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Optimal Tuning for Load Frequency Control Using Ant Lion Algorithm in Multi-Area Interconnected Power System

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ABSTRACT
This paper presents the use of a novel nature inspired meta-heuristic algorithm namely Ant Lion Optimizer (ALO), which is inspired from the ant lions hunting mechanism to enhance the frequency regulation and optimize the load frequency control (LFC) loop parameters. The frequency regulation issue was formulated as an optimal load frequency control problem (OLFC). The proposed ALO algorithm was applied to reach the best combination of the PID controller parameters in each control area to achieve both frequency and tie-line power flow exchange deviations minimization. The control strategy has been tested firstly with the standard two-area power system, followed by the IEEE three-area Western System Coordinating Council (WSCC) and, lastly, with the large three-area South-Western part of the Mediterranean interconnected power system (SWM): Tunisia, Algeria and Morocco. The dynamic performances of the test systems are compared to other approaches available in literature. The simulation results of this research show that ALO algorithm is able to solve LFC problem and achieve less frequency and tie-line power flow deviations than those determined by other methods used in this paper.

KEY WORDS: Ant Lion Optimizer (ALO); Frequency Regulation; Load Frequency Control (LFC); Optimal Control.

1 INTRODUCTION

FREQUENCY regulation plays an important role in operation planning and real time control of modern power systems. The primary task of a power system control is to maintain continuous supply of power with a good quality to all the consumers. Hence, the electrical network will be in balance when there is equilibrium between the power load and the production. Power load variations into power systems have posed serious challenges regarding security of electrical system (Y. Tang et al., 2015; K. Vrdoljak et al., 2010). They have led to a growing interest in the design of robust controllers to provide the ancillary services delivered by conventional units. In particular, the impact of demand change on the power system frequency stability is of primary concern for the transmission system operators (TSOs) in the process of restoring critical situations during disturbances.

Assuring frequency stability is a challenging technical issue, which has initiated an intensification of the research on the design of an efficient frequency controller. The classical frequency loop includes both the inertial response and the primary frequency control through the governor control system. Furthermore, to ensure the frequency stability in interconnected power systems, an additional secondary control loop is added to the frequency regulation system (T. Yu et al., 2012). This control action is also named Load Frequency Control (LFC) and it is activated during large frequency deviations or when the primary frequency control fail during disturbances. Where, the LFC system is considered as a supplementary control loop in the Automatic Generation Control (AGC) operator (H. Golpîra et al., 2011). The LFC loop regulates the power output of the selected unit in each control area in response to change in system frequency, tie-line power flow exchange, or both. For this reason, a Control Area Error (ACE) signal is measured, which combine both frequency and tie-line

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power deviations (N.EL.Y. Kouba et al., 2015a). This ACE signal is processed by a central controller. Usually a Proportional-Integral (PI) controller, which calculates the required change in production for the power units, is used to bring the ACE to zero and restore the frequency at nominal value. This generation control is made by a Dispatch Center (DC) (Tomas E. DY Liacco, 1967; S. Sondhi & Y. V. Hote, 2014).

Several studies regarding the contribution of optimized LFC have as objective to improve the controller capability to actively support the power system control. A lot of these papers proposed different nature inspired meta-heuristic techniques for solving optimal LFC problem. Demiroren and Zeynelgil (2007) have suggested AGC analysis in multi-area interconnected power system after deregulation, where the Genetic Algorithm (GA) technique was used to reach the optimal integral gains and bias factors. H. Shayeghi et al. (2008) have proposed particle swarm optimization (PSO) based multi-stage fuzzy control. Haluk Gozde et al. (2012) have proposed a comparative performance analysis of Artificial Bee Colony (ABC) algorithm in AGC of interconnected reheat thermal power system. E.S. Ali et al. (2011) have been suggested an optimized LFC based on Bacteria foraging optimization algorithm (BFOA). R. K. Sahu et al. (2013) have proposed LFC analysis using Differential Evolution Algorithm (DEA) based parallel 2- Degree Freedom of PID controller for interconnected power system. Sanjoy Debbarma et al. (2014) have proposed AGC of multi-area power systems with fractional order PID controller optimized employing Firefly Algorithm (FA). R. K. Sahu et al. (2014) have proposed an optimal gravitational search algorithm (GSA) for AGC systems. Puja Dash et al. (2015) have proposed AGC of multi-area thermal system using optimized PD-PID cascade controller based on Bat algorithm (BA). Several hybrid algorithms were also proposed such as: Sidhartha Panda et al. (2013) have been suggested hybrid bacteria foraging optimization and particle swarm optimization (hBFOA-PSO) algorithm for AGC of linear and nonlinear interconnected power systems. R. K. Sahu et al. (2015a) has proposed a hybrid firefly algorithm and pattern search technique for AGC systems. R. K. Sahu et al. (2015b) have proposed a hybrid PSO-PS optimized fuzzy PI controller for AGC systems.

This paper proposes the use of a novel meta-heuristic approach called Ant Lion Optimizer (ALO) to solve optimal LFC problem. The ALO technique is recently proposed by Seyedali Mirjalili (2015), which mimics the intelligent hunting behavior of ant lions (AL) in nature. Therefore, the authors have adopted this newly developed method in order to enhance frequency stability in multi-area interconnected power system. This technique is suggested to design an optimized LFC controller.

The organization of the present paper is as follow. Section 2 discusses the frequency regulation issue, which is formulated as an LFC problem. Then a brief description of the ALO strategy with their implementation to solve the optimal LFC problem is presented in Section 3. Section 4 is devoted to the presentation and discussion of the simulation results, also a comparative study with some meta-heuristic methods is performed. Finally, the conclusion of this paper is included in Section 5.

Frequency Regulation Problem

1.1 General Overview of LFC

In large-scale power systems, to satisfy the increasing need for electrical energy and ensure a good quality of power, fast and flexible frequency control strategies are required. In addition, with the increasing trend apparition of sudden load changes, the power system control and operation must meet a strong ability to rapidly isolate faulty parts from the rest of the network, and have a reasonable capability to withstand abnormal system operating conditions (Umesh K Rout et al., 2013; H. Bevrani et al., 2010). For this reason, the design of a robust frequency restoration strategy to diminish the load change effects on system frequency has been addressed in several research works. The control center regulates the frequency supply taking into account the current power system regulations and the electricity market rules (N.EL.Y. Kouba et al., 2015b).

Moreover, the control model includes the values for power production, demand and the power exchange between interconnected neighboring areas. Hence, based on these data, the control system balances all control areas through AGC system (N.EL.Y. Kouba et al., 2015c). The LFC system is considered as a vital control loop in interconnected power system. This system measures the frequency deviation from its nominal value and the possible power mismatch between productions, system load and power exchange with neighboring areas (Edmarcio A et al., 2008; N.EL.Y. Kouba et al., 2015d). In normal functioning mode, the block diagram of the frequency regulation levels including: primary, secondary and tertiary control loops is sketched in Figure 1 (Olle I. Elgerd, 1981; Saad N. Al-Duwaish, 1999; Naimul Hasan, 2012).

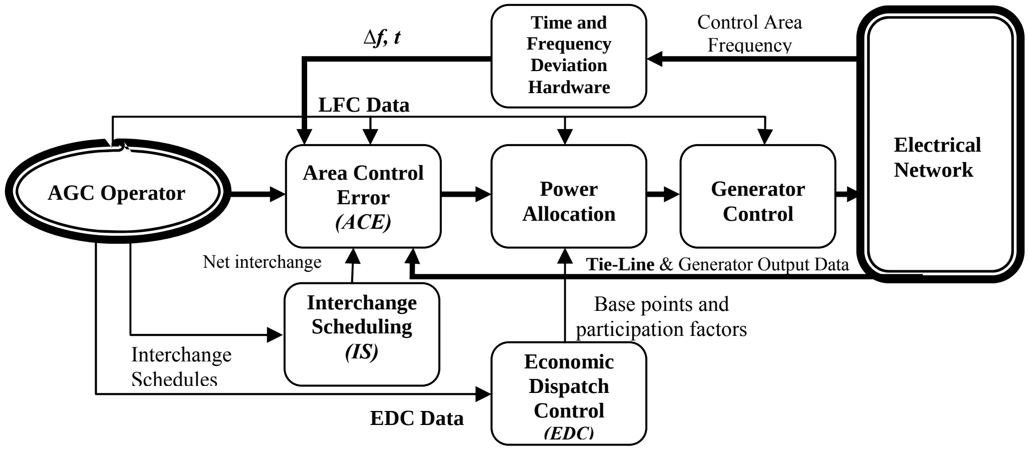

Figure 1. Time and Frequency Deviation Measurement Hardware (Olle I. Elgerd, 1981).

As shown in Figure 1, frequency and tie-line power flow exchange are the most important key factors in the frequency regulation loop. Their indices are weighted together by a linear combination to a single variable namely: the Area Control Error (ACE). Where, this ACE presents the sum of $\Delta Ptie$ with the product of Δf and system frequency bias factor (βf). The frequency bias factor is determined from the droop characteristics of all power plants taking part in the primary response. The ACE signal is processed by a central controller, like PID controller, which calculates the required change in production for the power plants to bring the ACE to zero and maintain constant frequency (Ibraheem et al., 2005).

The modeling of a typical control area-i, which includes n generating units, from a Z-control area power system is presented with three major components: generator, turbine, governor. The state space model of such system is given by:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX \end{cases} \tag{1}$$

The governor power is given by:

$$\frac{d\Delta Pv_{mi}}{dt} = \frac{1}{T_{H_{mi}}}\left(U_{mi} - (\frac{1}{R_{mi}} * \Delta f_i) - \Delta Pv_{mi}\right) \tag{2}$$

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

$$\frac{d\Delta P_{T_{mi}}}{dt} = \frac{1}{T_{T_{mi}}}\left(\Delta Pv_{mi} - \Delta P_{T_{mi}}\right); \qquad m=1....n \tag{3}$$

The frequency of the system is given by:

$$\frac{d\Delta f_i}{dt} = \frac{K_{PS}}{T_{PS_i}}\left(\sum_{l=1}^{l=n} \Delta P_{T_{li}} - \Sigma \Delta Ptie_i - \Delta P_{D_i} - D_i.\Delta f_i\right) \tag{4}$$

The power deviation ΔP_{Tij} between the attached area i and area j is expressed by:

$$\frac{d\Delta P_{Tij}}{dt} = T_{ij}(\Delta f_i - \Delta f_j) \tag{5}$$

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

$$ACE_i = \Delta P_{Tij} + \beta f_i \Delta f_i \tag{6}$$

where the frequency bias factor for area i, βf_i can be calculated using:

$$\beta fi = \sum_{i=1}^{i=n} \frac{1}{R_i} + \sum_{i=1}^{i=n} D_i \tag{7}$$

The control function u_i in each area is given by:

$$u_i = K_p.ACE_i + K_i.\int ACE_i\,dt + K_d.\frac{dACE_i}{dt} \tag{8}$$

1.2 Systems Under Study

1.2.1 Two-Area Interconnected Power System

The two equal non-reheat thermal areas interconnected system shown in Figure 2 (Sidhartha Panda et al., 2013; R. K. Sahu et al., 2015b) is used for the simulation. The system is widely used in the literature for the design and analysis of LFC system.

1.2.2 Extension to the Three-Area Interconnected Power System

The Western System Coordinating Council (WSCC) IEEE 3-machine, 9-bus shown in Figure 3 (R, Patel et al.,2002) was used as test system for the evaluation of the optimal LFC strategy in multi-area power system. This system is widely used in the literature for power system stability and control studies. The system was divided into three interconnected control areas.

1.2.3 Extension to the Large Mediterranean Interconnected Power System

To prove the robustness of the proposed approach in solving LFC problem in large-scale multi-machine interconnected multi-area power systems, the South-Western Mediterranean Block (SWMB) is considered for the simulation. The Maghrebian interconnected network in the west part of the Mediterranean is composed basically of three interconnected areas as shown in Figure 4 (N.EL.Y. Kouba et al., 2015d; Cartographer). This interconnection was adapted since 1953, where a 220 kV lines are installed in the aim to realize the interconnection between the Algerian and Moroccan power systems, the first between Ghazaouet (Algeria) - Oujda (Morocco), and the second between Tlemcen (Algeria)-Oujda (Morocco). In the other side the interconnection between the Algerian and Tunisian electrical networks is composed of four lines: a 220 kV line between El Aouinet (Algeria) and Tajerouine (Tunisia), and a 150 kV line between Djebel Onk (Algeria) and Metaloui (Tunisia), thereby with two 90 kV lines tied El Aouinet (Algeria) - Tajerouine (Tunisia) and El Kala (Algeria) - Fernana (Tunisia) (N.EL.Y. Kouba et al., 2015d). The interconnected Maghrebian network is connected with the European network (UCTE) via two 400 kV aero-submarines lines between Morocco and Spain. In scheduled mode, the exchange is limited to 100 MW between Algeria and Morocco or Tunisia, and in the case of any disturbances, the defense plan acts via dedicated protections and automatic disconnections (Haj Hamida et al., 2014).

In the aim to ensure an adequate transfer of power and hold the balance in the interconnected network, it is necessary to define rules for the operation and coordination between the systems operators of the Maghrebian countries. To satisfy these objectives the LFC study is needed to solve some faced problems and propose new solutions to improve the interconnection between the Maghrebian countries (N.EL.Y. Kouba et al., 2015d; Cartographer).

Ant Lion Optimizer "ALO"

1.3 Overview

In recent years, many nature inspired meta-heuristic strategies have been developed to solve different problems (H. Shayeghi, 2009). Most of these methods were inspired from the analysis behavior of many nature and creatures phenomena's such as: insects and animals. All of these strategies have received a considerable interest as powerful algorithms for solving optimization problems (H. Shayeghi et al., 2009; A.K. Barisal, 2015). The recently developed Ant Lion Optimizer (ALO) algorithm is a new meta-heuristic optimization approach. The ALO was first introduced by Seyedali Mirjalili (2015).

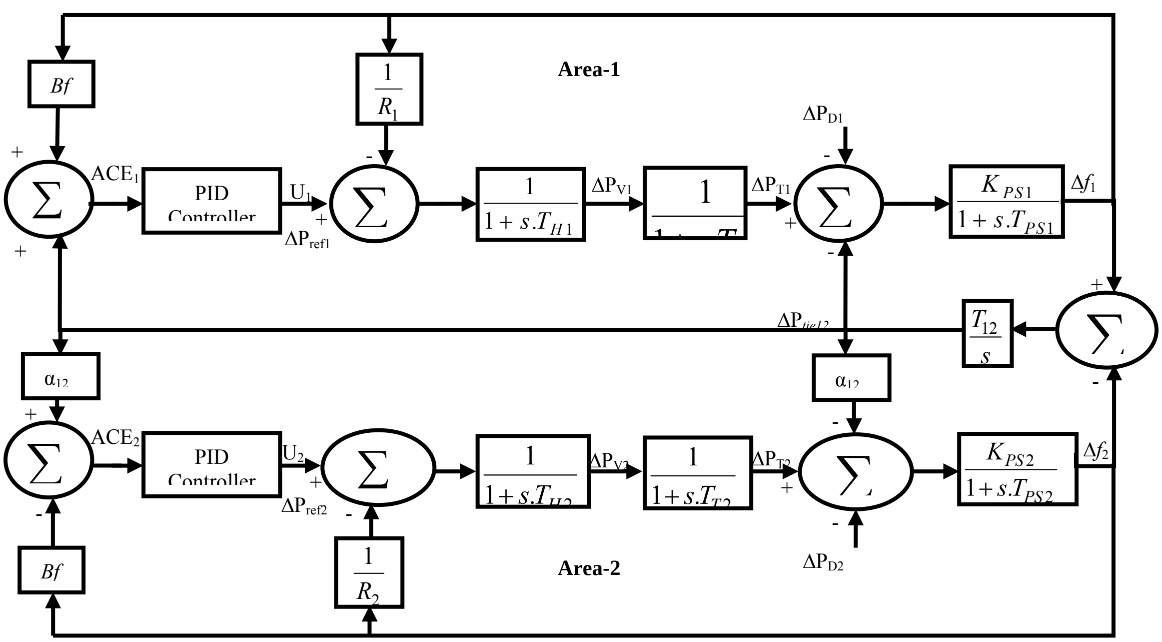

Figure 2. LFC model of Two-Area Interconnected Power System.

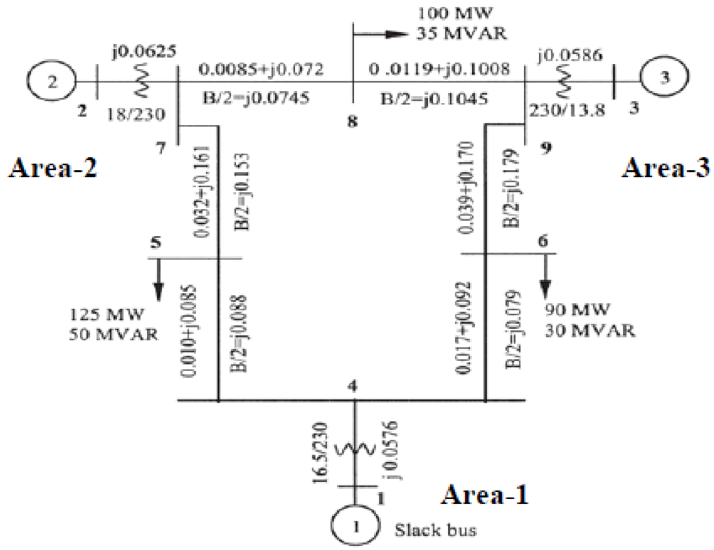

Figure 3. IEEE (WSCC) 3-machine, 9-bus Interconnected Power System Model.

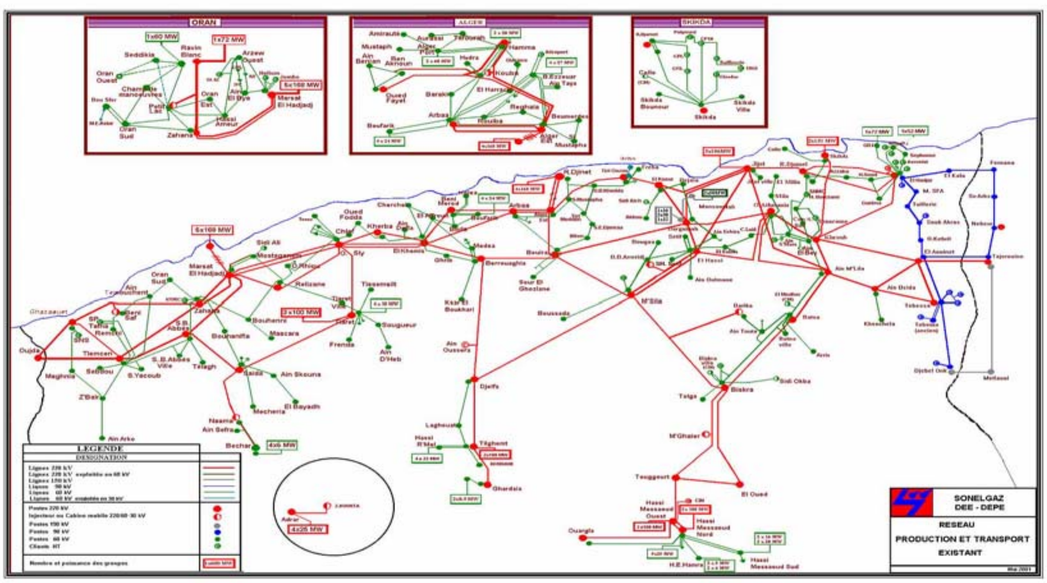

Figure 4. South-Western Mediterranean (SWM) Interconnected Power System (N.EL.Y. Kouba et al., 2015d; Cartographer).

As a novel intelligent technique, the ALO algorithm has been proven to be competitive with the other developed and tested optimization algorithms including genetic algorithm (GA), particle swarm optimization (PSO), bacterial foraging optimization algorithm (BFO), Artificial Bee Colony (ABC), Bat Algorithm (BA), Firefly Algorithm (FA) and many others. The inspiration of the ALO algorithm has come from the real life analysis of the Ant Lion (or Antlion) hunting mechanism in nature. This behavior include five main steps of hunting prey like the random-walk of ants, building traps, entrapment of ants in traps, catching preys, and re-building traps (Seyedali Mirjalili, 2015).

As stated in (Seyedali Mirjalili, 2015), the lifecycle of antlions includes two main stages: larvae and adult as shown in Figure 5. Note that the typical length of a larva is up to 1.2 cm, while this length can be estimated up to 4 cm in case of an adult (Goodenough J et al., 2009; Grzimek B et al., 2004; Griffiths D, 1986). A total period of natural life might take up three years, which happens especially in the larvae (only 3-5 weeks to adulthood). Similar to other predators that hunt with the same strategy: sit-andwait, the larvae of ant lions is generalist predators that catch small arthropods which enter their pits traps.

As shown in Figure 6 (a) (Marke Hauber, 1999), the antlion larvae prepare a cone-shaped pit in sand by moving along a circular trajectory. During this operation, they use their huge jaw to throw out the sands as shown in Figure 6 (b) (Seyedali Mirjalili, 2015). After preparing the trap, the larvae hides underneath the bottom of the cone and waits for their prey as shown in Figure 6 (c, d). After this brief description of Antlions hunting mechanism, a mathematical model is presented in the next subsection. Note that, all the mathematical model was inspired from (Seyedali Mirjalili, 2015).

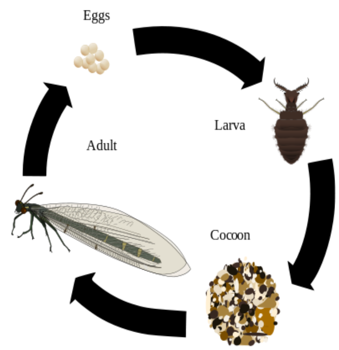

Figure 5. Antlion Lifecycle.

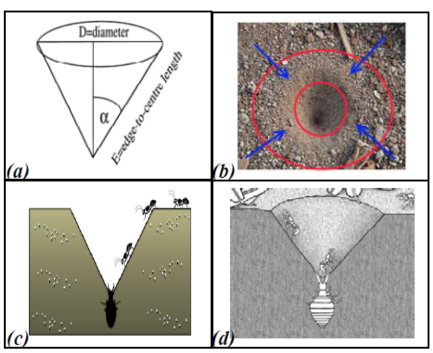

Figure 6. Pit trap and hunting behavior of Antlions.

1.4 Mathematical model

As the ants are the preferable prey for the antlions, the ALO algorithm imitates the interaction among the antlions and the ants in the pit trap. These interactions can be modeled mathematically to simulate the foraging activity in the real life of this type of insects. The antlions catch the ants that are estimated to move over the search space using the digged traps (Griffiths D, 1986; Marke Hauber, 1999). In nature, ants move following a stochastic trajectory when they searching food. For this reason, a random-walk is devoted to model ants' movement. The mathematical equation that represents this movement can be written as follows (Seyedali Mirjalili, 2015) :

$$X(t) = \begin{bmatrix} 0, & cumsum(2r(t_1)-1), & \dots & \dots \\ & cumsum(2r(t_2)-1), & & \\ & \dots. & & \\ & cumsum(2r(t_n)-1) & & \end{bmatrix} \tag{9}$$

Note that, the *cumsum* represents the cumulative sum, *t* shows the step of random-walk (iteration number), *n* is the maximum number of generation (iteration) and *r (t)* is a stochastic function stated as follows (Seyedali Mirjalili, 2015):

$$r(t) = \begin{Bmatrix} 1 \;\; If\ rand > 0.5 \\ 0 \;\; If\ rand \le 0.5 \end{Bmatrix} \tag{10}$$

where *rand* is a random number generated with uniform distribution in an interval between $[0,1]$.

The positions of ants are stored in the matrix M_{Ant} to be used during the optimization process, where the position of an ant refers the parameters for a particular solution. During optimization, each ant was assessed using an objective function, while the fitness value of all ants was saved in the matrix M_{OA} (Seyedali Mirjalili, 2015).

$$M_{Ant} = \begin{bmatrix} A_{1,1} & A_{1,2} & \dots & \dots & A_{1,d} \\ A_{2,1} & A_{2,2} & \dots & \dots & A_{2,d} \\ : & : & : & : & : \\ : & : & : & : & : \\ A_{n,1} & A_{n,2} & \dots & \dots & A_{n,d} \end{bmatrix} \tag{11}$$

$$M_{OA} = \begin{bmatrix} f([A_{1,1} \;\; A_{1,2} \;\; \dots \;\; A_{1,d}]) \\ f([A_{2,1} \;\; A_{2,2} \;\; \dots \;\; A_{2,d}]) \\ : \\ : \\ f([A_{n,1} \;\; A_{n,2} \;\; \dots \;\; A_{n,d}]) \end{bmatrix} \tag{12}$$

The elements $A_{i,j}$ shows the value of the *j-th* variable (size) of *i-th* ant, *n* is the number of ants, *d* is the number of variables and *f* is the fitness function. Moreover, the antlions are also assumed to be hiding somewhere in the search space. In the aim to memorize the positions of these predators, the matrix $M_{Antlion}$ is used. Furthermore, a matrix M_{OAL} is used to save the fitness of each antlion (Seyedali Mirjalili, 2015).

$$M_{Antlion} = \begin{bmatrix} AL_{1,1} & AL_{1,2} & \dots & \dots & AL_{1,d} \\ AL_{2,1} & AL_{2,2} & \dots & \dots & AL_{2,d} \\ : & : & : & : & : \\ : & : & : & : & : \\ AL_{n,1} & AL_{n,2} & \dots & \dots & AL_{n,d} \end{bmatrix} \tag{13}$$

$$M_{OAL} = \begin{bmatrix} f([AL_{1,1} & AL_{1,2} & \dots & AL_{1,d}]) \\ f([AL_{2,1} & AL_{2,2} & \dots & AL_{2,d}]) \\ & \vdots & & \\ & \vdots & & \\ f([AL_{n,1} & AL_{n,2} & \dots & AL_{n,d}]) \end{bmatrix} \quad (14)$$

where each element $AL_{i,j}$ represents the *j-th* dimension's value of *i-th* antlion, *n* is the number of antlions, and *d* is the number of variables and *f* is the objective function.

Min–Max normalization was used to hold the random-walks of ants inside the search space according to the following formula (Seyedali Mirjalili, 2015):

$$X_i^t = \frac{(X_i^t - a_i).(d_i - c_i^t)}{(d_i^t - a_i)} + c_i \quad (15)$$

where, the minimum and the maximum of the random-walk of *i-th* variable are given by a_i and b_i respectively. While, c^t_i and d^t_i represent the minimum and the maximum of *i-th* variable at *t-th* iteration respectively.

In order to ensure the occurrence of random-walks inside the search space, the Eq. (15) should be applied at every iteration. It's assumed that the antlions traps affect the random-walks of ants according to the following equations:

$$\begin{Bmatrix} c_i^t = Antlion_j^t + c^t \\ d_i^t = Antlion_j^t + d^t \end{Bmatrix} \quad (16)$$

Note that, c^t represents the minimum of all variables at *t-th* iteration, *dt* indicates the vector including the maximum of all variables at *t-th* iteration, c^t_j is the minimum of all variables for *i-th* ant, d^t_j is the maximum of all variables for *i-th* ant, and $Antlion^t_j$ shows the position of the selected *j-th* antlion at *t-th* iteration. As indicate in (Seyedali Mirjalili, 2015), the antlions hunting capacity was modeled using a roulette wheel. This latter gives more chances to the fitter antlions for hunting ants. Another important activity is that the antlions shoot sands outwards the center of the pit once they realize that an ant is in the trap. This mechanism slides down the trapped ant that is trying to escape (Marke Hauber, 1999). This behavior is mathematically modeled by the following equations (Seyedali Mirjalili, 2015):

$$\left\{ c^t = \frac{c^t}{I} \quad d^t = \frac{d^t}{I} \right\} \quad (17)$$

where *I* represent a ratio:

$$I = 10^w \frac{t}{T} \quad (18)$$

With *t* is the current iteration, *T* is the maximum number of iterations, and *w* is a constant defined based on the current iteration, note that the accuracy level of exploitation can be adjusted by this constant.

$$\begin{cases} w = 2 \; when t > 0.1T. \\ w = 3 \; when t > 0.5T. \\ w = 4 \; when t > 0.75T. \end{cases} \begin{cases} w = 5 \; when t > 0.9T \\ w = 6 \; when t > 0.95T \end{cases}$$

The final step is attained when the prey (ant) is hunted. After that, the antlions consumes the ant body inside its pit. In order to improve its chance of hunting a novel ant, antlion update its position to the latest position of the hunted ant. This activity can be modeled using the following equation (Seyedali Mirjalili, 2015):

$$Antlion_j^t = Ant_i^t \left(if \right) f(Ant_i^t) > f(Antlion_j^t) \quad (19)$$

As an important feature of evolutionary algorithms, Elitism is needed to maintain the best solutions achieved at any level of the optimization process. At every iteration the best antlion is stored as elite, while this latter is considered as the fittest antlion. Consequently, it is supposed that each ant randomly-walks around a selected antlion by the roulette wheel and the elite simultaneously as given in this equation (Seyedali Mirjalili, 2015):

$$Ant_i^t = \frac{R_A^t + R_E^t}{2} \quad (20)$$

where *t* represents the current iteration, $Antlion^t{}_j$ shows the position of selected *j-th* antlion and Ant^t_i indicates the position of *i-th* ant at the *t-th* iteration respectively, R^t_A is the random-walk around the antlion selected by the roulette wheel and R^t_E is the random-walk around the elite at the *t-th* iteration respectively.

According to the discussed ALO operators above, the ALO optimization algorithm is defined as a three-tuple function (*A, B* and *C*) that approximates the global optimum for optimization problems as follows (Seyedali Mirjalili, 2015):

$$\text{ALO (A; B; C)} \quad (21)$$

More details of *A*, *B*, and *C* functions are available in (Seyedali Mirjalili, 2015), where these functions are defined as follows:

$$\begin{cases} \phi \xrightarrow{function(A)} \{M_{Ant}, M_{OA}, M_{Antlion}, M_{OAL}\} \\ \{M_{Ant}, M_{Antlion}\} \xrightarrow{function(B)} \{M_{Ant}, M_{Antlion}\} \\ \{M_{Ant}, M_{Antlion}\} \xrightarrow{function(C)} \{true, false\} \end{cases} \tag{22}$$

1.5 Application of ALO to Solve LFC Problem

This paper presents the application of ALO algorithm for solving the LFC problem mainly includes the search of the optimal PID controller parameters of the LFC control loop to minimize the fitness function. At the beginning, the search dimension, number of search agents and the maximum iteration are set.

In the aim to find the objective function, the LFC block is executed in MATLAB to obtain the frequency and the tie-line power flow deviations. After that ALO algorithm is used to minimize the objective function given in Eqs. (23 and 24) and obtain the optimal PID controller parameters. The simulation is repeated until satisfy the maximum iteration number. The time multiplied by absolute error (*ITAE*) has been employed as fitness function for the proposed ALO algorithm to solve LFC problem, where the implementation of ALO strategy in solving LFC problem is shown in Figure 7.

In case of two-area:

$$Fit = ITAE = \int_0^{tsim} t.\left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{T12}|\right).dt \tag{23}$$

In case of three-area:

$$Fit = ITAE = \int_0^{tsim} t.\begin{pmatrix} |\Delta f_1| + |\Delta f_2| + |\Delta f_3| + |\Delta P_{T12}| \\ + |\Delta P_{T13}| + |\Delta P_{T23}| \end{pmatrix}.dt \tag{24}$$

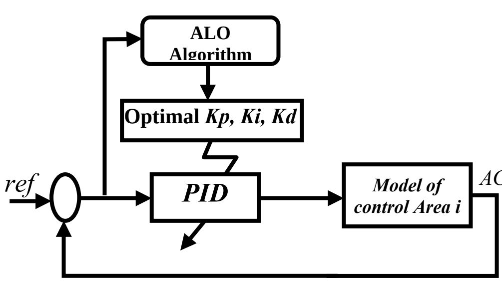

Figure 7. Proposed ALO based PID controller model.

In the above equations, Δf_1, Δf_2 and Δf_3 represent the system frequency deviations; ΔP_{T12}, ΔP_{T13} and ΔP_{T23} are the tie-lines power flow exchange deviations; t_{sim} represents the simulation time. The problem constraints are the PID controller parameter bounds. Therefore, the design problem sketched in Figure 7 can be formulated as the following optimization problem:

- Minimize the objective function *Fit (ITAE)* given in Eqs. (23, 24)
- Subject to:

$$\begin{cases} K_{p\,min} \le K_p \le K_{p\,max} \\ K_{i\,min} \le K_i \le K_{i\,max} \\ K_{d\,min} \le K_d \le K_{d\,max} \end{cases} \tag{25}$$

2 SIMULATION RESULTS

IN order to illustrate the effectiveness of the proposed ALO algorithm, the standard Two-area, the IEEE (WSCC) 3-machine, 9-bus, and the large South-Western Mediterranean (SWM) interconnected three-area power systems are considered for the simulation. Initially, similar PID controllers are considered to regulate the system frequency in each area. The ALO algorithm is used to reach the best optimal controller parameters and improve LFC loop. The fitness function is calculated in MATLAB .m file and used in the ALO algorithm.

A step load change is considered as disturbance. To show the potential of the proposed method in solving LFC problem, the performances of the proposed ALO algorithm is compared with those of Ziegler-Nichols (Z-N), GA, PSO, BFO, FA, ABC and BA techniques for similar power system.

2.1 Two-Area Power System

Case 1: Load step change in area-1

A 10 % load step change is considered at t = 5s in area-1. The frequency fluctuations in area-1 is shown in Figure 8. The impact of LFC controller in frequency regulation is analyzed. The results are tabulated as a comparative performance in terms of peak overshoot and settling time as shown in Table 1 and the optimized PID controller parameters are given in Table 2. It is clear from the presented results that a significant improvement is observed with proposed ALO optimized PID controller compared to other recently reported approaches given in (E.S. Ali et al., 2011; Sidhartha Panda et al., 2013; H. Bevrani et al., 2010).

The frequency and the tie-line power flow exchange are suppressed if each control area is equipped with a secondary control loop. Using the ITAE as the objective function, in the optimization process based ALO algorithm, the time of suppressing the fluctuation is very short compared with the time given by other applied methods. From this simulation, the LFC loop presents good performances. From the obtianed results, it is seen that the proposed ALO is able to give best results in terms of minimizing fluctuations of frequency and tie-line power flow as shown in Table 1. From the presented results, compared with the Z-N, GA, PSO, BFOA, ABC , FA and BA approaches, the ALO algorithm gives better performances. The results also show the superiority of the proposed approach and confirm its potential to improve the frequency regulation loop and solve LFC problem over disturbances. The comparative study shows that the ALO algorithm could rapidly converge to the correct optimal solution and give the best PID controller parameters.

Table 1. Comparative Study with Different Approaches.

Methods		Z-N	GA	PSO	BFO	FA	ABC	BA	ALO
Area-1	Max Deviation [Hz]	0.09746	0.07683	0.1102	0.1227	0.07683	0.1139	0.0468	0.0464
	Settling time [s]	5.9	4.565	2.869	2.768	2.6653	2.765	5.47	2.465
Area-2	Max Deviation [Hz]	0.05419	0.04148	0.0652	0.07816	0.03498	0.06926	0.01497	0.01404
	Settling time [s]	5.57	6.17	2.965	4.365	3.365	4.165	4.743	2.743
Tie-line$_{12}$	Max Deviation [Pu]	0.01939	0.01732	0.02205	0.02724	0.01125	0.02387	0.005598	0.005395
	Settling time [s]	5.873	6.97	3.465	4.265	2.865	4.665	5.57	2.765

Table 2. PID Controller Parameters.

Methods	Controller Parameters		
	Kp	*Ki*	*Kd*
Z-N	0.4511	2.6305	0.6575
GA	0.9917	0.9776	0.8731
PSO	0.8592	2.6844	0.4161
BFO	0.3875	1.0602	0.4048
FA	1.9917	4.9775	0.8729
ABC	0.8136	1.2950	0.4118
BA	1.3249	13.8026	2.5739
Proposed ALO	2.8457	11.1406	2.3190

Case 2: Load step change in area-1and area-2

To demonstrate the ability of the proposed method to solve LFC problem under multi load change disturbances, a load change variation is applied in both areas. For comparative study, the step load increase by 10% in area-1 and by 20% in area-2 are considered simultaneously. Figure 9 shows the frequency deviation in area-1. It is clear that the proposed ALO algorithm achieves good dynamic performance for the same test system compared to the other applied approaches.

Case 3: Sensitivity Analysis

To show the capacity of ALO algorithm in solving LFC problem, a sensitivity analysis is carried out to study the robustness of the system. Since optimized PID controller based ALO algorithm is a robust controller, there is no need of retuning its parameters when the system is subjected to either variation in loading condition or variation in system parameter.

The change in operating load condition affects the power system parameters K_{PS} and T_{PS}. To check the robustness, the time constants of speed governor control system (T_H), turbine (T_T) and tie-line power flow (T_{12}) are varied from their nominal values in the range of +50% to −50% in steps of 25%. The test system variables and time constants are calculated for diverse state and used in this simulation. Similar to case 1, a step load increase of 10% is applied at t = 5 s in area-1. The control loop parameters were achieved using the same fitness function that given in Eq.23. Table 3 depicts performance of the test system under nominal and different conditions with proposed ALO algorithm. The obtained results are shown in Figure 10.

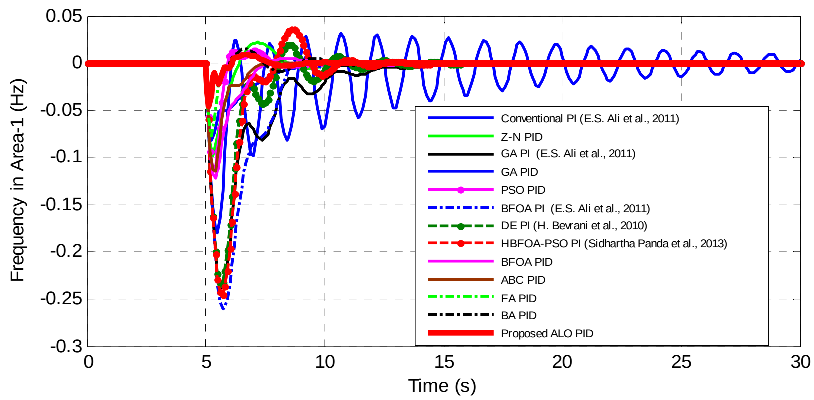

Figure 8. Frequency deviation in Area-1.

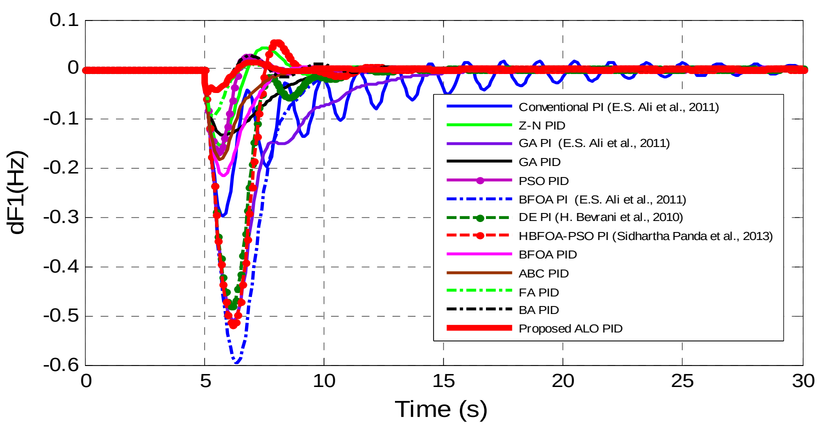

Figure 9. Frequency deviation in Area-1 for multi step load disturbances.

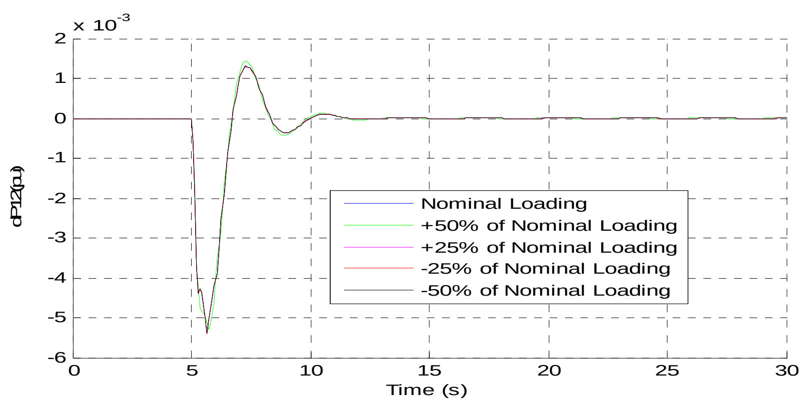

Figure 10. Change in tie-line power deviation with change in loading condition.

Table 3. Robustness analysis for two-area system.

Parameter variation	Change%	Performance index with proposed approach			
		Settling time *Ts (s)*			
		Δf_1	Δf_2	ΔP_{12}	*Fit(ITAE)*
Nominal Loading Condition	0%	2.465	2.743	2.765	0.0818
	+50%	2.465	2.743	2.765	0.0820
	+25%	2.465	2.743	2.765	0.0819
	-25%	2.465	2.743	2.765	0.0817
	-50%	2.465	2.743	2.765	0.0815
T_H	+50%	2.474	3.011	2.915	0.0777
	+25%	2.478	3.138	3.052	0.0794
	-25%	4.292	4.843	4.911	0.0837
	-50%	4.464	4.838	4.889	0.0859
T_T	+50%	4.058	4.429	4.684	0.0964
	+25%	4.005	4.582	4.848	0.0868
	-25%	4.119	4.635	4.876	0.0787
	-50%	4.298	4.756	4.898	0.0785
T_{12}	+50%	4.113	4.621	4.77	0.0782
	+25%	3.996	4.53	4.879	0.0795
	-25%	4.17	4.661	4.98	0.0839
	-50%	4.215	4.791	5.095	0.0848

It can be observed from Table 3 and the obtained results, that during variation of the operating load conditions and system parameters from their nominal values, the dynamic system performances are maintained within an acceptable range. In addition, the frequency and the tie-line power flow responses change according to the system parameters variation. As the ACE signal depends on frequency and tie-lie deviations, this latter will change also. Hence, the error input to the PID controller varies depending on ACE change. Because of these reasons, an intrinsic robustness of the LFC controller is reached even if the uncertainties of the parameters are not modeled in the design stage. Therefore, it can be concluded that, the suggested LFC control strategy based ALO algorithm is stable and provides an effective control satisfactorily.

2.2 Extension To The IEEE WSCC Interconnected Power System

The popular IEEE WSCC 3-machine, 9-bus, 3-area power system is considered in this simulation. The base system is 100 MVA, and the system frequency is 60 Hz. The system has been simulated with a classical IEEE steam governor-turbine model. A load variation of 10 % is applied in area-1. The fluctuations in system frequency in area-1 and the tie-line power flow are shown in Figures 11 and 12 respectively.

The ALO results are compared to the once obtained using GA and PSO algorithm. It is clear from the comparative study that the ALO algorithm gives batter results in term of settling time, peak overshoot and undershoot.

2.3 Extension To The SWM Three-Area Interconnected Power System

To demonstrate the capability of the proposed ALO algorithm to face with large-scale power system with various controller parameters, the study is further extended to the South-Western Mediterranean (SWM) interconnected multi-area power system with different PID coefficients for each control area. Each control area in the SWM system is modeled with an aggregated generating unit, where a PID controller is considered for each unit. For comparative study, the ALO results were compared to conventional integral I controller and optimized PI controller based PSO. A multi step increase in load are considered as follow: 10 % in Area-1 (Tunisia) at t = 10s, 15 % in Area-2 (Algeria) at t=100s and 20% in Area-3 (Morocco) at t=150s. The fluctuations in the frequency and the tie-line power flow are shown in Figures 13 and 14 respectively. The results are tabulated as a comparative performance in view of peak overshoot and settling time as shown in Table 4. The optimized parameters for each control area are given in Table 5.

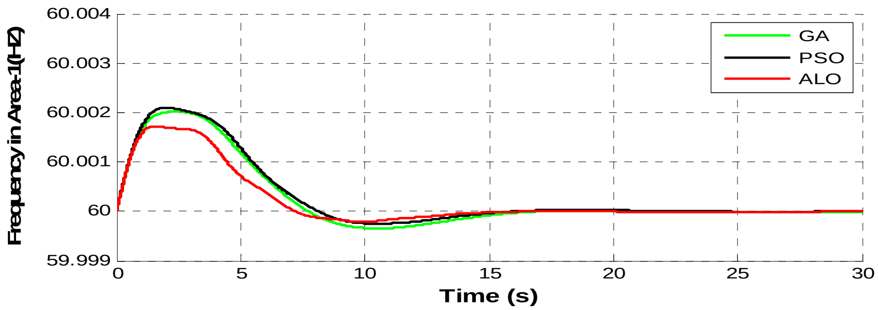

Figure 11. Frequency deviation in Area-1.

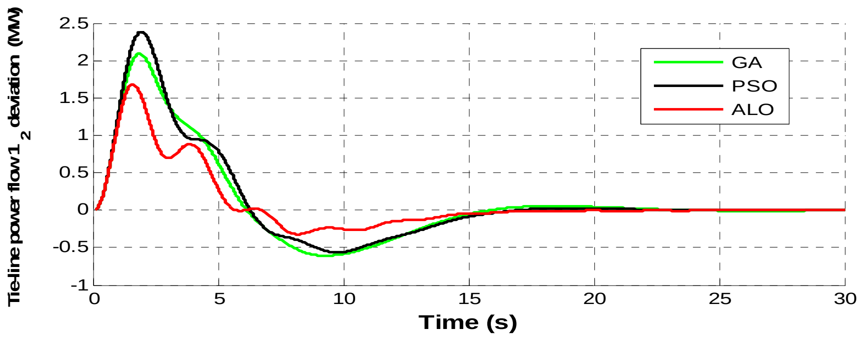

Figure 12. Tie-line power flow deviation between Area-1 and Area-2.

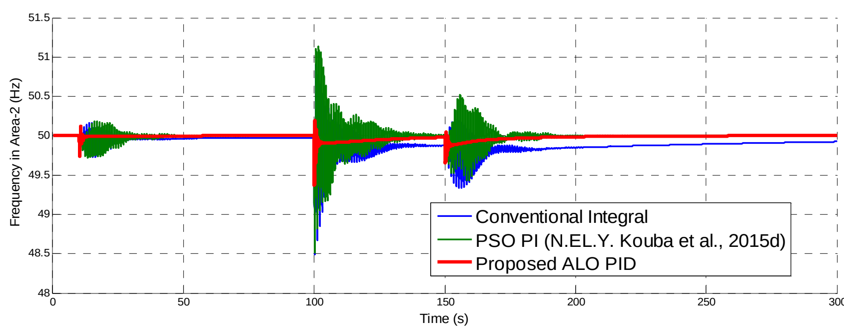

Figure 13. Frequency deviation in Area-2 (Algeria).

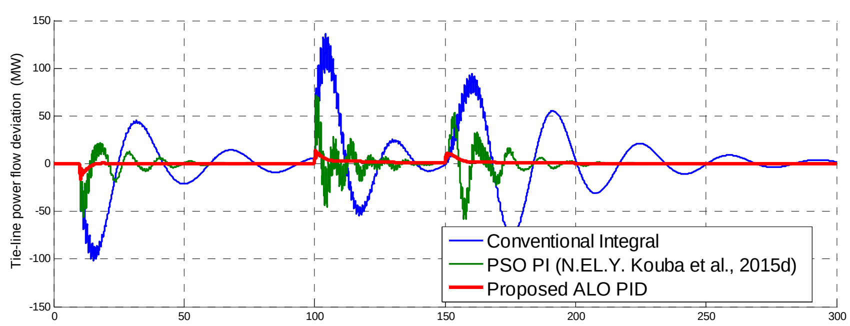

Figure 14. Tie-line power flow deviation ΔP_{12} between Tunisia and Algeria.

Table 4. Comparative Study with Three Step Increase in load: 10 % in Area-1, 15 % in Area-2 and 20% in Area-3.

Methods		Frequency in Area-1 [Hz]	Frequency in Area-2 [Hz]	Frequency in Area-3 [Hz]	Tie-line$_{12}$ [p.u]	Tie-line$_{23}$ [p.u]
Conventional Integral	Max Deviation	0.47	0.65	2.12	93.88	198.2
	Settling time [s]	> 150	> 150	> 150	> 150	> 150
PSO PI (N.EL.Y. Kouba et al., 2015d)	Max Deviation	0.27	0.55	2.04	55.36	99.41
	Settling time [s]	71.3	63.1	75.6	76.8	61.7
Proposed ALO PID	Max Deviation	0.15	0.33	0.82	9.74	23.86
	Settling time [s]	60	40.8	53.5	26.2	15.4

Table 5. I, PI and PID Controllers Parameters.

Methods	Areas	Controller Parameters		
		Kp	*Ki*	*Kd*
Conventional Integral	Area-1 (Tunisia)	-	0.76	-
	Area-2 (Algeria)	-	0.357	-
	Area-3 (Morocco)	-	0.7328	-
PSO PI (N.EL.Y. Kouba et al., 2015d)	Area-1 (Tunisia)	0.1023	4.7923	-
	Area-2 (Algeria)	0.1579	6.4924	-
	Area-3 (Morocco)	0.1278	8.5935	-
Proposed ALO PID	Area-1 (Tunisia)	29.0352	15.5849	8.5793
	Area-2 (Algeria)	20.7577	2.2450	22.3497
	Area-3 (Morocco)	22.3259	4.4572	24.2960

In a sever condition (Multi-disturbances), performance of the ALO algorithm based PID controller is examined following a large step load disturbance. Additionally, for a verification of the LFC strategy in a more sever power contingency, the dynamic performance of the test system is examined on several load disturbances without changing the optimal controllers' parameters. In this case also the proposed optimal control method provides a much better performance, specifically in settling time characteristic point of view. A better performance of the proposed control strategy is clearly visible from system frequency response, and the proposed optimal controller could eliminate the system frequency and tie-lines power flow deviations.

It is clear from Figures 13 and 14 that significant enhancement in frequency stability and control is observed. As shown, the proposed optimal PID controller based ALO algorithm regulates the system frequency following disturbance. This controller has suitable performance in terms of settling-time, as well as control effort and minimizing of frequency deviations (red curves). While, using the proposed ALO method based on the ITAE as objective function, the time of suppressing the fluctuation is very short compared with the time given by other methods and the LFC loop presents good performances.

Critical analysis of the system responses clearly reveals that dynamic performance of the system is significantly enhanced with proposed algorithm. In these three scenarios with one, two and three step load variation, the integral controller shows poor dynamic performance compared to the optimized PI and PID controllers. In contrast, the optimized PI controller based PSO (N.EL.Y. Kouba et al., 2015d) shows an acceptable performance in terms of peak overshoot and stabilization time. In the other side, from the comparative study in Table 4 and the presented figures, the optimized PID controller based ALO algorithm gives the best performances. It can be concluded PID controller based on the proposed ALO approach gives the best optimal solution to improve the LFC loop.

3 CONCLUSION

THIS paper has investigated an optimal PID controller for load frequency control to improve frequency regulation against load changes in multi-area power systems. A new meta-heuristic algorithm namely Ant Lion Optimizer (ALO) was used to solve the LFC problem under load disturbances. The performance of ALO was evaluated using three case studies. The impact of the optimal LFC controller on the fluctuations caused by the load changes was examined. Furthermore, robustness analysis was performed by varying the loading conditions and system parameters. Simulation results demonstrated that the ALO technique is effective for solving LFC problem. From the obtained results, ALO seems to be the most effective and robust as the frequency and the tie-line power flow deviations are relatively small compared to other techniques. The obtained results are promising and prove the potential of the proposed LFC strategy based ALO algorithm to ensure power system frequency stability.

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