Implementation of Harris Hawks optimization for load frequency control of hydropower plant

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ABSTRACT

Hydropower has been used for many years and is essential to meet the renewable energy ambition of the world at present. In a hydroelectric power plant, voltage and frequency control are required, but, the voltage control could be done on the load side. In the present paper, frequency control using Harris Hawks optimization (HHO) for improved performance has been presented. Simulations are performed on the dynamic model of the hydropower plant and results are compared with the conventional PID that is designed using the Ziegler-Nichols method. The efficacy of the proposed algorithm is also tested at dynamic conditions of the hydropower plant.

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1. INTRODUCTION

Hydropower is clean and lowers costs in long run. It is a great contributor to renewable energy these days and is also used as a spinning reserve. Typically, a hydropower plant comprises different subsystems as shown in Figure 1 [1]. Frequency control in the good range is crucial for hydropower plants as power demand is increasing these days. However, the technologies involved in the hydropower plant are conventional, people still prefer gain scheduling for load frequency control but this is not suitable for more range of operating points. Many researchers proposed load frequency controllers with optimization methods for interconnected power systems [2]–[10]. Some works have been presented on load frequency control of hydropower plants using nonlinear controllers [11]–[14]. Artificial intelligence-based controllers using fuzzy and ANN controllers are proposed for load frequency control in [15]–[23]. A nonlinear load frequency controller is developed in [8], also with sliding mode controller in [24], [25], however, they have more mathematical intricacies. More new optimization methods are implemented for this problem in [20]–[23].

In literature, very few of them are based on nature-inspired optimization methods for control of frequency in a typical hydropower plant to the best of the knowledge of the authors. In the present paper, Harris Hawks optimization (HHO) for improved performance of frequency control for a hydropower plant has been presented. The benefits of the proposed method are: i) simple control strategy with lesser
mathematical complexities, ii) easy to implement the control parameters like PID values in off-line for the real-time system, iii) cost-effective and consume less time in implementation, and iv) effective working on non-linear hydropower plant. The remaining paper is structured as follows: the dynamic equations of hydropower plant are described in section 2, proposed Harris Hawks optimization (HHO) is detailed in section 3, the result analysis and conclusions are described in section 4 and section 5 respectively.

Figure 1. Hydropower plant and its subsystems

2. THE DYNAMIC EQUATIONS GOVERNING THE HYDRO-ELECTRIC POWER PLANT

The equations which are governing the liquid flow penstock and output power of the turbine are detailed as below to represent the dynamic model of the Hydropower plant.

\[
\frac{du}{dt} = \frac{1}{tw} \left( h_o - \left( \frac{u_t}{g} \right)^2 \right)
\]

\[ h_t = \left( \frac{u_t}{g} \right)^2 \]

\[ p_m = (u_t - u_{nl}) \left( \frac{u_t}{g} \right)^2 \]

The transfer function model of the servo system that is used to control the motion of the wicket gate system is shown below. Where, the gate position change due electric servo system is given by (6). In (7) represents the generator model and (8) represents the state-space model of the entire hydropower plant.

\[
\frac{\Delta x_e(s)}{u(s)} = \frac{1}{tps+1}
\]

\[
\frac{\Delta g(s)}{x_e(s)} = \frac{1}{tgs+1}
\]

\[ \Delta g = g - g_0 \]

\[ M \frac{d\omega}{dt} = \bar{p}_m - p_e - D\omega \]

\[ \dot{x} = f(x) + g(x)u \]

Where,

\[
f(x) = \begin{bmatrix}
\frac{1}{M} x_2 x_3 - \frac{u_{nl} x_2^2}{M x_3} - \frac{D}{M} x_1 - \frac{D}{M} \omega_{ref} - \bar{p}_e \\
-\frac{1}{tw} x_2^2 + \frac{1}{tw} h_o \\
\frac{1}{t_g} x_4 - \frac{1}{t_g} x_3 + \frac{p_0}{t_g} \\
-\frac{1}{t_g} x_4
\end{bmatrix}
\]

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\[
g(x) = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \tag{10}
\]

\[
x(t) = \begin{bmatrix} x_1 \\
x_2 \\
x_3 \\
x_4 \end{bmatrix} = \begin{bmatrix} \Delta \tilde{\omega} \\
\bar{u}_t \\
g \\
\bar{x}_e \end{bmatrix} \tag{11}
\]

Where, \( \Delta \tilde{\omega} = \tilde{\omega} - \tilde{\omega}_{ref} \) \( \tag{12} \)

3. **HARRIS HAWKS OPTIMIZATION (HHO)**

This algorithm is realized by imitating the capture of prey by harries hawks and their behavioral steps during this process. One may find its image in Figure 2. It involves exploratory and exploitative phases such as exploring prey, surprise pounce, and various ways of attacking the prey. This method is successful as it has main features of: (i) population-based approach and (ii) gradient-free method. The main behavior steps are described as given in [26]. In the proposed HHO algorithm, the position of the hawk and its best position is expressed in (13).

\[
f(t + 1) = \begin{cases}
    f_{\text{rand}}(t) - m_1 |f_{\text{rand}}(t) - 2m_2 f(t)| & x \geq 0.5 \\
    f_{\text{rabbit}}(t) - m_3(t) - m_3(Lb + Ub - Lb) & x < 0.5
\end{cases} \tag{13}
\]

Where, \( f(t + 1) \) is next iteration position, \( f_{\text{rabbit}}(t) \) is rabbit position at instant \( t \), current position is \( f(t) \), \( m_1 \), \( m_2 \), \( m_3 \), and \( x \) are random numbers updated in each iteration step and they lie in between \{0,1\}. \( Lb \) & \( Ub \) are lower and upper bound of the variable respectively, randomly a hawk being selected from the population is represented by \( f_{\text{rand}}(t) \), and the average position is \( f_m \). It is calculated using (14). Energy-related to prey is mathematically described as in (15) and will decrease during escaping considerably. It will also randomly vary in every iteration and lies in \{-1,1\}. When energy increases towards 1 from 0 indicates that the prey (or rabbit) is physically strengthening and is decreasing from 0 to -1, indicating that the prey is flagging. This aforesaid energy variation in the prey and its behavior for every iteration is mathematically shown by (16).

\[
f_m(t) = \frac{1}{N} \sum_{i=1}^{N} f_i(t) \tag{14}
\]

The energy of prey, \( E = 2E_0(1 - \frac{t}{T}) \)

\[
f(t + 1) = \Delta f(t) - E\{f_{\text{rabbit}}(t) - f(t)\} \tag{15}
\]

Where, \( \Delta f(t) = f_{\text{rabbit}}(t) - f(t) \), in which \( \Delta f(t) \) is position difference of prey with respect to previous position and randomly lies between \{0, 1\}. The \( J = 2(1 - m_3) \), is the movement of the rabbit (prey) in each iteration. Hard encircle of the prey will happen when \( x \geq 0.5 \) and \( |E| < 0.5 \), it indicates the low energy level of the prey and very difficult to escape. Hence harries hawks do not encircle and implement the surprise pounce at this condition. Then the present positions are updated as given in (17).

\[
f(t + 1) = f_{\text{rabbit}}(t) - E|\Delta f(t)| \tag{16}
\]

For \( |E| \geq 0.5 \) but \( x \leq 0.5 \), the prey will have sufficient energy to escape. Thus, harries hawks execute a plan of soft besiege just before deciding the surprise pounce. Now the concept of levy flight (LF) is used to mathematically model this intelligent behavior in the HHO algorithm as in (18). When the prey is moving more irregular and deceptive then movements are described mathematically in (19).

\[
y = f_{\text{rabbit}}(t) - E\{f_{\text{rabbit}}(t) - f(t)\} \tag{17}
\]

\[
y = y + s \times LF(D) \tag{18}
\]

Where, \( LF(f) = 0.01 \times \frac{|y|^{\beta}}{\Gamma(1 + \beta)} \)

\[
\sigma = \frac{\Gamma(1+\beta)\sin\left(\frac{\beta\pi}{2}\right)}{\left[\Gamma\left(1+\frac{\beta}{2}\right)\sin\left(\frac{\beta\pi}{2}\right)\right]^\frac{1}{\beta}} \tag{19}
\]

\[
\sigma = \frac{\Gamma(1+\beta)\sin\left(\frac{\beta\pi}{2}\right)}{\left[\Gamma\left(1+\frac{\beta}{2}\right)\sin\left(\frac{\beta\pi}{2}\right)\right]^\frac{1}{\beta}} \tag{20}
\]

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Where the random values \( u, v \) in the range between \([0, 1]\), \( \beta = 1.5 \). Hence, the final soft besiege phase position is modelled as (22). When \(|E| < 0.5\), the prey has very low energy to escape and it is a hard besiege stage to catch and kill the prey. It is governed by (23).

\[
f(t + 1) = \begin{cases} 
y & \text{if } g(y) \text{ less than } g(f(t)) 
z & \text{if } g(z) \text{ less than } g(f(t)) 
\end{cases}
\] (22)

\[
f(t + 1) = \begin{cases} 
y & \text{if } g(y) < g(x(t)) 
z & \text{if } g(z) < g(x(t)) 
\end{cases}
\] (23)

Where, \( y = f_{\text{rabbit}}(t) - E[f_{\text{rabbit}}(t) - f_m(t)] \)

\( z = y + s \times LF(D) \) (24)

\( \text{Figure 2. Harris Hawk} \)

Here is the HHO algorithm [10]:

**Inputs:** Enter total population \((N)\) and iterations \((T)\)

**Outputs:** Prey position and fitness value \( f_i \) \((i = 1, 2, \ldots, N)\)

**While** (terminate when the statement is failed) do

Keep \( f_{\text{rabbit}} \) as best location of the prey

for (every hawk \((f(i))\)) do

Update the \( E_0 \) and \( J \)

\( E_0 = 2 \times \text{rand} - 1; \)

\( J = 2 \times (1 - \text{rand}) \)

Update the \( E \) if \(|E| \geq 1\)

\( E = 2E_a(1 - \frac{t}{T}) \)

Update the current location vector using below equations

\[
f(t + 1) = \begin{cases} 
f_{\text{rand}}(t) - m_1[f_{\text{rand}}(t) - 2m_2f(t)]x \geq 0.5 
f_{\text{rabbit}}(t) - f_m(t) - m_3(LB + m_4(UB - LB))x < 0.5 
\end{cases}
\]

if \(|E| < 1\) then \(< < \text{exploitation_phase} >>\)

if \((x \geq 0.5 \land |E| > 0.5)\) then \(< < \text{Soft besiege} >>\)

Update the position using the following equation

\[
f(t + 1) = \Delta f(t) - E[f_{\text{rabbit}}(t) - f(t)], \text{ where } \Delta f(t) = f_{\text{rabbit}}(t) - f(t)
\]

else if \((r \geq 0.5 \land |E| < 0.5)\) then \(< < \text{Hard besiege} >>\)

else if \((r < 0.5 \land |E| \geq 0.5)\) then \(< < \text{Soft besiege} >>\)

else if \((r < 0.5 \land |E| < 0.5)\) then \(< \text{Hard besiege} >>\)

Position update using the following equation

\[
f(t + 1) = \begin{cases} 
y & \text{if } g(y) < g(f(t)) 
z & \text{if } g(z) < g(f(t)) 
\end{cases}
\]

Return \( f_{\text{rabbit}} \)
In this paper, an objective function is the minimization of the integral square error of frequency deviation as shown in (26), and the remaining optimization parameters are with lower bound (lb) = -1; upper bound (ub=100) and with number iterations are 50.

\[
 f = \min \left( \int_{0}^{t_{f}} (\omega_r - \omega)^2 dt \right)
\]  

(26)

4. RESULT ANALYSIS

Harris Hawks optimization (HHO) for frequency control of a hydropower plant has been executed and tested comprehensively for frequency control. In MATLAB/Simulink environment, the proposed method is tested at different conditions with parameters shown in Table 1. In frequency control, the controller is mostly PID control and the gains of this controller are tuned using Ziegler Nichols (ZN) method. However, it will not provide better control for dynamic changes and is a tedious procedure. The HHO is used to optimally tune the PID gains in this paper and thereby, control the frequency effectively. The PID gains obtained while running the algorithm are \( k_p = 100; \ k_i = 100 \) and \( k_d = 79.94717 \), with convergence shown in Figure 3. Figure 4 illustrates the frequency deviation (normalized) value during control and the remaining figures show the variation of the other variables, i.e., Figure 5, Figure 6, and Figure 7 shows the normalized gate opening, water velocity in turbine, and change in the pilot actuator position respectively during this operation. In comparison to the conventional (ZN) technique, the frequency deviation is lower and the steady-state is reached within less than 2 seconds as shown in Figure 4. The traditional method took longer, taking more than 20 seconds to reach negligible frequency deviation. At the same time, the proposed control technique causes relatively little disruption in gate opening, turbine water velocity, and change pilot location.

The usefulness of the proposed work is also tested for ±10% dynamic change in the normalized water velocity. Figure 8 and Figure 9 shows the \( \Delta \omega \) plot for +10% sudden increments in the normalized water velocity and its zoomed view. Similarly, Figure 10 shows the \( \Delta \omega \) plot for -10% sudden decrement in the normalized water velocity and the corresponding zoomed view is shown in Figure 11. From Figure 8 to Figure 11, when this system is subjected to dynamic conditions, such as a sudden change in water velocity, the frequency deviation is greatly reduced using the proposed control approach. In addition, as compared to the traditional ZN technique, the turbine water velocity is within the safe range. When comparing the suggested HHO algorithm based frequency controller to the ZN-based controller, the dynamic functionality of the presented technique is superior with the proposed HHO algorithm based frequency controller.

| Table 1. Simulation parameters | Parameter | Value |
|--------------------------------|-----------|-------|
| Equivalent damping (D)        | 1         |       |
| Net head of water (h₀)        | 1 pu      |       |
| Equivalent inertia constant (M)| 6         |       |
| Normalized output power (pₑ)  | 0.05 pu   |       |
| Servo time constant of the main gate (tₑ) | 0.2 sec |       |
| Time constant of the pilot actuator (tₚ) | 0.02 sec |       |
| Time constant of water starting (tₜ) | 1.3 sec |       |
| Velocity water at no load (u₀) | 0.068 pu |       |

Figure 3. Convergence curve during the control of Hydropower plant

Figure 4. Frequency deviation \( \Delta \omega \)

Figure 5. Normalized gate opening (\( \bar{g} \))

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5. CONCLUSION

Frequency control using Harris Hawks optimization (HHO) for improved performance has been successfully presented in this paper. The hydropower plant is simulated using its dynamic model and PID gains of load frequency controller are optimally tuned using the HHO algorithm. The efficacy of the proposed frequency controller is tested at dynamic conditions on the hydropower plant and is also compared with the conventional ZN method. It is experiential that the efficacy of the proposed approach is better than the conventional ZN method for frequency control of Hydropower plants.

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