CHAPTER 5

FREQUENCY RESPONSE ENHANCEMENT IN HYBRID MICROGRID POWER SYSTEM

5.1 CHAPTER OVERVIEW

In the previous chapters, the load frequency control of interconnected power system network with macrogrids of similar and different power generation systems was attempted with the various types of controllers. In the present chapter, two hybrid microgrid (MG) systems have been designed and the techniques for their frequency response enhancement have been discussed. The conventional sources of power are not good for the environment as well as are depleting at a fast rate. The solution to this problem lies in the power generation from the renewable energy sources. The power production by the renewable energy sources is unpredictable and uncontrollable, therefore the complete dependency on them is not a viable alternative. The most suitable solution for the same is to use both the type of sources in integration which results in a hybrid power system. These hybrid systems are generally placed near to the load centers so the power can be generated at distribution level voltage. The generation capacity is also less for hybrid systems. The sources of hybrid microgrid power plants have small ratings maximum up to 25 MW, these systems are mostly connected at the distribution voltage level [25, 124].

Hybrid power systems have become one of the most promising ways to supply power to remote areas that otherwise depend on conventional diesel generators. Different microgrids with diesel generation (DG) operations are investigated to analyze their support in LFC of the microgrids, where the microgrid operation in island mode and grid connected mode are demonstrated with different software simulations along with fault analysis [125, 126]. These studies have not used the computational intelligent techniques for fast and accurate frequency response enhancement along with use of generating margin of WECS. Wind energy is one of the most prominent sources of
renewable energy that can be used in areas with an abundance of wind power. Generally, the wind power plants operate at maximum power production to pursue the maximum economic benefit. This type of operation at maximum power production does not help to preserve the generating margin that responds to frequency. The wind power is a variable source of energy, the control of a wind turbine to generate the necessary active power output for frequency enhancement is a very challenging task [128, 129, 130]. The grid interface of wind farm is a complex task due to variable wind turbine speeds and various voltage sags in the system.

The first type of hybrid power system consists of wind energy conversion system and diesel power plant. The generation-load balance has been maintained by using the PI controller optimized by the particle swarm optimization (PSO) technique for diesel power plant as well as preserving the generating margin of wind energy conversion system (WECS). Although the scheme does not make use of maximum wind power production, it still proves to be economical for microgrids which have less number of interconnected generation units as energy storage systems with high installation costs are not required [131-136].

The second type of hybrid microgrid is a combination of offshore wind turbine generator (WTG), photovoltaic (PV) system, fuel cell (FC), aqua electrolyzer (AE) and diesel engine generator (DEG) along with the energy storage elements like flywheel energy storage system (FESS), ultra-capacitor (UC) and battery energy storage system (BESS). In the second microgrid with multiple numbers of small generating units, the firefly algorithm (FA) is applied to tune the parameters of fractional order PID (FOPID) controller. Thus, the LFC in various hybrid microgrid power systems is attained with the proposed intelligent controllers.
5.2 OBJECTIVES OF THE CHAPTER

This chapter addresses the challenges of designing the load frequency controllers for hybrid micro grid systems. The frequency response enhancement and load sharing is attained for the two hybrid microgrids. The first type of microgrid comprises of wind energy conversion system and diesel generator (WECS-DG) without energy storage devices and the second type of microgrid system taken into consideration includes many small rating renewable generating units and energy storage systems. The objectives of this chapter are as given below:

1. Designing of wind–diesel hybrid power system with PI controller for diesel plant and generating margin for wind energy conversion system (WECS).
2. Designing of microgrid system with offshore wind (WTG), photovoltaic (PV), fuel cell (FC), aqua electrolyzer (AE) and diesel engine generator (DEG) along with the energy storage elements like flywheel energy storage system (FESS), ultra-capacitor (UC) and battery energy storage system (BESS).
3. To design suitable controllers for frequency response enhancement in both the hybrid microgrid systems.

The chapter is divided into various sections and subsections to elaborate the terminology, devices, modelling of microgrid systems, load frequency controllers, optimization techniques and performance analysis. The details and transfer function models of different generating and storage units making the microgrids are explained in Sections 5.3 and Section 5.4. The modelling of hybrid microgrid plant with wind energy conversion system and diesel generator (WECS-DG), frequency control technique and simulation results are explained in Section 5.5. The modelling of one more microgrid with large number of sources, frequency controller along with tuning method and its simulation results are given in Section 5.6.
5.3 GENERATING UNITS OF VARIOUS HYBRID POWER SYSTEMS

The load frequency response and power sharing among various units of microgrid systems has been presented in this work. This section elaborates the transfer functions of different generating units of these two hybrid microgrid systems.

5.3.1 Doubly Fed Induction Generator

The wind farm has more stable operation when doubly fed induction generator (DFIG) is used in place of conventional synchronous generator and singly-fed squirrel cage generator because they draw heavy magnetizing current from the grid after the transient state which can cause a large voltage drop [141]. The voltage source converter is connected to DFIG rotor through slip rings and voltage can be controlled depending upon the variable wind speed to give optimum power generation. Many inertial and speed-droop controls of wind turbines for frequency response have been proposed [68, 94]. The general connection diagram of DFIG in grid connected mode is shown in Figure 5.1. The stator of DFIG is connected to three phase supply through the grid and rotor is connected through voltage source converters through common DC link [142, 143].

![General connection diagram of DFIG connected with grid](image)

Figure 5.1: General connection diagram of DFIG connected with grid
This variation in energy due to variable wind speed can be 3-28% depending on the wind conditions and the design of variable speed wind turbine. Although, the wind turbine system based on fixed speed can be connected directly to the grid, still, wind turbine with variable speed is used as it decreases the mechanical stress, noise and ease of various power controls. The proper regulation of the d-axis rotor current ($i_{dr}$) of the DFIG can help to achieve active power control in wind power plants. This property is mainly due the fact that $i_{dr}$ affects the electromagnetic torque, which in turn changes the turbine torque [144]. The regulated electromagnetic torque and thus, the controlled rotor speed can give the variable active power output of a DFIG. Furthermore, pitch angle control is initiated when the output power of the wind turbine exceeds the rating of the machine [146]. In the present work, the wind speed is assumed to generate a turbine output that is always less than its rated power, so pitch angle control is not required.

### 5.3.2 Diesel Generator

Diesel generator (DG) can produce the power as per the load demand with the help of governor control and speed droop. DG is primarily used in microgrid systems to share the peak loads and as standby source of power. The synchronous generator is driven by the diesel engine which acts as turbine [115, 125]. The governor regulates the flow of fuel to the engine as per the desired speed and the diesel generator act as a feedback system. The transfer function of the governor of diesel engine can be given as:

$$G_{dgt}(s) = \frac{K_{dgt}}{1 + sT_{dgt}}$$

(5.1)

where $K_{dgt}$ and $T_{dgt}$ are the gain and time constant of the governor of diesel engine respectively.

The diesel generator transfer function is given as:

$$G_{dgg}(s) = \frac{K_{dgg}}{1 + sT_{dgg}}$$

(5.2)

where $K_{dgg}$ and $T_{dgg}$ are the gain and time constant of the diesel generator respectively.
5.3.3 Photovoltaic Power Generation

Photovoltaic (PV) power generation is increasing exponentially due to its availability in abundance. The input parameters while modeling the PV system are solar irradiance \( \phi \) (W/m\(^2\)), ambient temperature (°C), PV voltage (V) and the only output is photovoltaic current. The PV generation is at very small voltage rating [149, 150]. The boost converter is used to raise the low DC voltage to a suitable level. The next step is to convert the DC voltage to AC through inverter which generally operate in current control mode. The inverter takes the DC power from DC link bus and supply AC power to the grid [151].

The transfer function of PV generation system is given as:

\[
G_{pv}(s) = \frac{K_{pv}}{1 + sT_{pv}} = \frac{\Delta P_{pvPG}}{\Delta \phi}
\]  

(5.3)

where \( K_{pv} \) and \( T_{pv} \) are gain and time constant of PV generation system respectively.

5.3.4 Aqua Electrolyzer

Aqua electrolyzer (AE) is a DC voltage based device which stores the energy in the form of hydrogen (H\(_2\)) when the microgrid produces the excess power. The current due to the excess power passes through the electrodes of aqua electrolyzer and water decomposes into oxygen and hydrogen [31]. The chemical reaction of decomposition is governed by:

\[
H_2O \rightarrow H_2 \uparrow + \frac{1}{2}O_2 \uparrow
\]  

(5.4)

The rate of hydrogen production is given by Faraday’s law as shown below:

\[sH_2(s) = \frac{2}{2F} \times I(s)\]  

(5.5)

The transfer function of an aqua electrolyzer is given by equation (5.6) as below:

\[G_{ae}(s) = \frac{K_{ae}}{1 + sT_{ae}}\]  

(5.6)

Where \( K_{ae} \) and \( T_{ae} \) are the gain and time constant of the aqua electrolyzer.
5.3.5 Fuel Cell

Fuel cell (FC) is an energy conversion device which converts the chemical energy (stored hydrogen) into electrical energy (DC power) at the time of peak load periods. It can compensate the renewable energy source like wind power or PV solar power generation when the generation is less than the demand. It requires the voltage source convertor (VSC) to operate with microgrid.

The transfer function of FC is given as [153]:

\[ G_{fc}(s) = \frac{K_{fc}}{1 + sT_{fc}} \]

where \( K_{fc} \) and \( T_{fc} \) are the gain and time constant of the fuel cell respectively.

The power delivered by fuel cell is given by:

\[ H_{2fc}(t) = \frac{1}{VF} \int P_{fc}(t) dt \]

where \( V \) is the DC voltage, \( F \) is Faraday’s constant, \( P_{fc} \) is power from fuel cell. The concept of aqua electrolyzer and fuel cell is depicted in Figure 5.2 below and has been incorporated in the model.

![Block diagram of H\(_2\) storage system with aqua electrolyzer](image)

Figure 5.2: Block diagram of H\(_2\) storage system with aqua electrolyzer [115]
5.4 ENERGY STORAGE DEVICES IN HYBRID POWER SYSTEM

When the electrical power production by the renewable energy sources is more than the demand, the excess energy is stored in different energy storage devices like flywheel energy storage system (FESS), battery energy storage system (BESS) and ultra-capacitor (UC). The stored energy is converted into electrical energy when the demand rises or the power production from the sources is less than the demand.

5.4.1 Flywheel Energy Storage System

Flywheel energy storage system (FESS) is an energy storage device which stores the kinetic energy by constant spinning of the flywheel rotor. The flywheel rotor can produce the electrical power in the microgrid for a short duration. The flywheel keeps rotating due to inertia. The flywheel kinetic energy is given as:

\[ E_K = K \cdot m \cdot r^2 \cdot \omega^2 \]  \hspace{1cm} (5.9)

Where \( E_K \) is stored kinetic energy, \( m \) is the mass of the rotor flywheel (kg), \( r \) is the radius of rotor (m), \( \omega \) is rotational speed of flywheel (rpm). The transfer function of FESS is given by equation (5.10).

\[ G_{FESS}(s) = \frac{K_{FESS}}{1 + sT_{FESS}} = \frac{\Delta P_{FESS}}{\Delta f} \]  \hspace{1cm} (5.10)

where \( K_{FESS} \) and \( T_{FESS} \) are the gain and time constant of the flywheel energy storage system respectively. \( \Delta P_{FESS} \) is the change in power due to flywheel and \( \Delta f \) is change in frequency of microgrid system.

5.4.2 Battery Energy Storage System

Battery energy storage systems (BESS) are the fast acting DC devices which are used effectively in microgrid to damp the oscillations. Whenever there is sudden change in the power requirement the BESS supplies or draws the energy to bring the system back to steady state. After supplying the energy to the microgrid system, BESS is charged back to the steady state value in order to handle the next disturbance in the system [92, 115]. Voltage source converter (VSC) is required for microgrid operation of BESS.
The transfer function of BESS is given as:

\[ G_{be}(s) = \frac{K_{BESS}}{1 + sT_{BESS}} = \frac{\Delta P_{BESS}}{\Delta f} \]  

(5.11)

where \( K_{BESS} \) and \( T_{BESS} \) are the gain and time constant of the battery energy storage system respectively and \( \Delta P_{BESS} \) is the change in power due to battery energy storage systems. Two control loops as shown in Figure 5.3 and 5.4 have been proposed to handle the issues related to charging and discharging of battery.

Figure 5.3: Scheme for making battery power zero in steady state

Figure 5.4: Scheme to bring back the charge in the battery to its pre-disturbance condition
5.4.3 Ultra Capacitor

Ultra capacitor (UC) is a double layer capacitor which stores the energy by separating positive and negative charges. The charging or discharging of real power takes place in UC during the load variation, peak loads and transient fault. The UC device is designed in such a manner that it can smooth the power fluctuation which takes place during the charging or discharging of capacitor. The voltage across the capacitor \( V_c \) and the energy stored \( E \) by ultra capacitor are given in equation (5.12) and equation (5.13) respectively [155, 158].

\[
V_c = \frac{Q}{C} \quad (5.12)
\]

\[
E = \frac{1}{2} CV^2 \quad (5.13)
\]

where \( Q \) is the charge and \( C \) is capacitance of the ultra capacitor. The important parameters of UC are working DC voltage, leakage current, specific power and specific energy. The transfer function of ultra capacitor is given by:

\[
G_{UC}(s) = \frac{K_{UC}}{1 + sT_{UC}} = \frac{\Delta P_{UC}}{\Delta f} \quad (5.14)
\]

where \( K_{UC} \) is the gain of UC, \( T_{UC} \) is the time constant of the ultra capacitor energy storage system and \( \Delta P_{UC} \) is the change in power due to ultra capacitor.

5.5 WIND-DIESEL HYBRID POWER SYSTEM

The wind energy is used mostly in the areas where high speed wind is available. If the wind plant is operating with maximum power production then the generating margin cannot be used for the frequency control, although there can be economic benefits. For the optimum use of wind power the grid codes have been defined which support not only the conventional power generation sources but also the renewable sources of power. The wind system operation can be fixed speed or variable speed. Maximum
wind power can be generated if the variable wind speed system is connected in the network for the production of energy [162, 164, 166]. When doubly fed induction generator (DFIG) of wind energy conversion system (WECS) is connected to small non-renewable energy system like diesel generator (DG) to make hybrid system the general connection diagram can be shown as below in Figure 5.5.

![Block diagram of Wind–Diesel hybrid power system](image)

Figure 5.5: Block diagram of Wind–Diesel hybrid power system

In this system, the PI controller can be used for controlled sources like diesel generator. The hybrid system shares the power in such a way that the load on non-renewable energy sources is minimum. Further, the DFIG also support frequency control in small grids by using the power from the generating margin.

5.5.1 Mathematical Modeling

The proposed self-sufficient remote microgrid (MG) consists of a small rating wind power plant (310 kW) and a diesel generator (40 kW), as shown in Figure 5.5. The net power available to the load is the sum of the powers from the renewable and controllable sources. A remote microgrid is not connected to the utility and operates mostly with decentralized control methods. The maximum power use is limited to local
customers only. The transfer functions of the governor $G_{dg}(s)$ and turbine $G_{dt}(s)$ of the diesel generators are given by first-order transfer functions as follows:

$$G_{dg}(s) = \frac{K_{dg}}{1+sT_{dg}} \quad (5.15)$$

$$G_{dt}(s) = \frac{K_{dt}}{1+sT_{dt}} \quad (5.16)$$

where $T_{dg}$ and $T_{dt}$ are the time constants of governor controller and turbine of the diesel generator, respectively. The $K_{dg}$ and $K_{dt}$ are the gains of governor and turbine of the diesel generator. The parameters of the diesel generator (DG) and WECS are given in Table 5.1

Table 5.1: Parameters of Wind-Diesel Power System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of air</td>
<td>1.25 kg/m³</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>70</td>
</tr>
<tr>
<td>Radius of turbine blade</td>
<td>45 m</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>7.5-8.5 m/s</td>
</tr>
<tr>
<td>Inertia constant (H)</td>
<td>5 sec</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DG governor gain ($K_{dg}$)</td>
<td>1 sec</td>
</tr>
<tr>
<td>DG turbine gain ($K_{dt}$)</td>
<td>1 sec</td>
</tr>
<tr>
<td>DG governor time constant ($T_{dg}$)</td>
<td>2 sec</td>
</tr>
<tr>
<td>Damping coefficient (D)</td>
<td>0.012 MW/Hz</td>
</tr>
<tr>
<td>Actual time constant of WTG ($T_i$)</td>
<td>3 sec</td>
</tr>
<tr>
<td>Main time constant of WTG ($T_{pt}$)</td>
<td>10 sec</td>
</tr>
<tr>
<td>Generation rate constraint ($GRC_{dg}$)</td>
<td>3%</td>
</tr>
<tr>
<td>DG turbine time constant ($T_{dt}$)</td>
<td>20 sec</td>
</tr>
</tbody>
</table>

When the power demand on any source increases or decreases, it cannot respond instantaneously and the power output follows a ramp rate. This ramp rate limit is called the generation rate constraint (GRC), which is taken into consideration for the diesel generator. The suitable GRC that is taken into account for a diesel power plant is generally found to be 3%/min [115]. The modified GRC was considered to obtain the same value of the input signal and the output collected from the GRC of the microgrid.
as shown in Figure 5.6. The proper selection of the governor droop or governor speed regulation parameter R (Hz/p.u. MW) is also very important for to obtain the zero steady state error in frequency. Thus R is also optimized with the PSO technique along with the gains $K_p$ and $K_i$ of the PI controller for the diesel power plant.

![Diagram](image)

*Figure 5.6: GRC for diesel power generation*

When load on wind power system changes or the wind speed varies then the generating margin of the unit can be used for frequency response enhancement. The generating margin is equivalent to spinning reserve of conventional power plants. In case of generating margin the full power generation capacity of wind plant is not used and generally 10% is kept as a reserve which is used during the increase in load or reduction in wind speed [40, 164]. The scheme of generating margin in wind power generation for achieving LFC is shown in Figure 5.7. The wind model has been designed for free running mode for medium wind speed condition when pitch angle is kept fixed. First, a set point command ($P_{cmd}$) is sent to the rotor of DFIG which is added to the speed droop ($\Delta P$) and corresponding reference signal ($P_{ref}$) is generated. This signal generates a reference torque ($T_{cmd}$) and the inertial response adjusts the $T_{cmd}$ and the corresponding signal generated will drive the DFIG which produces the $P_{grid}$.

The different participating units to regulate service should reserve a certain amount of generating margin for governor actions, a similar idea has been applied to the wind power plant in Figure 5.7, which illustrates the frequency response control scheme for WECS [162]. The wind power plant is designed for medium wind speed condition in the range of 7.5 – 8.5 m/s.
The generating margin \( P_{\text{reserve}} \) of the wind power plant for a given speed is calculated as in equation (5.17).

\[
P_{\text{reserve}} = P_{\text{wtmax}} - P_{\text{grid}}
\]  

(5.17)

The maximum power output \( P_{\text{wtmax}} \) of the doubly fed induction generator (DFIG) is given as in equation (5.18).

\[
P_{\text{wtmax}} = 0.5 \ C_p (\lambda_w, \beta_w) \ \rho A V_w^3
\]  

(5.18)

where \( V_w \) is the wind speed (m/s), \( \rho \) is the air density (kg/m\(^3\)), \( A \) is the cross section of the rotor for the DFIG, \( C_p \) is the power coefficient (kW), \( \beta_w \) is the pitch angle (radian) and \( \lambda_w \) is the tip speed ratio.
The power coefficient \( Cp(\lambda_w, \beta_w) \) of a wind turbine is given in equation (5.19)

\[
Cp(\lambda_w, \beta_w) = \sum \propto \beta_w \lambda_w
\]  
(5.19)

The equivalent speed droop \( (1/R_{wt}) \) depends on the set frequency band \( (\Delta F_{BD}) \). The speed droop \( (1/R_{wt}) \) for fixed frequency band \( (\Delta F_{BD}) \) is given in equation (5.20)

\[
1/R_{wt} = P_{reserve} \times 1/(\Delta F_{BD})
\]  
(5.20)

The speed droop yields the power adjustment \( (\Delta P) \) according to the frequency deviation, \( \Delta F \), in equation (5.21)

\[
\Delta P = - \Delta F \times 1/R_{wt}
\]  
(5.21)

The reference power \( (P_{ref}) \) given in equation (5.22) is reduced to the torque reference, which is added to the inertial response to give the torque command \( T_{CMD} \) for the rotor of DFIG.

\[
P_{ref} = P_{cmd} + \Delta P
\]  
(5.22)

\[
T_{ref} = T_{CMD} + \Delta T
\]  
(5.23)

### 5.5.2 Simulation of Wind–Diesel Generating System

The Wind–Diesel hybrid generating system has been simulated in MATLAB/SIMULINK environment. The part of the simulink model related to DFIG and generating margin as shown Figure 5.8 is developed with the help of equations (5.17) to (5.22) as mentioned in section 5.5.1. The wind speed has been considered in medium range which is generally 7.5 to 8.5 m/s. The equations (5.15) and (5.16) have been used to develop the diesel generator model section in Figure 5.8.
Figure 5.8: MATLAB/SIMULINK model of Wind-Diesel hybrid system
The total load is shared among the wind generation system and diesel generator system in such a way that the minimum load is on the diesel system. The generating margin is preserved in wind system and PI controller is used in diesel plant for frequency control. The active power output of the wind power plant can be changed with the d-axis rotor current control as it affects the electromagnetic torque.

5.5.3 Tuning of PI Controller of Diesel Generator using PSO

The fully optimized PI controller has been used for diesel power plant to enhance the frequency response during load variation. The proportional gain ($K_p$), integral gain ($K_i$) and governor droop (R) have been optimized with particle swarm optimization (PSO) technique. The integral square error (ISE) is taken as objective function of the system for optimization as given in equation (5.24):

$$ISE = \int\{ (\Delta f_i)^2 + (\Delta P_{tie-j})^2 \} dt$$  \hspace{1cm} (5.24)

where $\Delta f_i$ is the frequency deviation in area-$i$ and $\Delta P_{tie-j}$ is the change in tie-line power. The PSO algorithm aims to find the minimum value of the performance index (PI). If the performance index is not properly selected, the algorithm may be stopped in the local minima points. The important parameters of the PSO algorithm are the number of particles, particle dimension, particle velocity interval ($V_{max}$, $V_{min}$), $C_1$, $C_2$, the particle place interval ($X_{max}$, $X_{min}$) and $W$ (inertia weight). The initialization of the algorithm parameters is very important because the algorithm may never converge to the minimum point if these parameters are not carefully selected [59, 158]. The PSO algorithm can be summarized in the following ten steps:

1. The algorithm parameters, such as the particle dimension, particle velocity interval ($V_{max}$, $V_{min}$), particle place interval ($X_{max}$, $X_{min}$), $C_1$, $C_2$ and $W$ (inertia weight), are selected.
2. The particles ($x_i(t)$, $V_i(t)$) are properly initialized.
3. The pbest vectors for all of the particles, such as $K_p$, $K_i$ and $R_i$ in the present work, are initialized using the random initial values obtained in step 2 for the position vectors. The initial values of $x_i(t)$ are chosen as zero and the population size is 100.

$$K_{min} = [1 1 1]*0;$$
K_max = [1 1 1]*6;

pop=100;

itermax=150;

The equations of maximum particle velocity $v_{\text{max}}(n)$ and minimum particle velocity $v_{\text{min}}(n)$ are given as:

\[
v_{\text{max}}(n) = 0.1 \cdot (K_{\text{max}}(n) - K_{\text{min}}(n));
\]

\[
v_{\text{min}}(n) = -0.1 \cdot (K_{\text{max}}(n) - K_{\text{min}}(n));
\]

4. The system parameters, such as $K_p$, $K_i$ and $R_i$ in the present study, are updated using the particle position vector $x_i(t)$ and the cost function.

5. The gbest value is determined using the objective values of the particles.

6. The particle velocity vectors ($V_i$) and positioning vectors ($x_i$) are updated according to steps (4) and (5).

7. The parameters of the system are updated by the position vector of each particle and the objective value is calculated for each particle.

8. The pbest value is updated for each particle ($K_p$, $K_i$ and $R_i$) as shown below:

   for n = 1: pop
     if(eval_fit(n) < fit_best(n))
       fit_best(n) = eval_fit(n);
       pbest(n,:) = population(n,:);
     end
   
9. The value of gbest is updated.

   \[
   [A B] = \text{min}(\text{fit}_{\text{best}});
   \]

   \[
   \text{gbest} = \text{pbest}(B,:);
   \]

   If the objective value of $g_{\text{best}}(t+1)$ is better than the objective value of $g_{\text{best}}(t)$, then

   \[
   g_{\text{best}}(t+1) = g_{\text{best}}(t)
   \]
10. When the stop condition i.e. ISE in the hybrid power system becomes zero, the PSO algorithm will stop and the optimal parameter values of \( K_p \) and \( K_i \) of the PI controller and frequency regulation parameter \( R_i \) are reached. Otherwise, the algorithm returns to step 6.

5.5.4 Simulation Results and Discussion

In this section, the simulation results of wind-diesel plant have been discussed under the different load conditions. The load frequency control (LFC) and optimum power sharing between these two sources is attained through PSO tuned PI controller and preserving generating margin in wind energy conversion system (WECS). The WECS system has been designed in such a way that the active power output from the plant does not attain its maximum generating capacity, thereby, preserving the generating margin. The generating margin from wind power plant is possible when active power output of the wind turbine can be controlled. For preserving the generating margin, a suitable power command to the wind turbine is given which is generally 90% of the total maximum power generation possible [41, 94]. The remaining 10% of power is kept as generating margin which is extracted from the system when there is some load variation or change in wind speed.

The simulation work is carried out to observe the effect of load variation on the power generation from different units in the wind–diesel system. During the load varying conditions, the wind speed has been taken as constant. The maximum generating capacity of wind plant is 310 kW and that of diesel plant is 40 kW. The total generating capacity of the wind–diesel system is 350 kW. The system developed is put on a total load of 295 kW and 306 kW at different time intervals. The power is shared among the wind and diesel power plants under the different load conditions. The total power generation of the WECS-DG system to serve the loads at different time intervals is shown in Figure 5.9. The wind plant generation is 275 kW and 276 kW respectively during different loads due to medium wind speed as shown in Figure 5.10 and diesel power generation is 20 kW and 30 kW as shown in Figure 5.11. The results show that the frequency deviation is minimum and steady state error is zero during both the load variations as shown in Figure 5.12. The ISE of the system has been taken as
performance index and it becomes minimum as the frequency deviation approaches to zero as shown in Figure 5.13.

In addition to frequency regulation, two more advantages are attained with this set up, first is the load shared by the non-renewable energy source i.e. diesel generator is not maximum and power generation capacity of wind plant is also not utilized to the maximum limit hence the generating margin of the wind power plant is preserved. The dependency on the fossil fuel is reduced. The system is not using any storage device and is a self-sustained system. The results show that the active power generation of wind and diesel plant is optimized as shown in Figure 5.14 during the load variation on the system and frequency can be maintained within suitable limits.

The PI controller gains and governor droop (R) for diesel system are optimized with PSO technique. The population size in PSO is taken as 100 and maximum number of iterations are taken as 150. The values of $K_p$, $K_i$ and R after the optimization are 2.231, 0.065 and 0.227 respectively for the load of 295 kW and $K_p$, $K_i$ and R for a load of 306 kW are 2.053, 0.066 and 0.422 respectively.

![Figure 5.9: Power wind and diesel power system](image-url)
Figure 5.10: Power generated by wind power plant

Figure 5.11: Power generated by diesel power plant
Figure 5.12: Frequency variation for wind – diesel system under load variation

Figure 5.13: Performance Index of the system under different load conditions
The LFC for wind-diesel system is designed in such a manner that the load is shared between them in an optimum manner as per the wind speed and thus the wind power generation. The PSO tuned integral controller used for diesel power plant optimize the system parameters such as integral gain, proportional gain and speed droop so that maximum load is served by wind power system and remaining load is shared by diesel power plant.

5.6 HYBRID POWER SYSTEM WITH DIFFERENT ENERGY STORAGE SYSTEMS

In the section, the more complex hybrid power system with multiple interconnected generating and storage units is considered for analyzing the load frequency control and power sharing. The hybrid system consists of various energy resources along with storage systems [42, 166, 167]. The two wind generator (WTG), photovoltaic cell (PV), fuel cell (FC) and diesel generator (DG), the aqua-electrolyzer (AE) are used to generate
the power. Some portion of produced power from wind or/and PV is used for hydrogen
production to be utilized by fuel cells (FC). The consistent power supply to the
connected load [29] can be achieved by the dissimilar blends of energy storage system.
The energy storage systems such as battery energy storage system (BESS), flywheel
energy storage system (FESS) and ultra capacitor (UC) store energy throughout the
surplus generation which is used efficiently through the peak-load demand. The
integrated hybrid energy resources that are available in the microgrid power system are
displayed in Figure 5.15. The standby generator which can make up for the discrepancy
in power demand is diesel engine generator (DEG).

5.6.1 Modeling of Hybrid Microgrid System

The total power generation (P) by the hybrid system is given as:

\[ P = H(P) = (P_{BESS} \text{ or } P_{UC}) \]  
(5.27)

\[ H(P) = P_T + P_{DEG} + P_{FCPG} \]  
(5.28)

\[ P_T = \left( \sum_{i=1}^{n} P_{WTG_i} \text{ or } P_{PV_i} \right) - P_{AE} \]  
(5.29)

\[ P_T = K_n P_{WTG} \]  
(5.30)

\[ K_n = \frac{P_T}{P_{WPG} \text{ or } P_{PVG}} \]  
(5.31)

where \( H(P) \) is power generation by wind turbine generator (WTG), photovoltaic cell
(PV), fuel cell (FC) and diesel generator (DG), the aqua-electrolyzer (AE). \( P_{BESS} \) is
power storage by battery and \( P_{UC} \) is power storage by ultra capacitor.

The change in power \( (\Delta P_e) \) due to difference in power generation \( (P_H) \) and load \( (P_L) \)
is given as:

\[ \Delta P_e = P_H - P_L \]  
(5.32)
The change in frequency $\Delta f$ due to change in load is given as:

$$\Delta f = \frac{\Delta P_e}{K_{sys}}$$  \hspace{1cm} (5.33)

$$G_{sys} = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys}(1 + sT_{sys})} = \frac{1}{D + Ms}$$ \hspace{1cm} (5.34)

$G_{sys}$ is the transfer function of the system, $K_{sys}$ is the gain of the system, $M$ is the inertia constant and $D$ is the ratio of percent change in load by percent change in frequency of the system.

Figure 5.15: Configuration of Hybrid Energy resources/storage systems of microgrid
The MATLAB/SIMULINK model of the microgrid system is developed using the transfer function of the renewable energy sources and storage devices. The transfer functions of WTG, PV, FC, DEG and AE are analyzed and described in Section 5.3. The transfer functions of the storage systems BESS, FESS and UC are represented in Section 5.4. The structure of proposed controller based hybrid system (HS) is presented in Figure 5.16 with two WTG, one FC, one AE and one DEG system. Amalgamations of FESS–BESS or FESS–UC associated with the microgrid though the power converters help in load frequency control (LFC) of the proposed hybrid system. The nominal parameters of this microgrid system are given in Table 5.2. The following equation postulates the resultant power generation:

\[ P_H = P_{WPG} + P_{DEG} + P_{FCPG} - P_{AE} \pm P_{FESS} \pm (P_{BESS} \text{ or } P_{UC}) \]  

(5.35)

**Table 5.2: Nominal Parameters of Hybrid Microgrid**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{WTG} )</td>
<td>1.00</td>
<td>( T_{WTG} )</td>
<td>1.5</td>
</tr>
<tr>
<td>( K_{AE} )</td>
<td>0.002</td>
<td>( T_{AE} )</td>
<td>0.5</td>
</tr>
<tr>
<td>( K_{FC} )</td>
<td>0.01</td>
<td>( T_{FC} )</td>
<td>4.0</td>
</tr>
<tr>
<td>( K_{PV} )</td>
<td>1.0</td>
<td>( T_{PV} )</td>
<td>1.8</td>
</tr>
<tr>
<td>( K_{FESS} )</td>
<td>0.01</td>
<td>( T_{FESS} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( K_{BESS} )</td>
<td>0.003</td>
<td>( T_{BESS} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( K_{UC} )</td>
<td>0.7</td>
<td>( T_{UC} )</td>
<td>0.9</td>
</tr>
<tr>
<td>( K_{DEG} )</td>
<td>0.003</td>
<td>( T_{DEG} )</td>
<td>2.0</td>
</tr>
<tr>
<td>( K_{HVDC} )</td>
<td>0.005</td>
<td>( T_{HVDC} )</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Figure 5.16: Block diagram for proposed modified FOPID controller based hybrid microgrid
5.6.2 FOPID Controller Design for LFC of Hybrid Microgrid System

The proposed fractional order PID (FOPID) controller based load frequency control method is analyzed in the sub section. The most extensively applied controller for industrial applications because of its ease in understanding and tuning is the classical Proportional-Integral-Derivative (PID) controller. The delay of imitative and combination order from integral to fractional order has much suppleness in design of the controller and thus takes in charge of the extensive range of dynamics of a system. Fractional order PID (FOPID) controller has proportional \((k_p)\), integral \((k_i)\) and derivative \((k_d)\) constants of the PID controller as well as additional parameters as integral order \((\lambda)\) and derivative order \((\mu)\). Thus, the usage of two additional operators augments two extra degree of freedom to the controller and creates the possibility of more effective performance of the traditional PID controllers [26, 113]. In order to determine the fractional order Proportional-Integral-Derivative (FOPID) controller, the fractional order differential equation is utilized.

The differential equation of fractional order PID controller is described as:

\[
{u(t) = k_pe(t) + k_iD_t^{-\lambda}e(t) + k_dD_t^\mu e(t)} \tag{5.36}
\]

\[
e(t) = \Delta P_{ie}(t) + B_t\Delta \omega(t) \tag{5.37}
\]

where \(e(t)\) is the error signal and \(u(t)\) is the control signal. \(K_p, K_i\) and \(K_d\) are the proportional, integral and differential gains respectively. \(\lambda\) is integral order and \(\mu\) is derivative order. The structure of FOPID controller is shown as:

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As shown in Figure 5.17 the FOPID controller generalizes the conventional integer order PID controller and expands it from point to plane. This extension of integral and derivative order will provide much more flexibility and accuracy in PID controller design. The optimal values of FOPID controller parameters for minimizing the fitness function are tuned by using a modified firefly algorithm (FA) and fuzzy logic control (FLC) as a hybrid technique.

5.6.3 Modified Firefly Algorithm (FA) for Tuning of FOPID Parameters

Firefly Algorithm (FA) is an optimization algorithm which is based on the intermittent performance of fireflies. The bioluminescence procedures are accountable for flashing light of fireflies. There are various theories concerning the reason and position of flashing light in firefly’s life cycle but most of them congregate to coupling phase. Attracting mating partner is the rudimentary objective of flashing light. The designing of algorithm depends upon the rhythm of flashes, rate of flashing and amount of time for which flashes are perceived. This arrangement entice in cooperation with the males and females to both and female of a species answer back to specific configuration of male of identical species [172, 173].
Inverse square law states that intensity of the light ($I_L$) goes on reducing as the distance ($r_f$) upsurges as given below:

$$I_L \propto \frac{1}{r_f^2} \quad (5.38)$$

Air also performs as absorbent and light gets feebluer with more distance. The three ideal rules combined into the unique firefly algorithm (FA) are: i) all fireflies are unisex so that a firefly is fascinated to every other fireflies; ii) a firefly’s attraction is proportional to its illumination perceived by other fireflies and so for any two fireflies, the hazier firefly is appealed by the perkier one and moves in the direction of it, nevertheless if there are no brighter fireflies nearby, a firefly moves unsystematically and iii) the intensity of a firefly is proportional to the worth of its objective function. Based on the degree of attractiveness of a firefly by the above three rules, the FA equation is as following:

$$\beta = \beta_0 e^{-\gamma r^2} \quad (5.39)$$

where $\beta$ is the degree of attractiveness of a firefly at a distance $r$, $\beta_0$ is the degree of attractiveness of a firefly at a distance $r=0$, $\gamma$ is the light absorption coefficient, $r$ is the distance between any two fireflies.

The Euclidean distances of fireflies are evaluated from the following equation:

$$r = \left\| x_i - x_j \right\| \quad (5.40)$$

$$r = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (5.41)$$
The movement of the dimmer firefly $i$ towards the brighter firefly $j$ in terms of the dimmer one’s updated location is determined by the following equation:

$$x_{i+1} = x_i + \beta_0 e^{-\alpha^2} \left( x_j - x_i + \alpha \left( rand - \frac{1}{2} \right) \right)$$  \hspace{1cm} (5.42)

The third term in above equation is comprised for the case when there is no brighter firefly than the one being measured and $rand$ is a random number in the range of $[0, 1]$. An enhanced firefly algorithm (FA) is suggested to tune the parameters of FOPID controller in hybrid power system. The proposed algorithm is upgraded by modifying the searching idea of traditional firefly algorithm. The detailed analysis has been given to apply the modified FA with genetic algorithm (GA) for tuning of FOPID controller. The firefly algorithm is enhanced by hybridizing the GA with classical firefly algorithm to verify the random movement factor. In firefly algorithm, the subsequent movement of firefly depends on the progress factor. But the movement factor is determined arbitrarily, so the most excellent movement of firefly has the possibility to miss due to the random number. Therefore, the random movement parameter of FOPID has to be tuned precisely.

Genetic algorithm (GA) based optimization algorithm is suggested to find out the optimal random movement factor ($\alpha$) of fireflies in this work. According to the proposed modified firefly algorithm, the optimal parameters of FOPID controller are tuned and minimize the deviation of load frequency of power system. According to the searching concept of traditional firefly algorithm, the proposed algorithm is improved. The steps of the proposed improved firefly algorithm can be summarized as the following:

**Step 1:** Initially, the FOPID controller parameters are initiated randomly such as $K_p$, $K_i$, $K_d$, $\lambda$ and $\mu$ respectively. The voltage and power of the hybrid power system are also initialized. The initialized system parameters considered as a function which is denoted as $x_i$. The algorithm parameters are predetermined such as maximum
attractiveness ($\beta_0$), absorption coefficient ($\gamma$), initial distance of fireflies ($r$) and random factor ($\alpha$) respectively.

$$x_i = (x_{i1}, \ldots, x_{in})$$

**Step 2:** From the initialized values, the random solution is generated. To control the system when load varies, the load frequency deviation is determined and the power of the integrated system is also evaluated. So, the $x_i$ is to be varied according to the number of optimal variables ($K_p, K_i, K_d, \lambda, \mu$). The output function ($F_i$) depends on the error signal of the system. The output function is described as follows:

$$F_i = \min(e(t))$$

**Step 3:** Start the iteration count and determine the optimal parameter of FOPID. At the end of iteration, rank the solution by using the above equation and determine the current best solution as per the rank.

**Step 4:** In this step, the optimal random movement factor is optimized by GA. Initialize, the random movement factor ($\alpha(0,1)$) for counting the iteration level. The range of random movement factor is described as follows:

$$\alpha_{\text{min}} \leq \alpha \leq \alpha_{\text{max}}$$

From the initialized random movement factor, the fitness is evaluated. The fitness depends on the distance updating formula of the fireflies. Apply genetic algorithm operators like cross over, mutation and selection. The best selection i.e. optimal random movement factor depends on the distance of the fireflies. If the distance is low then select minimum level random factor $\alpha_{\text{min}}$. If the distance of the fireflies is high then select maximum level random factor $\alpha_{\text{max}}$. According to the optimal output $\alpha_{\text{op}}$ of GA, the next location of fireflies is rearranged. The optimal results are stored and updated the random movement factor of FA.

**Step 5:** The location of fireflies rearranged by equation (19) and the equation is represented as follows:
where $\propto_{op}$ is the optimal random movement factor.

**Step 6:** Check the optimal parameter of FOPID controller is at the end of the maximum iteration. If, it does not reach the optimal parameters then go to step 3 and increase the number of iteration.

The pseudo code of the proposed modified FA algorithm for optimal gain selection is explained as follows:

```
Input:
\[ x_i = (x_1, \ldots, x_n) \]

Output:
\[ F_i = \min(\epsilon(t)) \]

(Optimal parameter of FOPID)

Begin

For \( i = 1 \) to \( t \)

Generate the FOPID parameters with assumed values as initial solution.

End

Repeat

\[ x_{min}^i \] arguments \( F_{min}^i \)

For \( i = 1 \) to \( t \) do

If

\[ F(x_j) < F(x_i) \]

then move firefly \( j \) towards \( i \)

Optimize the random movement factor $\propto$ by GA

For \( k = 1 \) to \( n \) do
```
\[ x_{i}^{k+1} = x_{i}^{k} + \beta_{0} e^{-\gamma \alpha} (x_{i}^{k} - x_{j}^{k}) + \alpha_{op} \]

5.6.4 Optimizing the Movement Factor of Firefly Algorithm using Genetic Algorithm

The mechanics of natural selection and natural genetics is supported by genetic algorithms. In every generation, a new set of artificial creatures i.e. strings are created by using bits and pieces from the fittest of the old, an occasional new part is used for good measure. Genetic algorithm is basically a derivative of a simple model of population genetics. Reproduction, crossover and mutation are the prime operators related with the genetic algorithm. The variable parameters represent the chromosomes in GA solution. Procedure by which individual strings are clichéd conferring to their fitness values is called as reproduction [115, 121]. There are mainly six fundamental steps of GA such as chromosome representation, selection function, genetic operators, initialization, termination and evaluation function. The various steps of GA are described as follows:

5.6.4.1 Generating Original Population Set

The population set is created in the beginning by using random numbers in between the lower and upper limits of variables to be optimized. This is equivalent to creation of population of chromosomes. These random numbers are then coded in binary form and single binary string. The group of these strings represents the population set. For each
member of population set the objective function has unique value. Representation of an individual or chromosome can be binary, floating point, integer, real values, matrices etc.

5.6.4.2 Reproduction, Crossover and Mutation

In the evolution process two members are randomly selected from the original population set by using the method of Roulettetree Wheel Selection. These members are called parents and they reproduce their offsprings. Similarly, there are several other schemes for the parent selection process namely scaling techniques, tournament, elitist models, ranking method and normal geometric method. During the reproduction process, the best offsprings are generated due to the interchange of binary information between two parents and replacing the weaker population with the better half population. This is achieved through two important processes namely crossover and mutation.

In the crossover process, the selected individuals recombine to produce offsprings through exchanging genetic information between the pairs of the individuals in the current population. The principle of survival of the fittest is followed in GA to produce the fittest population and thus the optimized variables. The equal numbers of original population of parents is mixed with the newly generated offsprings. Each member in the population gives different value of objective function of the system which is called the fitness value of that member in the population. The members are sorted according to their fitness values. The weaker half is removed and the better half replaces the original population. A new genetic structure can get produced with a given probability for each individual during the random process called mutation in the population. After several crossover and mutation processes the members of the population get fittest and finally converge to an optimum set of variables which minimizes the objective function. The GA process will stop when any of the following three criteria is fulfilled:

1. When the pre-defined maximum number of iterations have been achieved.
2. All fitness functions have same value.
3. The value of the objective function is minimized and attains the value below the threshold value.
In the present case GA method is used to optimize the random movement factor (\(\propto\)) of firefly algorithm (FA) given by equation (5.41). The steps of GA for optimizing the random movement factor (\(\propto\)) are given as:

1. Select the population of chromosomes \(S_i (i=1, 2, 3...N)\) arbitrarily. \(N\) symbolizes the population size in genetic algorithm.
2. Measure the fitness function of every chromosome and the uppermost fitness value is preferred as the finest one.
3. One or more parent chromosomes are designated and transmit out the solitary point cross over.
4. In mutation procedure, the chromosome standards are fluctuated rendering to the option of obtaining the novel chromosome.
5. The current chromosome is replaced with the novel chromosome in this phase.
6. If the fitness value of novel chromosome is superior to the existing chromosome, select that chromosome as the finest chromosome.

Flowchart for the GA is illustrated in Figure 5.18 and the GA parameters chosen in this work are shown in Table 5.3.

Table 5.3: GA Parameters for Tuning the Random Movement Factor of Firefly Algorithm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Size (N)</td>
<td>50</td>
</tr>
<tr>
<td>Crossover Probability ((p_c))</td>
<td>0.8</td>
</tr>
<tr>
<td>Mutation Probability ((p_m))</td>
<td>0.004</td>
</tr>
<tr>
<td>Elitism Probability ((p_e))</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum no. of iterations</td>
<td>50</td>
</tr>
<tr>
<td>Threshold error ((\varepsilon))</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Figure 5.18: Flowchart of Genetic Algorithm
5.6.5 **Fuzzy Logic controller**

Using the fuzzy system, prediction of optimal control parameter is performed. The detailed procedure of fuzzy system is made cleared in the beneath segment.

5.6.5.1 **Fuzzy system**

The fuzzy system is proposed for the prediction which is discussed in this part of the study. The comprehensive process tangled in the proposed fuzzy system is shown in Figure 5.19. The greatest imperative philosophies at the back of a fuzzy system utilizes the idea of linguistic variables to decide depending on fuzzy rules and hence get a healthier reply linked to a system with help of crisp values [105].

5.6.5.2 **Designing of fuzzy system**

Proposing of fuzzy system has Four significant steps 1) Fuzzification 2) Fuzzy inference engine 3) Decision Making 4) De-fuzzification.

**Fuzzification:** modifies the crisp input to a linguistic variable with the membership function collected in the fuzzy knowledge base.

**Fuzzy inference engine:** with the assist of If-Then type fuzzy rules, fuzzy inference engine alters the fuzzy input into the fuzzy output.

---

Figure 5.19: Working process of fuzzy logic controller
The membership function can be engaged in both fuzzification and de-fuzzification layers. The membership function is generally cast-off to enumerate the linguistic term., it charts the non-fuzzy input standards to fuzzy linguistic terms and in divergence of the fuzzification and de-fuzzification layers, fuzzy linguistic positions to non-fuzzy input values. The membership function can be characterized in numerous procedures like triangular, gaussian, trapezoidal etc.

**Decision Making:** The fuzzy values make the base of fuzzification process and these can be used to generate every feature procedure for the fuzzy rules. The choice made is based on the above rules. The overall method of fuzzy rule is "If A then B". The "If" portion of the fuzzy rule is called as "antecedent", similarly, the "then" portion of the rule is called as "conclusion". The decision making process can be depicted with following equation:

\[
D_f^I(t) = [CS_f^I(t)] 
\]  

(5.44)

where \(CS_f^I(t)\) is output signal.

**De-Fuzzification:** This procedure de-fuzzifies the fuzzy values to the crunchy output values. The de-fuzzification is on basis of the membership function of the output variable [109, 110]. It yields a database of the system. The equation pertaining to de-fuzzification is given as:

\[
CS_f^d(t) = CS_f^{cz}(t) 
\]  

(5.45)

Fuzzification is essential as a degree of membership is quantified for every member of set. The fuzzy system predicts the consequences further accurately with the improved membership function.

### 5.6.6 Simulation Results and Analysis of Hybrid Microgrid (MG) System

In this section, the genetic algorithm (GA) based modified firefly algorithm (FA) is implemented for tuning of FOPID controller in MATLAB/Simulink platform. The GA-FA based FOPID controller is used to minimize the deviation of load frequency of hybrid microgrid power system. The proposed method is tested with the hybrid
renewable energy system, which is formed with two wind generation systems (WTG), one aqua electrolyzer (AE), one fuel cell (FC) and one diesel engine generator (DEG) to analyze the load frequency control. The photovoltaic power generation (PV) is considered as zero and it does not share the power with other sources in the microgrid. The storage devices like battery energy storage system (BESS), ultra capacitor (UC) and flywheel energy storage system (FESS) are also connected in system.

The MATLAB/SIMULINK model of the system is shown in Figure 5.20. At the point when HVDC connection is reflected to communicate the wind power generation, the DC power output is rehabilitated to AC power by appropriate converter and is fed to the load. A share of total wind power (\( P_{WPG} \) or \( P_{HVDC} \)) is used in the aqua-electrolyzer (AE) to yield hydrogen as a fuel for the fuel cell (FC). The FC harvests DC control which is rehabilitated to AC power (\( P_{FCPG} \)) via DC–AC converter. \( P_{FCPG} \) is combined with DEG output (\( P_{DEG} \)) and \( P_{WPG} \) or \( P_{HVDC} \) as normal power source to fed the associated loads. In order to estimate the performance of the proposed GA-FA-FOPID tuning controller, the simulation results are compared with those of PID, Fuzzy-FOPID and FA-FOPID controllers [136,172]. The implementation parameters of proposed firefly algorithm are given in Table 5.4

<table>
<thead>
<tr>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Generation of Fireflies</td>
<td>50</td>
</tr>
<tr>
<td>Initial distance of fireflies (r)</td>
<td>5</td>
</tr>
<tr>
<td>Random movement factor (( \alpha ))</td>
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</tr>
<tr>
<td>Attractiveness coefficient (( \beta ))</td>
<td>1</td>
</tr>
<tr>
<td>Absorption coefficient (( \gamma ))</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5.20: MATLAB/Simulink model of microgrid system with modified FOPID controller
An attempt is made for the LFC of hybrid microgrid system with two wind power generation plants (WTG), one aqua electrolyzer (AE), one fuel cell (FC) and one diesel engine (DEG) plant. At the different time instants, the frequency changes are analyzed and the simulation results are evaluated with the proposed system. The power management among different sources of the proposed model for the change in load is analyzed. The set of graphs in the Figure 5.22, Figure 5.23, Figure 5.24 and Figure 5.25 reflect the power due to two offshore wind turbines to yield wind power ($P_{WT}$) in the system, diesel generator power ($P_{DG}$), aqua electrolyzer power ($P_{AE}$) and fuel cell power ($P_{FC}$) while using PID controller, Fuzzy-FOPID, FA-FOPID and proposed GA-FA-FOPID controller respectively for LFC of the microgrid system. The comparison results of frequency response with proposed control method with GA-FA-FOPID controller and existing methods such as PID controller, Fuzzy-FOPID, FA-FOPID [35,36,136] used for LFC of the hybrid microgrid system are illustrated in the Figure 5.21.

Figure 5.21: Frequency response of microgrid using various controllers
Figure 5.22: Analysis of various source powers using PID controller

Figure 5.23: Analysis of various source powers using Fuzzy-FOPID
Figure 5.24: Analysis of various source powers using FA-FOPID

Figure 5.25: Analysis of various source powers using proposed GA-FA-FOPID controller
It can be well understood from above plots that wind, diesel, aqua electrolzer and fuel cell organize their performance for different load conditions during different time intervals. When the system is not able to meet the power demand, the power in need will be taken from the battery. The battery is recharged when the power produced exceeds the required power demand.

The PID, Fuzzy-FOPID and FA-FOPID controllers take high setting time to decrease the load frequency deviation in comparison to proposed GA-FA-FOPID controller. The time taken to achieve the transient steady state level of proposed controller is less. The novelty of the proposed approach is the better response in terms of peak overshoot and peak undershoot in comparison with other approaches as shown in Figure 5.21. In this figure, it can be seen that there is no abrupt change in the frequency while using GA-FA-FOPID controller and system is stable under the extensive range of dynamics of the microgrid. By using the proposed controller, the integrated system achieves better frequency response with lower error when compared to that of other controllers. The actual frequency deviation with various control methods such as modified GA-FA- FOPID, FA-FOPID, Fuzzy-FOPID and PID controller techniques are evaluated with different time instants. From the above analysis, the load frequency control performance of the modified GA-FA-FOPID controller is highly superior to that of the other controllers. The above results show that the proposed control system operates optimally by coordinating the various units of integrated system to meet the total power demand. Therefore, the performance of the proposed method has achieved better results.

5.7 SUMMARY

Frequency regulation is very important for AC microgrids under varying load conditions and during the uncertainties of power production from renewable energy sources. First type of hybrid power system has been designed with a wind energy conversion system (WECS) and diesel power (DG) plant in an isolated mode. This system is designed for the remote coastal areas which cannot be connected to the main grid but they have abundance of wind energy. The problem arises when there is
reduction in wind speed or increase in load on the generation system. There can be large frequency deviation if the power generation does not match with the load demand. Two methods have been implemented for frequency response enhancement of the system. Firstly, the power generation from wind plant is reserved to meet the increase in load demand. Secondly, the power is generated by the diesel power plant which is controlled through fully optimized PSO-based PI controller and shares the load requirement with wind power generation system. The simulation results using MATLAB/SIMULINK show that the PI controller used for the diesel power plant and generating margin of wind energy conversion system effectively controls the frequency change along with the load change and wind speed variation.

The frequency response enhancement of one more hybrid microgrid power system with offshore wind (WTG), photovoltaic (PV), fuel cell (FC), aqua electrolyzer (AE) and diesel engine generator (DEG) along with the energy storage elements like flywheel energy storage system (FESS), ultra capacitor (UC) and battery energy storage system (BESS) is also attained in this chapter. Genetic algorithm (GA) based modified firefly algorithm (FA) is applied to tune the parameters of fractional order PID (FOPID) controller. The performance of proposed GA-FA-FOPID controller is compared with traditional PID controller, Fuzzy-FOPID and FA-FOPID controller.