Optimal Power Flow With Emerged Technologies of Voltage Source Converter Stations in Meshed Power Systems

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ABSTRACT It is no doubt that the optimal power flow (OPF) has great importance in electric power systems. It aims at assigning the adequate operating levels in order to meet the required demands with the objective of minimizing combined economic and environmental concerns. Integration of emerged technologies of voltage source converter (VSC) stations in AC meshed power systems changes foremost their corresponding operation and control features. This paper presents an improved manta ray foraging optimizer (IMRFO) for solving the OPF in electric power systems with and without emerged technologies of VSC stations. The proposed IMRFO aims at minimizing the total fuel costs, the total environmental emissions, and the total electrical losses. The MRFO simulates the foraging behaviors of the manta rays. MRFO is improved to handle multi-objectives by incorporating an outward store for the non-dominated Pareto individuals. The form of the fitness function is adaptively varied by iteratively changing their weights. Furthermore, a technique for order preference by similarity to ideal solution (TOPSIS) is applied to extract a suitable operating point among the resulted Pareto set. Several applications of the proposed IMRFO are presented for conventional IEEE 30-bus system, as an AC meshed power system, and modified IEEE 30-bus with emerged VSC stations, as a hybrid AC/MDC meshed power system. Simulation results declare that the proposed algorithm has great effectiveness and robustness features compared to the others. Also, various well-distributed Pareto solutions are obtained based on the proposed algorithm with adequate techno-economic-environmental characteristics.

INDEX TERMS Optimal power flow, AC/MDC meshed power system, VSC stations, manta ray foraging optimizer.

I. INTRODUCTION

The optimal power flow (OPF) problem is considered one of the old and modern studies. As 60 years ago after studying the OPF problem by Carpentier [1], the OPF problem still receives considerable attention because of the challenging nature of the problem and its important role in power system planning and operation. OPF aims at assigning the most adequate values of generators output powers, generators voltages, transformers tap settings, outputs of VAr compensators, FACTS parameters and setting, and other parameter of newly connected devices to minimize the predefined objective functions while satisfying the operating system constraints. OPF searches for the combined economic and environmental operation of electrical power systems by finding the effective operating points of the power systems, which can overcome previous problems satisfactorily. This optimal condition is distinct with respect to objective functions reducing generation costs, increasing system loadability, reducing transmission losses, reducing environmental emissions, improving voltage performance, and improving system reliability and security while maintaining different equality and inequality constraints [2].

Although many modern optimization methods have been applied to the OPF problem, including general nonlinear optimization techniques, interior point methods,
and meta-heuristic optimization methods [3], challenges remain for power systems operators and planners due to the continuous changes in electrical power systems. Integrated multi-terminal high voltage direct current transmission MTHVDC grids with AC networks changes the operation and control strategies of conventional grids [4]. Classical operation methodologies of power systems such as the economic dispatch, state estimation and optimal power flow, etc. need to be modified and adapted to this new context of integrated MTHVDC grids. Due to the importance of the OPF in operational and grid expansion planning as well as economic studies, OPF necessitates structural and formation changes to accommodate large-scale hybrid AC/DC power systems [5].

Nowadays, the capability of decoupled control of active and reactive power of the VSC enables the control of injected/absorbed reactive power to/from connected AC grids accordingly voltage control of AC side. As well, the VSC technology can controls the active and reactive power at the same time at each terminal independent of the DC power transmission. Modular Multilevel Converters (MMC) enables parallel connection of VSCs, which allows to form a Multi terminal high voltage direct current grids [6]. These merits increase the expand opportunities of integrated AC/MDC systems. Zhangbei project is the first meshed HVDC grid worldwide is designed in China to integrate massive amounts of renewable power in the heavily populated area around Beijing, being capable of supplying around 9 million people with clean energy. The first phase of this project, 4 terminals in a ring connection are planned, with 2 more coming in the second phase with a 648 km length of DC-grid [7]. Different HVDC transmission projects are under planning and execution worldwide [8]. Champa-Kurukshetra ultra HVDC project in India is completed with a 1305 km transmission link which can transmit 4.5 GW of electricity. This project will enable transmitting electricity from power generating plants located across the state of Chhattisgarh to a GE-built rectifier station in Champa [9]. Nelson River HVDC transmission system in Manitoba is the backbone of power supply to southern Manitoba from the northern hydroelectric generating stations on the Nelson River. In that project, bipolar 1 has a rating of 1854 MW at ±463kV and transmits the power from the northern terminal at Radisson Station over approximately 900 km to the Dorsey terminal near Winnipeg. Bipole 2 has a rating of 2000 MW at ±500 kV and transmits the power to approximately 40 km [10]. The Egyptian/Saudi electrical interconnection project aims to exchange a capacity of 3000 MW between the two countries using HVDC bipolar transmission technology on 500 kV through one substation in Egypt and two substations in Medina & Tabuk in KSA with overhead lines on both and a submarine cable crossing the Gulf of Aqaba [11].

Different grid technologies of MDC grids are possible: shore-to-shore, radial, meshed, cluster with multi way interconnectors, and a combination of interconnectors, amongst others. Growing penetration of offshore wind and ocean energy includes wave, tidal current, tidal range, osmotic, and ocean thermal energies are expected to have higher power soon [12]. This requires increased reliance on power transmission with HVDC to reduce the investment costs [13]. Voltage regulation capability of the VSC enhances the performance of connected AC grid by generating or consuming reactive power. A predefined power flow along a certain transmission cable can be quickly achieved using the VSC based HVDC. Then, MDC grids can achieve the needed reliability, flexibility and controllability to meet the main grid code requirements such as the operating frequency range, active and reactive power control, support during voltage dips, and fault ride-through capabilities [14].

One of the adopted solutions of the increased consumer demand over the capability limits of the ageing power grids and increased penetration of non-dispatchable renewable sources is the optimal power flow (OPF). OPF aims at assigning the most adequate values of generators output powers, generators voltages, transformers tap settings, outputs of Var compensators, FACTS parameters and setting, and other parameter of newly connected devices to minimize the predefined objective functions while satisfying the operating system constraints. OPF searches for the combined economic and environmental operation of the electrical power systems by searching for the effective operating points of the power systems, which can overcome previous problems satisfactorily. This optimal condition is distinct with respect to objective functions reducing generation costs, increasing system loadability, reducing transmission losses, reducing environmental emissions, improving voltage performance, and improving system reliability and security while maintaining the different equality and inequality constraints [2], [15].

Integration of HVDC grids with AC networks changes the operation and control strategies of conventional grids. Classical operation methodologies of power systems such as the economic dispatch [16], state estimation [17] and optimal power flow [18], etc. need to be modified and adapted to this new context of integrated MDC grids. Due to the importance of the OPF in operational and grid expansion planning as well as economic studies, OPF necessitates structural and formation changes to accommodate large-scale hybrid AC/DC power systems. The OPF problem becomes even more non-linear, non-convex and complex problem when applied to integrated AC/MDC systems where it involves many optimization variables and system constraints [19]. Several literatures dealt with OPF either for separate AC networks [20], [21] or separate DC grids [22], [23]. Lately, mathematical formulation of OPF for AC/MDC networks got a great attention in literatures such as [5], [24]–[27]. The assessment of VSC-HVDC systems in a lot of these papers were limited to two-terminal configuration. While, the embedded of meshed DC grids into an AC grid increases the complexity of operation and control analysis of such systems [24], [28]. A few researchers ignore the modelling of some elements of AC/MDC to simplify the problem such as neglecting the DC power-flow equations [29]. Although, the VSC systems.
have been included into power flow calculation of a hybrid AC/MDC systems in many previous literatures as mentioned earlier, but fewer literatures consider VSC systems under an optimization context. Peñalbaa et al. [4] solved the hybrid network using the second-order cone programming (SOCP) technique. Cao et al. [30] applied the Primal-Dual Interior Point (PDIP) algorithm as well as modified Jacobian and Hessian matrices. Feng et al. [24] solved this problem using the Interior Point Optimizer (IPOPT) to seek solutions for the non-linear model built in General Algebraic Modelling System. Zhao et al. [26] introduced an extended OPF model to consider loss modelling of different converter operation modes. In those papers, the effect of transformer-tap settings and VAr compensation in AC grid were ignored whilst the utilized tools are based on the initial starting point with some simplifications that reduces the required accuracy.

Manta Ray Foraging Optimizer (MRFO) is a recent optimization algorithm that is designed for handling real-valued optimization applications. It has been firstly proposed by Zhao et al. [31], and it is inspired based on the intelligent and unique strategies of the manta rays in their foraging the plankton. In [31], its performance is assessed with itemized comparisons with other recent optimizers in optimizing several benchmark and real-world engineering design functions. In [32], a successful attempt of applying the MRFO has been carried out for extracting the electrical parameters of proton exchange membrane fuel cells.

In this paper, an improved manta ray foraging optimizer (IMRFO) to solving the OPF in electric power systems with and without emerged technologies of VSC stations. It is improved to handle multi-objectives by incorporating an outward store for the non-dominated Pareto individuals. The form of the fitness function is adaptively varied by iteratively changing their weights. Furthermore, a technique for order preference by similarity to ideal solution (TOPSIS) is applied to extract one of the Pareto set as a suitable operating point. Simulation results show the capability of the proposed technique has been checked with detailed assessment with other recent techniques in terms of its solution quality and robustness.

The rest sections of this work present the following: Section 2 shows the principle of the optimal operation of hybrid grids. Section 3 shows the optimal IMRFO based operation procedure. Section 4 reports the simulation results for three hybrid AC/MDC grids. Section 5 concludes the salient findings.

II. OPF IN CONVENTIONAL AC POWER SYSTEMS

A. OPF OBJECTIVES

The OPF problem mathematical model in conventional power systems is generally formulated as follows:

\[
\text{Min } OF = \{F_1(x,y), F_2(x,y), \ldots, F_M(x,y)\} \\
\text{Subject to: } g(x,y) = 0 \\
h(x,y) \leq 0
\]

where, OF is the vector of M objective functions; x and y are the decision and dependent variables, respectively. Therefore, the OPF is a nonlinear, multimodal, and multi-objective optimization problem for minimizing the fuel generation costs (FGC) and the total environmental emissions (TEE) of the generation stations. Besides that, the total transmission losses are considered. The FGC are modeled considering the multiple ripples that are accompanied to the valve point loading effect, as in practical power system. Thus, the fuel generation costs can be modeled as rectified sinusoids added to the polynomial quadratic costs and it is expressed as follows as:

\[
FGC = \sum_{i=1}^{N_g} a_i P_{gi}^2 + b_i P_{gi} + c_i + |e_i (\sin f_i (P_{gi,\text{min}} - P_{gi}))|
\]

where, \(P_{gi}\) is the MW active power output of each generator i; \(a_i, b_i, \) and \(c_i\) are the corresponding cost coefficients; \(P_{gi,\text{min}}\) is the lower limit of the active power output; \(e_i\), and \(f_i\) are the valve point loading coefficients.

In power systems, the fossil-fueled generators are the main source of the atmospheric pollutants where sulphur oxides (Sox), nitrogen oxides (NOx) and second carbon oxide (CO2) are emitted. The total environmental emissions (TEE) in ton/hr of these pollutants can be modeled as the summation of quadratic and exponential function in terms of the output power as follows:

\[
TEE = \sum_{i=1}^{N_g} (\gamma_i P_{gi}^2 + \beta_i P_{gi} + \alpha_i)/100 + \xi_i e^{\lambda_i P_{gi}}
\]

where, \(\gamma_i, \beta_i, \alpha_i, \xi_i, \) and \(\lambda_i\) are the emission coefficients of the atmospheric pollutants.
Also, the total transmission losses in AC power systems is another objective to be minimized as:

\[
\text{TTL}_{AC} = \sum_{i,j\in N_{AC,b}} G_{ij} \left( V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij} \right)
\]  

(6)

### B. OPF CONSTRAINTS IN AC POWER SYSTEMS

For the OPF problem in AC power systems, the decision variables are the power outputs of the generators \((P_{G1}, P_{G2}, \ldots, P_{G_{Ng}})\), its voltages \((V_{G1}, V_{G2}, \ldots, V_{G_{Ng}})\), VAR injection of the reactive power sources \((Q_{C1}, Q_{C2}, \ldots, Q_{C_{Ng}})\), and transformer tap settings \((\text{Tap}_{1p}, \text{Tap}_{2p}, \ldots, \text{Tap}_{Np})\) where, \(Ng, Nq, \text{and} Nt\) are the number of generators, the number of the VAR sources, and the number of tap changing transformers, respectively. On contrary, the dependent variables are load voltage magnitudes \((VL_{1}, VL_{2}, \ldots, VL_{NPQ})\), VAR outputs of the generators \((Q_{G1}, Q_{G2}, \ldots, Q_{G_{Ng}})\), and transmission line power flow \((SF_{1}, SF_{2}, \ldots, SF_{NF})\) where, \(NPQ\) and \(NF\) are the number of load buses and lines, respectively.

Firstly, the equality constraints of the load flow balance equations must be maintained as follows:

\[
Q_{C_i} - QL_i + Q_{V_i} - \sum_{j=1}^{N_b} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0, \quad i = 1, 2, \ldots, NPQ
\]  

(7)

\[
P_{G_i} - PL_i - \sum_{j=1}^{N_b} V_j(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}) = 0, \quad i = 1, 2, \ldots, N_b - \text{slack}
\]  

(8)

where, \(N_b\) is the number of buses; \(PL\) and \(QL\) are the active and reactive power demand, respectively; \(G_{ij}\) and \(B_{ij}\) are mutual conductance and susceptance between bus \(i\) and \(j\), respectively.

Secondly, the operational variables have to be satisfied within the corresponding constraints as follows [33], [34]:

\[
P_{G_i}^{\text{min}} \leq P_{G_i} \leq P_{G_i}^{\text{max}}, \quad i = 1, 2, \ldots, Ng
\]  

(9)

\[
V_{G_i}^{\text{min}} \leq V_{G_i} \leq V_{G_i}^{\text{max}}, \quad i = 1, 2, \ldots, Ng
\]  

(10)

\[
Q_{C_i}^{\text{min}} \leq Q_{C_i} \leq Q_{C_i}^{\text{max}}, \quad i = 1, 2, \ldots, Nq
\]  

(11)

\[
\text{Tap}_{k}^{\text{min}} \leq \text{Tap}_{k} \leq \text{Tap}_{k}^{\text{max}}, \quad k = 1, 2, \ldots, Nt
\]  

(12)

\[
Q_{C_q}^{\text{max}} \leq Q_{C_q} \leq Q_{C_q}^{\text{max}}, \quad q = 1, 2, \ldots, Nq
\]  

(13)

\[
V_{L_i}^{\text{min}} \leq V_{L_i} \leq V_{L_i}^{\text{max}}, \quad i = 1, 2, \ldots, NPQ
\]  

(14)

\[
|SF| \leq SF^{\text{max}}, \quad L = 1, 2, \ldots, NF
\]  

(15)

where the superscripts “min” and “max” indicate the minimum and maximum limits of the related variable.

### III. OPTIMAL POWER FLOW IN HYBRID AC/MDC POWER SYSTEMS

#### A. VSCS MODEL IN AC/MDC POWER SYSTEM

The equivalent circuit of a VSC station is illustrated in Fig. 1. As shown, the VSC is modeled as a controlled voltage source \((V_{c_i})\) that is connected to the AC system buses via its phase reactor and transformer which have equivalent impedance \((R_{ik} + jX_{ik})\). \(V_{sk}\) refers to the bus voltage at AC system. Thus, the injection of MVA \((S_{ki})\) into VSCs from the AC system is given by:

\[
S_{ki} = P_{ki} + jQ_{ki} = V_{sk}I_{ki}^2, \quad i = 1, \ldots, N_{VSC}, \quad k = 1, \ldots, N_{ac}
\]  

(16)

where, \(P\) and \(Q\) are the injected active and reactive power, respectively. \(N_{VSC}\) and \(N_{ac}\) are the number of VSCs and the connected AC buses, respectively. \(I_{ki}\) is the corresponding injected current which can be calculated as:

\[
I_{ki} = \frac{V_{sk} - V_{ci}}{R_{ik} + jX_{ik}}
\]  

(17)

From (1) and (2); the active and reactive power at each converter side \((P_{ci} + jQ_{ci})\) and the corresponding AC connected side \((P_{sk} + jQ_{sk})\) can be represented as:

\[
P_{ci} = -V_{ci}^2G_{ik} + V_{sk}V_{ci}[G_{ik}\cos(\theta_{ki}) + B_{ik}\sin(\theta_{ki})]
\]  

(18)

\[
Q_{ci} = -V_{ci}^2B_{ik} - V_{sk}V_{ci}[G_{ik}\sin(\theta_{ki}) + B_{ik}\cos(\theta_{ki})]
\]  

(19)

\[
P_{sk} = V_{sk}G_{ik} - V_{sk}V_{ci}[G_{ik}\cos(\theta_{ki}) + B_{ik}\sin(\theta_{ki})]
\]  

(20)

\[
Q_{sk} = -V_{sk}^2B_{ik} - V_{sk}V_{ci}[G_{ik}\sin(\theta_{ki}) - B_{ik}\cos(\theta_{ki})]
\]  

(21)

where, \(G\) and \(B\) are the conductance and susceptance of the DC line, respectively; \(\theta_{ki}\) is the phase angle difference between the VSC and the connected AC bus.

#### B. OPF FORMULATION IN HYBRID AC/MDC POWER SYSTEMS

In hybrid AC/MDC power systems, the OPF problem targets the similar multi-objective functions without jeopardizing the regarded constraints to both AC and MDC power transmission systems. It is handled as a multi-objective optimization problem for minimize the FGC, TEE and TLL. The TLL in hybrid AC/MDC power systems is formulated in Eq. (22) which are three parts incorporating the power losses in the AC power systems of Eq. (6), VSCs stations of Eq. (23), and MDC power systems of Eq. (24).

\[
\text{TLL} = \text{TLL}_{AC} + \text{TLL}_{DC} + \text{TLL}_{VSC}
\]  

(22)

\[
\text{TLL}_{DC} = \sum_{i,j\in N_{DC,b}} R_{ij}I_{ij}^2
\]  

(23)

\[
\text{TLL}_{VSC} = \sum_{i=1}^{N_{VSC}} \phi_{1,i}I_{1,ci}^2 + \phi_{2,i}I_{2,ci} + \phi_{3,i}
\]  

(24)

![FIGURE 1. Equivalent circuit of the VSC station [35].](image-url)
where \( \varphi_1 \), \( \varphi_2 \), and \( \varphi_3 \) are the loss coefficients related to each VSC. As shown, the VSC losses are generalized in a quadratic formula with the injected VSC current (\( I_c \)) [36]:

1) DECISION AND DEPENDENT VARIABLES OF THE OPF IN HYBRID AC/MDC POWER SYSTEMS

In AC/MDC power systems, the decision variables can be classified into two categories. Firstly, the conventional controls in the AC grids which are previously mentioned in Section II.B. Secondly, the advanced control of the VSC type devices where there are four classes of the control strategies [36]:

- \( V_{dc} - Q_c \) constant control: This mode provides constant voltage at DC side with constant reactive power at AC side.
- \( V_{dc} - V_c \) constant control: This mode provides constant voltage at DC and AC sides.
- \( P_{dc} - Q_c \) constant control: This mode provides constant active power transferred in the DC line with constant reactive power at AC side.
- \( P_{dc} - V_c \) constant control: This mode provides constant active power transferred in the DC line with constant AC voltage.

Similarly, the dependent variables can be classified related to AC side and MDC side. For the AC side, the dependent variables are the same as mentioned in Section II.B. For the MDC side, the dependent variables are the DC bus voltages and the power flow through the DC lines.

2) CONSTRAINTS OF THE OPF IN HYBRID AC/MDC POWER SYSTEMS

In addition to Eqs. (7) and (8), the DC system power flow must be considered as equality constraints as:

\[
P_{dc,i} = V_{dc,i} \sum_{j=1}^{N_{VSC}} G_{dc,ij}(V_{dc,i} - V_{dc,j})
\]

where, \( P_{dc,i} \) is the injected power at bus \( i \). Moreover, the operational variables for the DC systems, in addition to Eqs. (9) and (15), must be satisfied within the corresponding constraints as follows:

\[
P_{q_i}^{\min} \leq P_{q_i} \leq P_{q_i}^{\max}, \quad i = 1, 2, \ldots, N_{VSC}
\]

\[
Q_{s_i}^{\min} \leq Q_{s_i} \leq Q_{s_i}^{\max}, \quad i = 1, 2, \ldots, N_{VSC}
\]

\[
V_{c_i}^{\min} \leq V_{c_i} \leq V_{c_i}^{\max}, \quad i = 1, 2, \ldots, N_{VSC}
\]

\[
V_{dc,i}^{\min} \leq V_{dc,i} \leq V_{dc,i}^{\max}, \quad i = 1, 2, \ldots, N_{DC}
\]

\[
d_i^{\min}/2 \leq \sqrt{(P_{i} - P_0)^2 + (Q_{i} - Q_0)^2} \leq d_i^{\max}/2, \quad i = 1, 2, \ldots, N_{DC}
\]

where, \( (P_0, Q_0) \) is the circles centre related to the VSC PQ-capability curve with diameter of \( d \). \"min\" and \"max\" superscripts indicate the minimum and maximum limits of their related variable. Eq. (30) represents the PQ capability curve of each VSC that must be maintained.

IV. PROPOSED IMRFO FOR OPF IN HYBRID AC/MDC POWER TRANSMISSION SYSTEMS

A. MRFO ALGORITHM

Manta Ray Foraging Optimizer (MRFO) is a recent algorithm [31], which is inspired from the intelligent and unique strategies of the marine manta rays in their foraging. It mimics three distinct individual foraging organizations of the manta rays. The first one is the chain foraging where some of the manta rays forage in a small cooperative way since they are organized in an orderly line to funnel the greatest quantity of plankton into their gills. The second is the cyclone foraging where many manta rays are linked up in a spiral shape to create a centralized spiraling peak. This forces the water up towards the surface and withdraws the plankton inside their mouths. The latter strategy is the somersault foraging. The manta rays search for the planktons’ position and swim towards them. The manta rays indicate the individuals in the search space that seek for the minimum fitness which is the planktons’ position.

The MRFO begins with initialization stage after identifying the population number \((N_P)\) of the manta rays and the maximum number of iterations \((M)\). Thus, the \( D \)-dimensional individuals \((Y)\) can be initially created as:

\[
Y_{m,n} = Y_{n}^{\min} + r.(Y_{n}^{\max} - Y_{n}^{\min}) \quad \forall m \in N_P & n \in D
\]

where, \( Y_{m,n} \) is the individual of each decision variable \((n)\) of each manta ray \((m)\); \( r \) indicates a random uniformly distributed number within range \([0, 1]\). The superscripts ‘min’ and ‘max’ refer to the bounds of the decision variables.

In the first strategy, which is the chain foraging, every individual is updated as follows:

\[
Y_{m,n}^* = \begin{cases} Y_{m,n} + (Y_{B,n} - Y_{m,n})(r + \sigma) & \text{if } m = 1 \\ Y_{m,n} + r(Y_{m-1,n} - Y_{m,n}) + \sigma(Y_{B,n} - Y_{m,n}) & \text{otherwise} \end{cases}
\]

where, \( Y^* \) and \( Y \) are the new and old position of the manta ray at the following iteration. \( Y_B \) is the best position of the plankton food that has the highest concentration or fitness. \( \sigma \) is a weight coefficient that is varied each iteration as:

\[
\sigma = 2.r.\sqrt{\log(r)}
\]

As shown, the new position of the manta ray is generated based on the best individual and the preceding one.

In the second strategy, which is the cyclone foraging, the iterations are equally divided into two parts. The first half focus on improving the exploration of the MRFO. Consequently, each individual is updated, in the first half of iterations, as follows:

\[
Y_{m,n}^* = \begin{cases} Y_{R,n} + (Y_{R,n} - Y_{m,n})(r + \beta) & \text{if } m = 1 \\ Y_{R,n} + r(Y_{m-1,n} - Y_{m,n}) + \beta(Y_{R,n} - Y_{m,n}) & \text{otherwise} \end{cases}
\]

where, \( Y_R \) is a created individual in a random way within the considered bounds as follow:

\[
Y_{R,n} = Y_{n}^{\min} + r(Y_{n}^{\max} - Y_{n}^{\min}) \quad \forall n \in D
\]
where, $\beta$ is an adaptive weight coefficient which is varied by the following equation:

$$\beta = 2 e^{r_1 \left(\frac{M_{It} - It + 1}{M_{It}}\right)} \cdot \sin(2\pi r_1) \quad (36)$$

where, $It$ is the current iteration and $r_1$ a random uniformly distributed number within range $[0, 1]$. The second half of the iterations focus on improving the exploitation of the MRFO. Regarding to that, each individual is updated as follows:

$$Y^*_{m,n} = \begin{cases} Y_{B,n} + (Y_{B,n} - Y_{m,n})(r + \beta) & \text{if } m = 1 \\ Y_{B,n} + r(Y_{m-1,n} - Y_{m,n}) + \beta(Y_{B,n} - Y_{m,n}) & \forall m = 2:P_N \end{cases} \quad (37)$$

In the third strategy, which is the somersault foraging, the position of each manta ray is updated around the best extracted position as follows:

$$Y^*_{m,n} = Y_{m,n} + S(r_2 Y_{B,n} - r_3 Y_{m,n}) \quad \forall m \in P_N \& n \in D \quad (38)$$

where $S$ is the somersault coefficient ($S = 2$) that controls the somersault domain of the manta rays and, $r_2$ and $r_3$ are random numbers within range $[0, 1]$.

### B. PROPOSED IMRFO FOR MULTI-OBJECTIVE OPF IN AC/MDC POWER SYSTEMS

In the MRFO, the new positions are generated based on the chain foraging strategy of Eq. (32), the cyclone foraging strategy of Eqs. (35 and 37), or the somersault foraging of Eq. (38). The MRFO is fundamentally sensitive to the best position of the plankton food. Therefore, the proposed IMRFO creates an adequate adaptation to the fitness function based on dynamic variation of the shape of the fitness in each iteration using dynamic weighting factor. Therefore, the objective function can be formulated as follows:

$$O = \sum_{i=1}^{M} \omega_i \frac{F_i}{F_{i,\text{max}}} \quad (39)$$

$$\omega_1 = \begin{cases} 1 & \text{if } It < M_{It}/3 \\ 1 - \frac{It}{M_{It}} & \text{else} \end{cases} \quad (40)$$

$$\omega_i = 1 - \omega_1 \cdot i = 2,3,\ldots M \quad (41)$$

where, $\omega_i$ is the weight factor related to each objective ($i$). Based on (40–41), the considered fitness function is dynamically changed in a single simulation operation which results in a better exploitation of the MRFO.
For creating Pareto individuals, the proposed IMRFO is evolved incorporating an external repository to store the non-dominated solutions and so Pareto dominance is utilized to update this repository. In each iteration, the updated individuals are compared to existed Pareto solutions in the repository to exclude the dominated solutions. Consequently, it is updated and if it is fulfilled, a removing strategy is applied by deleting some of the Pareto candidates in the most crowded areas via roulette wheel selection [37].

For handling the OPF problem, the balance equations in AC power system of Eqs. (7 and 8) and in MDC power system of Eq. (25) are guaranteed inherently via sequential AC/DC power flow method [38]. For the operational limits of the decision variables, they are started satisfying their bounds and if any of them is violated during the iterations, it is randomly re-generated within the following appropriate range. For the operational limits of the dependent variables in AC/MDC power transmission systems, they are augmented in the considered objective functions using quadratic penalty terms. On this basis, the solution, which causes any violation in the constraints of the dependent variables, couldn’t be selected in the next iteration. Thus, each new position is compared to its equivalent in preceding iteration in terms of the attained objectives. The new position substitutes the prior one.
if the new position doesn’t be dominated by it. This method preserves the diversity and ameliorates the solution quality. Therefore, a set of pareto optimal solutions is generated and stored. Fig. 2 depicts the flowchart of the proposed IMRFO for optimal operation of for OPF in hybrid AC/MDC power systems.

To extract the compromise operating point, a technique for order preference by similarity to ideal solution (TOPSIS) is implemented to select a compromise solution to achieve the operator requirements. TOPSIS is a technique to choose the optimal alternative (A) from multi alternatives with multi criteria (X) [39]. Table 1 shows the initial table for proposed TOPSIS method. In table, the alternatives are the hundred optimal solutions that are stored in the archive while each of criteria is represented by one of the OFs as follow:

\[
X_{ij} = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{15} \\ x_{21} & x_{22} & \ldots & x_{21} \\ \vdots & \vdots & \ddots & \vdots \\ x_{1001} & x_{1002} & \ldots & x_{1005} \end{bmatrix} \tag{42}
\]

where, \(X_{ij}\) is the alternative for each Pareto solution (i) and regarded criteria (j). As each of criteria has a different measuring unit, each alternative is represented by a set of normalized parameter value as follow:

\[
da_{ij} = w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{100} x_{ij}^2}} \tag{43}
\]

where, \(w\) is the weighting factor of each OF; \(i\) is the number of the current alternative and \(j\) is the number of the current criteria; \(A\) is the normalized decision matrix. If the weighting factors are equal, the coordinates \(a^*_j\) of the positive ideal
solution $A^*=(a_1^*, a_2^*, \ldots, a_5^*)$ is selected according to the type of the OF (maximization or minimization) using the formula:

$$a_j^* = \begin{cases} 
\max a_{ij} & j = 1, \ldots, 5 \text{ for maximization OF} \\
\min a_{ij} & j = 1, \ldots, 5 \text{ for minimization OF} 
\end{cases} \quad (45)$$

If some of the alternative $A_i$ is equal to $A^*$ so $A_i$ is the optimal solution. If it is not TOPSIS continues. Selecting the coordinates $a_j^\Diamond$ of the negative ideal solution $A^\Diamond=(a_1^\Diamond, a_2^\Diamond, \ldots, a_5^\Diamond)$ according to the type of the problem (maximization or minimization) using the formula:

$$a_j^\Diamond = \begin{cases} 
\min a_{ij} & j = 1, \ldots, 5 \text{ for maximization OF} \\
\max a_{ij} & j = 1, \ldots, 5 \text{ for minimization OF} 
\end{cases} \quad (46)$$

Then, the Euclidean distance between each normalized decision vector and the ideal solutions is calculated as follows:

$$d_i^* = d(A_i, A^*) = \sqrt{\sum_{j=1}^{5} (a_{ij} - a_j^*)^2} \quad (47)$$

$$d_i^\Diamond = d(A_i, A^\Diamond) = \sqrt{\sum_{j=1}^{5} (a_{ij} - a_j^\Diamond)^2} \quad (48)$$

where, $d_i^*$ and $d_i^\Diamond$ are the deviational values from and the positive and negative ideal solution, respectively.

After that, the relative closeness parameter ($D_i$) for each Pareto solution ($i$) is estimated as:

$$D_i = \frac{d_i^\Diamond}{d_i^* + d_i^\Diamond} \quad (49)$$

V. SIMULATION RESULTS

The proposed IMRFO is applied on two power systems. The first system is the conventional IEEE 30-bus system, as an AC meshed power system, while the second one is the modified IEEE 30-bus with emerged VSC stations, as a hybrid AC/MDC meshed power system.

A. SIMULATION RESULTS OF THE IEEE 30-BUS TEST SYSTEM

This system originally consists of 30 buses, 41 lines, 6 generators, 4 on-load tap changing transformers and 9 shunt capacitive sources as depicted in Fig. 3.

All data of transmission lines, system buses, and the limits of reactive power generations are taken from [40]. The maximum and minimum limits of the load buses voltages and tap changing transformer are 1.1 and 0.9 p.u., respectively. The maximum and minimum values for the generator voltage are 1.1 and 0.95 p.u., respectively. The VAR injections of the capacitive sources are limited by 5 MVA [41]. The proposed IMRFO is applied with number of solutions of 25 and maximum number of iterations of 300.

Six cases are considered for this system including single and multi-objectives as;
TABLE 5. Simulation results for Case 1 of the AC/MDC system.

| Case  | Objective Function | Vg 1 | Vg 2 | Vg 3 | Vg 4 | Vg 5 | Vg 6 | Vg 7 | Vg 8 | Vg 9 | Vg 10 | Vg 11 | Vg 12 | Vg 13 | Vg 14 | Vg 15 | Vg 16 | Vg 17 | Vg 18 | Vg 19 | Vg 20 | Vg 21 | Vg 22 | Vg 23 | Vg 24 | Vg 25 | Vg 26 | Vg 27 |
|-------|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1     | Minimization of the FGC | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 | 0.08 | 0.05 |
| 2     | Minimization of the TLL | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| 3     | Minimization of the TEE | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 4     | Minimization of the FGC and TEE bi-objective functions | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 5     | Minimization of the FGC, the TLL bi-objective functions | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 6     | Minimization of the sinusoidal model of FGC, the TEE and the TLL tri-objective functions | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

1) RESULTS OF SINGLE OBJECTIVE OPF

Tables 2 tabulates the optimal values of the decision variables and the related results of the algorithm for a single objective of FGC, TLL and TEE minimization for Cases 1-3 respectively.

Firstly, the FGC objective model of Eq. (4) is considered which as Case 1A and the proposed IMRFO is applied. From Table 2, the FGC objective is reduced from 975.64 to 830.6795 $/h with a reduction of 14.86% compared with the initial case. Secondly, the quadratic model of the FGC objective is considered in Case 1B neglecting the valve loading point. In this case, the proposed algorithm can minimize the FGC to 798.99 $/h. Table 3 provides comparisons for minimizing the FGC (Case 1A) for the IEEE 30-bus system considering several reported algorithms in the literature. As shown, the proposed algorithm has great outperformance compared with artificial bee colony (ABC) [42], teaching-learning algorithm [43], differential evolution (DE) [41], symbiotic organisms search (SOS) [44], moth swarm algorithm (MSA) [45], developed grey wolf algorithm (DGWA) [46], improved moth flame algorithm (IMFA) [47], grasshopper optimizer (GO) [48], adaptive grasshopper optimizer (AGO) [48].

In the second case, the TLL objective is reduced from 5.596 to 2.846 MW with a reduction of 49.14% compared with the initial case. In the third case, the TEE objective is reduced from 0.2390963 to 0.204754 ton/h. Table 4 provides comparisons for minimizing the TEE (Case 3) for the
IEEE 30-bus system considering several reported algorithms in the literature. As shown, the proposed algorithm has great outperformance compared to artificial bee colony (ABC) [42], krill herd algorithm (KHA) [49], stud krill herd algorithm (SKHA) [49], adaptive real coded biogeography-based optimization (ARBO) [50], teaching learning-based optimization (MTLBO) [51], modified teaching learning-based optimization (MTLBO) [51], grasshopper optimizer (GO) [48], adaptive grasshopper optimizer (AGO) [48].

Figs. 4 a, b, and c display the convergence characteristics of the proposed algorithm for the Cases 1-3 that describe the high capability of the proposed IMRFO in finding the minimum considered objective. The progress through the iterations illustrates the ability to evolutionarily search for the optimal solution.

### RESULTS OF MULTI-OBJECTIVE OPF OPTIMIZATION

In this subsection, a multi objective optimization of OPF is performed using the proposed IMRFO for bi-objective (Cases 4 and 5) and tri-objective functions (Case 6). Table 2 shows the values of the decision variables and the corresponding results for Cases 4-6. Figs. 5-7 display, respectively, the Pareto set solutions for OPF with bi-objective functions FGC and TEE minimization (Case 4), bi-objective functions FGC and TLL minimization (Case 5) and tri-objective functions FGC, TEE and TLL minimization (Case 6). The obtained result in these figures clarify that the capability of the proposed IMRFO to extract best compromise of the objective functions. In comparison with Cases 1-3, the best compromise FGC, TEE and TLL are close to the single objective achieved values. Fig. 8 shows the voltage profile of...
the AC power system for the initial case, single objective OPF cases, and multi-objective cases using the proposed IMRFO. As shown, all the buses voltages are within the allowable limits. In addition, high improvement is illustrated since the minimum voltage at the initial case of 0.9012 pu. at bus 30 becomes 1.0712 pu. for Case 1A, 1.07056 pu. for Case 1B, 1.06912 pu. for Case 2, 1.02923 pu. for Case 3, 1.0501 pu. for Case 4, 1.0303 pu. for Case 5, and 1.0272 pu. for Case 6.

B. SIMULATION RESULTS OF THE MODIFIED IEEE 30-BUS WITH EMERGED VSC STATIONS

The IEEE 30-bus is modified with emerged VSC stations, as a hybrid ac/mdc meshed power system. The modified system has two MDC grids [28] as depicted in Fig. 9. The control mode of the VSCs in the first MDC grid of the modified 30-bus system are; VSC 1 is $V_{dc}-Q_c$ control mode, VSCs 2 and 3 are in $P_{dc}-V_{c}$ constant control. In the second MDC grid, VSC 4 is $V_{dc}-Q_c$ control mode whilst VSCs 5 and 6 are in $P_{dc}-V_{c}$ constant control. The converting power for the VSCs are considered of 100 MVA where the maximum and minimum voltages of the VSCs and DC buses are 1.1 and 0.9 pu., respectively. The VAR injections of the capacitive sources are limited by 5 MVA. To evaluate the effectiveness of the proposed IMRFO, various recent algorithms are employed for the same target such as GWO [52]; PSO; SSA [38]; MVO [53]; dragonfly algorithm (DA) [54]; crow search optimization algorithm (CSO) [55], [56]; Bat algorithm (BAT) [57], [58]; Marine predator optimizer (MPO) [59] are employed to solve the considered problem. The competitive algorithms have the same number of solutions (50) while the IMRFO has half these number as it provides two function evaluation in the iteration. They are 15 independent runs are considered.

1) RESULTS OF SINGLE OBJECTIVE OPF

In this subsection, the proposed IMRFO and several competitive techniques are applied for optimal operation of hybrid AC/MDC system with a single objective of FGC, TLL and
TEE minimization for Cases 1-3, respectively. The optimal values of the decision variables and the regarded results are given in Tables 5-7, respectively. As shown, from the obtained results the FGC, given in Table 5, is reduced from 975.64 to 840.3 $/h with a reduction of 13.87% compared with the initial case using the IMRFO, while the reduction percentage using the GWO, PSO, SSA, MVO, DA, CSO, BAT and MPO are 12.42%, 13.26%, 9.24%, 12.96%, 12.01%, 12.99%, 12.56% and 13.75%, respectively, compared with the initial case. Fig. 10 displays the convergence rates of the compared algorithms for handling Case 1. It declares the great characteristics of the proposed IMRFO in developing the best solution compared to the others.

Also, the proposed technique succeeds in achieving the minimum TLL which is the primary objective function in Case 2. It is superior to other techniques as listed in Table 6. The total power losses are reduced from 11.924 MW to 8.57 MW with a reduction of 28.12% using the proposed MRFO while the reduction achieved by other competitive techniques are 9.02%, 23.87%, -7.36%, 24.48%, 17.78%, 19.68%, 20.79% and 26.62% using the GWO, PSO, SSA, MVO, DA, CSO, BAT and MPO, respectively. For handling Case 2, Fig. 11 displays the convergence rates of the
compared algorithms which states the great characteristics of the proposed IMRFO in developing the best solution compared to the others.

Similarly, the proposed technique succeeds in achieving the minimum TEE, Case 3, which is reduced from 0.242 to 0.203 ton/hr by a reduction of 16.11%, while other techniques...
can’t achieve this value as given in Table 7. In this table, another achievement is noticed in the technical point of view with power losses reduction by 24.3 %. Fig. 12 shows the convergence rates of the proposed algorithm compared to the other recent algorithms for Case 3. From this figure, the high capability of the IMRFO in finding the minimum considered objective is clarified compared to the others. The progress through the iterations illustrates the ability to evolutionarily search for the optimal solution.

These results illustrate that the proposed algorithm outperforms the others to optimally operate the hybrid AC/MDC power system for single objective cases with significant achievement for each separate objective function.

Also, the voltage profile of the Ac grids is greatly improved with the proposed technique as shown in Fig. 13.

2) RESULTS OF MULTI-OBJECTIVES OPF FOR THE AC/MDC SYSTEM
The complexity of OPF of the hybrid AC/MDC systems as well as the variety of the decision variables makes it difficult for most of the competitive techniques to achieve the optimal solution especially for multi-objective cases. Therefore, a multi-objective OPF optimization in hybrid AC/MDC systems are handled via the proposed IMRFO for bi-objective and tri-objective functions.

Table 8 shows the decision variables' settings and the corresponding results for the three multi-objective cases. Figs. 14-16 depict, respectively, the Pareto set solutions for optimal operation of AC/MDC with bi-objective functions FGC and TEE minimization (Case 4), bi-objective functions FGC and TLL minimization (Case 5) and tri-objective functions FGC, TEE and TLL minimization (Case 6). The obtained results in these figures clarify that the proposed IMRFO gives best compromise of the objective functions. In comparison with Cases 1-3, the best compromise FGC, TEE and TLL are close to the single objective achieved values. In Case 4, the available compromise solutions, between FGC minimization and TEE minimization, are obtained starting from FGC about 840 ($/hr) and TEE about 0.44 (ton/hr) to FGC about 10432 ($/hr) and TEE about 0.209 (ton/hr) passing through the optimal solution FGC of 870.9 ($/hr) and TEE of 0.295 (ton/hr) as shown in Fig. 14.

In Case 5, several compromise solutions are obtained between FGC minimization and TLL minimization starting from FGC about 848 ($/hr) and TLL about 14.3 (MW) to FGC about 994 ($/hr) and TLL about 9.5 (MW) passing through the optimal solution FGC of 873.8 ($/hr) and TLL of 11.73 (MW) as shown in Fig. 15. Similarly, in Fig. 16 well-distributed solutions are obtained including the optimal compromise solution of FGC of 882.6 ($/hr), TEE of 0.2649 (ton/hr) and TLL of 10.85 (MW). Fig. 17 shows the voltage profile of AC grid for the initial case, and multi-objective cases using the proposed IMRFO, where all buses voltages are within the allowable limits.
VI. CONCLUSION

In this paper, an improved version of manta ray foraging algorithm (IMRFO) has been presented for the optimal operation of AC meshed and hybrid AC/MDC meshed power systems with emerged VSC stations. The multi-objective formulation of optimal operation of the hybrid grid aims at minimizing the total fuel costs, the total atmospheric environmental emissions related to the generation stations and minimizing the total power losses in the VSCs stations, AC, and MDC power systems. The proposed IMRFO mimics three distinct individual foraging organizations of the manta rays. It is upgraded integrating an external Pareto repository to conserve the non-dominated manta ray’s positions. Furthermore, a TOP-SIS is utilized to select the final candidate operating point of the hybrid AC/MDC power grid. The applicability of the proposed IMRFO has been verified through conventional IEEE 30-bus system, as an AC meshed power system, and modified IEEE 30-bus with emerged VSC stations, as a hybrid AC/MDC meshed power system. Assessment of the proposed solution methodology is employed with significant improvements compared with several recent algorithms. Significant technical improvements are achieved with reducing the power losses as well as the environmental emissions. The simulation results demonstrate the effectiveness and preponderance of the proposed algorithm with great stability indices over the others for single and multi-objective cases. Nevertheless, the proposed method has well-diversified Pareto solutions while a compromise operating point is effectively produced to satisfy the operator requirements.

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