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Parameters estimation of AC transmission line by an improved moth flame optimization method

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Abstract
The parameters calculation for a transmission line is described in the proposed work, and the estimation of transmission line parameters is essential for properly managing transmission and distribution networks. The research work deals with the concept of optimization of the transmission line parameters. To this purpose, an improved moth flame optimization technique is applied to different test cases of the transmission lines. Moth movement with respect to the light source is the basis for improved moth flame optimization. In this research work, simulations are performed on various test cases to determine the effectiveness of the suggested method. Results from the suggested method are compared with those from other methods mentioned in the literature. The comparison shows that the proposed method rapidly and smoothly converges to the best-obtained value. The improved moth flame optimization performs better than other algorithms in terms of solution quality and feasibility, proving its effectiveness and competence. The optimal values obtained for capacitance in (μF) are 0.22406, 0.022935, and 0.0049734, and for inductance in (mH) are 0.65055, 0.41258, and −0.76593, respectively.

Keywords: Transmission line, Improved moth flame optimization, Bundle conductors, Parameters

Introduction

The power transmission line is fundamental to building a power system model. In the analytical calculations, the electrical parameters are used within empirical formulas [1, 2]. This limitation in estimating the parameters may have different reasons for obtaining an updated and accurate estimate of the power transmission line parameters. Transmission line parameters are needed to solve many problems in the power system, such as steady-state and transient analysis, state optimization, protection, and setting up control relays. Consequently, novel values for these parameters ought to be refreshed and accurate. They are calculated because the proper detection setting, protection systems, propagation faults' location, and information characteristics are mandatory. Classical techniques measure the electrical transmission line parameters configuration using the conductor tower properties and configuration. However, these methods are vulnerable to imprecision; meanwhile, they ignore the ever-changing variation of working variables such as the temperature around them, climate circumstances, and skin impact [3]. Instead of parameters with recorded currents and voltage, both ends of the line are used in either a distributed or lumped model approximating the electrical grid's transmission line dynamics. Many of the methods discussed in the literature focus on measurements that employ data obtained from the ends of the transmission line. Recorded data can be distinguished into two types: Frequency-domain data can be collected by PMU and SCADA systems for synchronized voltage and current phasor measurement. The major drawback of such frequency-domain approaches is that filter-based phasor subjects' calculations have found error parameters. Transposed transmission line parameters are calculated using synchronized phasors on both terminals with the Laplace transform. A post-synchronization approach is used if there is no synchronization. Using synchronized data, researchers commonly used the sequence concept to estimate the parameters of the lines when the positive sequence parameters are defined.

The latter was calculated online, utilizing the SCADA method to trace transmission line parameters using voltage magnitude and active and reactive power data measured at the transmission line's ends. Some researchers have suggested an orthogonal distance regression method to resolve the problem of zero-sequence parameter estimation, considering noise in the estimation problem of both current and voltage synchronous phasor measurements. The approach is proposed to measure the power–frequency parameter. First-order coupled, ordinary differential equations generated from the three-phase representation of transmission lines are solved using time-domain fault data and the least squares approach to determine the line parameters. The π-circuit utilized by Dasgupta and Soman [4] is used by Costa and Kurokawa [5]. However, the latter converted the phase-domain into a coupled phase-domain differential equation coupled with an ordinary differential equation. Synchronous time-domain error is recorded with the least amount of data. The method of squares was solved with modal decomposition [6]. The transmission line parameters are calculated by empirical formulas using analytical techniques to measure the information needed directly from the line in offline situations [7]. However, these methods are not accurate enough. In designing a transmission line, parameters must be accurate, with fewer errors [8]. To find an efficient estimation of parameters in the modern power system. To overcome this problem, demand and other factors, such as expansion in the power system, made it challenging for engineers and technicians to maintain system stability [9, 10].

Classical approaches include LMI [11], H∞ optimization [12], and pole placement technique [13]. These optimization approaches are gaining popularity since they need less computing effort to get optimal values for the issue. Some literature surveys demonstrate that the GA [14] is getting popular in a PSS design. Furthermore, BF is the evolutionary algorithm [15]. The traditional PSS has been designed utilizing tabu search [16], FA [17], evolutionary programming [18], CS [19] and BAT [20], hill climbing [21], B-hill climbing [22], simulated annealing [23] and GWO [24].

Seyedali Mirjalili [25] suggested the MFO approach as a nature-inspired method of guiding moths in nature called transverse orientation in 2015, but it has gained little attention in the power framework. As a result, this paper aims to use a new tool, the MFO, to solve the optimum calculation of transmission line parameters [26]. Because of the explosiveness at which this method searches, it is superior. IMFO technique is used in this study to obtain accurate transmission line parameters in various bundle conductors. Authors have adopted improved moth flame optimization (IMFO) in the proposed work because of the following advantages as given below:

- Fast convergence rate.
- Less parameters to control.
- Less computing time.
- Derivative free.
- Does not get easily trapped in local minima.
- Best accuracy even after many trials.

The article proposed an IMFO for calculating the optimum parameters of overhead transmission lines. This research work has the following significant contributions:

- IMFO calculates the transmission line parameters for a three-phase system.
- When calculating transmission line parameters, six different cases are taken into account.
- Qualitative results demonstrate that IMFO is more capable of providing coverage.

Design parameter and the effect of bundle conductor on transmission line

Proximity effect

The proximity [27] factor is defined as:

$$\beta_R = \frac{R_0}{R_{Dc}} \tag{1}$$

Equation (2) shows the ac resistance for two conductors as follows:

$$\beta_R = \left(1 + \left(\frac{a'_w}{r'_1} - \frac{a'_w}{r'_2}\right)\right) \tag{2}$$

Equation (3)–(5) shows the proximity factor of phases A, B, and C

$$\beta_{A1B} = \frac{1}{p_{A1B}/a'_w - 1} - \frac{1}{p_{A1B}/a'_w + 1} \tag{3}$$

$$\beta_{A1C} = \frac{1}{p_{A1C}/a'_w - 1} - \frac{1}{p_{A1C}/a'_w + 1} \tag{4}$$

$$\beta_{A1N} = \frac{1}{p_{A1N}/a'_w - 1} - \frac{1}{p_{A1N}/a'_w + 1} \tag{5}$$

Power capacity

For the balance condition, the transmission line's length between two supported voltage buses of the same amplitude [28, 29], the power capacity is expressed as:

$$P_{12} = P_{SIL} \frac{\sin(\theta_1 - \theta_2)}{sin\left(2\pi fl/3x10^5\right)} \tag{6}$$

$$P_{SIL} = |V_{ll}|^2/Z_o \tag{7}$$

Surge impedance

The transmission line [30, 31] has a surge impedance $Z_{0,}$ which is inversely proportional to the surface integral of $\left|\hat{\overline{E}}_{SIL}\right|^2$.

$$Z_0 = \eta_0\left|\overline{V}_{ll}\right|^2/\iint_S\left|\hat{\overline{E}}_{SIL}\right|^2 = \left|\hat{V}_{ll}\right|^2/P_{SIL} \tag{8}$$

Capacitance and inductance per unit length

Equation (9) shows the capacitance/length of the transmissions line, which has a direct proportion [32] with the surface integral of $\left|\hat{\overline{E}}_{SIL}\right|$.

$$C = \sqrt{\mu_0\varepsilon_0/z_0} = \varepsilon_0\left(\iint_S\left|\hat{\overline{E}}_{SIL}\right|^2 ds\right)/\left|\hat{V}_{ll}\right|^2 \tag{9}$$

Furthermore, Eq. (10) shows the inductance per unit length

$$L = \mu_0\varepsilon_0/C \tag{10}$$

Mathematical modeling of transmission line

During the modeling process for the transmission line parameters three-phase transmission line voltage, its parameters are calculated from the available data. In this research work, a single line equivalent pi circuit of the transmission line for modeling, as shown in Fig. 1, shows the different bundle configurations.

At 50 Hz operating frequency, the inductance of an AC transmission line becomes

$$X = Nln(d/r) \tag{11}$$

Equation (12) shows that the GMR can be obtained by a bundle of radius R and the subconductors r_r. The GMR is expressed as:

$$G_{MR} = R\left[n\frac{r'}{r}\right]^{1/n} \tag{12}$$

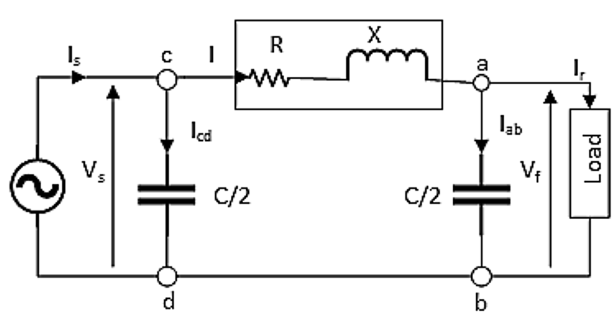


Fig. 1 Equivalent circuit of transmission line

GMR calculates transmission line parameters' inductance and capacitance, and GMR becomes 0.7788r.

$$L_c = \frac{\mu_0\mu_r}{2\pi} Nln\left(\frac{d}{G_{MR}}\right) \tag{13}$$

Both sub-conductors are bound in parallel, as shown by Eqs. (14). The GMR rises as the number of sub-conductors increases, lowering the line inductance and increasing power handling capability. The capacitance of a bundle conductor is denoted by the following:

$$C_c = \frac{2\pi\varepsilon_0}{nln/2D/G_{MR}} \tag{14}$$

Furthermore, Eqs. (15) and (16) represent the three-phase transmission line capacitance and inductance [33].

$$\Delta_L = \sum_{i=1}^{n-1}\left(0.2ln\frac{D}{G_{MRL}}\right)\frac{mH}{\text{km}} \tag{15}$$

$$\Delta_C = \sum_{i=1}^{n-1}\left(\frac{0.056}{ln\frac{D}{G_{MRC}}}\right)\frac{\mu\text{F}}{\text{km}} \tag{16}$$

Objective function

The mathematical representation of the parameters of the overhead transmission line for three-phase systems is represented mathematically as:

$$f(\Delta_L, \Delta_c) \tag{17}$$

Problem objectives

This research's main objective is to reduce transmission line parameters for three-phase, which are calculated by considering the minimized inductance and capacitance values. The objective function that follows is applied mathematically in this case.

$$F_{opt} = f(\Delta_L, \Delta_c) \tag{18}$$

Minimize inductance and capacitance in a transmission line parameter is expressed in Eqs. (15) and Eqs. (16). As a result, the objective problems can be expressed accurately as

$$\text{minimize}F_{,opt} \tag{19}$$

This research paper provides a method for estimating transmission line parameters through IMFO based on this problem formulation. In addition, the effects of bundle conductors on inductance and capacitance were investigated in this study.

Moth flame optimization

This research utilizes the MFO method to approximate transmission line parameters with different bundle conductors [34]. The central concept of MFO is focused on the natural navigation system of moths known as transverse orientation. Moths migrate at night by keeping a constant angle to the sky, which is an effective method for flying a long distance in a straight line. The MFO function is used in this study to execute optimization distances. The candidate solutions in this study are assumed to be moths, and the problem's variables are the moths' positions in space. As a result, by shifting their location vectors, the moths may fly in 1_D, 2_D, 3_D, or hyperdimensional space. The proposed algorithm is a population-based algorithm whose convergence is guaranteed. Compared to other approaches, MFO is computationally efficient and highly robust. As a result, the MFO methodology is proposed as a method for calculating transmission line parameters.

Moths cannot differentiate between moonlight and artificial light; thus, they follow a deadly twisted path while taking care of a similar light angle to that of artificial light. The MFO algorithm is often expressed as follows.

$$M = \begin{bmatrix} MO_{1,1} & MO_{1,2} & \cdots & \cdots & MO_{1,d} \\ MO_{2,1} & MO_{2,2} & \cdots & \cdots & MO_{2,d} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ MO_{n,1} & MO_{n,2} & \cdots & \cdots & MO_{n,d} \end{bmatrix} \quad (20)$$

The important aspect of the MFO algorithm is that it flames a matrix similar to the moth matrix written as follows:

$$F = \begin{bmatrix} F_{1,1} & F_{1,2} & \cdots & \cdots & F_{1,d} \\ F_{2,1} & F_{2,2} & \cdots & \cdots & F_{2,d} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{n,1} & F_{n,2} & \cdots & \cdots & F_{2,d} \end{bmatrix} \quad (21)$$

The MFO algorithm is a three-fold method that approximates the following global optimization process:

$$MFO = (II, P, T) \quad (22)$$

$$M_i = S\left(M_i, F_j\right) \quad (23)$$

$$S\left(M_i, F_j\right) = D_i.e^{bt}.\cos(2\pi t) \ + F_j \quad (24)$$

$$Di = \left|\mathrm{F_j} - \mathrm{M_i}\right| \quad (25)$$

The moths position is obtained by Eq. (25), and the distance between the moth and flame is controlled by t. The twisting motion of the moth describes how to update its position around the flame.

Proposed improved moth flame optimization (IMFO)

If the moth n position is updated while searching for space, the result is opposed to achieving the optimal solution. The formula below is used to balance space exploration with exploitation.

$$flame\ number = round\left(N - maximum\ ietartion * \frac{N-1}{T}\right) \tag{26}$$

The improved MFO, known as IMFO, is proposed to increase solution quality and accelerate global convergence. First, a crossing approach is proposed to improve MFO catch flame behavior. The horizontal crossover is the numerical intersection of two randomly produced flames in all dimensions. Reduces the blind zone that the parent cannot explore by sampling the new position of the search area with a low probability through the horizontal crossover. Two flames were selected randomly, *Fid* and *Fjd*, for horizontal crossing and can be defined as [35].

$$M_{hc(i,d)} = \left|c_1.F_{id} - F_{jd}\right|.e^{bt}.\cos(2\pi t) + F_{id} \tag{27}$$

$$M_{hc(j,d)} = \left|c_2.F_{jd} - F_{id}\right|.e^{bt}.\cos(2\pi t) + F_{jd} \tag{28}$$

The vertical crossing is the mathematical crossing of two dimensions of a flame. Vertical crossover avoids local optimum in the initial search. Cross the d_1th and d_2th column of the *i* flame to get the offspring $M_{vc(i,d_1)}$.

$$M_{vc(i,d_1)} = |c.F_{id1} - F_{id2}|.e^{bt}.\cos(2\pi t) + F_{id} \tag{29}$$

Every vertical crossover produces a descendant, which helps to improve the jump out of the optimal solution in the current location. Secondly, a better solution should be kept after each horizontal or vertical crossing. This competitive mechanism accelerates the population's movement to the fitness values search area and the optimum global convergence. In the end, the MFO flame behavior is kept and merged with the crossbar method. Only when the population size is smaller than or equivalent to flame, no does horizontal crossover occur. Only when the number of columns reaches flame, no does vertical crossing happen. As a result, the capacity of optimization techniques is guaranteed, and optimization efficiency is improved. The flowchart of the proposed IMFO algorithm is shown in Fig. 2.

Result and discussion

Meta-heuristics are inherently stochastic, meaning their performance will vary from one run to the next while generating optimal solutions in multiple runs. As a result, in this section, the suggested IMFO efficiency is demonstrated through various simulation tests. Each optimization technique has been experimented with 30 times using MATLAB 2012a. A suite of IMFO techniques is proposed to implement the power transmission line's capacitance and inductance/length. This section will address the feedback of various variables for each case of bundle conductors.

Test case 1: three-phase transmission line with capacitance for two-bundle conductors

In the proposed case, 30 trials have been considered to optimize the parameter identification problem of a three-phase transmission line, which includes capacitance for two-bundled cables. The optimal value for two-bundled capacitances is 0.22406. The comparison of an IMFO with other different optimization techniques is presented

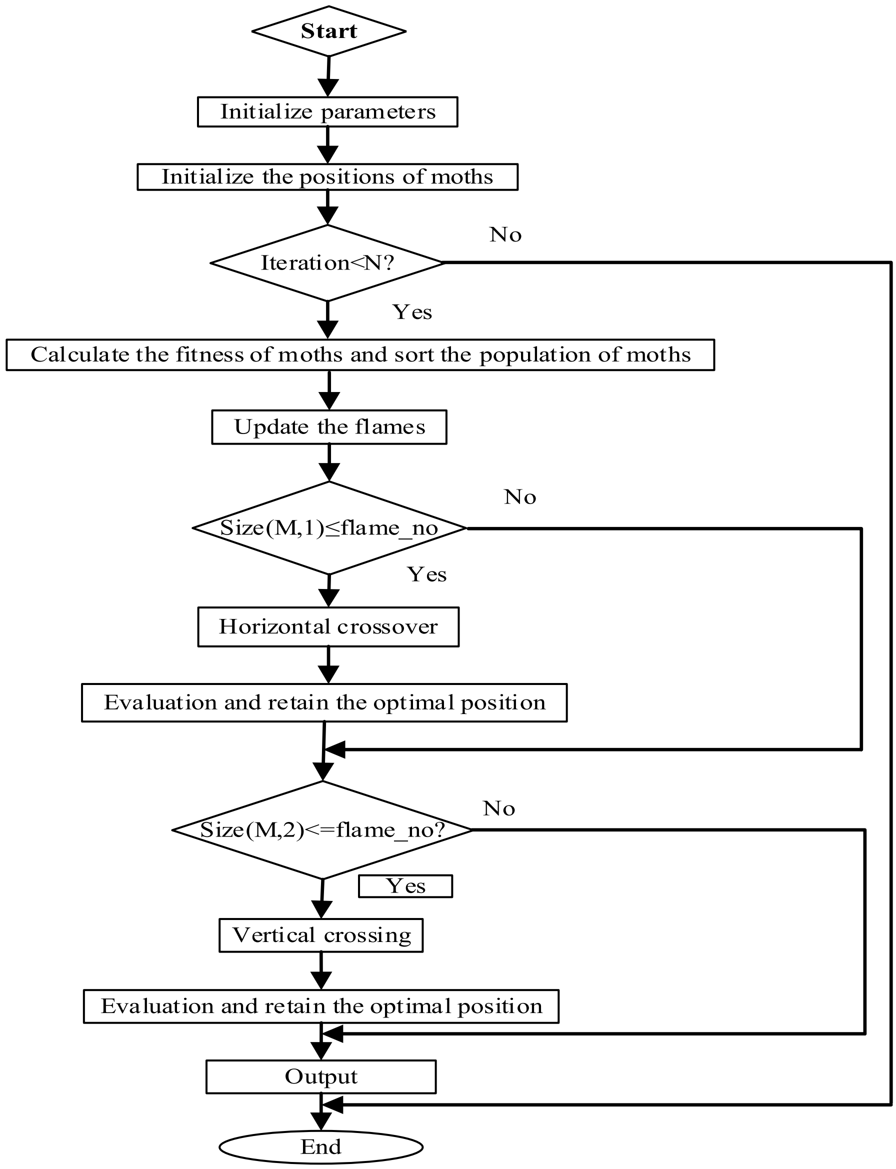


Fig. 2 Flowchart of the proposed IMFO algorithm

in Table 1. In addition, Fig. 3a shows the transmission line capacitance convergence curve when two-bundled conductors are considered.

Test case 2: 3-phase transmission line with capacitance for three-bundle conductors

In this test case, the capacitance of three-bundled conductors on the three-phase transmission line is presented. The comparison results are shown in Table 1, where the best optimal values of 0.022935 are also identified, along with the suggested IMFO technique. Figure 3b represents the convergence curve for this test system.

Table 1 Comparative analysis of three-phase transmission line parameters for capacitance/length (μF)

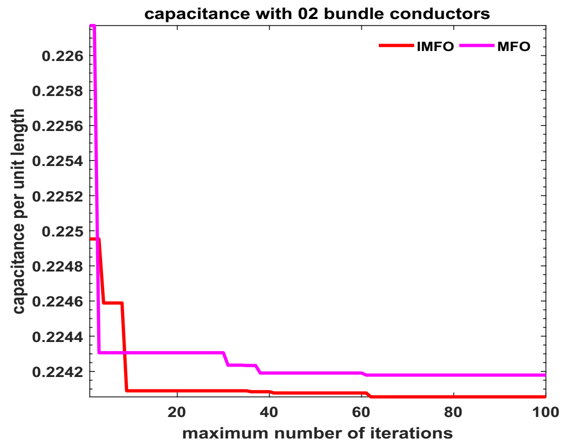
Case Number	IMFO	MFO	MWOA [36]	GWO [37]
Test Case 1	−0.15434	0.05772	0.89000	0.15084
	−0.00766	−0.03311	0.89000	−0.00204
	0.93000	0.91000	−0.10580	0.57367
	0.93000	−0.91000	0.630020	0.00041
	−0.58829	0.91000	0.214190	− 0.10258
	Best optimal value			
	0.22406	0.22418	0.22482	0.22634
Test Case 2	0.94000	0.91000	0.90000	0.00025
	0.94000	0.91000	0.90000	0.64927
	−0.94000	−0.91000	0.72970	0.16326
	0.94000	−0.91000	0.90000	−0.02038
	0.94000	0.91000	0.90000	−0.00209
	Best optimal value			
	0.02294	0.02352	0.02371	0.027884
Test Case 3	1.02200	1.02100	1.02000	1.00000
	1.02200	1.02100	1.02000	1.00000
	1.02200	−1.02100	1.02000	−0.01876
	−1.02200	−1.02100	1.02000	0.51761
	1.0220 0	1.02100	1.02000	− 0.48557
	Best optimal value			
	0.00497	0.00505	0.00513	0.00670

Test case 3: 3-phase transmission line with capacitance for four-bundle conductors

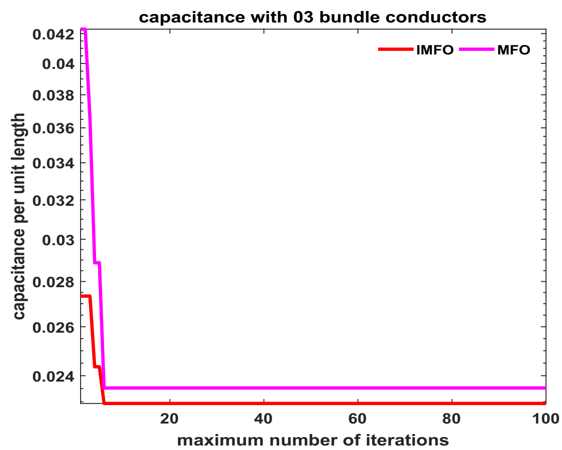
The IMFO, a three-phase feedline with capacitance for four-bundled conductors, is examined to validate the suggested approach's efficacy. The results of the IMFO are compared with different existing algorithms, including the modified MWOA, the GWO, and MFO, to verify the practicality of the suggested algorithm. For 30 iterations, Table 1 demonstrates that the IMFO results in the optimal value compared with the MFO, the GWO, and the MWOA, as presented in Table 1. Although the outcomes of the IMFO are reasonable, their performance is established by comparing them to other optimization methods. The convergence position for the IMFO algorithm for a transmission line with four-bundled conductors capacitance is presented in Fig. 3c. It can be confirmed that the IMFO algorithm convergence improves the exploration and exploitation potential.

Test case 4: three-phase transmission line with inductance for two-bundle conductors

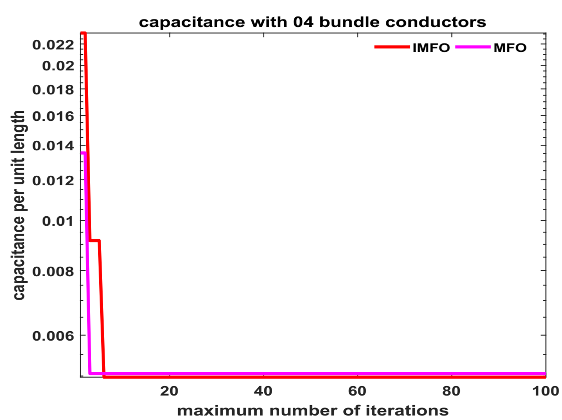
The IMFO algorithm is analyzed to calculate the inductance of two-bundled conductors of a three-phase system. The IMFO results are presented in Table 2 compared with the MWOA, the GWO, and the MFO, which indicates that the IMFO has determined the minimum inductance value and better performs. The inductance of a three-phase feedline for two-bundled conductors is shown in Fig. 4a. The IMFO leads to more efficient exploitation and exploration. The best result, 0.65055, is obtained when the IMFO algorithm is employed to compare various algorithms, as shown in Table 2.



(a) Two bundle capacitance



(b) Three bundle capacitance



(c) Four bundle capacitance

Fig. 3 Convergence curve for three-phase transmission line

Table 2 Comparative analysis of three-phase transmission line parameters for inductance/length (mH)

Case Number	IMFO	MFO	MWOA [36]	GWO [37]
Test Case 4	0.00725	0.05453	−0.00033	0.1128
	1.25000	1.23000	1.01000	0.02587
	1.25000	−1.23000	1.01000	−0.00084
	−1.25000	−1.23000	−0.00775	−0.03310
	−1.25000	1.23000	1.01	−0.01074
	Best optimal value			
	0.65055	0.65157	0.66063	0.78216
Test Case 5	0.00782	−0.01721	0.08447	0.00164
	2.20000	2.10000	0.07832	0.00040
	2.20000	−2.10000	1.17590	−0.00914
	2.20000	−2.10000	0.31235	−1.69450
	2.20000	2.10000	0.06741	0.00002
	Best optimal value			
	0.41258	0.42763	0.42000	0.43000
Test Case 6	1.20000	−1.10000	−1.10000	1.00000
	−1.20000	−1.10000	−1.10000	−1.00000
	−1.20000	1.10000	−1.09040	−1.00000
	−1.20000	1.10000	−1.10000	−0.38073
	1.2	−1.10000	−1.10000	0.00766
	Best optimal value			
	−0.76593	−0.66622	−0.66622	−0.57457

Test case 5: three-phase transmission line with inductance for three-bundle conductors

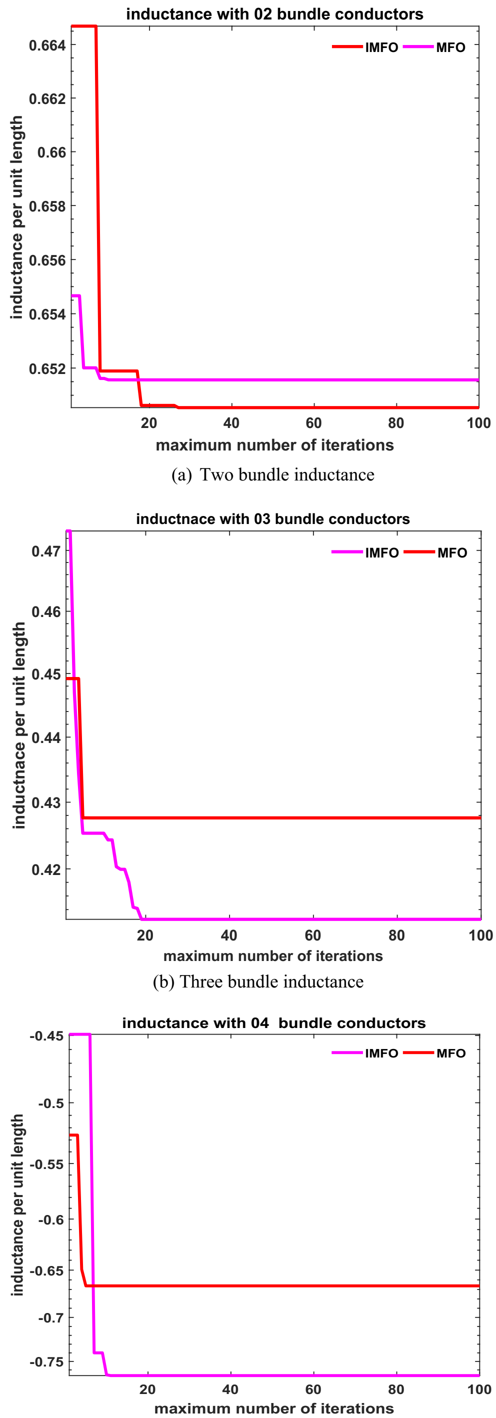
The transmission line inductance is measured by employing three-bundled conductors for each iteration of a three-phase transmission line, providing the minimized value, as shown in Fig. 4b. When the number of search agents is 30, an optimal value of 0.41258 is achieved using IMFO. The convergence curve of IMFO optimization for inductance considering three-bundled conductors is shown in Fig. 4b.

Test case 6: three-phase transmission line with inductance for four-bundle conductors

A three-phase transmission line with four-bundle conductor inductance is evaluated to verify the IMFO algorithm in this test case. The obtained result shows that IMFO compared with the existing algorithms, including the GWO, the MWOA, and the MFO, has better performance in terms of better convergence. The optimal value of −0.76593 is obtained for inductance which shows that the IMFO is more trustworthy than other techniques, as presented in Table 2. Figure 4c also shows the convergence curve of a three-phase transmission line with four-bundled conductors inductance.

Conclusion

To improve MFO, a heuristic stochastic methodology based on moth motions and behaviors is applied. Validating the suggested method's utility involves using it in various situations to assess its effectiveness for exploration and exploitation. The proposed method yields superior outcomes when compared to other contemporary algorithms.



(a) Two bundle inductance

(b) Three bundle inductance

(c) Four bundle inductance

Fig. 4 Convergence curve for three-phase transmission line

The recommended approach is also used to establish the best overhead transmission line parameters for analyzing bundle conductors. The results demonstrate the recommended approach's effectiveness, speed, efficiency, and adaptability for resolving transmission line parameter estimate challenges. According to the obtained result, the IMFO approach offers more accuracy and dependability for determining global or nearly global optimal controlling independent variables.

Abbreviations

BAT	Binary bat algorithm
BF	Bacteria foraging
CS	Cuckoo search
FA	Firefly algorithm
GA	Genetic algorithm
GWO	Grey wolf optimization
H∞	*H-infinity*
IMFO	Improved moth flame optimization
LMI	Linear matrix inequality
MFO	Moth flame optimization
MWOA	Modified whale optimization
PMU	Phasor measurement units
PSS	Power system stabilizer
SCADA	Supervisory control and data acquisition
TS	Tabu search

Symbols

Δ_L	Change in inductance
Δ_c	Change in capacitance
R_{DC}	DC resistance
$a_w^{'}$	Conductor radius
$r_1^{'}$ and $r_2^{'}$	Distance between two conductors
β_{A1B}	β_{A1C}, β_{A1N}, Proximity factors
θ_1 and θ_2	Phase angles
P_{SIL}	Power capacity,
V_{ll}	Line-to-line voltage
f	Operating frequency
Z_o	The impedance of the line
η_0	The impedance of free space
s	Surface plane over the cross-sectional areas of the conductor
$\widehat{\overline{E}}_{SIL}$	Surge impedance loading
μ_0	Permeability of free space
ε_0	The permittivity of free space.
d	Spacing between the two conductors
r	Geometric mean radius between conductor
G_{MR}	Geometric mean radius
G_{MRC}	The geometric mean radius of the capacitance
G_{MRL}	The geometric mean radius of the inductance
μ_r	Relative permeability
D	Distance
N_n	Total number of flames
c_1 and c_2	Constant value
$M_{hc(i,d)}$ and $M_{hc(j,d)}$	Moderation process for the offspring off F_{id} and F_{jd}
M_i	Number of i^{th} moths,
F_j	Indicates the number of *j*th flames
S	Twisting function
D_i	Distance between moth and flame
b	Constant value
R_o	AC resistance
N	Number of bundle conductors
n	Number of sub-conductors
R	The radius of the bundle conductor
r′	0.7788R
d_1	Number of columns of matrix *M*
n	Number of moths
d_2	Dimension of the moth matrix.
l	Function
P	Flight of the moth in search of space
T	Maximum number of iterations
t	A random number between [−1,1]

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MSS wrote the manuscript and provided data for all tables and figures, SR conducted the interviews, and MI and WK conducted all statistical analyses. All authors have reviewed and approved the manuscript.

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Declarations

Competing interest
The authors declare that they have no competing interests.

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