Minimum-Order Observers for hybrid Wind Turbine and Fuel cell System

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***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 thus, necessitates the incorporation of an observer in the existing system which estimates the state variables continuously. This paper proposes a novel method of designing 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. Two different configurations are made use for the simulation. The plant model alone in its closed loop form and the plant with the designed minimum order observer with closed loop 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. Matlab/Simulink is used for validating the proposed idea.**

***Keywords*--Minimum Order Observer, Renewable Energy Sources, Wind Turbine, State model, Fuel cells, Impulse Response, Stability, PMSG, Ackermann's formula, Gain matrix.**

I. 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 gains attention.

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

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], it 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, the kinetic energy of the air (for WECS) and the inverter current, inductor current etc., (for Fuel Cells) need to be continuously monitored. 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.

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 that of the FC and the FC based inverter system are directly taken from [8] and [9] respectively. After the design of the observer, the transfer function of it and the system are connected in two different configurations as explained in 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 are stable.

II. PROPOSED METHOD

A. *Block Diagram*

The state model of the wind turbine and the fuel cell are obtained as discussed in the later sections.As 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 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.

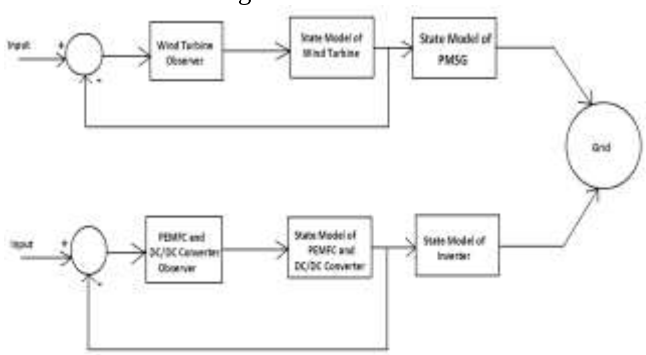

Figure 1. Grid integrated system with the implementation of minimum order observer.

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 are optimized. This is actually equivalent to connecting 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.

B. *State Model of WT PMSG 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:

$$x_1 = x \tag{1}$$

$$x'_1 = x_2 = v \tag{2}$$

$$x'_2 = x_3 = E \tag{3}$$

$$x'_3 = P = mx_2 + 193998u \tag{4}$$

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

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

where,

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

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

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

$$V_d = R_s i_d + P\varphi_d - \omega_r \varphi_q \tag{7}$$

$$V_q = R_s i_q + P\varphi_q + \omega_r \varphi_d \tag{8}$$

Such that the state model of PMSG is

$$\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -338.23 & 314 \\ -314.15 & -338.23 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 24 \\ 10 \end{bmatrix} u \tag{9}$$

C. *State Model of FC-Inverter System*

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

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

$$u = [u_1]^T = [d]^T \tag{11}$$

$$y = [y_1 \quad y_2]^T = [i_L \quad V_c]^T \tag{12}$$

The state variables are defined as follows:

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

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

$$V'_{CFC} = \frac{1}{c}\left(i_L - \frac{V_c}{r_0}\right) \tag{15}$$

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

$$V'_{CFC} = \frac{1}{c}\left(i_L + \frac{V_c}{r_0}\right) \tag{16}$$

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

The state equation is,

$$[i'_L \quad V'_c \quad V'_{CFC}]^T = \begin{bmatrix} \frac{R_{ohm}}{L} & \frac{-1}{L} & \frac{1}{L} \\ 0 & \frac{-1}{Cr_0} & 0 \\ \frac{1}{c} & 0 & \frac{1}{Cr_0} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \\ V_{CFC} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{1}{L} \\ 0 & \frac{2}{Cr_0} \\ 0 & 0 \end{bmatrix} u \tag{17}$$

On substituting values for the parameters in the matrix,

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

$$B = \begin{bmatrix} 13157.8 & 13157.8 \\ 0 & 2772 \\ 0 & 0 \end{bmatrix} \tag{19}$$

The output equation of the model is,

$$y = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ V_c \\ V_{CFC} \end{bmatrix} \qquad (20)$$

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

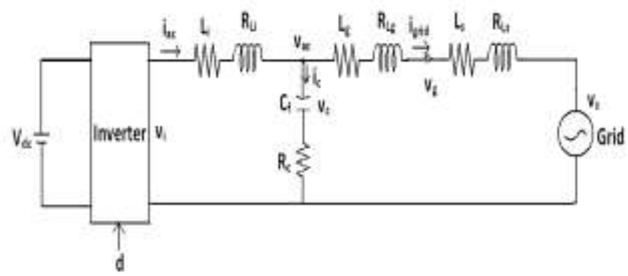

Fig ure 2. DC/AC inverter equivalent circuit

The state model of the DC/AC inverter, obtained from its equivalent circuit shown in fig(2) is,

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

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_z *and* V_i are the control inputs.

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

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

The transfer function of the DC/AC inverter is

$$T(s) = \frac{7901.2}{-0.0816s - 9.9160} \qquad (22a)$$

III. MINIMUM ORDER OBSERVERS FOR WIND TURBINE & FUEL CELL.

Let the closed loop poles be located at,

$$s_1 = -2 + j2\sqrt{3} \qquad (23)$$
$$s_2 = -2 - j2\sqrt{3} \qquad (24)$$
$$s_3 = -6 \qquad (25)$$

Let the desired observer poles are located at,

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

The characteristic equation for minimum order observer is,

$$|sI - A_{bb} + K_e A_b| = (s - \mu_1)(s - \mu_2) \qquad (27)$$

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

$$K_e = \varphi(A_{bb}) \begin{bmatrix} A_{ab} \\ A_{ab}A_{bb} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad (28)$$

Where,

$$\varphi(A_{bb}) = A_{bb}{}^2 + \widehat{\alpha_1} A_{bb} + \widehat{\alpha_2} I = A_{bb}{}^2 + 20A_{bb} + 100I \qquad (29)$$

$$K_e = \begin{bmatrix} 20 \\ 101 \end{bmatrix} \qquad (30)$$

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

$$T(s) = C\,[sI - A]^{-1}B, \qquad (31)$$

The transfer function of wind turbine is

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

Its corresponding observer's transfer function is

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

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

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

The transfer function of fuel cell is

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

Its corresponding observer's transfer function is

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

IV. SIMULINK CIRCUITS

The simulink circuits are shown and discussed as below.

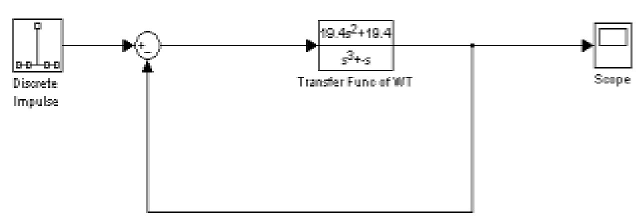

Figure 3. Wind Turbine in closed loop configuration

The transfer function of wind turbine obtained as before is the plant model, to 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.

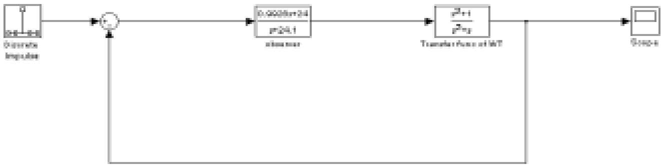

Figure 4. Closed loop configuration of the Wind Turbine with observer.

The transfer function of wind turbine obtained as before is the plant model, which is connected, is series with 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.

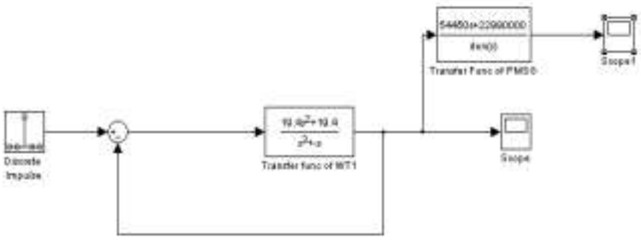

Figure 5. Wind Turbine driven PMSG in closed loop configuration.

The transfer function of wind turbine obtained as before is the plant model is connected in series with the PMSG, to 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.

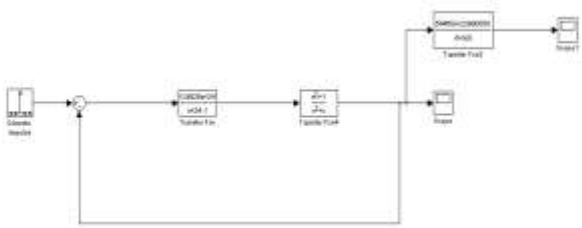

Figure 6. Wind Turbine driven PMSG in closed loop configuration with minimum order observer

The transfer function of wind turbine obtained as before is the plant model, which is connected, is 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.

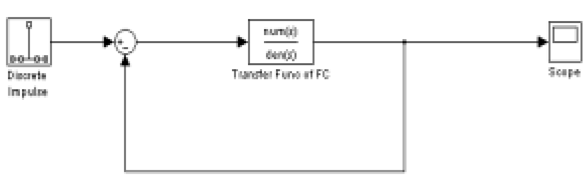

Figure 7. Simulink circuit of the model of fuel cell in closed loop configuration.

The transfer function of fuel cell obtained as before is the plant model, to 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.

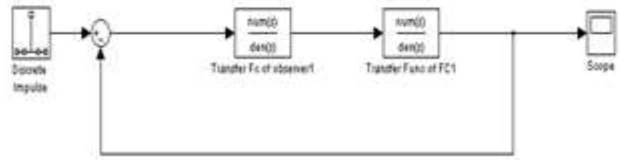

Figure 8 . Simulink circuit of the model of fuel cell system in closed loop configuration with minimum order observer.

The transfer function of fuel cell system obtained as before is the plant model, which is connected, is 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.

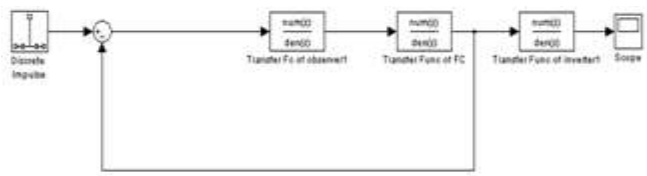

Figure 9. Simulink circuit of the model of fuel cell system interfaced to DC/AC inverter in closed loop configuration with the implementation minimum order observer.

The transfer function of fuel cell system obtained as before is the plant model, which is connected, is 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.

V. Results and Analysis

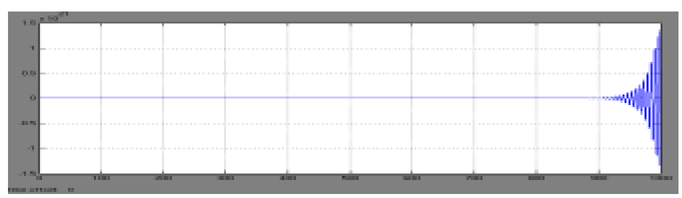

Figure 10. Impulse Response of the WTS in closed loop configuration.

Pertaining to figure 3, it can be observed from figure 10 that the response oscillates as the time progresses. It can thus be concluded that the system is unstable.

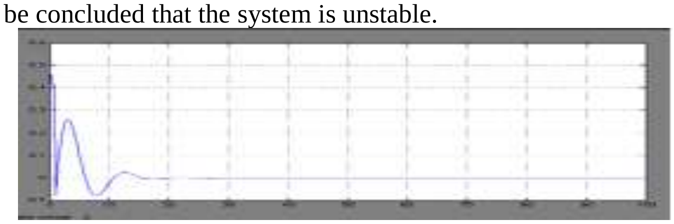

Figure 11. Impulse Response of the model of WT in closed loop Configuration with observer.

With reference to the circuit in figure 4, figure 11 shows that the response settles down to zero gradually, concluding that the system is stable.

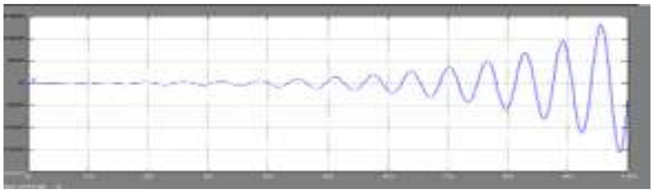

Figure 12. Impulse Response of the WT driven PMSG in closed loop Configuration.

Corresponding to figure 5, it can be observed from figure 12 that the response oscillates as the time progresses. It can thus be concluded that the system is marginally stable.

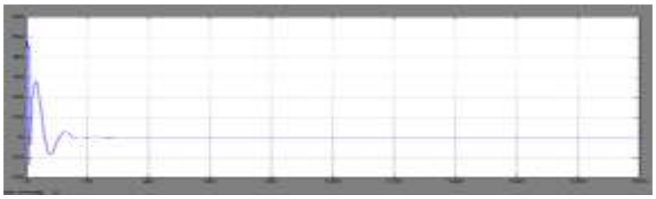

Figure 13. Impulse response of the overall system with minimum order observer.

With respect to figure 6, it can be observed from figure 13 that the response dies out as the time progresses which shows the system is stable.

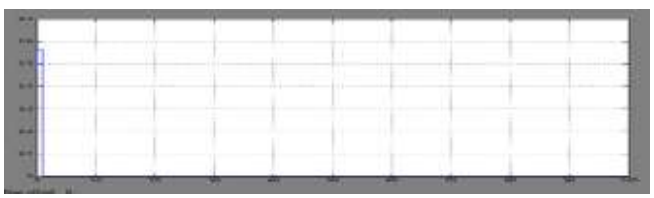

Figure 14. Impulse response of the model of fuel cell in closed loop configuration.

It can be observed from figure 14 which corresponds to figure 7 that the response settles down to zero gradually, showing that the system is stable.

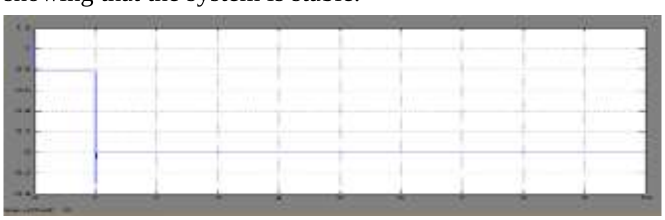

Figure 15. Impulse response of the model of fuel cell system in closed loop configuration with minimum order observer.

Figure 15 with respect to figure 8 shows the system is stable as the response dies out to zero.

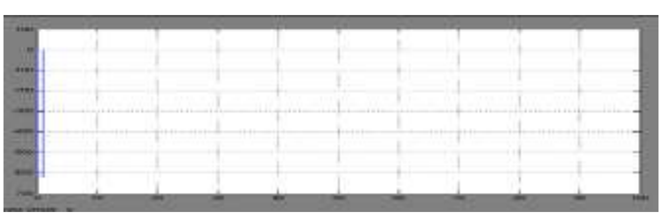

Figure 16. Impulse Response of the model of fuel cell in closed loop configuration with the implementation minimum order observer.

Figure 16 shows the response that corresponds to figure 9. It can be understood that the system is stable as the impulse response settles down to zero as the time progresses.

CONCLUSION

For renewable energy sources in a practical system, continuous monitoring of the output 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 cell system which are used for the continuous estimation of state variable.

Two different configurations, were simulated, namely the wind turbine and fuel cell system under closed loop configuration with and without observer. In closed loop configuration without the observer, the system may or not be stable. In this there is continuous monitoring of the system but there is no continuous estimation of state variables. However, under closed loop configuration with the observer, the state variables are monitored and estimated continuously. Also impulse response of the system dies out to zero which shows the system is stable. MATLAB/SIMULINK is used to validate this. The impulse responses obtained are shown and the inferences are made.

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