

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

Bharat Pariyar¹ Raju Wagle²

¹Narvik University College, 8514 Narvik, Norway

²Pokhara University, School of Engineering, Lekhnath 12, Kaski, Nepal

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.[1,2] 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 [3-5].

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 [6-10]. Different strategies are priority switched load control [5], fly wheel [6], dump load control [9], battery energy storage [10] and superconducting magnetic energy storage [8]. These strategies are expensive and they have their own limitations. In an isolated wind-diesel-Solar PV hybrid power system, load frequency control (LFC) scheme is used. This strategy is used to obtain the acceptable frequency and hence it is useful for maintaining the system's performance [11].

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.

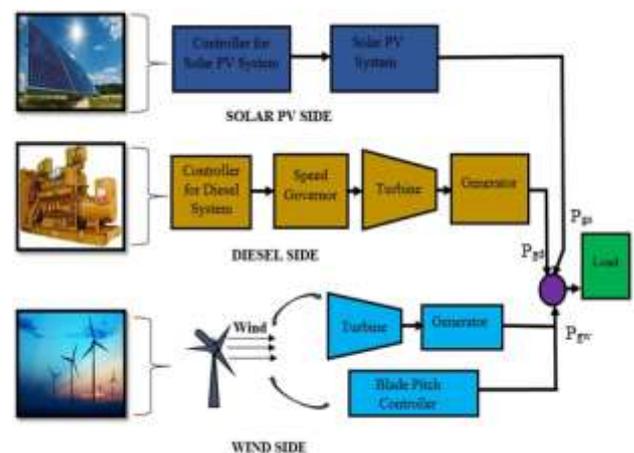


Figure 1: Configuration of an isolated Wind-Diesel-Solar PV hybrid power system

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 p-n diode and hence current passes from one side to the other side [12]. The equivalent circuit of a solar cell is shown in figure 2.

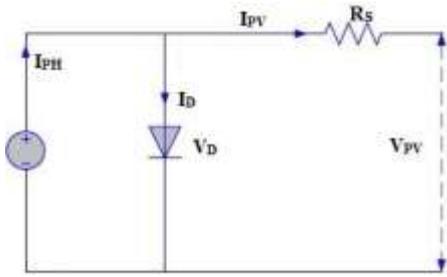


Figure 2: Equivalent circuit of solar cell

I_{ph} is used as the reference current and R_s is equivalent to the total resistance. The equations are as follows [12]

$$I_{pv} = I_{ph} - I_{SAT} \left(\frac{q(V_{pv} + I_{pv} R_s)}{AKT - 1} \right) \quad (1)$$

$$I_{ph} = \left(\frac{\lambda}{1000} \right) [I_{sc} + K_1(T - 25)] \quad (2)$$

we use MPPT controller for regulating PV output voltage and boost converter to achieve AC regulating voltage. The relevant circuit is shown in figure 3.[12]

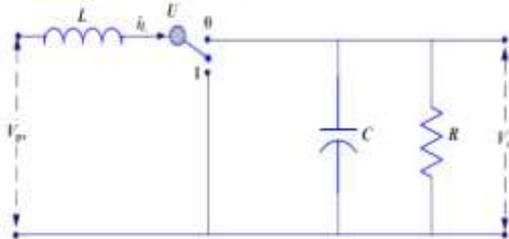


Figure 3: Boost Converter equivalent circuit

U switch shown in this figure 3 is composed of an IGBT and Diode. When $U=0$, Diode is ON and IGBT is OFF and vice versa.

Switch operation can be divided into two different time periods [13]. First period occurs when the switch is turned ON, it means $0 \leq t \leq t_{ON}$, the relevant equations are as follows:

$$L \frac{di_L}{dt} = V_{PV} \quad (3)$$

$$C \frac{dv_o}{dt} + \frac{v_o}{R} = 0 \quad (4)$$

Now another time period belongs to turned OFF switch, it means $t_{ON} \leq t \leq T_s$

$$L \frac{di_L}{dt} + V_o = V_{PV} \quad (5)$$

$$i_L - C \frac{dv_o}{dt} + \frac{v_o}{R} = 0 \quad (6)$$

T_s represents a switching time period.

First, the transfer function model of MPPT, filter, inverter and PV panel are derived [14, 15] and hence the transfer function model of the PV panel can be find out from the above equations 1 and 2.

MPPT is done by the boost converter and we have to consider the boost converter's ON state and OFF state mode of operations [14], which are given by the equations 3, 4, 5 and 6. Combining all these equations, transfer function model of the PV Panel is obtained. It is given in the equation 7.

$$G_{BC} = \frac{-18s+900}{s^2+100s+50} \quad (7)$$

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.

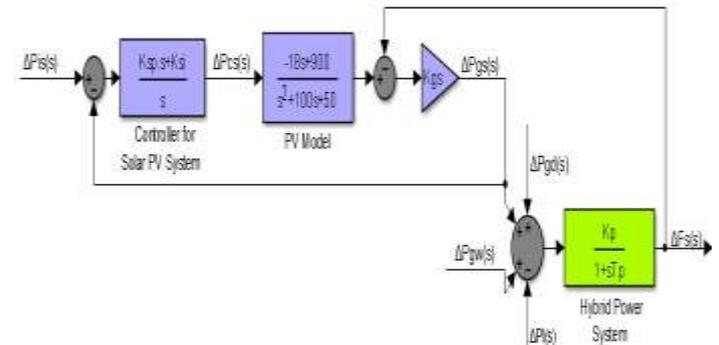


Figure 4: Transfer function model of solar PV system

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.

$$\frac{K_d(1+sT_d1)}{(1+sT_d2)(1+sT_d3)} = \frac{K_1}{(1+sT_d2)} + \frac{K_2}{(1+sT_d3)} \quad (8)$$

Where

$$K_1 = \frac{K_d(1+sT_d1)}{(1+sT_d3)} = \frac{K_d(T_d2 - T_d1)}{(T_d2 - T_d3)} \text{ at } s = -\frac{1}{T_d2} \quad (9)$$

And

$$K_2 = \frac{K_d(1+sT_d1)}{(1+sT_d2)} = \frac{K_d(T_d3 - T_d1)}{(T_d3 - T_d2)} \text{ at } s = -\frac{1}{T_d3} \quad (10)$$

T_{d1} , T_{d2} 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 ΔX_{ED11} and ΔX_{ED21} ,

$$\frac{K_d(1+sT_d1)}{(1+sT_d2)(1+sT_d3)} [\Delta P_{cd}(s) - \frac{1}{R_d} \Delta F_s(s)] = \Delta X_{ED11}(s) + X_{ED21}(s) \quad (11)$$

Where R_d is the speed regulation due to the governor speed action and from equation (8) and equation (11), we get

$$\Delta X_{ED11}(s) = \frac{K1}{(1+sT_{d2})} \left[\Delta P_{cd}(s) - \frac{1}{R_d} \Delta F_s(s) \right] \quad (12)$$

And

$$\Delta X_{ED21}(s) = \frac{K2}{(1+sT_{d3})} \left[\Delta P_{cd}(s) - \frac{1}{R_d} \Delta F_s(s) \right] \quad (13)$$

Therefore, the state differential equations of the mechanical speed governing mechanism are written in equations (14) and (15).

$$\frac{d}{dt} \Delta X_{ED11} = -\frac{1}{T_{d2}} \Delta X_{ED11} - \frac{K_d(T_{d2}-T_{d1})}{R_d T_{d2}(T_{d2}-T_{d3})} \Delta F_s + \frac{K_d(T_{d2}-T_{d1})}{T_{d2}(T_{d2}-T_{d3})} \Delta P_{cd} \quad (14)$$

$$\frac{d}{dt} \Delta X_{ED21} = -\frac{1}{T_{d3}} \Delta X_{ED21} - \frac{K_d(T_{d3}-T_{d1})}{R_d T_{d3}(T_{d3}-T_{d2})} \Delta F_s + \frac{K_d(T_{d3}-T_{d1})}{T_{d3}(T_{d3}-T_{d2})} \Delta P_{cd} \quad (15)$$

The transfer function equation for the change in diesel power generation ΔP_{gd} , can be written in terms of the state variables as

$$\Delta P_{gd}(s) = \frac{1}{(1+sT_{d4})} \left[\Delta X_{ED11}(s) + \Delta X_{ED21}(s) \right] \quad (16)$$

$$\frac{d}{dt} \Delta P_{gd} = -\frac{1}{T_{d4}} \Delta P_{gd} + \frac{1}{T_{d4}} \Delta X_{ED11} + \frac{1}{T_{d4}} \Delta X_{ED21} \quad (17)$$

The transfer function block diagram of the diesel-generating unit is shown in figure 5.

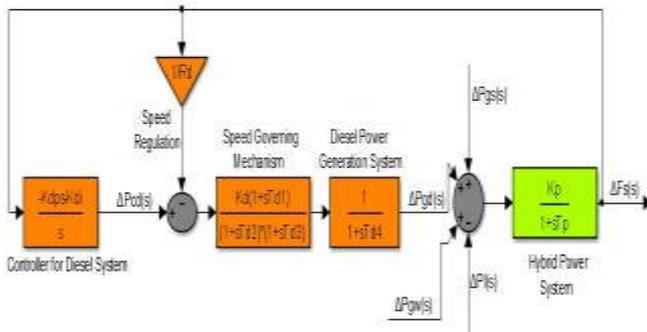


Figure 5: Transfer function model of diesel system

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,

$$\Delta F_t(s) = \frac{1}{1+sT_w} \left[-\Delta P_{gw}(s) + \Delta P_{iw}(s) + \Delta P_{cw}(s) + K_{tp} \Delta F_t(s) \right] \quad (18)$$

and

$$\Delta P_{gw}(s) = K_{ig} \left[\Delta F_t(s) - \Delta F_s(s) \right] \quad (19)$$

Where

T_w is the time constant of the wind-turbine power generation system in sec.

K_{ig} is a function of slip and is the part of power supplied by wind-power generation to load.

K_{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

$$\frac{d}{dt} \Delta F_t(s) = -\frac{(1+K_{ig}-K_{tp})}{T_w} \Delta F_t + \frac{K_{ig}}{T_w} \Delta F_s + \frac{1}{T_w} \Delta P_{iw} + \frac{1}{T_w} \Delta P_{cw} \quad (20)$$

The real power load change ΔP_l or change in wind power generation ΔP_{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 ΔP_{gd} . The net surplus power ΔP_1 will be absorbed by the system either by increasing the kinetic energy of the system or by increased load consumption.

The surplus power is,

$$\Delta P_1 = \left[\Delta P_{gd} + \Delta P_{gw} - \Delta P_l \right] \quad (21)$$

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).

$$\Delta F_s = \frac{K_p}{1+sT_w} \left[\Delta P_{gd}(s) + \Delta P_{gw}(s) - \Delta P_l(s) \right] \quad (22)$$

Where

$$K_p = \frac{1}{D}$$

$$D = \frac{\partial P_l}{\partial f}$$

$$T_p = \frac{2H}{F_s D}$$

H = P.U. Inertia constant

F_s = Nominal system frequency

D = Damping coefficient

The state differential equation is represented by equation (23).

$$\frac{d}{dt} \Delta F_s = -\frac{1+K_{ig}K_p}{T_p} \Delta F_s + \frac{K_p}{T_p} \Delta P_{gd} + \frac{K_{ig}K_p}{T_p} \Delta F_t - \frac{K_p}{T_p} \Delta P_l \quad (23)$$

The combined transfer function of different blocks of the blade pitch control mechanism is given in equation (24).

$$\left[\frac{K_{pc}K_{p3}}{1+sT_{p3}} \right] \left[\frac{K_{p2}}{1+sT_{p2}} \right] \left[\frac{K_{p1}(1+sT_{p1})}{(1+s)} \right] \Delta P_{cu}(s) = \Delta P_{cw}(s) \quad (24)$$

Where

T_{p1} , T_{p2} are the time constants of the hydraulic blade pitch actuator in sec

T_{p3} is the time constant of the data fit pitch response unit

K_{p1} and K_{p2} are gain constants of the hydraulic pitch actuator

K_{p3} is the gain constant of the data fit pitch response unit

K_{pc} is the blade characteristic constant

Equation (24) can be written as

$$\left[\frac{K_{pc} \cdot K_{p3}}{1+sT_{p3}} \right] \left[K_{p1} \left\{ T_{p1} + \frac{(1-T_{p1})}{(1+s)} \right\} \left[\frac{K_{p2}}{1+sT_{p2}} \right] \right] \Delta P_{cu}(s) = \Delta P_{cw}(s) \quad (25)$$

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

$$\Delta P_{cw}(s) = \left[\frac{K_{pc} \cdot K_{p3}}{1+sT_{p3}} \right] \left[K_{p1} \cdot \Delta P_{C1}(s) + K_{p1} \cdot T_{p1} \cdot \Delta P_{C2}(s) \right] \quad (26)$$

$$\Delta P_{C1}(s) = \frac{(1-T_{p1})}{(1+s)} \Delta P_{C2}(s) \quad (27)$$

$$\Delta P_{C2}(s) = \frac{K_{p2}}{1+sT_{p2}} \Delta P_{cu}(s) \quad (28)$$

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

$$\frac{d}{dt} \Delta P_{cw} = -\frac{1}{T_{p3}} \Delta P_{cw} + \frac{K_{pc} \cdot K_{p3} \cdot K_{p1}}{T_{p1}} \Delta P_{C1} + \frac{K_{pc} \cdot K_{p3} \cdot K_{p1}}{T_{p3}} \Delta P_{C2} \quad (29)$$

$$\frac{d}{dt} \Delta P_{C1} = -\Delta P_{C1} + (1-T_{p1}) \Delta P_{C2} \quad (30)$$

$$\frac{d}{dt} \Delta P_{C2} = -\frac{1}{T_{p2}} \Delta P_{C2} + \frac{K_{p2}}{T_{p2}} \Delta P_{cu} \quad (31)$$

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

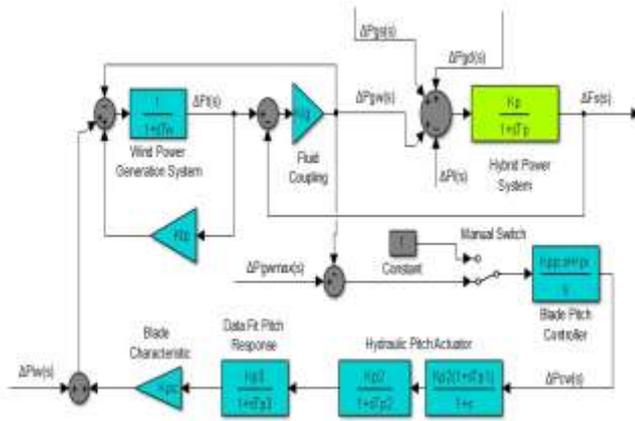


Figure 6: Transfer function model of wind system

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, ΔPgw 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).

$$\dot{X} = AX + Bu + \Gamma p \quad (32)$$

Where

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

A, B and Γ are 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].

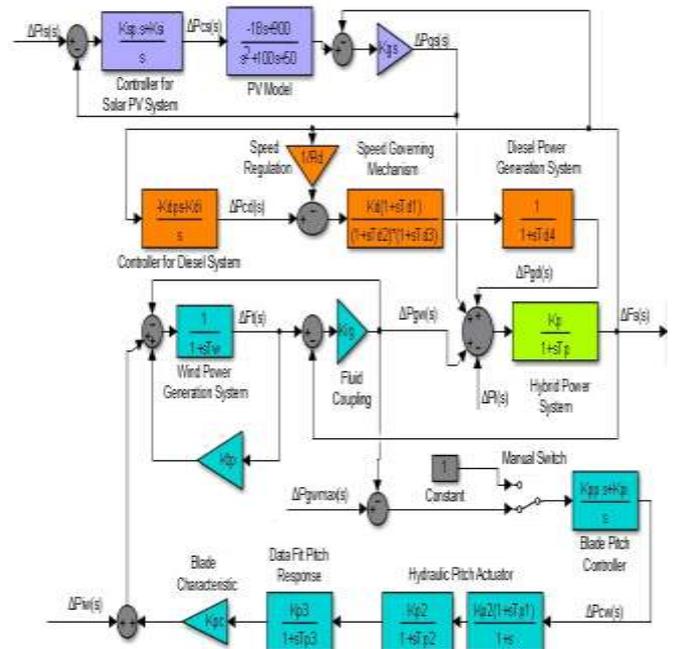


Figure 7: Transfer function block diagram for an isolated Wind-Diesel-Solar PV hybrid power system with controllers

3. Conventional Pi Controller for LFC

3.1 Introduction of Pi Controller

PI controller is most widely used for load frequency control schemes. The importance of such controller is for reducing the steady-state error to zero. The block diagram of PI controller is shown in figure 8. [11].

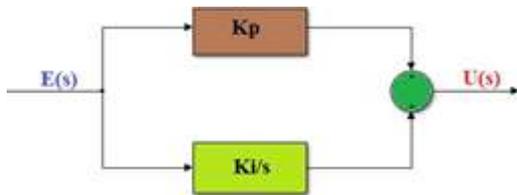


Figure 8: Block diagram of PI controller

Mathematically, transfer function of PI controller can be represented as,

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \quad (33)$$

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). [23].

$$\dot{x}_{n+1} = \Delta F_s \quad (34)$$

$$\dot{x}_{n+2} = \Delta F_t \quad (35)$$

Therefore, the additional state differential equations can be written as

$$\dot{\hat{x}}_{n+1} = \Delta F_s \quad (36)$$

$$\dot{\hat{x}}_{n+2} = \Delta F_t \quad (37)$$

Equations (36) and (37) can be written in matrix form as

$$\begin{bmatrix} \dot{\hat{x}}_{n+1} \\ \dot{\hat{x}}_{n+2} \end{bmatrix} = A_1 X \quad (38)$$

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).

$$\dot{\hat{x}} = \begin{bmatrix} A & O_1 \\ A_1 & O_2 \end{bmatrix} \hat{X} + \begin{bmatrix} B \\ O_3 \end{bmatrix} u + \begin{bmatrix} \Gamma \\ O_4 \end{bmatrix} p \quad (39)$$

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)

$$u = H \hat{X} \quad (40)$$

Where

$$H = \begin{bmatrix} -K_d p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_d i & 0 \\ K_i g K_p p & 0 & 0 & 0 & -K_i g K_p p & 0 & 0 & 0 & 0 & K_i g K_p i & -K_i g K_p i \end{bmatrix} \quad (41)$$

Now the final augmented set of differential equations can be written as

$$\dot{\hat{X}} = \hat{A} \hat{X} + \hat{\Gamma} p \quad (42)$$

Where

$$\hat{A} = \begin{bmatrix} A & O_1 \\ A_1 & O_2 \end{bmatrix} + \begin{bmatrix} B \\ O_3 \end{bmatrix} H \quad (43)$$

And

$$\hat{\Gamma} = \begin{bmatrix} \Gamma \\ O_4 \end{bmatrix} \quad (44)$$

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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Author Profile



Bharat Pariyar received his Bachelor Degree in Electrical Engineering from Kathmandu Engineering College (Tribhuvan University) and Masters Degree in Electrical Engineering from Narvik University College Norway in the year 2015. His research interest includes Hydropower, Power system operation and control, Energy system management and Load frequency control in hybrid power system. He is a member of Nepal Engineering Council (NEC) and is working as an Electrical Engineer in Oslo, Norway.



Raju Wagle received his Bachelor degree in Electrical Engineering from Institute of Engineering, Pulchowk campus in the year 2010 and his master's degree in Electrical Engineering from Narvik University College,

Norway in 2015. His research interests are not only limited to renewable energies, power system integration, operation and control of grid and isolated power system, power electronics and many more. He is the permanent faculty of Electrical and Electronics Department, School of Engineering, Pokhara University. Besides he is also engaged in an Energy related sector in Nepal.

Appendix

List of Symbols And Abbreviations

Symbols

Kpc	Blade characteristic constant, pu kW / deg.
Kpi	Blade pitch controller integral gain
Kpp	Blade pitch controller proportional gain
Ksi	Integral gain of solar PV controller
Ksp	Proportional gain of solar PV controller
ΔP_{cw}	Change in blade angle position
ΔP_{cd}	Change in diesel engine speed changer position
ΔP_{gd}	Change in diesel power generation, pu kW
ΔP_{gs}	Change in solar PV generation, pu kW
ΔP_{is}	Change in input solar PV power
ΔP_{iw}	Change in input wind power due to change of wind velocity
ΔP_I	Change in net surplus power absorbed by the system
ΔP_l	Change in real power load
ΔP_{gw}	Change in wind power generation, pu kW
ΔF_t	Change in wind turbine speed
Ktp	Coefficient that depends on the slope of C_p, λ curves of the wind turbine
B	Control Matrix
U	Control vector
D	Damping coefficient
Kd	Derivative gain
Γ	Disturbance Matrix
P	Disturbance vector
Kp1, Kp2	Gain constant of hydraulic blade pitch actuator
Kp3	Gain constant of the data fit pitch response unit
ΔX_{ED}	Incremental change in governor valve position
Ki	Integral gain
Kdi	Diesel controller integral gain
Kdp	Diesel controller proportional gain
Fs	Nominal system frequency
η	Performance index
Kp	Power system gain
Tp	Power system time constant in sec.
KP	Proportional gain
H	P.U. Inertia constant
Rd	Speed regulation to the governor action in Hz / pu kW
X	State vector
ΔF_s	System frequency deviation, Hz
A	System Matrix
Td1, Td2, Td3	Time constant of diesel engine speed governing mechanism in sec.
Tp1, Tp2	Time constant of the hydraulic blade pitch actuator in sec.
Kd	The part of power supplied by diesel power generation to the load
Kgs	The part of power supplied by Solar PV to the load
Kig	The part of power supplied by wind to the load
Td4	Time constant of diesel power generation in sec.
Tp3	Time constant of the data fit pitch response unit in sec.
Tw	Time constant of the wind-turbine in sec.

- 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
Kig = 0.9969 pu kW/Hz ;	Kd = 0.3333 pu kW/Hz
Ktp = 0.003333 pu kW/Hz	Kgs = 0.20 pu kW/Hz
Kp = 72 ;	Tp = 14.4 sec