Mathematical Modeling of Isolated Wind-Diesel-Solar Photo Voltaic Hybrid Power System for Load Frequency Control

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Abstract: This research presents the mathematical model of an isolated wind-diesel-solar PV hybrid power system with conventional proportional-plus-integral controllers for load frequency control (LFC). In order to enhance the reliability of the power supply, renewable sources such as wind and solar energy are integrated with diesel electric power generation system to supply the power for isolated loads. Isolated hybrid power system is designed to minimize the mismatch between supply and demand. Due to the unstable generation of power from wind, solar PV sources, and frequent change in load, there exist fluctuations of power generation and hence fluctuations also occur in system frequency and voltage. Conventional PI controllers are used for the load frequency control of the system to make the frequency deviation to an acceptable range. In this paper the complete mathematical modeling of system consisting of a wind turbine induction generator unit, a diesel engine synchronous alternator unit and solar photovoltaic (PV) panels with maximum power tracking converter is presented.

Keywords: Wind Turbines, Diesel Generator, Photo Voltaic, Load Frequency Control

1. Introduction

There are several important reasons that make renewable energy important for the future of our society. By using renewable energy instead of fossil fuels, we can significantly decrease the current levels of greenhouse gas emissions. Renewable energy such as solar energy and wind energy are endless resources as compared to the conventional fossil fuels. Owing to high demand of electricity in modern society and wide gap between supply and demand it is very difficult to fulfill the need of electricity only with the conventional sources. Therefore, renewable energy sources such as solar, wind, biomass etc. are emerging in today world. However both wind and solar energy are intermittent in nature which not only changes the generation but also affect the system voltage and frequency. Hence, solar PV and wind power generations are integrated with diesel system in order to supply reliable, secure and economical power to the isolated loads.

Due to the fluctuations in frequency, system becomes unstable and hence effective controllers are required for maintaining the system frequency to an acceptable range either by maintaining the load fluctuation or by controlling the generation. There are different control strategies to control the mismatch between load and generation. Different strategies are priority switched load control, fly wheel, dump load control, battery energy storage and superconducting magnetic energy storage. These strategies are expensive and they have their own limitations.

In this research, detailed analytical study for an isolated wind-diesel-solar PV hybrid power system with complete mathematical modeling under transient conditions by considering a small signal transfer function model is done. The configuration of an isolated wind-diesel-solar PV hybrid power system is shown in figure 1.

![Figure 1: Configuration of an isolated Wind-Diesel-Solar PV hybrid power system](image)

2. Mathematical Modeling of System

2.1 Mathematical modeling of solar PV system

PV panel model consists of solar cells and each panel is made from the different series-parallel combination of these solar cells. Every solar cell acts as a p-n diode and hence current passes from one side to the other side. The equivalent circuit of a solar cell is shown in figure 2.
The change in temperature and irradiation is the step input in the PV panel.

From the mathematical model of the solar photo voltaic, the transfer function block diagram of the solar PV generating system is developed as shown in Figure 4.

**2.2 Mathematical modeling of Diesel System**

The conversion of fuel energy (diesel or bio- diesel) into mechanical energy and then into electric energy is due to the act of diesel generator sets [16]. Imbalance occurs between the real power generation and the load demand (plus losses) which causes kinetic energy of rotation to be either added to or taken from the generating units (generator shaft either speed up or slow down). This varies the frequency of the system [17], and the governor maintains the balance between the input and output by changing the turbine output and the PI controller uses a system frequency deviation of the power system as a feedback input.

The transfer function of the mechanical speed-governing system in diesel unit can be written in partial fraction form as in equation 8.

\[
\frac{\Delta P_{cd}(s)}{\Delta T_d(s)} = \frac{K_1}{(1+Ts)} + \frac{K_2}{(1+Ts)^2} \tag{8}
\]

Where

\[
K_1 = \frac{K_d(1+Ts_1)}{(1+Ts_2)(1+Ts_3)} \text{ at } s = -\frac{1}{Ts_2} \tag{9}
\]

And

\[
K_2 = \frac{K_d(1+Ts_1)}{(1+Ts_2)(1+Ts_3)} \text{ at } s = -\frac{1}{Ts_3} \tag{10}
\]

\(T_{d1}, T_{d2} \text{ and } T_{d3} \) are the time constants of the speed governing mechanism and \(K_d\) is the part of power supplied by diesel power generation to the load. Equation (8) can be written in terms of the canonical state variables \(\Delta X_{E_1}, \Delta X_{E_2}\),

\[
\frac{K_d(1+Ts_1)}{(1+Ts_2)(1+Ts_3)} \left[ \Delta P_{cd}(s) - \frac{1}{R_d} \Delta F(s) \right] = \Delta X_{E_1}(s) + X_{E_2}(s) \tag{11}
\]
Where Rd is the speed regulation due to the governor speed action and from equation (8) and equation (11), we get
\[
\Delta X_{\text{ED11}}(s) = \frac{K_1}{1+stD_2} \left( \Delta P_{\text{cd}}(s) - \frac{1}{Rd} \Delta F_t(s) \right) \tag{12}
\]
And
\[
\Delta X_{\text{ED21}}(s) = \frac{K_2}{1+stD_3} \left( \Delta P_{\text{cd}}(s) - \frac{1}{Rd} \Delta F_t(s) \right) \tag{13}
\]
Therefore, the state differential equations of the mechanical speed governing mechanism are written in equations (14) and (15).
\[
\frac{d}{dt} \Delta X_{\text{ED11}} = \frac{1}{T_d} \Delta X_{\text{ED11}} - \frac{K_d T_d (T_d D_2 - T_d D_3)}{T_d D_2 T_d (T_d - D_2)} \Delta F_t + \frac{K_d D_2}{T_d D_2} \Delta P_{\text{cd}} \tag{14}
\]
\[
\frac{d}{dt} \Delta X_{\text{ED21}} = \frac{1}{T_d} \Delta X_{\text{ED21}} - \frac{K_d T_d (T_d D_3 - D_3)}{T_d D_3 T_d (T_d - D_3)} \Delta F_t + \frac{K_d D_3}{T_d D_3} \Delta P_{\text{cd}} \tag{15}
\]
The transfer function equation for the change in diesel power generation \( \Delta P_{\text{gd}} \), can be written in terms of the state variables as
\[
\Delta P_{\text{gd}}(s) = \frac{1}{1+stD_4} \left( \Delta X_{\text{ED11}}(s) + \Delta X_{\text{ED21}}(s) \right) \tag{16}
\]
\[
\frac{d}{dt} \Delta P_{\text{gd}} = \frac{1}{T_d} \Delta P_{\text{gd}} + \frac{1}{T_d} \Delta X_{\text{ED11}} + \frac{1}{T_d} \Delta X_{\text{ED21}} \tag{17}
\]
The transfer function block diagram of the diesel-generating unit is shown in figure 5.

Figure 5: Transfer function model of diesel system

2.3 Mathematical Modeling of Wind System

In the wind-turbine generating unit, blade pitch controller constantly maintains the wind power generation. The intermittent wind power may affect the power quality of an isolated wind-diesel-Solar PV hybrid power system and the deviations in generating power and frequency fluctuations are eliminated by blade pitch control mechanism, which continuously monitors the wind turbine speed and acts accordingly in an active feedback control system added to the turbine.

The transfer function equation for the wind generation system is,
\[
\Delta F_t(s) = \frac{1}{1+stT_w} \left[ -\Delta P_{\text{gw}}(s) + \Delta P_{\text{iw}}(s) + \Delta P_{\text{cw}}(s) + K_{\text{tp}} \Delta F_t(s) \right] \tag{18}
\]
and
\[
\Delta P_{\text{gw}}(s) = K_{\text{ig}} \left[ \Delta F_t(s) - \Delta F_s(s) \right] \tag{19}
\]
Where
\( T_w \) is the time constant of the wind-turbine power generation system in sec.
\( K_{\text{ig}} \) is a function of slip and is the part of power supplied by wind-power generation to load.
\( K_{\text{tp}} \) is the co-efficient that depends on the slope and curve of the wind turbine \[18\]

From Equation (18) and Equation (19) the state differential equation can be written as
\[
\frac{d}{dt} \Delta F_t(s) = -\frac{1+K_{\text{ig}} K_{\text{tp}}}{T_w} \Delta F_t + \frac{K_{\text{ig}}}{T_w} \Delta F_s + \frac{1}{T_w} \Delta P_{\text{cw}} \tag{20}
\]
The real power load change \( \Delta P_l \) or change in wind power generation \( \Delta P_{\text{gw}} \) experienced by the hybrid system deviates the power generation from a specified level and the power generation of the hybrid system can be maintained by the diesel engine controller by changing its power generation by an amount \( \Delta P_{\text{gd}} \). The net surplus power \( \Delta P_{\text{gd}} \) will be absorbed by the system either by increasing the kinetic energy of the system or by increased load consumption.

The surplus power is,
\[
\Delta P_{l} = [ \Delta P_{\text{gd}} + \Delta P_{\text{gw}} - \Delta P_{l} ] \tag{21}
\]
The transfer function equation of the system subjected to change in real power load or input wind power can be written as in equation (22).
\[
\Delta F_s = \frac{K_{\text{p}}}{1+sT_w} \left[ \Delta P_{\text{gd}}(s) + \Delta P_{\text{gw}}(s) - \Delta P_{l}(s) \right] \tag{22}
\]
Where
\[
K_{\text{p}} = \frac{1}{D}
\]
\[
D = \frac{\partial P_l}{\partial F_s}
\]
\[
T_p = \frac{2H}{F_s D}
\]
\( H \) = P.U. Inertia constant
\( F_s \) = Nominal system frequency
\( D \) = Damping coefficient

The state differential equation is represented by equation (23).
\[
\frac{d}{dt} \Delta F_t = -\frac{1+K_{\text{ig}} K_{\text{tp}}}{T_p} \Delta F_t + \frac{K_{\text{ig}}}{T_p} \Delta P_{\text{gd}} + \frac{K_{\text{ig}} K_{\text{tp}}}{T_p} \Delta F_t - \frac{K_{\text{ig}}}{T_p} \Delta P_{\text{gw}} \tag{23}
\]
The combined transfer function of different blocks of the blade pitch control mechanism is given in equation (24).
\[
[ \frac{K_{\text{p}} \cdot K_{\text{tp}}}{1+sT_p} ] \left[ \frac{K_{\text{p}}}{1+sT_p} \right] \left[ \frac{K_{\text{p}} (1+sT_p)}{1+s} \right] \Delta P_{\text{cu}}(s) = \Delta P_{\text{cw}}(s) \tag{24}
\]
Where
\( T_p \) and \( T_p \) are the time constants of the hydraulic blade pitch actuator in sec
\( T_p \) and \( T_p \) are the time constant of the data fit pitch response unit
\( K_{\text{p}} \) and \( K_{\text{p}} \) are gain constants of the hydraulic pitch actuator
\( K_{\text{p}} \) is the gain constant of the data fit pitch response unit
\( K_{\text{p}} \) is the blade characteristic constant
Equation (24) can be written as

$$\frac{Kp_c Kp_3}{1+sT_p} [Kp_1 (T_p1 + \frac{1}{(1+s)T_p1})] \frac{Kp_2}{1+sT_p2} \Delta Pcu(s) = \Delta Pcw(s)$$

Equation (25) can be expressed in terms of intermediate state variables as

$$\Delta Pcw(s) = \frac{Kp_c Kp_3}{1+sT_p3} \Delta Pcu(s) + Kp_1.Tp1.\Delta Pcw(s)$$

$$\Delta Pcw(s) = \frac{(1-T_p1)}{(1+s)Kp_2} \Delta Pct(s)$$

$$\Delta Pcw(s) = \frac{1}{1+sT_p2} \Delta Pcu(s)$$

The state differential equations for the transfer function Equation (26), Equation (27) and Equation (28) are given by equations (29), (30) and (31) respectively.

$$\frac{d}{dt} \Delta Pcw = -\frac{1}{Tp3} \Delta Pcw + \frac{Kp_c Kp_3 Kp_1}{Tp3} \Delta Pct + \frac{Kp_1.Tp1.\Delta Pcw}{Tp3}$$

$$\frac{d}{dt} \Delta Pct = -\Delta Pct + \frac{(1-T_p1)}{Tp1} \Delta Pcw$$

$$\frac{d}{dt} \Delta Pcu = -\frac{1}{Tp2} \Delta Pcu + \frac{Kp_2}{Tp2} \Delta Pcw$$

The transfer function block diagram of the wind-turbine generation system with blade pitch controller is shown in figure 6.

![Figure 6: Transfer function model of wind system](image)

2.4 Overall System Modeling

The transfer function block diagram of an isolated wind-diesel-Solar PV hybrid power system is shown in figure 7. PI controllers are included in the transfer function block diagram model of the hybrid system for load frequency control. The input power to the wind side and solar PV side are not controllable. There is small real power mismatch and the system dynamics may be described by linear differential equations [19-22]. The functions of the controllers are used to eliminate the mismatch created either by the small real power load change or due to a change in input power. Conventional PI controllers are designed for the load frequency control of an isolated wind-diesel-solar PV hybrid power system. PI controller for a governor in diesel side, blade pitch controller in wind side and PI controller in solar PV system are designed individually for performance improvement of an isolated wind-diesel-solar PV hybrid power system, which is shown in the figure 7. The input power to the renewable sources of power generation is fluctuating, particularly in case of wind by nature and in case of solar PV system due to uncertainty in the availability of solar power. In figure 7, ΔFs and ΔFt represent, respectively, deviations in system frequency (60 Hz) and speed of the wind-turbine induction generator. ΔPgd, ΔPgsw and ΔPgs represent deviations in diesel, wind and PV power generation, respectively.

The dynamics of the wind power generating unit is described by a first order system and a higher order model [23-24] and the continuous time dynamic behavior of the load frequency control system is modelled by a set of state space differential equations of the form as in equation (32).

$$X = AX + Bu + Gr$$

Where

X, u and p are the state, control and disturbance vectors, respectively.

A, Band Γare real constant system matrices of appropriate dimensions.

The elements of the matrices in (32) along with the principal data of the system under study are given in [20].

![Figure 7: Transfer function block diagram for an isolated Wind-Diesel-Solar PV hybrid power system with controllers](image)
Mathematically, the transfer function of PI controller can be represented as,
\[
\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \tag{33}
\]

3.2 Modeling of PI Controller

The task of this thesis is to investigate the problem in the control of system frequency for an isolated hybrid power system using PI controller designed here. For PI controller type load frequency controller of proportional plus integral type in isolated wind-diesel-Solar PV hybrid power system in case of continuous case, to achieve zero steady state error in frequency, can be obtained by augmenting the state vector in (32). \(x_{n+1}\) and \(x_{n+2}\) are two additional state variables which are defined in equations (34) and (35). \[\text{[23]}\]

\[
X_{n+1} = \int \Delta F s \, dt \tag{34}
\]

\[
X_{n+2} = \int \Delta F t \, dt \tag{35}
\]

Therefore, the additional state differential equations can be written as
\[
\dot{X}_n + 1 = A_1 X \tag{36}
\]

\[
\dot{X}_n + 2 = A_2 X \tag{37}
\]

Equations (36) and (37) can be written in matrix form as
\[
\begin{bmatrix}
\dot{X}_n + 1 \\
\dot{X}_n + 2
\end{bmatrix} = A_1 X \tag{38}
\]

Now the state vector in equation (3.32) is modified by including the state variables defined in equations (34) and equation (35).

The augmented set of differential equations is shown in equation (39).
\[
\dot{x} = \begin{bmatrix} A & O_1 \\ A_1 & O_2 \end{bmatrix} \dot{X} + \begin{bmatrix} B \\ O_3 \end{bmatrix} u + \begin{bmatrix} \Gamma \\ O_4 \end{bmatrix} p \tag{39}
\]

Where \(O_1, O_2, O_3\) and \(O_4\) are null matrices of appropriate dimensions and the control vector ‘u’ can be expressed in terms of the augmented state vector as in equation (40)
\[
u = H \dot{X} \tag{40}
\]

Where
\[
H = \begin{bmatrix}
-K_d p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
K_i g k p p & 0 & 0 & -k i g k p p & 0 & 0 & 0 & 0 & k i g k p i & -k i g k p i
\end{bmatrix} \tag{41}
\]

Now the final augmented set of differential equations can be written as
\[
\dot{X} = A\dot{X} + \Gamma_p \tag{42}
\]

Where
\[
A = \begin{bmatrix} A_1 & O_2 \\ A_1 & O_2 \end{bmatrix} \tag{43}
\]

\[
\Gamma = \begin{bmatrix} \Gamma \\ 0 \end{bmatrix} \tag{44}
\]

4. Conclusion

A complete mathematical model of an isolated wind-diesel-solar photo voltaic system on the basis of small signal transfer function model together with controller design of the load frequency controller is modeled in the paper. This model can be further used in load frequency control with various optimization techniques.

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ISC  Short circuit current (A)  
IPV  Photovoltaic current (A)  
IPH  Photo current (A)  
ISAT  Saturation current (A)  
ID  Diode current (A)  
q  Charge of electron = 1.602*10^{-19} (C)  
RS  Resistance  
λ  Solar Irradiance (w/m²)  
T  Temperature of solar array (°C)  
A  Diode quality factor  
KI  short-circuit current  
VPV (min)  Minimum output voltage  
VPV (max)  Maximum output voltage of PV  
vo (max)  Maximum output voltage  
fsw  Switching frequency  
Io  Load current  
L  Inductance  
C  Capacitance  

**Abbreviations**  
LFC  Load Frequency Control  
BPC  Blade Pitch Control  
PV  Photovoltaic  
PI  Proportional Integral  
GA  Genetic Algorithm  
HVDC  High Voltage Direct Current  

| Table 1: Rating of proposed hybrid system |
|-----------------------------------------|
| **Generation Capacity**                 |
| Wind Generation(kW) | Diesel Generation(kW) | PV Generation(kW) |
| 150 | 150 | 60 |
| Load of the system = (150 + 100 + 50) = 300 kW |

| Table 2: Values of system parameters |
|--------------------------------------|
| **System Parameters**                |
| Td1 = 1 s ;  Td2 = 2 s ;  Td3 = 0.025 s ;  Td4 = 3 s |
| Rd = 5 Hz/pu KW ;  Tw = 4 s ;  Kpc = 0.08 pu Kw/deg |
| Kp1 = 1.25 ;  Kp2 = 1 ;  Kp3 = 1.4 ; |
| Kp1*Kp2*Kp3 = 1.75 deg/pu KW ;  F = 60 Hz |
| Tp1 = 0.6 s ;  Tp2 = 0.041 s ;  Tp3 = 1 s |
| Kg = 0.9969 pu kW/Hz ;  Kd = 0.3333 pu kW/Hz |
| Ktp = 0.003333 pu kW/Hz ;  Kg = 0.20 pu kW/Hz |
| Kp = 72 ;  Tp = 14.4 sec |