Controlled active power generation with multi-terminal HVDC system using modified grey wolf optimization

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Abstract. This study is focussed on the integration of wind farm connected through high voltagedirect current (HVDC) link in the study of load frequency control (LFC). In the study, the designed test system is an interconnected two-area multi-generating unit power system. In each area of the studied test system, the generating sources are reheating thermal, hydro, gas, nuclear generating units, and the wind farm which is connected through the HVDC system. In the study, important physical constraints which are related to system dynamics like time delay, governor dead band and generation rate constraint are considered for the effective LFC study. The primary contribution of the work is to show the impacts of a wind farm through the multi-terminal HVDC system in LFC task. The concept of inertia control and droop control of the wind farm are used in the paper for primary frequency control. For LFC model design, modified grey wolf optimizer algorithm is taken into consideration for the optimal values of proportional-integral-derivative controller gains.

Keywords. System frequency regulation; power system; grey wolf optimizer algorithm; wind farm with HVDC line.

1. Introduction
The load frequency control (LFC) mechanism is an important activity for a network of electrical control systems responsible for satisfying power demand with certain parameters and satisfying its optimum value in terms of customer requirements. Load disturbances in the power system influence the produced power output that can be evaluated by the deviation of the system frequency and the deviation of the power line. Thereby, the correct coordination between these two may be recognized as an important condition for the better LFC performance [1]. The study becomes significant when non-conventional energy sources are connected to the grid. Due to the characteristics of large penetration
of wind farm when connected to the grid, wind farms can contribute to control the power system frequency [2-3]. Along with the increase in the rate of frequency change will lead to the extra regulation load on conventional units. In addition to this, the LFC study becomes significant when nuclear power units are connected to the system and acts as base load power. The study becomes critical when the grid links unconventional energy sources. For example, because of the characteristics of large wind farms entering the grid, the wind farms can help to monitor the frequency of the power systems [2-3]. However, the stochastic behaviour of wind farm when connected to the grid is difficult to model and study. Alongside, the rise in frequency change rates is observed, the increased regulatory burden on traditional units would result. Thereby, autonomous generation sources need to be installed in the interconnected power systems.

Frequency in the constant state must be the same in the synchronous power grid. The maintenance of an almost constant frequency (one can allow for frequency to differ over a very limited band) is an important necessity for the operation of the power system. Also, frequency is closely linked to electrical speed of synchronous generators in a power system. The difference between mechanical and electric torques governs the speed of a generator rotor. Therefore, mechanical input and electric output power must continuously be balanced in order to maintain a continuous speed.

To do this, various research work has been done in the past. LFC performance study with the adopted control techniques has a significant aspect in power system dynamic operation. Therefore, properly designed controllers are needed for the settlement of the system variations to sustain the stability, reliability, and optimum performance of the power system. Primarily, the LFC deals with the adjustment of the real power output of the generator and its frequency deviation within the specified limit [1-2]. Many researchers so far have proposed various control strategies for LFC that may be summarized in [4-13]. At present, researchers are more concern to determine new approach for LFC to correctly regulate the system frequency irrespective of variable power demands. It is examined that the research work is in progress with multi source interconnected power system that has been shown in [14-15].

In the proposed work, an interconnected two-area multi-unit multi source test system is studied to damp out the area frequency oscillations and tie-line power deviation. In this work, nuclear power generating units is added. Along with this, the impacts of wind farms through multi-terminal high voltage direct current (HVDC) link are included in this work. In frequency control, the system uses the inherent properties of the wind farm inertia and drop control. To make the analysis more meaningful, non-linearities are applied to system constraints already linked to system dynamics such as time delay, dead band governor (GDB), boiler dynamic (BD) and generation limit (GRC). The modified GWO algorithm is used in the simulation task to design the controller gains. This algorithm is chosen because of the disadvantages of the other algorithm as studied in [16].

The remainder of the text is structured as follows. The studied two-area test method is defined in section 2. In addition, the contribution of the wind farm to the frequency stabilisation is also demonstrated. Section 3 demonstrates the formulation of the mathematical problem. Section 4 presents the optimization algorithm for the optimization task under investigation. In Section 5, we will discuss simulation results/comments from the present simulation task. Finally, Section 6 completes the resulting findings.

2. System investigated
The studied test system is an interconnected two-area system with generating units like reheat thermal, hydro, gas, and nuclear generating units. The thermal unit is equipped with governor system with GDB, BD, reheat turbine with GRC whereas hydro section is supervised by governor, transient droop compensation and hydraulic turbine with GRC. A gas turbine power plant consists of valve positioned, speed governor, fuel system and gas turbine. The basic details of nuclear power plant subjected to LFC study is explained in [17-18]. The configuration of BD, GRC and nuclear turbine unit is shown in figure 1. In the studied model, the wind farm is connected through the HVDC system [19]. Full configuration and block details of the test model generation units are provided in figure 2. A boiler
The dynamics model adopted for analysis is taken from [20]. The test device parameters are specified in Appendix Section A.1. The Appendix section also displays the participation factor (PF) of each generating unit. Appropriate GRC for both thermal and hydro units and GDB for both thermal units are considered in [19].

2.1. Wind farm: Basic concept
Wind power generation plays a crucial role in power generation due to technical advancement, zero emission, diminishing of fossil fuels day by day and environment pollution. The wind turbine mechanical power is given as follows [3].

\[
P_w = \frac{1}{2} \rho A_r C_p V_w^3 \tag{1}
\]

\[
C_p = (0.44 - 0.0167 \beta) \sin \left[ \frac{\pi(\lambda - 3)}{15 - 0.3 \beta} \right] - 0.018(\lambda - 3) \beta \tag{2}
\]

where \( P_w \) is the wind turbine power, \( \rho \) is the density of air \((\text{Kg} / \text{m}^3)\), \( A_r \) is the area of blades swept \((\text{m}^2)\), \( V_w \) is wind speed and \( C_p \) is a function of both speed tip ratio \((\lambda)\) and the blade pitch angle \((\beta)\).

\[\begin{align*}
&\Delta X_E + \sum \Delta x_i \quad \text{Change in steam flow (} \Delta P_h \text{)} \\
&\Delta \sum \quad \text{Change in throttle pressure} \\
&\sum \quad \text{Change in fuel flow} \\
&\text{Boiler storage} \\
&\text{Pressure control unit} \\
&\frac{1}{C_D} s \\
&\frac{K_D (1 + s T_B)(1 + s T_{RB})}{s(1 + 0.1 s T_{RB})} \\
&\frac{e^{-T_D s}}{1 + s T_D} \\
&\text{Fuel system} \\
&\text{Change in fuel flow} \\
&\text{Boiler effect}\end{align*}\]

\[\begin{align*}
&\Delta P_g + \frac{1}{T_I} \quad \text{Fuel system} \\
&\alpha \\
&\Delta P_I \end{align*}\]
Figure 1. Configuration of the studied model: (a) Boiler dynamics, (b) GRC, (c) nuclear turbine unit.
Figure 2. Studied test system.
2.2. Wind farms with Inertia control
The wind turbine blade's kinetic energy is responsible for the wind farm's inertia response. This inertia use (due to the kinetic energy) can be used to avoid the maximum frequency change rate. The expression for active power \( P_{in} \) produced by the inertia control is given in (3) [19].

\[
P_{in} = -2H \frac{df}{dt} \tag{3}
\]

In (3), \( H \) is the inertia constant of a turbine. A negative sign indicates frequency shift rate.

2.3. Wind farms with droop control
To set the continuous state frequency response, the principle of droop control can be used by controlling the governor speed. It is available in the frequency control loop feedback direction. It is like the approach of a frequency decrease in a synchronous generator's speed regulation. With this concept of droop control \( R_{WF} \), the mathematical expression for active power produced is given in (4) [19].

\[
P_{in} = -\frac{\Delta f}{R_{WF}} \tag{4}
\]

2.4. Structure of PID controller
The controller actions are calculated through an automatic feedback controller via a certain mathematical analysis, which is implemented through automated systems. The essence of the mathematical feature is calculated based on the plant itself static and dynamic characteristics. The ultimate objective of the above power system model is to ensure that the steady state value is equal to the reference value.

It is possible to note that an automated controller may worsen the stability of the system unless it is constructed improperly. It should be noted that the controller steps should therefore be carefully planned. Also, the specification of the individual parameters of the controllers is not discussed during the design of the control rules. The actual benefit values are chosen based on compliance with certain conditions such as the maximum stable state failure, reliability, override and so on. In the LFC problem study, the transfer function based expression of PID \( K_{PID}(s) \) controller and its output \( U(s) \) may be stated in (5) [21] (refer figure 3).

\[
K_{PID}(s) = K_p + \frac{K_i}{s} + \frac{s K_d}{1 + s/N} \]

\[
U(s) = \left( K_p + \frac{K_i}{s} + \frac{s K_d}{1 + s/N} \right) \times \Delta ACE \tag{5}
\]

In the work done, a powerful optimization technique has been used for the design of optimal gains of controllers. This is done because of its significant contributions in other field of works that may be found in [22-32].
3. Problem formulations
The mathematical problem formulation is done to examine the capability of the proposed modified GWO algorithm in LFC task. This is performed by the objective function. Here, an ITAE objective function is used and the expression is stated in (6).

\[
ITAE = \int_0^{t_{sim}} \left( |\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}| \right) dt = \int_0^{t_{sim}} |ACE_i| t dt
\]  

The PID controller gains are limited in the optimization task studied. These parameters have to be defined in parametric limits. These limits of the model parameters may be framed in (7).

\[
\begin{align*}
K_{pi}^{min} \leq K_{pi} \leq K_{pi}^{max}, & \quad i = 1, 2 \\
K_{ii}^{min} \leq K_{ii} \leq K_{ii}^{max}, & \quad i = 1, 2 \\
K_{di}^{min} \leq K_{di} \leq K_{di}^{max}, & \quad i = 1, 2 \\
N_i^{min} \leq N_i \leq N_i^{max}, & \quad i = 1, 2 
\end{align*}
\]  

In (7), the min and max superscripts represent the lowest and highest values of the respective variables. The controller is configured according to the objective feature defined in Eq. (7). The further research uses other performance parameters such as the integrated time square error (ITSE), integral of square errors (ISE), and integral of absolute error, as indicated under (8)-(10), to perform the planned controller-based dynamic performance analysis.

\[
ITSE = \int_0^{t_{sim}} \left( \Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2 \right) dt = \int_0^{t_{sim}} \left( ACE_i \right)^2 dt
\]  

\[
ISE = \int_0^{t_{sim}} \left( \Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2 \right) dt = \int_0^{t_{sim}} \left( ACE_i \right)^2 dt
\]
$$IAE = \int_0^{t_{sim}} \left( |\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}| \right) dt = \int_0^{t_{sim}} |ACE_i| dt \quad (10)$$

4. Applied optimization technique
GWO is an algorithm characteristic of swarm intelligence influenced by the hierarchy of leadership and the hunting process in nature of grey wolves. Gray wolves are considered top predators; the average size of the population is 5-12. Alpha ($\alpha$) is the most dominant part of the group in the GWO hierarchical region. The rest is beta ($\beta$) and delta ($\delta$), helping to regulate most hierarchical wolves that are considered as ($\omega$). The oscillations of the wolves in the hierarchy are lowest. The details of the GWO algorithm can be found in [16].

5. Simulation results and analysis
This section studies the simulation results obtained by using the proposed modified GWO for the tuned multi-source two-area test method. The load profile used for the test system LFC output analysis is 0.01 p.u.MW. The implemented optimization techniques are run with the load profile, and the simulation results for 10 independent runs are recorded along with the objective function’s best found predicted minima. The impacts of GWO based built PID are being developed in the simulation work.

5.1. Dynamic response analysis for SLP applied in area-1
Time domain simulation results are analyzed after applying 1% SLP to area-1 by simultaneously considering the effects of plant physical constraint such as time delay, GDB, BD and GRC. The results of the modified GWO-based PID controller are investigated in this work. Table 1 collects the tuned PID controller gains. Table 2 shows the comparative output performance index values and the objective values after the simulation mission. Table 2 showed that the FOD values are 3.1284 for updated GWO based tuned controller. This table clearly showed that modified GWO based controller showed promising tuning capability as this LFC problem is the minimization problem.

| Controller type | $K_{p1}$ (-ve) | $K_{i1}$ (-ve) | $K_{d1}$ (-ve) | $N_1$ | $K_{p2}$ (-ve) | $K_{i2}$ (-ve) | $K_{d2}$ (-ve) | $N_2$ |
|----------------|----------------|----------------|----------------|------|----------------|----------------|----------------|------|
| modified GWO   | 1.9361         | 0.7801         | 0.1991         | 464.8675 | 0.6017        | 0.0011         | 0.0010         | 70.2056 |

| Controller type | FOD (ITAE) | ITSE | IAE | ISE |
|----------------|-----------|-----|-----|-----|
| modified GWO   | 3.1284    | 0.2529 | 0.0238 | 0.0027 |

Simulation results for this scenario are clearly shown in figure 4. Analyzing figure 4, the updated GWO-based PID controller shows a major improvement in the dynamic response of area-1 and area-2 frequency deviations as well as tie-line power deviation profiles. Note that because the load
disturbance applied is an increased load demand, the area frequency with undershoot at first decreases. It can be seen from figure 4 that the updated GWO-based PID controller adjusts deviations to zero easily.

![Graphs](a) ![Graphs](b) ![Graphs](c)

**Figure 4.** ASO based response profiles for random load: (a) $\Delta f_1$, (b) $\Delta f_2$, (c) $\Delta P_{tie12}$.

Finally, in the optimization task, the convergence profile curve of the studied algorithm is studied. The convergence mobility of the studied algorithms based on FOD values is shown in figure 5. The figure demonstrates the promising convergence characteristic of GWO technique.
6. Conclusion
In this article, a multi-terminal HVDC system connects the wind farm to improve frequency deviations control by inertia regulation and drop control. A feasible two-area model with system dynamic limitations and an effective way of optimising tuning method has been introduced. The key contribution to this work is the investigation of dynamic system efficiency and of multi-source units linked to the wind farm. For the dynamic controller action, the modified GWO has been introduced to enhance the tuning efficiency of the configured PID controller. The results of the simulation show that the algorithm proposed is tuned efficiently with a powerful dynamic response. This research can be further generalised by considering the deregulated power scenario.

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Appendix
A.1 Nominal data for the studied two-area multi-source test system [19]
System configuration: \( f = 60 \text{ Hz}, P_{r1} = P_{f2} = 2000 \text{ MW}, \) Total area load = 1740 MW, Base rating=2000 MW, Initial loading=87%.

For reheat turbine unit: \( T_{sg} = 0.06 \text{ sec}, T_t = 0.3 \text{ sec}, K_r = 0.3, T_r = 10.2 \text{ sec}, N_1 = 0.8, N_2 = \frac{-0.2}{\pi}, \) 
\( R_{lh} = 2.4 \text{ Hz/p.u.MW}, \) \( B_1 = B_2 = 0.4312 \text{ p.u.MW/Hz}, \) \( H = 5 \text{ MWsec/MVA}, \) \( D = 0.0145 \text{ p.u.MW/Hz}, \) \( K_{ps1} = K_{ps2} = 68.9655 \text{ Hz/p.u.MW}, \) \( T_{ps1} = T_{ps2} = 11.49 \text{ sec}. \)

For hydro turbine unit: \( T_{gh} = 0.2 \text{ sec}, T_{rs} = 4.9 \text{ sec}, T_{rh} = 28.749 \text{ sec}, T_w = 1.1 \text{ sec}, R_{hyd} = 2.4 \text{ Hz/p.u.MW}. \)

For gas turbine unit: \( B_g = 0.049 \text{ sec}, C_g = 1, X_g = 0.6 \text{ sec}, Y_g = 1.1 \text{ sec}, T_{cr} = 0.01 \text{ sec}, T_f = 0.239 \text{ sec}, T_{cd} = 0.2 \text{ sec}, R_g = 2.4 \text{ Hz/p.u.MW}. \)

Wind Farm \( T_{wT} = 1.5 \text{ sec}, k = 10.38, \) \( K_{DC} = 1.0, T_{DC} = 0.2 \text{ sec}, T_{HVDC} = 0.7 \text{ sec}. \)

Participation factor \( PF_{th} = 0.4347, PF_{hyd} = 0.25, PF_{g} = 0.130438, PF_{n} = 0.076084, PF_{wf} = 0.108778 \)

A.2 Determination of power system parameters at different loading conditions
Rated capacity $P_r = 2000$ MW, nominal load $\Delta P_L = 1740$ MW, nominal frequency $f = 60$ Hz, inertia constant $H = 5$ MWs/MVA, regulation parameter $R = 2.4$ Hz/p.u.MW. Assuming a linear load frequency dependence relationship:

\[
D = \frac{\partial P_L}{\partial f} = \frac{1740}{60} = 29 \text{ MW/Hz}
\]

$D$ in per unit (\(= D \text{ in p.u.MW/Hz/} P_r \)) \(= \frac{29}{2000} = 0.0145\) p.u.MW/Hz.

\[
T_{ps} = \frac{2H}{\partial f \times D} = \frac{2 \times 5}{60 \times 0.0145} = 11.49 \text{ sec}
\]

Power system parameters:

\[
K_{ps} = \frac{1}{D} = \frac{1}{0.0145} = 68.96 \text{ Hz/p.u.MW}
\]