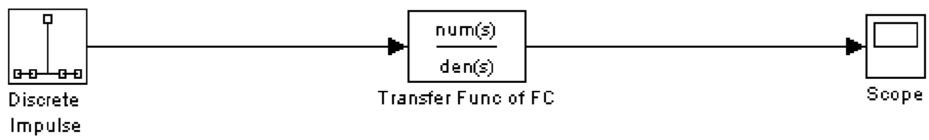

Figure 9. Simulink circuit of the model of fuel cell in open loop configuration

The transfer function of fuel cell obtained as before is the plant model, which discrete impulse signal is given as input and its response is obtained.

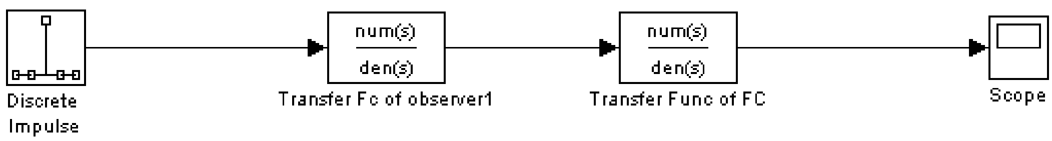

Figure 10. Simulink circuit of the model of fuel cell incorporated with minimum order observer in open loop configuration.

The transfer function of fuel cell obtained as before is the plant model is connected in series with the observer, which discrete impulse signal is given as input and its response is obtained.

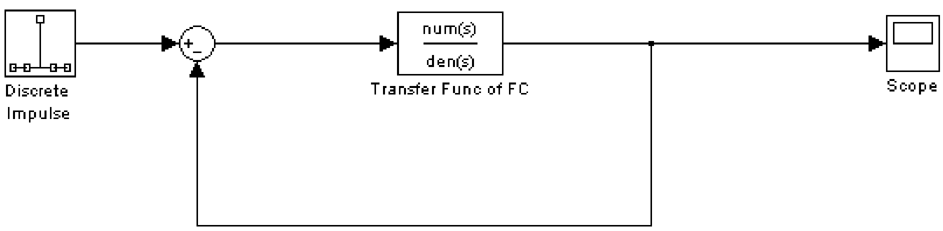

Figure 11. Simulink circuit of the model of fuel cell in closed loop configuration.

The transfer function of fuel cell obtained as before is the plant model, which discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

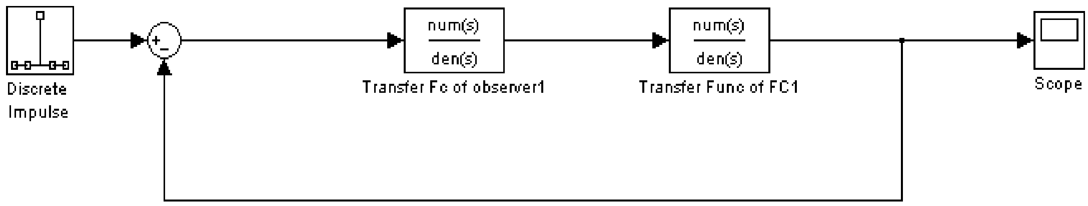

Figure 12. Simulink circuit of the model of fuel cell system in closed loop configuration with the implementation of minimum order observer.

The transfer function of fuel cell system obtained as before is the plant model, which is connected in series with an observer. This observer estimates the state variables of the fuel cell and compares this with the actual state variables of the actual model, thereby generates a control vector. Discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

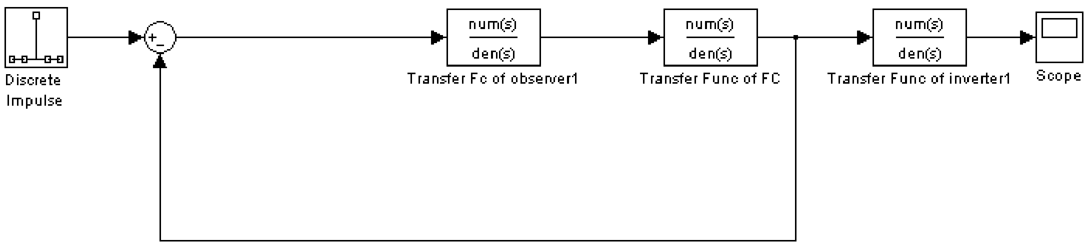

Figure 13. Simulink circuit of the model of fuel cell system interfaced to DC/AC inverter in closed loop configuration with the implementation minimum order observer.

The transfer function of fuel cell system obtained as before is the plant model, which is connected in series with inverter and an observer. This observer estimates the state variables and generates a control vector to provide the necessary control actions. Discrete impulse signal is given as input and a negative unity feedback is given to achieve closed loop configuration and its response is obtained.

4. Results and Analysis

The response of the model of WT in open loop configuration is shown in figure 14. It can be observed that the response goes infinite as the time progresses. It can be concluded that the system is unstable.

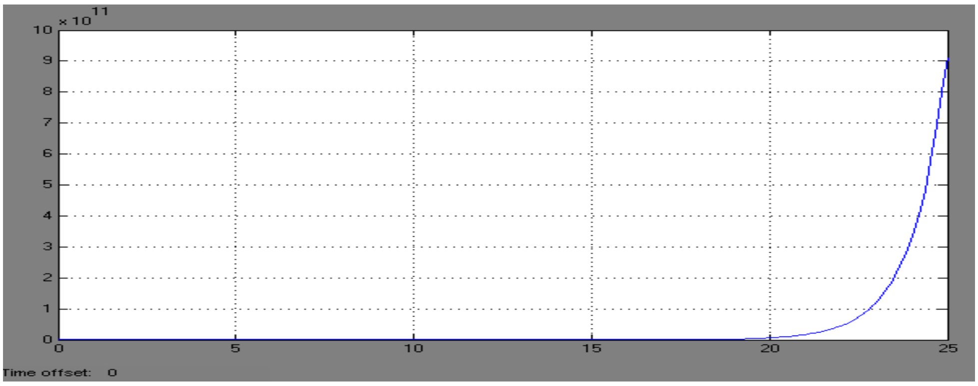

Figure 14. Impulse Response of WTS in open loop configuration.

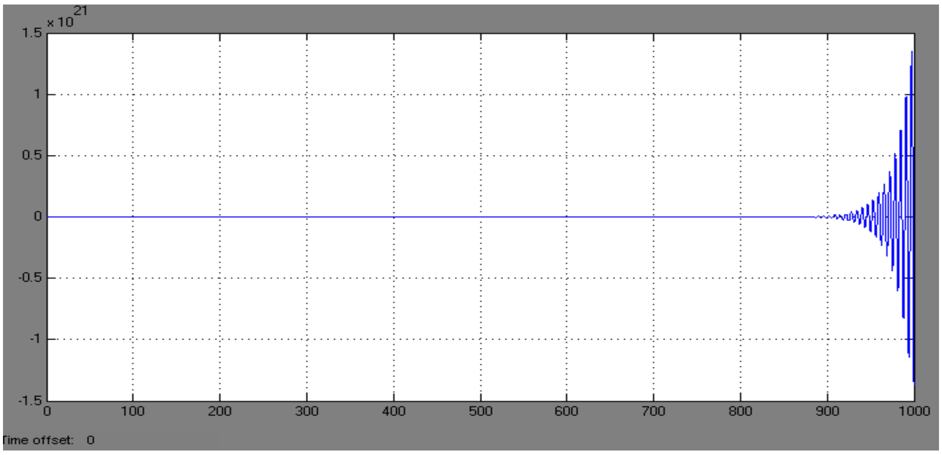

Figure 15. Impulse Response of the WTS in closed loop configuration.

The response of the model of WT in closed loop configuration is shown in figure 15. It can be observed that the response oscillates as the time progresses. It can be concluded that the system is unstable.

The response of the model of WT in closed loop configuration with the implementation of minimum order observer is shown in figure 16. It can be observed that the response settle down at zero gradually, results that the system is stable.

The response of the model of WT driven PMSG in open loop configuration is shown in figure 17. It can be observed that the response goes infinite as the time progresses. It can be concluded that the system is unstable.

The response of the model of WT driven PMSG in closed loop configuration is shown in figure 18. It can be observed that the response oscillates as the time progresses. It can be concluded that the system is marginally stable.

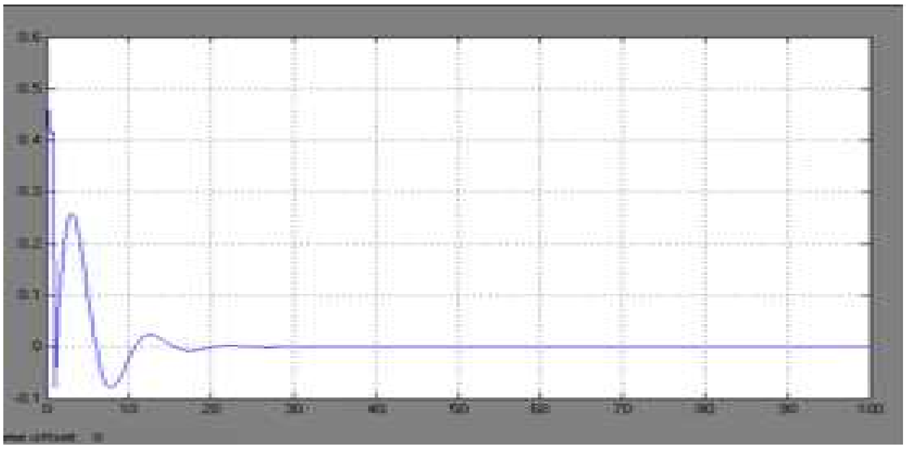

Figure 16. Impulse Response of the model of WT in closed loop Configuration with observer

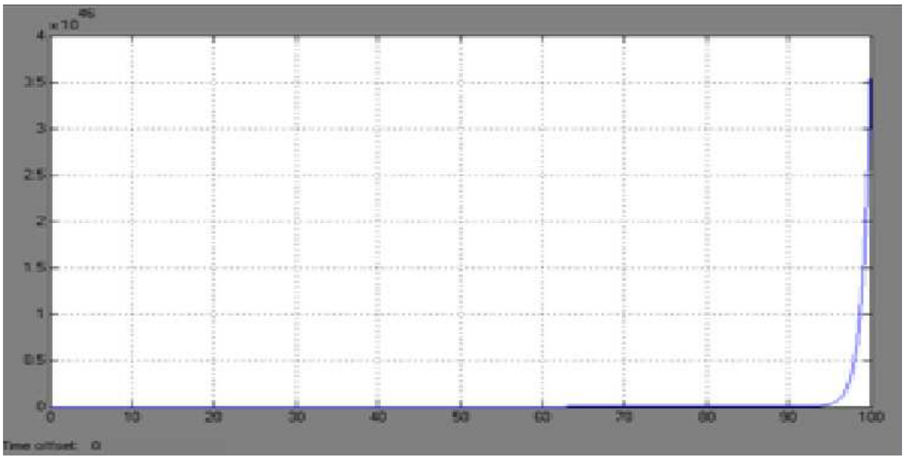

Figure17. Impulse Response of the WT driven PMSG in open loop configuration

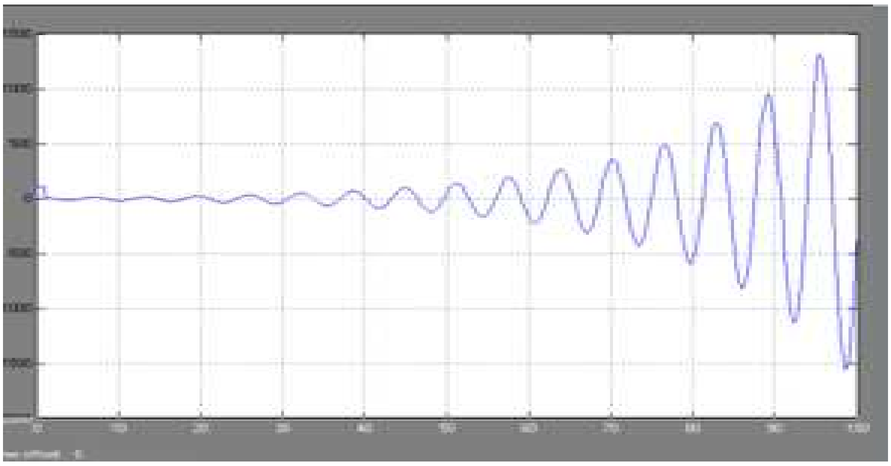

Figure 18. Impulse Response of the WT has driven PMSG in closed loop configuration.

The impulse response of the overall system which includes the observer is shown in figure 19. It can be observed that the response dies out as the time progresses. It can be concluded that the system is stable.

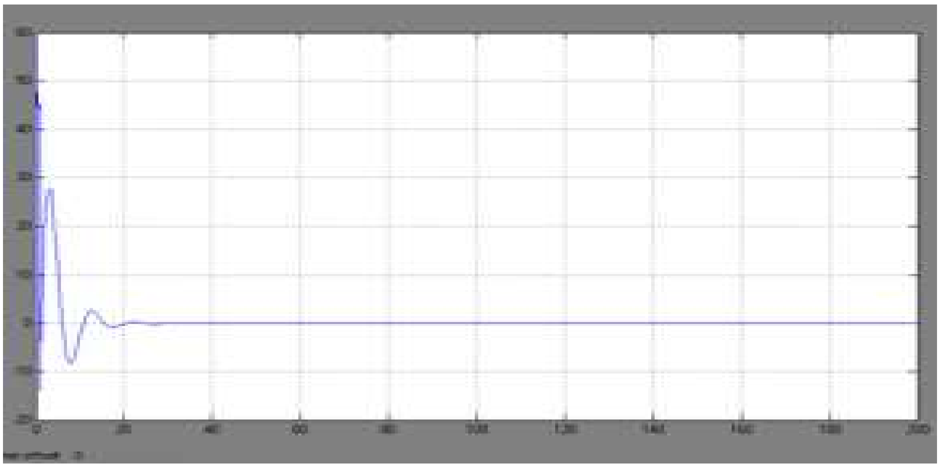

Figure19. Impulse response of the overall system with the implementation of the minimum order observer

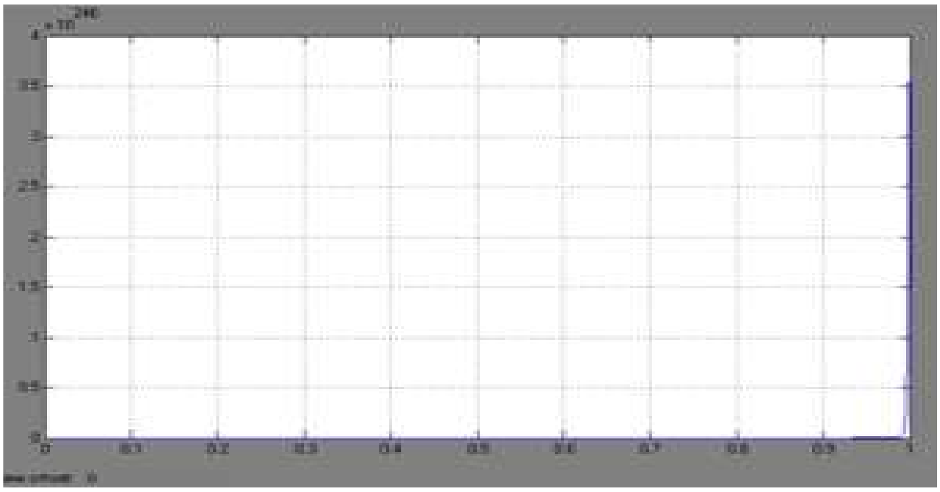

Figure 20. Impulse response of the fuel cell model in open loop configuration

The response of fuel cell model in open loop configuration is shown in figure 20. It can be observed that the response goes infinite as the time progresses. It can be concluded that the system is unstable.

The response of the fuel cell model incorporated with minimum order observer in open loop configuration is shown in figure 21. It can be observed that the response goes infinite as the time progresses. It can be concluded that the system is unstable.

The response of the model of fuel cell in closed loop is shown in figure 22. It can be observed that the response settle down to zero gradually, results that the system is stable.

The response of the model of fuel cell in closed loop configuration with the implementation of minimum order observer is shown in figure 23. It can be observed that the response settle down to zero gradually, results that the system is stable.

The response of the model of fuel cell incorporated in closed loop configuration with the implementation of minimum order observer is shown in figure 24. It can be observed that the response settle down to zero gradually, results that the system is stable

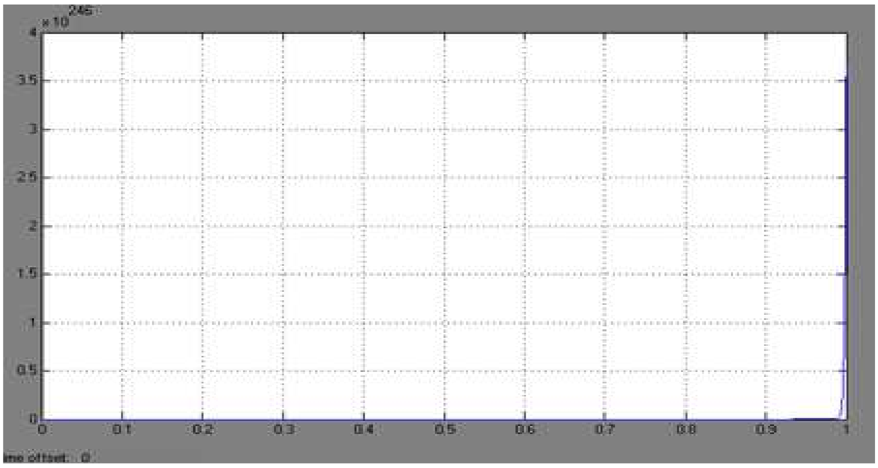

Figure 21. Impulse response of the model of fuel cell incorporated with minimum order observer in open loop configuration.

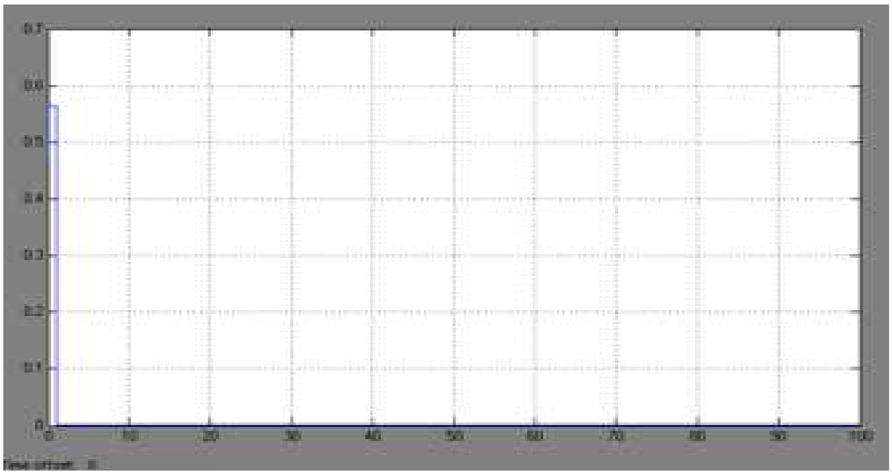

Figure 22. Impulse response of the model of fuel cell in closed loop configuration.

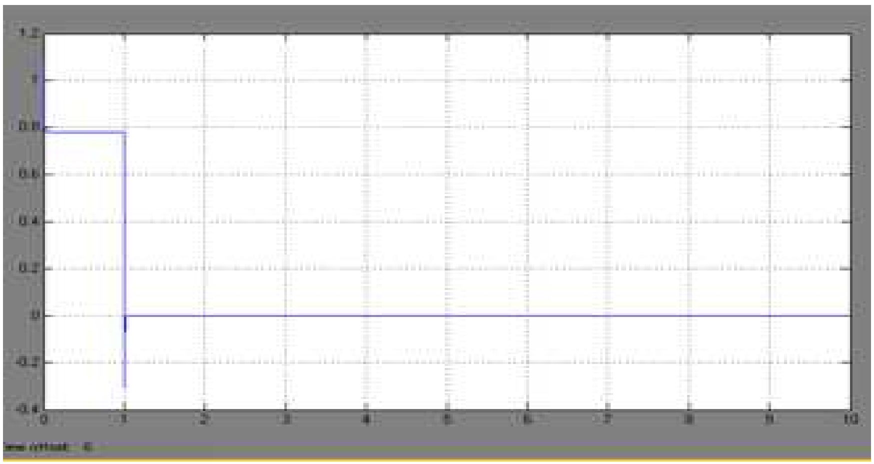

Figure 23. Impulse response of the model of fuel cell system in closed loop configuration with the implementation of minimum order observer.

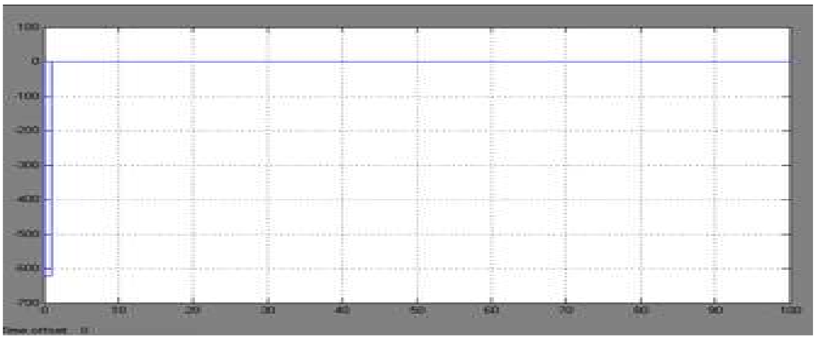

Figure 24. Impulse Response of the model of fuel cell system interfaced to DC/AC inverter in closed loop configuration with the implementation minimum order observer.

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5. Conclusion

For renewable energy sources in a practical system, continuous monitoring of the output of them is required which can be done by the use of state observers.

In this paper, minimum order observers have been designed independently for wind turbine and fuel cells which are used for the continuous estimation of state variable of wind turbine and fuel cell system.

Three different configurations were simulated, namely the wind turbine and fuel cell system under open loop configuration, closed loop configuration with and without observer. In open loop and closed loop configurations (without observer), the system may or not be stable. In the former one, there is no continuous monitoring of system and estimation of state variables and in latter, even though there is continuous monitoring of system, there is no continuous estimation of state variables. However, under closed configuration with the observer, the system should be stable, i.e. the impulse response of the system should tend towards zero.

It was observed that the wind turbine and fuel cell system incorporated with minimum order observer is stable due to continuous monitoring and estimation of state variables. MATLAB/Simulink is used to validate this. The impulse responses obtained are shown and the inferences are made.

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