Application of multi-verse optimiser-based fuzzy-PID controller to improve power system frequency regulation in presence of HVDC link

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Abstract: This paper presents the design of a novel optimal fuzzy-PID controller-based multi-verse optimiser (MVO) for load frequency control (LFC) of a two-area power system interconnected via high voltage direct current (HVDC) transmission link. The MVO algorithm was adopted to estimate the unknown parameters of the test system and model the HVDC link for the LFC analysis, and then, was used to optimise the fuzzy-PID controller parameters including the scaling factors of fuzzy logic and the PID controller gains. To demonstrate the effectiveness of the proposed control strategy, a two-area power system with HVDC link connection was investigated for the simulation. A comparative study of performance of proposed controller, fuzzy logic and conventional PID controller was performed. The obtained results satisfy the LFC requirements and reveal that the optimised fuzzy-PID controller-based MVO algorithm enhances power system frequency regulation in presence of HVDC link.

Keywords: multi-verse optimiser; MVO; PID controller; fuzzy logic controller; FLC; load frequency control; LFC; HVDC link.


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1 Introduction

At present and due to various reasons, the modern electrical networks have been operating as interconnected systems. Currently, frequency stability is the most challenging issue in power system analysis. Assessment of frequency stability is essential to study the dynamic behaviour of the grid. Increasing the size of the interconnected systems has been accompanied by the appearance of the frequency instability issue which may result in disconnection actions, loss of several lines, and zone isolation. In case of any unbalance between production and load of power the frequency control may be difficult (Kouba et al., 2014; Concha et al., 2014). To keep the equilibrium between supply and demand of power after a given disturbance, a control system named load frequency control (LFC) is designed to acts in the case of any disturbance (Bevrani and Daneshmand, 2012). The main goal of LFC system is to regulate the generation among the interconnected areas and ultimately control the frequency of the entire interconnected grid. The classical LFC loop designs are usually suitable for acting at specific operating points, and they are not more efficient for modern power systems, considering HVDC connected system (Kouba et al., 2015a, 2015b; Aouini et al., 2015).
Over the last decade, a deep research was conducted on power systems stability and controls enhancement to support the electricity customers worldwide with a good power quality and solve the world’s power issues such the blackouts. For the LFC scheme, different types of controllers are proposed, where the classical PI and PID controllers are the most used. Actually, conventional control schemes cannot give efficient control performance, which leads to implementation of intelligent strategies to get the best controller parameters that ensure a stable and robust system.

In the technical literature, there are some works focusing on the design of an optimal LFC loop using optimisation and heuristic algorithms. Many studies on this subject have been published due to the importance of the optimal tuning of the LFC parameters. In their works, Kouba et al. (2015a, 2015b) have designed an optimal LFC scheme-based PID controller using particle swarm optimisation (PSO), bacterial foraging algorithm (BFA) and hybrid BF-PSO. Bevrani and Daneshmand (2012) have proposed a fuzzy logic controller (FLC)-based LFC in presence of wind power generation. Similarly, various nature-inspired optimisation algorithms such genetic algorithm (GA) and artificial bee colony (ABC) (Kouba et al., 2015a, 2015b) are widely used by many researchers for the design of robust LFC schemes to enhance power system operation and control.

Additionally and due to the fast development of power electronic technology (PET), several supplementary controls such the static var compensator (SVC), high voltage direct current (HVDC) converters, flexible AC transmission system (FACTS) devices and phasor measurement units (PMUs), have been developed in the last years. Among the cited developed (PET), the HVDC power transmission system is a good example to analyse the impact of such supplementary controller on power system stability. The use of the HVDC devices between the different connected control areas is now widely used in the modern electric networks.

Recently, many works have investigated the impact of HVDC transmission link on frequency regulation analysis. Some studies analyse the impact of HVDC link on LFC loop in interconnected power systems (Aouini et al., 2015; Chen et al., 2016; Sharma et al., 2016). Where, many works shows the advantages of parallel hybrid AC/DC interconnections in enhancing the frequency regulation in interconnected power systems. Moreover, a lot of published paper investigated the effects of HVDC link in parallel with HVAC link on the frequency regulation issue. In case of two-area power system tied via only HVDC transmission link without a parallel AC link, the LFC loop for each controlled area has to be implemented through the HVDC link (Hamida et al., 2014). Consequently, it should produce certain effects on the secondary frequency control loop on both areas (Sanpei et al., 1994). In practice, such effects can be observed and modelled based on synchronised phasor measurements units (PMU) from two sides (Li et al., 2010a, 2010b).

The dynamic system performance improves in presence of HVDC transmission link during load changes have been investigated by many researchers. In a study conducted by Sanpei et al. (1994) they have proposed an application of multi-variable control for automatic LFC of HVDC transmission system in Japan. Li et al. (2010a) have proposed the modelling of the Kita-Hon HVDC link for LFC analysis in the Eastern Japan 50 Hz power system based on application of the CampusWAMS. Similarly, Li et al. (2010b)
have also proposed an analysis study of Kita-Hon HVDC link for LFC of Eastern Japan 50 Hz power system based on application of the CampusWAMS. Shanmukharao and Ramana (2012) have proposed a LFC scheme for multi-area deregulated power system connected with HVDC tie-line, where recently, Pham et al. (2016) have proposed LFC loop in presence of electric vehicles with consideration of diverse transmission links using distributed functional observers.

In the view of above discussion, the keys contributions of this paper are:

- investigates the impact of the HVDC transmission link on LFC system in an interconnected two-area power system
- a new optimisation algorithm namely multi-verse optimiser (MVO) was applied to estimate the HVDC link parameters
- design of a novel optimised LFC scheme-based fuzzy-PID controller using MVO algorithm to minimise the system frequency deviation during load changes
- the designed control strategy is implemented for single, multi and dynamic load disturbance in both areas
- the validity of the proposed approach was demonstrated by comparing the obtained results to other published results obtained by simulating the same system using the LSDFA in MATLAB optimisation toolbox available in literature
- a comparative study with fuzzy logic and conventional PID controller was also performed to show superiority and effectiveness of the proposed control strategy
- from all simulated scenarios, the potential of the proposed control strategy to improve LFC regulation in presence of HVDC tie-line and ensure frequency stability was confirmed.

The rest of the paper is organised as follows. Section 2 presents frequency control in presence of HVDC transmission link. Sections 3 describe the investigated MVO optimisation algorithm. Simulation results and discussions are given in Section 4. Finally, Section 5 concludes the paper.

2 Frequency control with HVDC link connection

2.1 System under study

In large interconnected power system, several control areas are tied with each other via AC, DC or AC/DC tie-lines power flow. In each area, LFC loop observes and monitors the system frequency and the tie-line power flows between the interconnected zones. To exploit the potential of the proposed control strategy, the Eastern Japan 50 Hz interconnected power system shown in Figure 1 (Li et al., 2010a) was used in this study as test system. Two control areas Hokkaido and Honshu are tied with only HVDC transmission link. The system is widely used in literature for frequency control analysis based on wide-area phasor measurements (Li et al., 2010b). The system is also used to analyse the DC link effects on frequency regulation system.
The HVDC system named Kita-Hon HVDC link for short is a 193 km long, a bipolar DC transmission system with an operating voltage of 250 kv and rated power of 600 MW for the interconnection of the AC grids of Hokkaido and Honshu (Takeda et al., 1995; Sakai et al., 2014). Both areas belong to the Eastern Japan 50 Hz power system. This system includes three interconnected power companies: HEPCO, TOHOKUEPCO and TEPCO as shown in Figure 2. According to Li et al. (2010a), the generation capacity is 6,500 MW for HEPCO, 17,140 MW for TOHOKUEPCO and 66,000 MW for TEPCO, respectively, by March 2007. As mentioned in Li et al. (2010a, 2010b), the main primary tasks of the Kita-Hon HVDC link is to support the LFC controller in the interconnected Hokkaido-Honshu system under normal operation condition as well as emergency situation.
As shown in Figure 3 the frequency signal from both controlled areas was used as an input to control the transmitted DC power and reduce the system frequency deviations in both sides. As a result, it can be expected that the HVDC link has certain effects on the LFC system of both areas.

Figure 3  Simulation model (see online version for colours)

To reduce the model complexity, the system of TOHOKU-EPCO and the system of TEPCO connected via the AC link are merged into one system namely area-2 and connected to the HEPCO system (area-1) with a DC link (Li et al., 2010a). The frequency deviations of these two areas are identically changing due to load variations. On the other hand, each system is simulated by an equivalent generator model equipped with governor and turbine control system. According to Li et al. (2010a), for area LFC scheme, HEPCO and TEPCO side are using flat frequency control (FFC), while TOHOKU-EPCO is using tie-line bias control (TBC). As a simplification, the HVDC controller for frequency regulation is represented by a proportional gain block and an integration block. The input signal of HVDC controller is the difference between the two-area frequency deviations. The frequency regulation system in both areas can be modelled as shown in Figure 3 (Li et al., 2010a, 2010b). The data of the test system are available in Li et al. (2010a, 2010b).

For the purpose of frequency control study and analysis, the model sketched in Figure 3 can be modelled as follow:

\[
\begin{align*}
\dot{X} &= AX + BU \\
Y &= CX
\end{align*}
\]  (1)
The governor power is given by:

\[
\frac{d\Delta P_{g1}}{dt} = \frac{1}{T_{g1}} \left( u_{c1} - \left( \frac{1}{R_1} \Delta f_1 \right) - \Delta P_{v1} \right)
\]

(2)

\[
\frac{d\Delta P_{g2}}{dt} = \frac{1}{T_{g2}} \left( u_{c2} - \left( \frac{1}{R_2} \Delta f_2 \right) - \Delta P_{v2} \right)
\]

(3)

The mechanical power from the turbine can be expressed as follow:

\[
\frac{d\Delta P_{h1}}{dt} = \frac{1}{T_{h1}} (\Delta P_{g1} - \Delta P_{f1})
\]

(4)

\[
\frac{d\Delta P_{h2}}{dt} = \frac{1}{T_{h2}} (\Delta P_{g2} - \Delta P_{f2})
\]

(5)

The frequency deviation of the system is given by:

\[
\frac{d\Delta f_1}{dt} = \frac{1}{M_1} (\Delta P_{h1} - \Delta P_{tie12} - \Delta P_{tie1} + D_1 \Delta f_1)
\]

(6)

\[
\frac{d\Delta f_2}{dt} = \frac{1}{M_2} (\Delta P_{h2} - (C_R \Delta P_{tie12}) - \Delta P_{tie2} + D_2 \Delta f_2)
\]

(7)

The power deviation \(\Delta P_{tie12}\) between the attached area-1 and area-2 is expressed by:

\[
\frac{d\Delta P_{tie12}}{dt} = \frac{1}{T_{dc}} \left( ((\Delta f_1 - \Delta f_2), K_{dc}) - \Delta P_{tie12} \right)
\]

(8)

The area control error (ACE) signal is given by the following equations:

\[
ACE_1 = \beta_1 \Delta f_1
\]

(9)

\[
ACE_2 = \beta_2 \Delta f_2
\]

(10)

Where, the frequency bias factor for area \(i\), \(\beta_i\) can be calculated as follow:

\[
\beta_1 = \frac{1}{R_1} + D_1
\]

(11)

\[
\beta_2 = \frac{1}{R_2} + D_2
\]

(12)

The control function \(u_{c}\) in each area is given by:

\[
u_{c1} = -K_{i1} \int ACE_1 \, dt
\]

(13)

\[
u_{c2} = -K_{i2} \int ACE_2 \, dt
\]

(14)

where
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\[ U = \begin{bmatrix} \Delta P_{i1} & \Delta P_{i2} & u_{c1} & u_{c2} \end{bmatrix} \] (15)

\[ Y = \begin{bmatrix} \Delta f_1 & \Delta f_2 & \Delta P_{tie} \end{bmatrix} \] (16)

\[ X = \begin{bmatrix} \Delta P_i & \Delta P_{\gamma_1} & \Delta f_1 & \Delta P_{\gamma_2} & \Delta f_2 & \Delta P_{tie} \end{bmatrix} \] (17)

The matrices \( A, B, \) and \( C \) are given as follow:

\[
A = \begin{bmatrix}
-1 & 0 & -1 & 0 & 0 & 0 & 0 \\
\frac{1}{T_{g1}} & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{M_1} & -D_1 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & \frac{-1}{T_{g2}} & 0 & \frac{-1}{R_2 \cdot T_{g2}} & 0 \\
0 & 0 & 0 & \frac{1}{T_{b2}} & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{M_2} & -D_2 & -CR \\
0 & 0 & \frac{K_{dc}}{T_{dc}} & 0 & 0 & \frac{K_{dc}}{T_{dc}} & -1 \\
0 & 0 & \frac{K_{dc}}{T_{dc}} & 0 & 0 & \frac{K_{dc}}{T_{dc}} & -1 \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 & \frac{-1}{M_1} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{-1}{M_2} & 0 \\
\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{T_{g2}} & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

In the above model, \( \beta_1 \) and \( \beta_2 \) are the frequency bias parameters; \( u_{c1} \) and \( u_{c2} \) are the control outputs from the controller; \( R_1 \) and \( R_2 \) are the governor speed regulation parameters; \( T_{g1} \) and \( T_{g2} \) are the speed governor time constants; \( M_1 \) and \( M_2 \) are the inertia constants; \( D_1 \) and \( D_2 \) are the damping coefficients; \( \Delta P_{\gamma 1} \) and \( \Delta P_{\gamma 2} \) are the governor output command; \( T_{b1} \) and \( T_{b2} \) are the turbine time constant; \( \Delta P_{tie} \) are the change in turbine output powers; \( \Delta P_{tie1} \) and \( \Delta P_{tie2} \) are the load demand changes; \( \Delta P_{tie} \) is the incremental change in tie-line; \( CR \) is the tie-line constant (\( CR = -1 \)); \( K_{i1} \) and \( K_{i2} \) are the
controller gains; $K_{dc}$ and $T_{dc}$ are the HVDC gains; $\Delta f_1$ and $\Delta f_2$ are the system frequency deviations.

2.2 Parameters estimation approach

In this work, a novel nature-inspired algorithm namely MVO was applied to estimate the DC link parameters and the classical controller gains as shown in Figure 4. Where, in this estimation level, only the parameters that play important role in the control area are selected to be determined for this simulation model. The unique MVO algorithm allows the fast parameters estimation and guarantees robustness and optimal regulation during disturbances.

During the estimation process, MVO uses the difference between the output signal ($Y$) from the actual system and the output signal from the estimated model ($Y^*$) to optimise the system parameters target. This error ($Y - Y^*$) is used as objective function to update the system parameters, which needs to be minimised.

Noted that, the estimated parameters model in reference (Li et al., 2010a) was used as actual system in this work, where the unknown parameters for the identified model are optimally adjusted by the proposed MVO algorithm. The results of this research were compared with the results obtained by simulating the same model with the nonlinear least-squares data-fitting algorithm (LSDFA) in MATLAB optimisation toolbox available in Li et al. (2010a, 2010b).

As shown in Figure 4, the actual system which is the estimated model from Li et al. (2010a) and the estimated model in this paper are excited by the same load disturbance. The simulated output of frequency deviation was compared to the reference frequency deviation given by an initial actual set of unknown parameters. The computed error between the two frequency deviations is used as input to MVO algorithm, which updates the estimated model parameters in such a way that this error is minimised.

The parameters that play an important role in the LFC analysis are selected to be estimated for this simulation model. Those parameters are marked with an asterisk mark in Table 1 (Li et al., 2010a, 2010b), where the MVO algorithm is illustrated in Section 3.
Table 1  

<table>
<thead>
<tr>
<th>Parameter meaning</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial constant [pu MW s/Hz]</td>
<td>$M_1$, $M_2$</td>
<td>0.2</td>
</tr>
<tr>
<td>Load damping coefficient [pu MW/Hz]</td>
<td>$D_1$, $D_2$</td>
<td>0.008</td>
</tr>
<tr>
<td>Area capacity ratio</td>
<td>CR</td>
<td>0.08</td>
</tr>
<tr>
<td>Time constant for governor [s]</td>
<td>$T_{g1}$, $T_{g2}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Time constant for turbine [s]</td>
<td>$T_{b1}$, $T_{b2}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Regulation ratio [Hz/pu MW]</td>
<td>$R_1$, $R_2$</td>
<td>*</td>
</tr>
<tr>
<td>FFC controller gain</td>
<td>$B_1$, $B_2$</td>
<td>*</td>
</tr>
<tr>
<td>FFC controller integration constant [s]</td>
<td>$K_{i1}$, $K_{i2}$</td>
<td>*</td>
</tr>
<tr>
<td>DC controller gain</td>
<td>$K_{dc}$</td>
<td>*</td>
</tr>
<tr>
<td>DC controller integration constant [s]</td>
<td>$T_{dc}$</td>
<td>*</td>
</tr>
</tbody>
</table>

2.3 Proposed control strategy

Recent decades have seen a fast development in nature-inspired algorithms and artificial intelligent techniques, among them fuzzy logic theory (FLT) that have gained a great interest in the design of robust control systems. Nowadays, the concept of fuzzy control is well-known and now implemented in many industries applications worldwide to solve practical issues more efficiently (Kouba et al., 2015c; Serraji et al., 2016; Faquir et al., 2016).

FLC is credited with being a suitable regulation technique for designing robust controller that is capable to provide good performances during contingencies case to avoid system failing compared to other classical controllers such the PI and PID controller. The FLC design is a model free technique, which present an effective solution for solving modern power system issues. The main fuzzy system design includes four elements (Yousef et al., 2014; Jain et al., 2015):

1. a rule-base (a set of if-then rules)
2. an inference mechanism
3. fuzzification as shown in Figure 5
4. defuzzification interface.

Figure 5  FLC inputs and output membership function
To overcome frequency regulation problem, the authors have developed a new optimal combined parallel fuzzy-PID controller as shown in Figure 6. Each controlled area was equipped with a fuzzy-PID controller, where the MVO algorithm was applied to optimise the proposed controller parameters including the scaling factors of fuzzy logic and the PID controller gains. The $ACE$s given in equations (18) and (19) are used as the fuzzy controller inputs, where the fuzzy logic output is used as the PID controller input in each area.

$$e_1 = ACE_1 = \Delta P_{net} + \beta_1 \Delta f_1$$  \hspace{1cm} (18)

$$e_2 = ACE_2 = \Delta P_{net} + \beta_2 \Delta f_2$$  \hspace{1cm} (19)

**Figure 6**  Structure of proposed combined fuzzy-PID controller (see online version for colours)

The proposed fuzzy-PID controller uses error ($e_1$, $e_2$) and derivative of error ($e_1$, $e_2$) as input signals. The outputs of the controller’s $u_{c_1}$ and $u_{c_2}$ are the control inputs of the power system. The input scaling factors are the tuneable parameters $k_e$ and $k_{ec}$. The proportional, integral and derivation gains of the PID controller are represented by $K_p$, $K_i$, and $K_d$ respectively. Triangular membership functions were used with five fuzzy linguistic variables such as negative big (NB), negative small (NS), zero (ZE), positive small (PS) and positive big (PB) for both the inputs and the output as shown in Table 2. Mamdani fuzzy interface engine was selected for this work. The FLC output was determined by using centre of gravity method of defuzzification.

**Table 2**  Control rules

<table>
<thead>
<tr>
<th>$dACE$</th>
<th>$ACE$</th>
<th>$NB$</th>
<th>$NS$</th>
<th>$ZE$</th>
<th>$PS$</th>
<th>$PB$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>NS</td>
<td>ZE</td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
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<tr>
<td>ZE</td>
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<td>PS</td>
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<td>PB</td>
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<tr>
<td>PB</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td></td>
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</table>
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2.4 Objective function

The recently heuristic MVO algorithm was adopted to design an optimal LFC scheme-based fuzzy-PID controller. The used MVO tool aims to minimise the global objective function given in equation (20), which uses the Integral of time multiplied absolute error (ITAE) criterion to reduce the settling time, peak undershoot, and peak overshoot of the investigated system dynamic responses. The problem constraints are the PID controller gains and the scaling factors of the fuzzy logic bounds given in equation (21).

\[
ITAE = \int_{0}^{t_{\text{sim}}} t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{\text{tie}}|) \, dt
\]  

(20)

Subject to:

\[
\begin{align*}
K_p_{\min} & \leq K_p & \leq K_p_{\max} \\
K_i_{\min} & \leq K_i & \leq K_i_{\max} \\
K_d_{\min} & \leq K_d & \leq K_d_{\max} \\
\end{align*}
\]

\[
\begin{align*}
(k_e_{\min} & \leq k_e & \leq k_e_{\max} ) \\
(k_{ec}_{\min} & \leq k_{ec} & \leq k_{ec}_{\max} )
\end{align*}
\]

(21)

In the above equations, \(\Delta f_1\) and \(\Delta f_2\) are the system frequency deviations; \(\Delta P_{\text{tie}}\) is the incremental change in the tie-line; \(t_{\text{sim}}\) is the time range of simulation, \(K_p, K_i,\) and \(K_d\) are the PID controllers gains, \(k_e\) and \(k_{ec}\) are the FLC scaling factors.

3 MVO toolbox

Over the last few decades, many heuristic optimisation algorithms inspired from swarm behaviours in nature have been developed (Kouba et al., 2015d; Goel et al., 2014; Mahmoodabadi et al., 2015). Recently, Mirjalili et al. (2016) have developed a novel heuristic optimisation tool called MVO. Similarly to the Big Bang theory, Multi-Verse theory is another recent and well-known theory between physicists. This theory also proposes that there might be different physical laws in each of the existed universes. MVO algorithm was inspired based on three concepts in cosmology: white hole, black hole, and wormhole.

During optimisation process, both of white hole and black hole concepts were utilised in order to explore search spaces. On the other hand, the wormholes assist MVO in exploiting the search spaces. According to Mirjalili et al. (2016), MVO has been used to solve 19 challenging test problems and applied to five real engineering problems to further confirm its performance. All steps of the MVO are explained as shown in the pseudo code depicted in Figure 7 (Mirjalili et al., 2016).
Figure 7  MVO pseudo code

Create random universes \((U)\)
Initialize WEP, TDR, and Best_universe
SU=Sorted universes
NI=Normalize the inflation rate (fitnesses) of the universes
while the end criterion is not satisfied
Evaluate the fitness of all universes
for each universe indexed by \(i\)
Update WEP and TDR
Black_hole_index\(=i;\)
for each object indexed by \(j\)
\(r_1=\text{random}(0,1);\)
if \(r_1<NI(U_i)\)
White_hole_index= Roulette Wheel Selection(-NI);
\(U(\text{Black_hole_index},j)=SU(\text{White_hole_index},j);\)
end if
\(r_2=\text{random}(0,1);\)
if \(r_2<\text{Wormhole_existence_probability}\)
\(r_3=\text{random}(0,1);\)
if \(r_3<0.5\)
\(U(i,j)=\text{Best_universe}(j) + \text{Travelling_distance_rate} \times (u_b(j) - l_b(j)) \times r_4 + l_b(j);\)
else
\(U(i,j)=\text{Best_universe}(j) - \text{Travelling_distance_rate} \times (u_b(j) - l_b(j)) \times r_4 + l_b(j);\)
end if
end if
end for
end while

where \(U_i\) shows the \(i^{th}\) universe, \(NI(U_i)\) is normalised inflation rate of the \(i^{th}\) universe, \(r_1, r_2, r_3\) and \(r_4\) are random numbers between the interval [0, 1], TDR is the travelling distance rate coefficient, WEP is the wormhole existence probability coefficient, \(l_b\) shows the lower bound of \(j^{th}\) variable, \(u_b\) is the upper bound of \(j^{th}\) variable.

4 Simulation results

To demonstrate the efficiency of the proposed LFC scheme, the two-area interconnected Hokkaido-Honshu of Eastern Japan 50 Hz power system with Kita-Hon HVDC transmission link was investigated for the simulation. Five scenarios are performed to
show the superiority of the MVO algorithm and to prove the robustness of the designed optimal combined fuzzy-PID controller during load changes.

In the first scenario, MVO was used to estimate the unknown parameters of the controlled system including the DC transmission link parameters and the integral controller gain. In the second scenario, MVO was employed to optimise the fuzzy-PID controller parameters including the scaling factors of fuzzy logic and the PID controller gains during single load change. In the third scenario, the optimum fuzzy-PID controller obtained from scenario 2 was tested during multi-step load disturbances. In the fourth scenario, a dynamic load disturbance was applied to show the potential of the designed controller to cope with a variable load change. Finally, robustness analysis was carried out in the fifth scenario by varying the system parameters from the nominal system values in the range of ±50% with a fixed step of ±25%.

The optimised fuzzy-PID controller performs well under various disturbances and was investigated successfully, which prove the high performance of the proposed MVO algorithm in estimation and optimisation of system parameters. In addition, it should be noted that the HVDC link gives a good improvement in frequency and tie-line power flow regulation.

4.1 MVO-based parameters estimation results

The proposed MVO algorithm was simulated for 0.08 pu load change disturbance in area-2 during 350 seconds to perform parameters estimation. The obtained results are compared with other existing results for the same test system using the nonlinear LSDFA in MATLAB optimisation toolbox available in Li et al. (2010a) as shown in Table 3 and Figure 8. Figure 8 is intended to compare the results of this study with the estimated results in Li et al. (2010a). The impact of the DC transmission link on the frequency regulation has been analysed.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Search range</th>
<th>LSDFA (Li et al., 2010a)</th>
<th>MVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>[1, 15]</td>
<td>8.21</td>
<td>4.9862</td>
</tr>
<tr>
<td>R2</td>
<td>9.89</td>
<td>10.2823</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>[0.1, 1]</td>
<td>0.26</td>
<td>0.0892</td>
</tr>
<tr>
<td>B2</td>
<td>0.16</td>
<td>0.1356</td>
<td></td>
</tr>
<tr>
<td>K_i1</td>
<td>[0.001, 0.1]</td>
<td>0.001</td>
<td>0.0042</td>
</tr>
<tr>
<td>K_i2</td>
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<td>0.0024</td>
<td></td>
</tr>
<tr>
<td>Kdc</td>
<td>[0.1, 10]</td>
<td>0.1</td>
<td>0.1596</td>
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<tr>
<td>Tdc</td>
<td>[0.1, 10]</td>
<td>0.3</td>
<td>0.2158</td>
</tr>
</tbody>
</table>

It is clear that the simulated system-based estimated parameters obtained by MVO algorithm gives the same responses compared with the simulated system using LSDFA optimisation toolbox in MATLAB available in reference (Li et al., 2010a). Also, it can be observed that the frequency system needs more time to reach the nominal frequency value. However, it should be noted that the HVDC link compensate the LFC loop based on only integrator controller in the aim to overcome system fluctuation due to load changes.
4.2 Single step load change results

In this scenario, a novel robust LFC scheme-based optimised fuzzy-PID controller employing MVO algorithm was designed to improve the frequency regulation in presence of a DC tie-line. The test system is simulated for a 0.08 pu load increase at area-2 within 10 seconds. A fuzzy-PID controller was performed in both areas. To show the validity of the proposed LFC scheme, a comparative analysis was carried out between the proposed control strategy, fuzzy-PID and conventional PID controller-based MVO algorithm. The optimum controller gains are sited in Table 4, while the frequency in both sides and the DC tie-line power flow deviations are shown in Figures 9 to 11.

Table 4 Controllers parameters

<table>
<thead>
<tr>
<th></th>
<th>(K_p)</th>
<th>(K_i)</th>
<th>(K_d)</th>
<th>(k_e)</th>
<th>(k_{ec})</th>
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<tr>
<td>Fuzzy-PID</td>
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<td>1.5</td>
<td>3.29</td>
<td>1</td>
<td>1</td>
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<tr>
<td>MVO-PID</td>
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<td>3.7050</td>
<td>9.4716</td>
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<td>-</td>
</tr>
<tr>
<td>MVO-fuzzy-PID</td>
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<td>50</td>
<td>11.3654</td>
<td>0.1478</td>
<td>0.4212</td>
</tr>
</tbody>
</table>

Figure 9 Frequency deviation in area-1 (see online version for colours)
Application of multi-verse optimiser-based fuzzy-PID controller

The changes in frequency deviation $\Delta f$ in each area and the deviation in the DC tie-line power flow between the interconnected zones $\Delta P_{tie}$ under the load disturbance are analysed. In addition, the influence of the HVDC link on the LFC system was evaluated. It can be seen from the obtained results that the use of the HVDC transmission link makes the power system more stable, which clearly shows the enhancement of the whole interconnected system dynamic responses in presence of the HVDC link.

Moreover, it can be revealed that using the proposed control design-based optimal fuzzy-PID controller using MVO algorithm, the time of suppressing the fluctuation is very short compared with the time given by the used fuzzy and PID controller. Additionally, it is clear that the system with HVDC link connection and optimised fuzzy-PID controller gives better performances in terms of settling time, peak undershoot and peak overshoot.

4.3 Multi-step load change results

In this scenario, the effect of load variation is examined. The test system was faced to multi-step disturbances in area-2 during 60s as shown in Figures 12 to 14. A step load of 0.1 pu, 0.07 pu, 0.05 pu, 0.06 pu are applied at $t = 10 s$, $t = 20 s$, $t = 30 s$, and $t = 40 s$ respectively. From the performed simulation in this case, it can be seen that the proposed control strategy gives good results even the system is under load changes.
It can be observed that using the optimal combined fuzzy-PID controller-based MVO algorithm, the frequency and the DC tie-line power flow deviations are suppressed most effectively with lesser settling time and zero steady state error compared to the results obtained with fuzzy and PID controller.
4.4 Dynamic load variation results

In this scenario, a dynamic load disturbance was applied in area-1. A random variation was used to simulate the dynamic behaviour of both load increase and decrease. The disturbance is applied at $t = 0$ s and the simulation is performed during 100 seconds. The obtained system responses are shown in Figures 15 to 17.

**Figure 15** Frequency deviation in area-1 (see online version for colours)

![Frequency deviation in area-1](image)

**Figure 16** Frequency deviation in area-2 (see online version for colours)

![Frequency deviation in area-2](image)

**Figure 17** HVDC tie-line power flow deviation (see online version for colours)

![HVDC tie-line power flow deviation](image)
It is observed that the responses fluctuate following the load variation and are not settling very smoothly as compared with the obtained results from the previous case studies. However, it is clear that the system fluctuation is suppressed the most effectively using the proposed control strategy, where the MVO algorithm gives the best results.

4.5 Robustness results

To check the robustness of the developed LFC scheme, the system parameters such inertia and damping coefficients ($M$ and $D$), time constants of governor ($T_g$) and Turbine ($T_b$) are varied from the nominal values in the range of ±50% with a step of ±25%, without changing the optimal values of the fuzzy-PID controller parameters. From the presented results in Figures 18 to 20, it is clear that the designed LFC controller is quite robust for power system considering DC transmission link.

**Figure 18** Tie-line deviation due to $M$ and $D$ variation (see online version for colours)

**Figure 19** Frequency deviation in area-1 due to $T_g$ variation (see online version for colours)
5 Conclusions

This paper is focused on optimisation-based fuzzy-PID controller design and development of a new intelligent LFC scheme in an interconnected power system with consideration of HVDC transmission link. A recently nature-inspired meta-heuristic algorithm namely MVO was applied in this paper. The MVO algorithm was employed to estimate the unknown parameters of the test system and then was applied to optimise the scaling factors of the fuzzy logic and the PID controller gains. To show the effectiveness of the proposed control strategy, a two-area power system with HVDC transmission link connection was used for the simulation. The test system was simulated under various load change disturbances, where five scenarios are performed. Furthermore, a comparative study of performance was carried out.

In summary and from the simulation results of this work it is revealed that, the proposed MVO algorithm presents a very powerful tool for enhancing frequency control capability and solving the LFC regulation issue. As future works, the proposed control strategy will be applied in a nonlinear deregulated power system with consideration of governor dead band (GDB) and generation rate constraint (GRC).

References


