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Application of monarch butterfly optimization algorithm for solving optimal power flow

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ABSTRACT

This paper proposes a highly flexible, robust, and efficient constraint-handling approach for the solution of the optimal power flow (OPF) problem and this solution lies in the ability to solve the power system problem and avoid the mathematical traps. Centralized control of the power system has become inevitable, in the interest of secure, reliable, and economic operation of the system. In this work, OPF is solved by considering the three distinct objectives, generation cost minimization, power loss minimization, and enhancement of voltage stability index. These three objectives are solved separately by considering the evolutionary-based monarch butterfly optimization (MBO) algorithm. This MBO algorithm is validated on the IEEE 30 bus network and the obtained results are compared with differential evolution, particle swarm optimization, genetic algorithm, and Jaya algorithm. The obtained results reveal that among the various optimization algorithms considered in this work, the MBO evolves as the best algorithm for all three case studies.

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1. INTRODUCTION

Electrical power systems are highly complex and they are constantly growing in size to meet the ever-increasing demands of the customers. An efficient economic operation and planning of power systems have always played a very important role in the power industry [1], [2]. Optimal power flow (OPF) is an efficient scheduling method of power network that has the goal of reducing the total production cost of participating generator units while satisfying all the constraints for safe and reliable power to the consumers. OPF is required for a stable, reliable, and secure power system, which basically involves optimizing an objective function [3], [4]. The goal of OPF is to find the values of control variables that satisfy the economic and technical factors of an entire power system. OPF has several applications as it has a major impact on the transmission system and it is considered a basic tool for real-time pricing in the electricity markets. Generally, there are 3 types of problems in the power network, i.e., economic dispatch (ED), load flow, and OPF [5]-[6]. The solution of OPF starts by solving the load flow equation. The tools of power systems including the various studies are used in energy management systems (EMS), to manage the transmission network safely and economically. The OPF program developed should be highly flexible and very versatile for use in the operation of the power system.

There are several desirable features when looking for an OPF program from a planning standpoint. Programs that are highly flexible and very versatile are the most useful. Minimization of loss received very little attention. Solution methods for load shedding have also been proposed. Contingency-security constraints have been integrated into OPF formulation. It was concluded that there is remarkable progress in network modeling, optimization models, and numerical techniques. The OPF algorithms that were commercially available satisfied the full set of non-linear models and set of constraints on variables. There are several methodologies developed in the literature for the solution of this OPF problem, including the conventional/traditional approaches such as Newton's method [7], gradient method [8], linear programming [9], non-linear programming [10], and interior-point [11] method. The evolutionary-based algorithms (artificial intelligence (AI) methods) like genetic algorithm (GA) [12], particle swarm optimization (PSO) [13], enhanced GA (EGA) [14], differential evolution (DE) [15], bacterial foraging algorithm [16], teaching learning-based optimization (TLBO) [17], Jaya algorithm [18], gravitational search algorithm (GSA) [19], and glowworm swarm optimization (GSO) algorithm [20].

The solution of any OPF is not sensitive to the selected initial point for easy decision-making for the operator. The complexity of the OPF has to be minimized and it should be user-friendly. Like conventional algorithms, evolutionary-based algorithms don't guarantee the absolute optimization solution, however, they provide a rational solution closer to the global optimal solution. Therefore, researchers are in search of finding new evolutionary algorithms for solving practical problems. These algorithms find their application in various power engineering problems such as power system planning, operation, and analysis. To name a few are generator expansion planning, optimal network feeder routing, capacitor placement, reactive power optimization, economic load dispatch, power loss minimization, contingency ranking for voltage stability, load management including demand response and load shedding, control of flexible AC transmission systems, power flow, OPFs, optimal allocation of FACTS, and load frequency control. In this work, the monarch butterfly optimization (MBO) algorithm is used for the solution of the OPF problem.

2. OPF: PROBLEM FORMULATION

OPF problem is solved to obtain the system control variables when the power system economy and security are of concern. An OPF is one of the components of the EMS. OPF is considered a complex and non-linear optimization problem, and its main aim is to get the best solution by determining the optimized control variables. It has been identified that the quality and the speed at which the OPF solution is achieved are greatly influenced by the load flow technique used for the solution of equality constraints and the optimization technique used for modifying the control variables.

In general, the OPF objectives are classified into single and multiple objectives. Here, OPF is solved by selecting 3 distinct objectives and they are formulated next. The main focus is to solve OPF by identifying the suitable control variables to achieve an optimum solution by satisfying the system control and operation constraints [21]. Here, the generator's active powers (P_{Gi}) and voltage magnitudes (V_{Gi}), settings of tap changing transformers (T_i) and shunt capacitor banks ($Q_{CB,i}$) are selected as control variables, and they are expressed as (1),

$$u^T = \left[P_{G2}, .., P_{G,N_G}, V_{G1}, .., V_{G,N_G}, T_1, .., \ T_{NT}, Q_{CB,1}, .., Q_{CB,N_{CB}}\right] \tag{1}$$

state variables for OPF are slack bus power (P_{slack}), load bus voltages (V_{Li}), generator reactive powers (Q_{Gi}) and power flow in transmission lines (S_{li}), and it is expressed as (2).

$$x^T = \left[P_{slack}, V_{Li}, \dots, V_{L,N_L}, Q_{G1}, \dots, Q_{G,N_G}, S_{l1}, \dots, S_{l,N_l}\right] \tag{2}$$

Here the power flow is performed by supplying the initial values of control variables from their range based on experience. One needs to check whether the given objective function is optimized or not. If not, it modifies the control variables using some conventional or evolutionary-based optimization technique and performs another power flow solution. This process is repeated until the objective function is optimized [22]. OPF solution is achieved after solving a large number of solutions of load flows in tune with a set of specified values of consumer demand. In this paper, OPF is solved by solving the three objectives and they are formulated next.

2.1. Objective 1: generation cost (GC) minimization

Total cost of generation is the sum of fuel costs of each generating unit [23], [24], and mathematically, it is formulated as (3),

$$\text{minimize GC} = \sum_{i=1}^{N_G} GC_i(P_{Gi}) \tag{3}$$

where,

$$GC_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (4)$$

a_i, b_i and c_i are the coefficients of generation costs. N_G is number of generators.

2.2. Objective 2: power loss minimization

This minimization of losses in a power network (P_{loss}) is considered as objective, and the control variables are regulated to achieve this objective. In every power network, there is a significant amount of transmission losses that cannot be eliminated completely but can be minimized to achieve the economical and reliable goals of the power system [25]-[27]. This objective is non-linear, and it is formulated as (5),

$$\text{minimize } P_{loss} = \sum_{i,j=1}^{N_{TL}} G_{ij}\left[v_i^2 + v_j^2 - 2v_i v_j cos\left(\delta_i - \delta_j\right)\right] \quad (5)$$

2.3. Objective 3: enhancement of voltage stability index (L-Index)

In this work, to monitor the voltage stability of the power network L-index is used. It is formulated as the minimization of squared L-indices [28], and it is expressed as (6),

$$\text{minimize L} - \text{index} = \sum_{j=N_G+1}^{n} L_j^2 = \sum_{j=N_G+1}^{n} \left|1 - \sum_{i=1}^{N_G} F_{ij} \frac{V_i}{V_j}\right|^2 \quad (6)$$

where j $= N_G + 1$,…,n. $F_{ij} = -[Y_{LL}]^{-1}[Y_{LG}]$ and it is obtained from the Y_{Bus} matrix by splitting it into generators and load buses.

2.4. Constraints

The goal of equality constraints is to achieve the balance between power generation, losses, and power absorbed by the loads [29], [30]. These constraints are expressed as (7) and (8).

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{n} V_j\left(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}\right) \quad (7)$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{n} V_j\left(G_{ij}sin\delta_{ij} - B_{ij}cos\delta_{ij}\right) \quad (8)$$

The real and reactive power output from the generator is restricted by [31].

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (9)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (10)$$

Bus voltages in the power network must be within the specified limits [32]. The voltage limits of generator and load buses are restricted by (11) and (12).

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \qquad i = 1,2, \dots, N_G \quad (11)$$

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max} \qquad i = 1,2, \dots, N_L \quad (12)$$

the reactive power support from the shunt capacitor banks is limited by [33],

$$Q_{CB,i}^{min} \leq Q_{CB,i} \leq Q_{CB,i}^{max} \qquad i = 1,2, \dots, N_{CB} \quad (13)$$

constraints on tap positions of transformers are limited by [34],

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad i = 1,2, \dots, N_T \quad (14)$$

the power flow in transmission lines is restricted by (15).

$$-S_{ij}^{max} \leq S_{ij} \leq S_{ij}^{max} \quad (15)$$

3. SOLUTION METHODOLOGY

Before running an OPF, initially, a power flow program is executed to obtain a base case solution. One needs to determine the dependent and control variables for performing the OPF. In general, the solution of traditional OPF methods is affected by the initial guess of the solution. Also due to the non-linear nature of OPF, the solution of traditional OPF may fall in local optimum solution instead of reaching a global optimum solution. From a functional point of view, OPF combines the power flow problem and the ED problem. It is the best way to instantaneously operate the power system.

MBO is an evolutionary-based technique that is developed based on the migration behavior of butterflies' migration between two regions [35], [36]. During this migration, butterflies produce offspring and replace the corresponding parents. Mathematically, the entire process is divided into 2 updating operators namely the butterfly migration operator (BMO) and the butterfly adjustment operator (BAO). The detailed implementation details of MBO are reported in references [37]-[39]. The flowchart of solving the OPF using MBO is depicted in Figure 1.

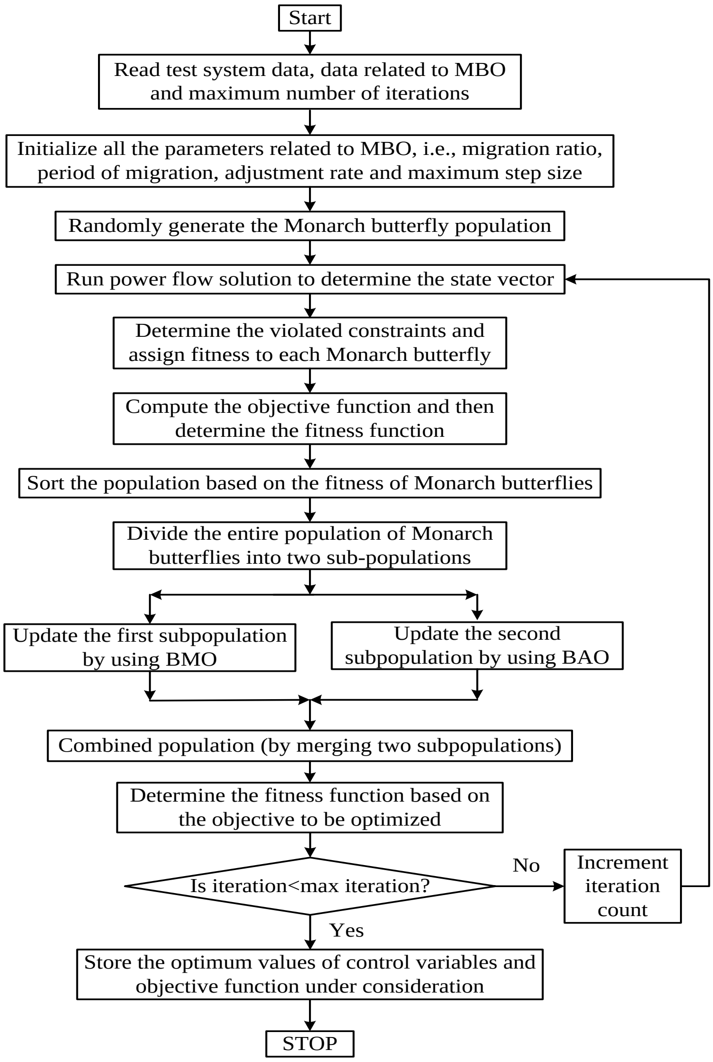

Figure 1. Flowchart of solving OPF using MBO

4. RESULTS AND DISCUSSION

The effectiveness of the MBO algorithm is validated on the IEEE 30 bus system which has a total generation capacity of 900.2 MW. The complete details of this test system are taken from [40]. Selected tuned parameters of MBO for the OPF problem are: the period of migration is 1.2, the migration ratio is 5/12, the maximum step size is 1.0, and the butterfly adjusting rate is 5/12. In this paper, three cases are considered with different objectives, and they are:

- Case 1: OPF with GC minimization.
- Case 2: OPF with power loss minimization.
- Case 3: OPF with L-index minimization.

4.1. Simulation results for case 1

The comparison of results obtained with GA, PSO, DE, JA, and MBO for the GC minimization objective (Case 1) is reported in Table 1. The optimum costs obtained by using the GA, PSO, DE, JA, and MBO are 799.52 ($/h), 802.19 ($/h), 799.29 ($/h), 799.034 ($/h), and 799.023 ($/h), respectively. Table 1 presents optimum values of control variables for obtaining the optimum GC and it also compares the corresponding values of power losses and L-index. The GC obtained by the MBO algorithm is slightly lower than that observed in other algorithms reported in Table 1.

Table 1. Optimum control variables for case 1

Control variables	Case 1: GC minimization				
	GA	PSO	DE	JA	MBO
P_{G1} (MW)	176.10	174.05	176.26	177.04	177.02
P_{G2} (MW)	49.10	48.71	48.56	48.68	48.81
P_{G5} (MW)	21.72	22.21	21.34	21.32	21.28
P_{G8} (MW)	21.09	23.93	22.06	21.10	21.19
P_{G11} (MW)	11.83	12.58	11.78	11.87	11.80
P_{G13} (MW)	12.22	12.00	12.02	12.00	12.0
V_{G1} (pu)	1.1	1.0	1.099	1.1	1.0879
V_{G2} (pu)	1.08	0.989	1.089	1.081	1.0714
V_{G5} (pu)	1.064	0.966	1.066	1.054	1.0788
V_{G8} (pu)	1.066	0.973	1.070	1.062	1.1
V_{G11} (pu)	1.06	1.062	1.096	1.1	1.1
V_{G13} (pu)	1.087	1.071	1.099	1.1	1.082
$T_{6,9}$ (pu)	1.05	0.9	1.043	1.022	1.025
$T_{6,10}$ (pu)	0.9375	0.9625	0.9179	0.9	1.025
$T_{4,12}$ (pu)	1.025	0.9625	1.019	0.9645	0.9650
$T_{28,27}$ (pu)	1.0	0.9	0.9896	0.9530	0.9375
GC ($/hr)	**799.52**	**802.19**	**799.29**	**799.034**	**799.023**
Power loss (MW)	8.66	10.083	8.615	8.612	8.604
L-index	0.1213	0.1226	0.1226	0.1260	0.1219

4.2. Simulation results for case 2

The comparison of results obtained with GA, PSO, DE, JA, and MBO for the power loss minimization objective (Case 2) is reported in Table 2. The optimum power losses obtained by using the GA, PSO, DE, JA, and MBO are 3.277 MW, 3.63 MW, 2.9473 MW, 2.843 MW, and 2.840 MW, respectively. Table 2 presents the optimum control variables values for obtaining optimum power loss and it also compares the corresponding values of GC and L-index. The power loss obtained by the MBO algorithm is slightly lower than that observed in other algorithms reported in Table 2.

Table 2. Optimum control variables for case 2

Control variables	Case 2: Power loss minimization				
	GA	PSO	DE	JA	MBO
P_{G1} (MW)	56.16	57.30	51.348	51.24	51.26
P_{G2} (MW)	77.82	79.06	80.0	80.0	79.99
P_{G5} (MW)	49.94	50.0	50.0	50.0	50.0
P_{G8} (MW)	34.75	35.0	35.0	35.0	35.0
P_{G11} (MW)	29.90	29.53	30.0	30.0	30.0
P_{G13} (MW)	38.11	36.14	40.0	40.0	40.0
V_{G1} (pu)	1.058	1.0	1.1	1.1	1.1
V_{G2} (pu)	1.051	0.996	1.1	1.093	1.097
V_{G5} (pu)	1.034	0.978	1.0864	1.075	1.076
V_{G8} (pu)	1.042	0.980	1.1	1.082	1.085
V_{G11} (pu)	1.089	1.032	1.1	1.1	1.1
V_{G13} (pu)	1.042	1.042	1.1	1.1	1.1
$T_{6,9}$ (pu)	1.0625	0.9	1.1	1.0526	1.0125
$T_{6,10}$ (pu)	1.0125	1.0	0.9	0.9	1.075
$T_{4,12}$ (pu)	1.025	0.95	0.9978	0.9836	0.925
$T_{28,27}$ (pu)	1.0125	0.9375	0.9984	0.9686	1.0
GC ($/hr)	957.82	956.45	967.03	967.05	962.13
Power loss (MW)	**3.277**	**3.630**	**2.9473**	**2.843**	**2.840**
L-index	0.1638	0.1286	0.1249	0.1258	0.1255

4.3. Simulation results for case 3

The comparison of results obtained with GA, PSO, DE, JA, and MBO for the L-index minimization objective (Case 3) is presented in Table 3. An optimum value of the L-index reported by using GA, PSO, DE, JA, and MBO is 0.1133, 0.1105, 0.1219, 0.1245, and 0.1096, respectively. Table 3 reports the optimum control variable values for obtaining the optimum L-index and it also compares the corresponding values of GC and power loss. The value of the L-index obtained by the MBO algorithm is slightly lower than that observed in other algorithms reported in Table 3. Figure 2 depicts the comparison of bus voltages for the three case studies by using the MBO algorithm, and it reveals that the bus voltages are low in case 1, higher in case 2, and moderate in case 3. The proposed MBO algorithm is found to exhibit faster convergence and offers a better solution when compared to GA, PSO, DE, and JA techniques.

Table 3. Optimum control variables for case 3

Control variables	Case 3: L-Index Minimization				
	GA	PSO	DE	JA	MBO
P_{G1} (MW)	117.97	133.83	171.66	53.43	91.793
P_{G2} (MW)	76.13	55.0	48.99	79.41	79.35
P_{G5} (MW)	30.99	37.86	22.29	49.69	50.00
P_{G8} (MW)	33.43	29.02	21.01	34.25	35.00
P_{G11} (MW)	19.0	19.59	17.33	29.95	19.65
P_{G13} (MW)	13.83	16.92	12.44	39.77	14.50
V_{G1} (pu)	1.04	1.02	1.077	1.099	1.035
V_{G2} (pu)	1.057	1.034	1.067	1.093	1.048
V_{G5} (pu)	1.072	1.046	1.083	1.087	1.085
V_{G8} (pu)	1.022	1.02	1.088	1.078	1.0452
V_{G11} (pu)	1.025	1.012	1.060	1.099	1.0659
V_{G13} (pu)	1.045	1.053	1.019	1.099	1.083
$T_{6,9}$ (pu)	0.925	0.9	0.9032	0.9791	1.0
$T_{6,10}$ (pu)	0.9125	0.95	0.9656	0.9063	0.950
$T_{4,12}$ (pu)	0.9	0.925	0.9181	0.9746	0.925
$T_{28,27}$ (pu)	1.075	0.925	0.9147	0.9437	1.075
GC ($/hr)	844.47	837.06	807.53	963.127	905.69
Power loss (MW)	8.052	8.821	10.32	3.1006	6.893
L-index	**0.1133**	**0.1105**	**0.1219**	**0.1245**	**0.1096**

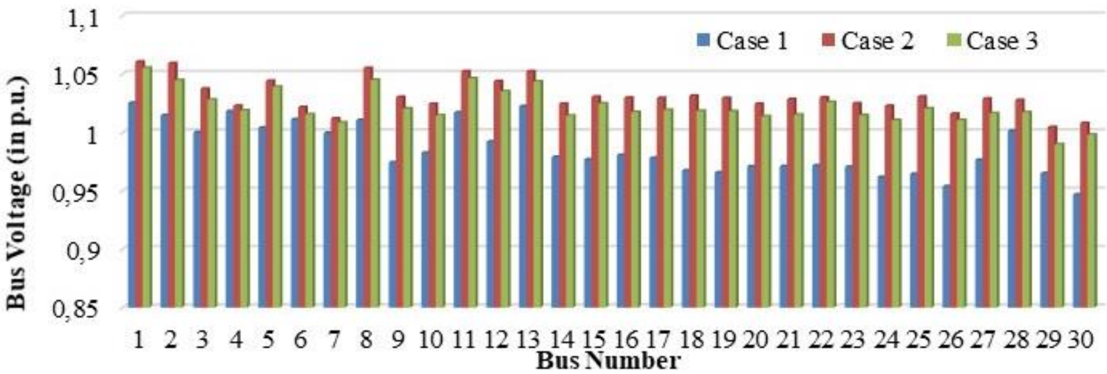

Figure 2. Comparison of bus voltages for the three case studies by using the MBO

5. CONCLUSION

The power network is complex and dynamic, and it is limited by various generators and transmission constraints. However, the traditional ED problem solves the power system problem by neglecting all these constraints. There are several desirable features when looking for an OPF program from a planning standpoint. Programs that are highly flexible and very versatile are the most useful. OPF is designed to achieve both economic and reliable operations. However, the complexity of the OPF problem must be reduced. Therefore, this work recognizes the significance of the OPF solution, and it is solved by selecting the different objectives for economic and secure operation and planning of power networks. The results on the 30-bus network reveal that among the various optimization algorithms considered in this work, the MBO evolves as the best algorithm for all three case studies.

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