Optimal Setting of STATCOM Based on Voltage Stability Improvement and Power Loss Minimization Using Moth-flame Algorithm

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***Abstract*— Static Shunt Compensator (STATCOM) is a powerful member of the Flexible AC transmission system (FACTS) based on voltage source converter. STATCOM is connected in shunt with the system to provide a voltage control of a certain bus by injecting or absorbing reactive power. This paper presents an efficient optimization technique called Moth-Flame Optimization (MFO) algorithm for determining the optimal location and parameter setting of STATCOM. MFO optimization technique is inspired from transverse orientation of the moth flame. STATCOM is incorporated in power system for voltage profile improvement, voltage stability enhancement and power loss minimization. The developed algorithm is validated using the standard IEEE 30-bus test system. However, the developed optimization algorithm including simplified STATCOM model is compared with the conventional particle swarm optimization technique (PSO). The simulation results show that the efficiency and superiority of the developed algorithm for determining the optimal setting of STATCOM moreover, the effectiveness of STATCOM for enhancing the voltage stability and power loss minimizing.**

Keywords—stability; optimization; FACTS; STATCOM.

I. INTRODUCTION

The progress increasing in load demands in power system leads to overloads of transmission lines and the power systems became insecure thereby, Flexible AC Transmission Systems (FACTS) devices are wildly applied to the electric power system to enhance system loadability, security and maximize utilization of transmission line. There are various types of transmission lines connected in series or in shunt or series- shunt connected controllers such as; Static Var Compensator (SVC), Thyristor-controlled Series Capacitor (TCSC), Interphase Power Controller (IPC), Static Synchronous Series Compensator (SSSC), interline power flow controller (IPFC), unified power flow controller (UPFC) and Generalized Unified Power Flow controller (GUPFC) [1–2].

Static Synchronous Compensator (STATCOM) is an elegant member of FACTS controller where, it is connected in shunt with a certain bus to control the bus voltage. STATCOM can inject or absorb reactive power from system based on the generated voltage by converters where, it inject reactive power if the generated voltage by converter is greater than the system voltage and it absorb reactive power if the generated voltage is less than the system bus voltage [3-4].

Recently, many optimization techniques are applied to solve the optimal power flow problem with incorporating FACTS devices such as Genetic Algorithm (GA) [5], Simulated Annealing (SA) [6], Particle Swarm Optimization (PSO) [7] and Evolutionary programming (EP)[8].

Moth-flame Optimization Algorithm (MFO) is a new optimization technique proposed by S. Mirjalili et. al. [9]. MFO is inspired from the motion of moth-flame where it moves in straight path when it follows the moon light but when it is trapped in spiral path due to artificial light.

In this paper, the MFO algorithm is used to determine the optimal parameters sitting and placement of STATCOM for different objective functions. The considered objective functions are minimization of power losses, voltage profile improvement and voltage stability enhancement. The optimal power flow is solved using MFO with and without incorporating STATCOM to realize the influences of this controller in term of the required objective functions. The obtained results by MFO are compared with results obtained by particle swarm optimization (PSO) algorithm to verify the effectiveness of MFO algorithm.

The rest of paper is arranged as follows: Section II presents modeling of STATCOM in load flow algorithm. Section III describes the optimal flow problem formulation, Section IV explains the procedures of Moth-flame Optimization Algorithm, and Section V shows the numerical results. Finally, the conclusions are presented in In Section VI.

II. MODEL OF STATCOM

STATCOM is a shunt connect controller, it can inject an AC current to control the bus voltage magnitude or the reactive power injected at the bus. STATCOM consists of voltage source converter connected to system by shunt-connected transformer as shown in Fig. 1. STATCOM is similar to synchronous condenser where, it can absorb or inject reactive power with zero active power generation. References [10-11] present simple methods for implementation of some shunt connected FACTS devices in load flow algorithm. Fig. 2(a) represents the equivalent circuit of STATCOM based on voltage source converter. To obtain the simple model of

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STATCOM firstly, the connected bus to STATCOM is converted to a generation (PV) bus then STATCOM is represented as synchronous condenser with zero generation power as shown in Fig. 2(b). The generated reactive power can be calculated using the balanced reactive power at the connected bus as follows:

$$Q_{sh} = \sum_{i=1}^{n} V_m V_n (G_{mn} \sin \delta_{mn} - B_{mn} \cos \delta_{mn}) + Q_m^{load} \quad (1)$$

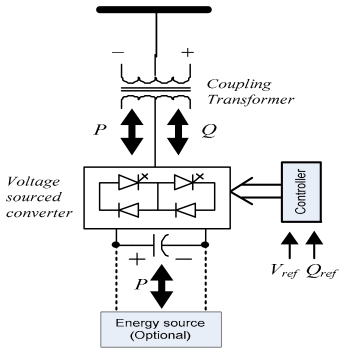
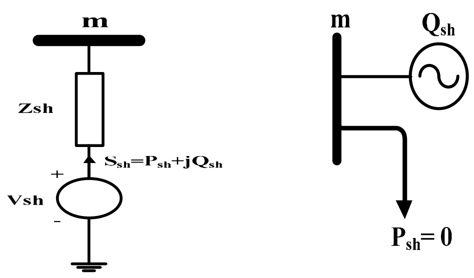


Fig.1. Static Shunt Compensator (STATCOM)



(a) (b)

Fig. 2. STATCOM model. (a) Equivalent circuit (b) Condenser representation

where, Q_m^{load} is the reactive power load at bus m, G_{mn} and B_{mn} are the conductance and susceptance between bus *m* and bus *n*, respectively. V_m and V_n are the voltages of bus *m and n respectively.*

The injected voltage of the STATCOM can be calculated using (2), where it is updated with iterative process of the load flow algorithm

$$V_{sh} = V_m + Z_{sh}\left(\frac{P_{sh}+jQ_{sh}}{V_m}\right)^* \quad (2)$$

III. Optimal Power Flow Problem Formulation

Generally, the optimization problem can be mathematically represented as follows:

$$Min \ F(x,u) \quad (3)$$

Subjected to

$$g_j(x,u) = 0 \quad j = 1,2,\dots,m \quad (4)$$

$$h_j(x,u) \le 0 \quad j = 1,2,\dots,p \quad (5)$$

where F acts the objective function, x is a vector represents the dependent variables, u is a vector represents the control variables, g_j and h_j represent equality and inequality constraints, respectively. m and p are number of equality and inequality constraints, respectively.

The dependent variables (*x*) in power system can be described as follows:

$$x = [P_{G1}, V_{L1} \dots V_{LNPQ}, Q_{G1} \dots Q_{GNPV}, S_{TL1} \dots S_{TLNTL}] \quad (6)$$

where P_{G1} is slack bus power, V_L is voltage of load bus, Q_G is the generator reactive power output, S_{TL} is the apparent power flow in transmission line, NPQ is number of load buses, NPV is number of generation buses and NTL is number of transmission lines.

The independent variables u of power system can be described as follows:

$$u = [P_{G2} \dots P_{GNG}, V_{G1} \dots V_{GNG}, Q_{C1} \dots Q_{CNC}, T_1 \dots T_{NT}] \quad (7)$$

where P_G is output active power of generator, V_G is voltage of generation bus, Q_C is the injected reactive power of shunt compensator, T is tap setting of transformer, NG is number of generators, NC is number of shunt compensator units.

3.1 Objective functions

3.1.1 Voltage profile improvement

The first objective function is the voltage profile improvement which can be achieved by minimizing the voltage deviations of load buses from a specified voltage. The required objective function can formulate as follows:

$$F_1 = \sum_{i=1}^{NPQ} (V_i - 1) \quad (8)$$

3.1.2 Voltage stability enhancement

Voltage stability index (L_{max}) is an important value proposed by Kessel and Glavitsch to indicate system stability [12]. This value is calculated for all load buses, which vary between 0 (no load case) to 1 maximum loading point (voltage collapse case) hence, the minimizing of this value keeps the system far away from voltage collapse of power system. However, this objective function can be formulated as follows:

$$F_2 = min(L_{max}) = min(max(L_j)) \quad j = 1,2, \dots, NPQ \quad (9)$$

where, L_j is the voltage stability index of bus j and it can be calculated as follows:

$$L_j = \left|1 - \sum_{i=1}^{NPV} F_{ij} \frac{V_i}{V_j}\right| \quad (10)$$

Where, V_i is the voltage of i[th] generator bus and V_j is the voltage of load bus. F_{ij} can be obtained from system Y_{bus} matrix as follows:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (11)$$

where, I_G, I_L are the complex currents and V_G, V_L are the complex voltages vectors at the generator and load buses. Y_{GG},Y_{LL}, Y_{GL},Y_{LG} are sub-matrices of system$Y_{bus}$by making some manipulation in(11)

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{12}$$

$where, F_{ij} = [F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}]$.

3.1.3 Real power losses minimization

The thrid objective function is minimizing of the active power loss which can be formulated as follows:

$$F_3 = P_{loss} = \sum_{i=1}^{NTL} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j cos\delta_{ij}) \tag{13}$$

where, G_{ij} the conductance of a transmission, NTL is number of transmission lines, and δ_{ij} is phase difference of voltages.

3.2 Constraints

3.2.1 Equality constraints

The equality constrains represent the balanced load flow equations as follows:

$$P_{Gi} - P_{Di} = |V_i| \sum_{j=1}^{NB} |V_j| \left(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}\right) \tag{14}$$

$$Q_{Gi} - Q_{Di} = |V_i| \sum_{j=1}^{NB} |V_j| \left(G_{ij}sin\delta_{ij} - B_{ij}cos\delta_{ij}\right) \tag{15}$$

where, P_{Gi} and Q_{Gi} are the generated active and reactive power at bus i, respectively. P_{Di} and Q_{Di} are the active and reactive load demand at bus *i*, respectively. G_{ij} and B_{ij} are the conductance and susceptance between bus i and bus *j*, respectively.

3.2.2 Inequality constrains

The inequality constrains can be classified as follows:

1) Generators active power output
$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad i = 1,2,\dots,NPV \tag{16}$$
2) Generators bus voltages
$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \quad i = 1,2,\dots,NPV \tag{17}$$
3) Generators reactive power output
$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad i = 1,2,\dots,NPV \tag{18}$$
4) Transformer tap settings
$$T_i^{min} \le T_i \le T_i^{max} \quad i = 1,2,\dots,NT \tag{19}$$
5) Shunt VAR compensator
$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \quad i = 1,2,\dots,NC \tag{20}$$
6) Apparent power flow in transmission lines
$$S_{Li} \le S_{Li}^{min} \quad i = 1,2,\dots,NTL \tag{21}$$
7) Voltage magnitude of load buses
$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \quad i = 1,2,\dots,NPQ \tag{22}$$
8) STATCOM controller constraints

$$V_{sh}^{max} \le V_{sh} \le V_{sh}^{min} \tag{23}$$

$$\theta_{sh}^{max} \le \theta_{sh} \le \theta_{sh}^{min} \tag{24}$$

where, V_{sh} is the injected voltage magnitude of STATCOM and θ_{sh} is the phase angle of the STATCOM injected voltage.

The operating constraints variables of system must be considered in the objective function. These variables can be easily limited in optimization solution by using the quadratic penalty formulation of objective function for all dependent variables; therefore the generalized objective function can be expressed as follows:

$$F_g(x,u) = F_i(x,u) + h_G\left(P_{G1} - P_{G1}^{lim}\right)^2 + h_Q \sum_{i=1}^{NPV}\left(Q_{Gi} - Q_{Gi}^{lim}\right)^2 + h_V \sum_{i=1}^{NPQ}\left(V_{Li} - V_{Li}^{lim}\right)^2 + h_S \sum_{i=1}^{NTL}\left(S_{Li} - S_{Li}^{lim}\right)^2 + h_F\left(V_{sh} - V_{sh}^{lim}\right)^2 + h_t\left(\theta_{sh} - \theta_{sh}^{lim}\right)^2 \tag{25}$$

where h_G,h_V,h_Q, h_S, h_F and h_t are the penalty factors, these values are high positive .x^{lim} acts the limit values of the dependent variable where,

$$x^{lim} = \begin{cases} x^{max}; & x > x^{max} \\ x^{min}; & x < x^{min} \end{cases} \tag{26}$$

It should point out here that the location of STATCOM is considered as a control variable (independent variable) and the location of STATCOM is a predefined value and can be determined by the optimization technique associate with number of load buses where the boundary of the location is restricted between bus No. 1 to bus No. 30 excluded the PV buses..

IV. Moth-Flame Optimization Algorithm

Moth-flame optimization algorithm is conceptualized from motion of moths in nature which known as transverse orientation. Moths flame can move in straight path for long distances in the night by maintaining a fixed angle with respect to the moon but the moths may move in deadly spiral path due to artificial light. In the MFO algorithm the moths are candidate of solutions while the control variable represent their location in space and also the flames are represented as candidate of solutions but the main different between the moths and flames is that the moths are considered as the search agents that move around the search space and the flames are the best solutions obtained by moths. Thereby, the flames are the flags to the moths hence, each moth move around the flames and update its location when a better solution is obtained [9].

A set of candidate solutions matrix is constructed represents the moths

$$M = \begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1d} \\ m_{2,1} & m_{22} & \cdots & m_{2,1} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n,1} & m_{n,2} & \dots & m_{n,d} \end{bmatrix} \tag{27}$$

where *n* is the number of moths and *d* is the number of variables (dimension). The obtained objective functions in term of moths can be represented as follows:

$$OM = [OM_1 \quad OM_2 \quad OM_3 \dots\dots\dots\dots OM_n]^T \tag{28}$$

By the same way a set of solutions matrix which represents the flames are constructed as follows:

$$F = \begin{bmatrix} F_{1,1} & F_{1,2} & \cdots & F_{1d} \\ F_{2,1} & F_{22} & \cdots & F_{2,1} \\ \vdots & \vdots & \ddots & \vdots \\ F_{h,1} & F_{h,2} & \dots & F_{h,n} \end{bmatrix} \quad (29)$$

where n is the number of flames and d is the number of variables (dimension). The obtained objective functions in term of flames can be represented as follows:

$$OF = [OF_1 \quad OF_2 \quad OF_3 \dots \dots \dots \dots OF_n]^T \quad (30)$$

The population of the MFO is constructed randomly as follows:

$$M(n, d) = (u_b(n, d) - l_b(n, d)) + rand * l_b(n, d) \quad (31)$$

where, u_b and l_b are the upper limit and the lower limit of the control variables, respectively. Then the objective functions are calculated in term of the obtained population.

As mentioned before that MFO algorithm is inspired from transverse orientation of moths and spiral movement due to artificial light, thereby the position of moths are updated using logarithmic spiral function as follows:

$$M_i = S(M_i, F_j) \quad (32)$$

$$S(M_i, F_i) = D_i e^{bt} \cos(2\pi t) + F_j \quad (33)$$

$$D_i = |F_j - M_i| \quad (34)$$

where,
M_i: The *i*-th moth.
F_i : The *j*-th flame.

S : The spiral function.

D_i: The distance of the *i*-th moth for the *j*-th flame.

b: constant for defining the shape of logarithmic spiral.

t: is a random number in the range [-1, 1].

For enhancing the searching process by the moths and compelling them to focus their searching on the global solution the flames are reduces in the last searching process as follows:

$$Flame\ number = round\ \left(N - l \times \frac{N-1}{T}\right) \quad (35)$$

where, l is number of current iteration, T is the maximum number of iteration and N is the maximum number of flames.

V. SIMULATION RESULTS

In this section the MFO is tested on IEEE 30-bus test system which consists of 6 generation units at buses 1, 2, 5, 8, 11 and 13. 41 at 6–9, 6–10, 4–12 and 27–28 and Nine VAR compensation units at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29. Forty one transmission lines. The system data are given in [13, 14]. The upper and lower limits of the control parameters are listed in Table I. The upper and lower of the load bus voltage are 1.05 p.u. and 0.95, respectively. The power flow limits in transmission line are listed in [13]. The program code was written using MATLAB 2009a and the simulation run on a PC with core i3 processor, 2.50 GHz and 2 GB RAM. For all studied cases. The selected parameters of MFO are: Number of search agents = 20, b =1 and maximum iterations=200. The selected parameters of PSO are specified as follows: population size = 20, maximum number of iteration =200, C1 =1.05 , C2 =, 1.1 ; ω_{max} =1 and ω_{min}= 0.3. The penalty factors are selected to be 100. It should point out that all system constraints aren't violated and the simulations are carried out for 30 trials for all studied cases and the best results are shown in addition, all PV buses are avoided for placement of STATCOM where, the generation units in these buses could provide the required reactive power supporting without needing FACTS for their buses. The working ranges of the magnitude and the phase angle of the injected voltage by STATCOM are [0.9, 1.1] and [-π, π], respectively. The studied cases are presented as follows:

5.1. Voltage profile improvement

Improving the voltage can be achieved by minimizing the voltage deviation of bus voltages. The obained results and the optimal control variables with and without incorporating STATCOM using MFO and PSO are listed in Table I and Table II and the bolded values highlight the best obtained results the values in the initial case are reported in [15]. The obtained voltage deviation without incorporating STATCOM using MFO and PSO is reduced to 0.0976 p.u (91.55%) and 0.1334 p.u (88.45 %) respectively compared to intial case. In case of incorporating the STATCOM, it is obvious that the voltage deviation is decreased to 0.0852 p.u (12.7 %) p.u and 0.1142 p.u (14.39 %) p.u using MFO and PSO respectively, compared to the same cases without incorporating STATCOM. Hence, the obtained results demonstrate the effectiveness of STATCOM for enhancing the voltage profile and validity of the MFO algorithm. The optimal location and parameter setting of STATCOM for this case are depicted in in Table III. The voltage profile with and without STATCOM using MFO and PSO are shown in Fig. 3 and Fig. 4. It is obvious that the voltage profile using MFO is better than PSO.

5.1.2 Voltage stability enhancement

In this case, the voltage stability enhancement can be achived by minimzation of the voltage stability index as dipicted in(9). The optimal control variables obtained by MFO and PSO with and without incorporating STATCOM are depicted on Table I and Table II. The obtained voltage stability index using MFO and PSO without incorporating STATCOM are 0.1258 p.u and 0.1279 p.u, respectively, i.e., the voltage stability is enhanced by (25.16 %) and (23.9 %) using MFO and PSO respectivly compared to the stability index in initial case. In case of incorporating STATCOM, the voltage stability index is reduced to 0.0774 p.u and 0.0820 p.u using MFO and PSO respectivly, i.e., the stability index is reduced by (38.47 %) and (35.88 %) using MFO and PSO respectivly compared to the same cases without incorporating STATCOM. Henece the obtained results reveal to the ability of STATCOM for enhancing of the voltage stability moreover, the superiority of MFO over PSO in terms of the voltge stability improvement objective function. The optimal placement and parameters setting of STATCOM for this case are listed in in Table III.

5.1.3 Real power losses minimization

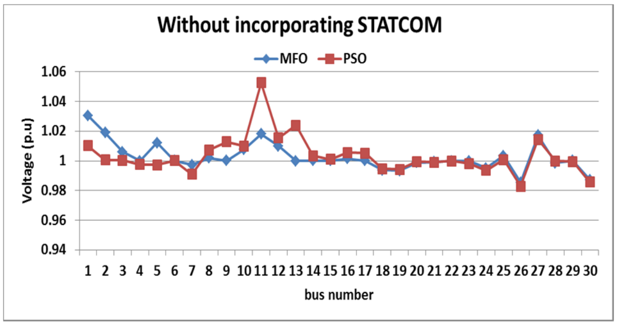
In this case, the required objective to be minimized is depicted in (13). The best control variables obtained by MFO and PSO

TABLE I. OPTIMUM CONTROL VARIABLES FOR DIFFERENT CASES WITHOUT INCORPORATING STATCOM

Variable	**Limit**		**Initial case[15]**	**Case1: Voltage profile improvement**		**Case2: Voltage stability enhancement**		**Case3: Real power loss minimization**	
	Max.	***Min.***		***MFO***	***PSO***	***MFO***	***PSO***	***MFO***	***PSO***
P1(MW)	200	50	0.9921	152.675	136.643	114.532	123.877	51.465	82.702
P2(MW)	80	20	0.8000	29.590	66.337	68.799	63.464	80.000	68.496
P5(MW)	50	15	0.5000	47.787	24.050	33.385	27.972	50.000	45.840
P8(MW)	35	10	0.2000	35.000	15.373	23.047	26.911	35.000	31.776
P11(MW)	30	10	0.2000	10.000	18.483	10.000	19.704	29.995	22.120
P13(MW)	40	12	0.2000	15.125	30.769	40.000	28.014	39.997	36.642
V1(MW)	1.1	0.95	1.0500	1.031	1.010	1.030	1.069	1.059	1.065
V2(MW)	1.1	0.95	1.0400	1.019	1.001	1.016	1.045	1.053	1.053
V5(MW)	1.1	0.95	1.0100	1.012	0.997	1.003	1.027	1.042	1.042
V8(MW)	1.1	0.95	1.0100	1.002	1.007	1.000	1.032	1.041	1.031
V11(MW)	1.1	0.95	1.0500	1.018	1.052	1.100	1.031	1.062	1.062
V13(MW)	1.1	0.95	1.0500	1.000	1.024	1.060	1.009	1.057	1.063
T11	1.1	0.90	1.0780	1.0165	0.977	1.061	0.991	1.003	0.995
T12	1.1	0.90	1.0690	0.96964	1.020	0.969	0.919	1.049	0.978
T15	1.1	0.90	1.0320	1.041	0.915	1.041	1.023	0.900	1.033
T36	1.1	0.90	1.0680	0.941	0.961	0.941	0.954	0.983	0.965
Q10 (MVAR)	5.00	0.00	0.0	3.839	1.716	5.000	3.217	0.001	2.630
Q12(MVAR)	5.00	0.00	0.0	5.000	2.639	5.000	2.942	5.000	3.148
Q15(MVAR)	5.00	0.00	0.0	3.131	0.551	5.000	0.702	4.982	0.496
Q17 (MVAR)	5.00	0.00	0.0	3.131	2.837	5.000	1.978	4.997	2.979
Q20 (MVAR)	5.00	0.00	0.0	5.000	4.233	4.996	4.216	5.000	1.327
Q21 (MVAR)	5.00	0.00	0.0	5.000	1.069	5.000	3.618	4.999	3.072
Q23 (MVAR)	5.00	0.00	0.0	4.976	3.518	5.000	4.542	2.947	2.630
Q24 (MVAR)	5.00	0.00	0.0	5.000	4.356	4.889	3.710	4.978	3.086
Q29 (MVAR)	5.00	0.00	0.0	0.949	1.733	5.000	4.487	2.365	3.276
VD (p.u)			1.1554	**0.0976**	**0.1334**	0.5449	0.5319	0.8801	0.6692
Lmax(p.u)			0.1681	0.1375	0.1391	**0.1258**	**0.1279**	0.1283	0.1299
P_{Loss} (MW)			5.5445	6.7771	8.2554	6.3628	6.5429	**3.0580**	**4.1760**

TABLE II. OPTIMUM CONTROL VARIABLES FOR DIFFERENT CASES WITH INCORPORATING STATCOM

Variable	**Case1: Voltage profile improvement**		**Case2: Voltage stability enhancement**		**Cas1: Real power loss minimization**	
	MFO	***PSO***	***MFO***	***PSO***	***MFO***	***PSO***
P1(MW)	123.963	134.084	51.774	154.582	51.336	78.102
P2(MW)	80.000	50.280	80.000	39.132	79.992	65.906
P5(MW)	50.000	40.912	49.836	24.232	50.000	48.673
P8(MW)	14.549	20.824	35.000	29.561	35.000	33.080
P11(MW)	10.000	23.368	29.999	16.334	30.000	25.923
P13(MW)	12.000	20.794	40.000	27.749	40.000	35.640
V1(MW)	1.019	1.019	1.056	1.049	1.100	1.047
V2(MW)	1.019	1.008	1.054	1.027	1.091	1.035
V5(MW)	1.023	1.010	1.029	1.016	1.073	1.010
V8(MW)	1.000	1.002	1.025	1.030	1.079	1.014
V11(MW)	0.993	1.047	1.090	1.024	1.076	1.037
V13(MW)	1.003	0.993	1.064	1.054	1.046	1.026
T11	0.976	0.992	1.021	0.937	1.018	0.952
T12	0.996	0.979	1.031	1.001	1.100	1.007
T15	0.900	0.961	0.914	0.940	0.946	1.009
T36	0.993	0.968	0.995	0.953	1.000	0.993
Q10 (MVAR)	3.507	2.093	0.000	4.058	5.000	3.028
Q12(MVAR)	5.000	1.780	4.267	1.624	4.986	2.154
Q15(MVAR)	5.000	3.451	5.000	2.501	4.181	3.669
Q17 (MVAR)	3.140	3.451	4.931	3.717	4.669	2.968
Q20 (MVAR)	4.900	4.341	4.670	3.342	3.801	3.263
Q21 (MVAR)	3.138	1.768	5.000	2.395	5.000	1.087
Q23 (MVAR)	4.969	2.353	4.997	3.418	3.071	2.883
Q24 (MVAR)	4.996	1.994	5.000	3.807	5.000	3.572
Q29 (MVAR)	4.995	3.401	5.000	3.455	0.000	1.767
VD (p.u)	**0.0852**	**0.1142**	0.9080	0.4461	1.0026	0.3863
Lmax(p.u)	0.0917	0.1217	**0.0774**	**0.0820**	0.1141	0.1122
P_{Loss} (MW)	7.1121	6.8626	3.2195	8.1912	**2.9277**	**3.9246**



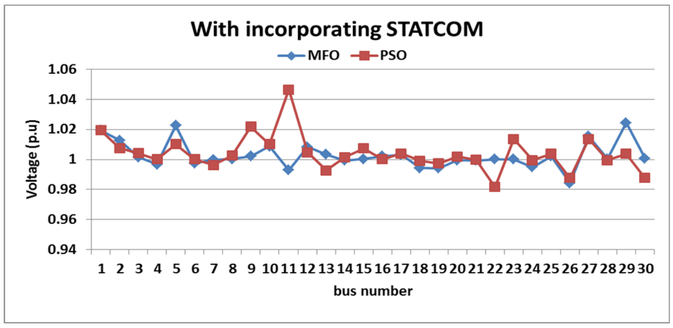


Fig. 3. System voltage profile with and without incorporating STATCOM using MFO and PSO.

TABLE III. THE PARAMTER SETTINGS OF STATCOM FOR DIFFERENT STUDIED CASES

Case	Algorithm	Location	V_{sh} (p.u)	θ_{sh}(deg.)	Q_{sh} (MVAR)
1	MFO	29	1.0291	-14.1112	4.89672
	PSO	15	1.0388	-24.6786	17.022
2	MFO	25	1.0441	-7.1015	3.946
	PSO	25	0.9955	-1.3047	-14.974
3	MFO	28	1.0727	-3.2706	-4.866
	PSO	21	1.1000	-30.4268	22.244

are listed in Table I and Table II. The power loss using MFO and PSO without incorporating STATCOM are 3.0580 MW and 4.1760 MW p.u, respectively, i.e., the power loss is decreased by (44.84 %) and (24.68 %) using MFO and PSO respectivly compared to the power loss in initial case. In case of incorporating STATCOM, the power loss is reduced to 2.9277 MW p.u and 3.9246 MW, i.e., the power loss is reduce by (4.26 %) and (6.02 %) with incorporating STATCOM using MFO and PSO respectivly compared to case of no STATCOM is exsited in system. hence, STATCOM is considered efficient controller for minimizing of the power loss. The optimal placement abd parmater setting of STATCOM are depicted in Table III for this case.

VI. CONCLUSIONS

In this paper, the Moth-flame optimization (MFO) technique has developed to determine the optimal location and parameter setting of Static Shunt Compensator (STATCOM) for voltage profile improvement, voltage stability enhancement and the power loss minimization. The developed optimization algorithm has validated using IEEE 30-bus test system and compared with the conventional particle swarm optimization technique. The optimal power flow problems are solved with and without incorporating STATCOM to verify the effectiveness of this device on power system performance. The obtained results show the superiority of the developed algorithm to determine the optimal location of STATCOM moreover, the capability of STATCOM for improving the voltage stability and minimization of the system power loss.

REFERENCES

[1] Y.-H. Song and A. Johns, *Flexible ac transmission systems (FACTS)*: IET, 1999.

[2] N. G. Hingorani and L. Gyugyi, *Understanding FACTS: concepts and technology of flexible AC transmission systems*: Wiley-IEEE press, 2000.

[3] S. Kamel, F. Jurado, and D. Vera, "A simple implementation of power mismatch STATCOM model into current injection Newton–Raphson power-flow method," *Electrical Engineering,* vol. 96, pp. 135-144, 2014.

[4] K. Ravi and M. Rajaram, "Optimal location of FACTS devices using improved particle swarm optimization," *International Journal of Electrical Power & Energy Systems,* vol. 49, pp. 333-338, 2013.

[5] D. Arabkhaburi, A. Kazemi, M. Yari, and J. Aghaei, "Optimal placement of UPFC in power systems using genetic algorithm," in *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on*, 2006, pp. 1694-1699.

[6] M. Ebeed, S. Kamel, "Optimal Location and Parameters Setting of SSSC Controller Using Simulated Annealing Approach," 17th International Middle East Power System conference (MEPCON 2015) Egypt, 5-17 December 1, 2015.

[7] M. Saravanan, S. M. R. Slochanal, P. Venkatesh, and P. S. Abraham, "Application of PSO technique for optimal location of FACTS devices considering system loadability and cost of installation," in *2005 International Power Engineering Conference*, 2005, pp. 716-721.

[8] K. Wong, J. Yuryevich, and A. Li, "Evolutionary-programming-based load flow algorithm for systems containing unified power flow controllers," *IEE Proceedings-Generation, Transmission and Distribution,* vol. 150, pp. 441-446, 2003.

[9] S. Mirjalili, "Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm," *Knowledge-Based Systems,* vol. 89, pp. 228-249, 2015.

[10] S. Kamel, F. Jurado, and J. P. Lopes, "Comparison of various UPFC models for power flow control," *Electric Power Systems Research,* vol. 121, pp. 243-251, 2015.

[11] S. Kamel, F. Jurado, Z. Chen, M. Abdel-Akher, and M. Ebeed, "Developed generalised unified power flow controller model in the Newton–Raphson power-flow analysis using combined mismatches method," *IET Generation, Transmission & Distribution,* vol. 10, pp. 2177-2184, 2016.

[12] P. Kessel and H. Glavitsch, "Estimating the voltage stability of a power system," *IEEE Transactions on Power Delivery,* vol. 1, pp. 346-354, 1986.

[13] O. Alsac and B. Stott, "Optimal load flow with steady-state security," *IEEE transactions on power apparatus and systems,* pp. 745-751, 1974.

[14] Power systems test case archive. University of Washington, Seattle. [Online]. Available: http://www.ee.washington.edu/research/pstca/

[15] M. Abido, "Optimal power flow using particle swarm optimization," *International Journal of Electrical Power & Energy Systems,* vol. 24, pp. 563-571, 2002.