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STATCOM Optimal Allocation in Transmission Grids Considering Contingency Analysis in OPF Using BF-PSO Algorithm

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ABSTRACT

In this paper, a combinational optimization algorithm is introduced to obtain the best size and location of Static Compensator (STATCOM) in power systems. Its main contribution is considering contingency analysis where lines outages may lead to infeasible solutions especially at peak loads and it commonly can be vanished by load-shedding. The objective of the proposed algorithm is firstly to prevent infeasible power flow solutions without undesired load-shedding, which is critical in contingency analysis; and secondly to mitigate overall power losses and costs. Moreover, active and reactive powers generation costs are considered in the proposed objective function. Since there are various constraints such as lines outages number, cost and their duration that must be taken to account, Bacterial Foraging oriented by Particle Swarm Optimization (BF-PSO) algorithm combined with Optimal Power Flow (OPF) is used to solve and overcome the complexity of this combinational nonlinear problem. In order to validate the accuracy of the proposed method, two test systems, including IEEE 30 bus standard system and Azarbaijan regional power system of Iran, are applied in simulation studies. All obtained optimization results show the effectiveness of the suggested combinational method in loss and cost reduction and preventing load-shedding.

KEYWORDS: BF-PSO Algorithm, Contingency Analysis, Optimal Power Flow, STATCOM Allocation.

1. INTRODUCTION

Nowadays power transmission systems planning become more increasingly important because of changes in power delivery policies. Reliability, stability and high quality beside avoiding interruption are major functions to supply loads in the competitive environment of electricity market. So, it is needed to design power systems more carefully. New technologies have been looked for to provide such delivery performance. However, it may be considered to install an additional device somewhere in the network. This could be happened in individual planning stage or later in expansion planning. Such devices are shunt reactors, capacitor banks, series reactors, automatic voltage regulators or recently developed flexible AC transmission systems (FACTS) technology such as static compensator (STATCOM).

The main advantages of STATCOM compared to the traditional reactive power compensation devices are the ability of strongly regulation, low harmonic content and low loss without operational problems such as resonance [1]. A STATCOM in association with a particular load can inject compensating current so that the total demand meets the specification for utility connection. It can also remove any unbalance and harmonic distortion from voltage of utility bus [1]. STATCOM would play a more serious role in power system loadability,

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reactive power compensation, loss reduction, voltage regulation, voltage balancing, and power quality and stability enhancement.

Presence of compensation components such as STATCOM with regards to their effects on operation point can trace on optimal grid reconfiguration. Since reactive power control is one of important means of power loss reduction and optimal power flow (OPF) is one of important means of generation cost reduction, the idea of coordinated application of these two objectives has been investigated. Several parameters such as new equipment installation cost, utilized equipment rate and location, optimal power flow in transmission system for generation cost minimization and loss reduction must be considered in power system planning [2].

Several works have investigated such combinational optimization problems but a few included consideration of contingency analysis. In [3] a multi-year mathematical model has been presented to determine optimal allocation of transformers over a planning horizon considering best utilization under single-contingency conditions. The proposed methods in [4] and [5] is for the elimination of the line overloads against contingencies, with optimal allocation methods for thyristor-controlled series capacitor (TCSC), where sensitivity index is introduced for ranking the optimal placement. Optimal allocation method for static var compensator (SVC) using reactive power spot price index for contingency has been proposed in [6].Voltage-sourced converter models such as unified power flow controllers (UPFC) and static synchronous series compensator (SSSC) have been proposed in [7] for effective sensitivity analysis, which are applied to device allocation problem to maximize their control effects. Priority list method for TCSC allocation for congestion management has been proposed in [8] based on the locational marginal prices (LMPs) in the security on strained optimal power flow. Reference [9] has presented an optimal allocation method for market-based power systems considering congestion relief and voltage stability.

The main concern of this paper is installation of STATCOM to mitigate losses and minimize total generation cost. Another operation task which can handle such a function is network reconfiguration. Reconfiguration could be done for several purposes such as service restoration, reliability improvement, loss reduction and voltage profile improvement. Another common and undesired reason of reconfiguration in transmission systems is outage especially unexpected outages that are not predictable. First and foremost problem in contingency analysis, which is considered in this paper, is optimal placement of STATCOM avoiding infeasible solution without load-shedding. Outages of some lines, which deliver high power, raise this problem whose common solution is to perform undesirable load-shedding.

Another important concern of this paper is installation of STATCOM considering OPF constraints including contingency analysis. The defined problem in this study is a combinational optimization problem because many variables must be determined appropriately by taking into account various constraints in real power transmission systems. To solve such a problem classical methods like linear programming, quadratic programming, etc. can be used [10]. But in some cases the mentioned methods fail to provide the global minima and may reach only local minima. However, some classic methods cannot handle the integer problems. Evolutionary methods can overcome the two aforementioned disadvantages [11]. A fast and somewhat newer method named Bacterial Foraging oriented by Particle Swarm Optimization (BF-PSO) is used to solve the problem of this paper.

In this paper, a new and generalized planning problem is defined which includes simultaneous STATCOM allocation and reconfiguration due to stochastic outages to minimize the cost of power losses and also to reduce the cost of power generation. The desired effect of

STATCOM on system performance is increased by determining its appropriate location and size among former planning parameters considering contingency analysis. Since outages of lines which deliver high-rate of power, have more serious effects on power flow (PF) and contingency analysis, so they are selected for evaluation of the proposed algorithms.

This paper is organized as follows: Section 2 presents the mathematical models, used in this paper for OPF and STATCOM. Section 3 includes a review on BF-PSO and also presents problem formulation. Simulation results of the proposed method on two examples which are IEEE 30-bus standard system and a regional transmission grid of Iran (Azarbaijan regional power system), will be presented in Section 4. In addition, based on extracted simulation results, some discussions will be made on suggested method of this paper, in Section 4, and finally Section 5 contains conclusions.

2. MATHEMATICAL MODELING

2.1. Formulation of optimization problem

The objective function of the constrained optimization problem could be assumed in two different modes. The first one could be considered as [12]:

$$FC1(x)=\sum_{i=1}^{N}\left(FC_{1i}(P_{gi})+FC_{2i}(Q_{gi})\right) \quad (1)$$

$$FC_{1i}(P_{gi})=a_i+b_i\times P_{gi}+c_i\times P_{gi}^{\;2} \quad (2)$$

$$FC_{2i}(Q_{gi})=e_i+f_i\times Q_{gi}+g_i\times Q_{gi}^{\;2} \quad (3)$$

Equation (1) is related to generation costs without considering any contingency. Equations (2) and (3) are active and reactive power generation costs, respectively where, $a_i \sim g_i$ are polynomial constants and N is the number of generators. Furthermore, P_{gi} and Q_{gi} are active and reactive generated powers, respectively, which are affected by x vector directly. The second objective function is written as [12]:

$$FC2(x)=\sum_{l=1}^{L}p_l FC_{cl}+\left(1-\sum_{l=1}^{L}p_l\right)FC1(x) \quad (4)$$

Equation (4) is related to generation costs with considering all line contingencies where L is line number and p_l is l-th line outage probability. Moreover, FC_{cl} denotes contingency-related costs for l-th line outage. Voltage magnitudes at each bus and power flows in each branch must be maintained within their limits.

This problem contains two sub-problems. The first one is optimal power flow (OPF) and next one is optimal STATCOM allocation and sizing. The OPF problem is formulated in terms of two groups of optimization variables, labeled x and z. The x variables are the OPF variables, including the voltage angles θ, and magnitudes V, at each bus, and active and reactive generator injections P_g and Q_g.

$$x=\begin{bmatrix}\theta\\ V\\ P_g\\ Q_g\end{bmatrix} \quad (5)$$

Other user defined variables are grouped in z.

The optimization problem could be expressed as follows:

$$\min_{x,y,z}\left\{\sum_{i=1}^{N}\left(FC_{1i}(P_{gi})+FC_{2i}(Q_{gi})\right)+\frac{1}{2}w^T Hw+C_w^T w\right. \quad (6)$$

where, H and C_w are $n_w\times n_w$ symmetric, spars matrix of quadratic coefficients and $n_w\times 1$ vector of linear coefficients, respectively.

Subject to:

1) Active power balance equations in each bus:

$$g_P(x)=P(\theta,V)-P_g+P_d=0 \quad (7)$$

where, $P(\theta,V)$, P_g and P_d are transmitted active power, active power generation and active power demand, respectively.

2) Reactive power balance equations in each bus:

$$g_Q(x)=Q(\theta,V)-Q_g+Q_d=0 \quad (8)$$

where, $Q(\theta,V)$, Q_g and Q_d are transmitted reactive power, reactive power generation and reactive power demand, respectively.

3) Apparent power flow limit of lines at sending end:

$$g_{S,s}(x)=\left|S_s(\theta,V)\right|-S_{\max}\leq 0 \quad (9)$$

4) Apparent power flow limit of lines at receiving end:

$$g_{S,r}(x) = |S_r(\theta,V)| - S_{\max} \le 0 \tag{10}$$

5) General linear constraints:

$$l \le A\begin{bmatrix} x \\ z \end{bmatrix} \le u \tag{11}$$

where *l*, *A* and *u* are the matrices that define the linear constraints.

6) Voltage and generation variable limits:

$$x_{\min} \le x \le x_{\max} \tag{12}$$

7) Limits on user defined variables:

$$z_{\min} \le z \le z_{\max} \tag{13}$$

2.2. STATCOM modeling

An accurate load flow model of STATCOM should compute the steady state losses such as transformer and inverter losses [13]. STAT-COM model on bus *k* is shown in Fig. 1. In which the equivalent circuit corresponds to the Thevenin equivalent as seen from bus k, with the voltage source V_{vR} being the fundamental frequency component of the VSC output voltage. The connection transformer can be modeled by its leakage admittance Y_{vR} [1].

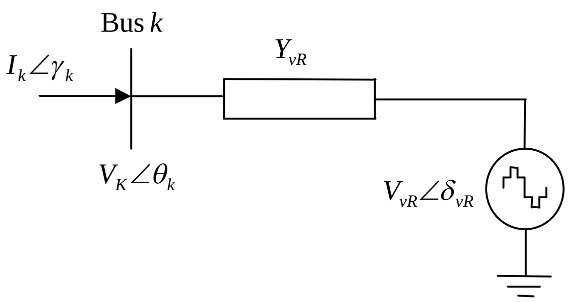

Fig. 1. STATCOM modeled in bus k [13]

3. OPTIMIZATION ALGORITHM

3.1. PSO-oriented bacterial foraging algorithm

In this paper, bacterial foraging algorithm (BFA) is used for optimization purposes. This algorithm is inspired by foraging behavior of bacteria for food. E coli, as an example of these bacteria, moves forward in a rotating manner [15]. This bacterium has a strong tendency to swarm into nutrientrich environments. This behavior of bacteria is called chemotaxis. Another movement of this bacterium is tumbling. Apart from chemotaxis, bacteria have another stage which is called reproduction. Besides, there are also elimination and dispersal events among bacteria.

3.1.1. Local search using PSO

This procedure is inspired by chemotaxis stage in which bacteria, considering their surrounding environment, determine their movement. In BFA, a step in the direction of last movement is considered as a displacement. After a movement step, position of *i*-th bacterium is expressed as follow:

$$\theta(\hat{i},\hat{j}+1,\hat{k},\hat{l}) = \theta(\hat{i},\hat{j},\hat{k},\hat{l}) + \Delta(\hat{i},\hat{j},\hat{k},\hat{l}) \tag{14}$$

In the conventional BF algorithm presented by Passino in [15] Δ is a random vector in the following form:

$$\Delta(\hat{i},\hat{j},\hat{k},\hat{l}) = c(\hat{i},\hat{j},\hat{k},\hat{l})\angle\phi(\hat{i},\hat{j},\hat{k},\hat{l}) \tag{15}$$

where, $c(\hat{i},\hat{j},\hat{k},\hat{l})$ is usually assumed constant. $\phi(\hat{i},\hat{j},\hat{k},\hat{l})$ determines movement direction of *i*-th bacterium. This direction is constant between every two tumble and changes when a tumble occurs. In order to make the search procedure directional and speed up its convergence in [16] particle swarm optimization (PSO) ability to exchange social information is used. Considering PSO parameters expressed in [11], new velocity of each bacterium is calculated as follows:

$$\begin{aligned} V &= w*V + C_1 * R_1(P_{lbest} - p_{current}) \\ &+ C_{2*}R_2(P_{gbest} - P_{current}) \end{aligned} \tag{16}$$

$$\Delta = V$$

where, *w*, R_1, R_2, C_1, and C_2 are constant numbers determined with respect to optimization problem. In every iteration, the parameter *V* is updated according to the above equation and is used as a substitute for Δ in BF algorithm in order to make each bacterium directional [16].

Therefore, in every step, instead of movement in a random direction determined by Δ, bacteria move in the direction of best local and global positions which are obtained so far. This procedure causes to convergence speed to be increased.

Between every two mutations, bacterium swims for maximum number of steps N_s. Swimming is carried on. After every swimming step the value of objective function $J(\hat{i},\hat{j},\hat{k},\hat{l})$ decreases continually as:

$$J(\hat{i},\hat{j},\hat{k},\hat{l}) = J(\hat{i},\hat{j},\hat{k},\hat{l}) + J_{cc}(\theta, p) \tag{17}$$

where, J_{cc} is the attractant and repellent between bacteria and is given as follows:

$$J_{CC}(\theta, P(\hat{j},\hat{k},\hat{l})) = \sum_{i=1}^{s} J_{cc}^{\hat{i}}(\theta, \theta^{i}(\hat{j},\hat{k},\hat{l}) = \sum_{\hat{i}=1}^{Nb}[-d_{attract}\exp(-\omega_{attract}\sum_{m=1}^{p}(\theta_m - \theta_m^{\hat{i}})^2 + \sum_{\hat{i}=1}^{NB}[h_{repellant}\exp(-\omega_{repellant}\sum_{m=1}^{p}(\theta_m - \theta_m^{\hat{i}})]^2 \tag{18}$$

where, $h_{repellant}$ is the height of the repellant signal and $w_{repellant}$ is the width of the repellant. $J_{CC}(\theta, P(\hat{j},\hat{k},\hat{l}))$ shows the combination of cell-to-cell attraction and repelling effects. $\theta=[\theta_1,\ldots,\theta_p]^T$ is one of the points on optimization domain. θ^i_m is the m-th variable of the i-th bacterium position (θ_i) and θ_m is the m-th variable of a typical bacterium. In the above equation $d_{attract}$ is the depth of the attractant and $w_{attract}$ is the width of the attractant signal. Besides, the equation $h_{repellant}=d_{attract}$ is true.

3.1.2. Reproduction

After the N_c movement steps, reproduction has taken place. If S_r (which is a positive even integer number) shows the number of population members who have sufficient nutrients, they will reproduce (split into two at the same location) without any mutation (like parents). As a result, the S_r bacteria will be in a good health and will reproduce and the S_r bacteria will die. Therefore, the number of bacteria will always be N_b.

$$S_r = N_b/2 \tag{19}$$

3.1.3. Elimination and dispersal

If the search space is a wide one, using only the swimming and reproduction operators the global solution cannot be determined. In order to resolve this problem another procedure namely elimination and dispersal will be used. In bacterial foraging after N_{re} reproduction stage, dispersal event is taken place. A bacterium, considering a pre-determined probability P_{ed}, is selected to be dispersed to a new position and move. The flowchart of BF-PSO algorithm is illustrated in Fig. 2.

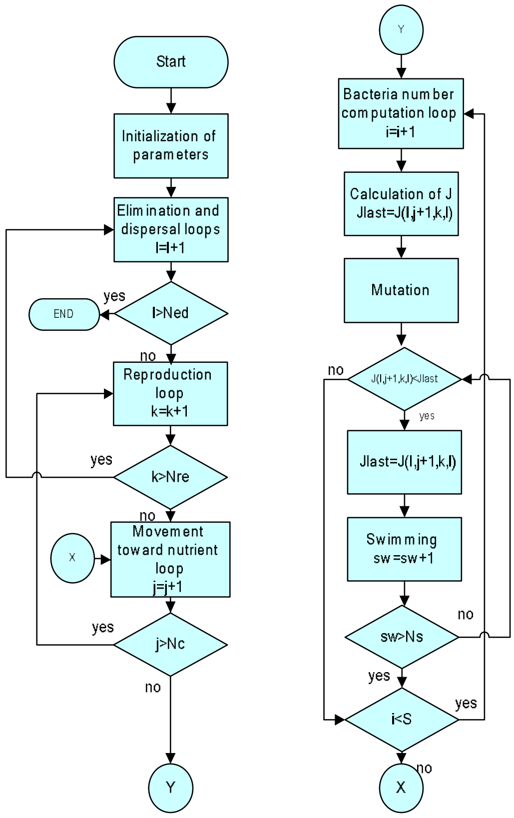

Fig. 2. The flowchart of the BFPSO algorithm

3.2. Contingency cost

This problem consists of two steps: the first one is finding of the FACTS element location in the network which is a discrete problem and solved by BF-PSO. The next one is solving OPF incorporating STATCOM solved by MATPOWER [17] using MATLAB software. Several lines in each case are loading near their maximum power rating and it is necessary to consider these lines outages and solve network again. The flowchart of this algorithm is demonstrated in Fig. 3.

4.SIMULATION, CASE STUDIES AND DISCUSSION

The goal of simulation studies is to find the appropriate location and size of STATCOM to firstly avoid infeasible solution of power flow without load-shedding and then to mitigate power losses and generation cost considering contingency analysis for certain lines which deliver major rate of power. Some programs using MATLAB software and its toolbox, MATPOWER, are developed to evaluate the proposed algorithm. Moreover, two test systems are considered to validate the effectiveness of the multi-objective proposed nonlinear optimization algorithm. IEEE 30 buses standard case study and Azerbaijan power transmission system have been investigated. The results are compared through the following cases:

Case 1: Original configuration of the system

Case 2: STATCOM allocation to mitigate power losses and generation cost

Case 3: STATCOM allocation to mitigate power losses and generation cost considering contingency

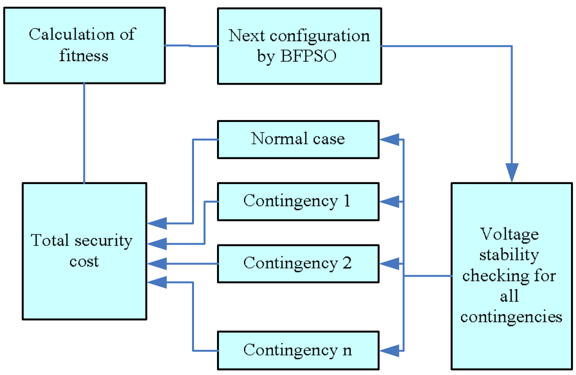

Fig. 3. The flowchart of the proposed algorithm considering contingency cost

4.1. Test system 1

IEEE 30 bus standard system shown in Fig. 4 is used as the first case study. The system consists of 41 branches and 6 generators while the load is assumed to be constant. The system's data are given in Table 1.The data of this power system are available in [17].

It is planned to install a single STATCOM in this test system to study aforementioned cases. Parameters values of BF-PSO algorithm are set to number of bacteria, $S=20$, number of swimming, $N_C=24$, number of movement steps towards nutrient, $N_s=10$, number of reproduction, $N_{re}=5$, and number of elimination-dispersal loops, $N_{ed}=3$.

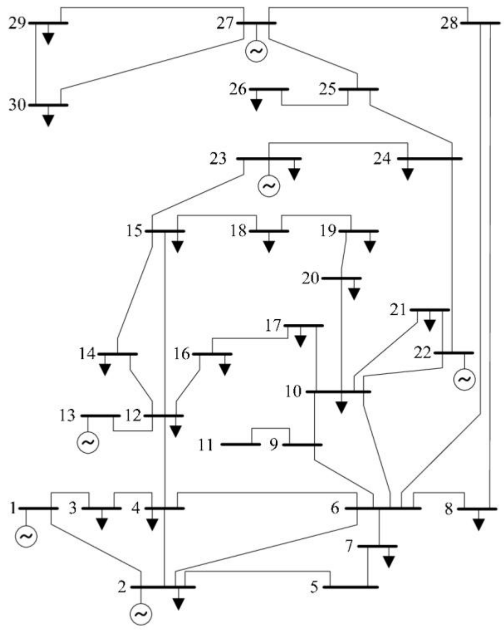

Fig. 4. IEEE 30 bus standard system

The optimal cost and loss of objective function in the case 1 has been calculated 576.89 \$/hr and 2.861 MW, respectively. Table 2 has summarized the results of each case. These results have obtained for the objective function in which only the active power costs are considered (only first term of (1)). Also, optimal cost and loss in the case 2 has been calculated 573.84 \$/hr and 2.243 MW, respectively. In this case the best location of STATCOM is bus 8 with 33.92 MVAr capacity. Voltage profile of cases 1 and 2 are shown in Fig. 5. According to the obtained results, as expected, STATCOM has improved power losses, voltage profile and total cost. However, investigation of case 3 is not as simple as the previous cases, which highlights effectiveness of the proposed evolutionary algorithm. In this case, (2) is considered as the objective function used in evolutionary algorithm whose value is obtained 577.03. Total cost and other parameters mentioned in this Table are obtained from the worst line outage *i.e.* line 12-13 (see Table 3). Its voltage profile is shown in Fig. 5. For more clearance some selected results are shown in Table 3. In this Table, outages of some selected lines which deliver high power, have been verified with/without STATCOM installation.

Table 1. IEEE 30 bus standard system bus data (Type1 means load bus & Type2 means generator bus) [17]

Bus No.	Type	P_d (MW)	Q_d (MVar)	Voltage constraints (p.u.)
1	2	0	0	0.95-1.05
2	2	21.7	12.7	0.95-1.1
3	1	24	1.2	0.95-1.05
4	1	7.6	1.6	0.95-1.05
5	1	0	0	0.95-1.05
6	1	0	0	0.95-1.05
7	1	22.8	10.9	0.95-1.05
8	1	30	30	0.95-1.05
9	1	0	0	0.95-1.05
10	1	5.8	2	0.95-1.05
11	1	0	0	0.95-1.05
12	1	11.2	7.5	0.95-1.05
13	2	0	0	0.95-1.1
14	1	6.2	1.6	0.95-1.05
15	1	8.2	2.5	0.95-1.05
16	1	3.5	1.8	0.95-1.05
17	1	9	5.8	0.95-1.05
18	1	3.2	0.9	0.95-1.05
19	1	9.5	3.4	0.95-1.05
20	1	2.2	0.7	0.95-1.05
21	1	17.5	11.2	0.95-1.05
22	2	0	0	0.95-1.1
23	2	3.2	1.6	0.95-1.1
24	1	8.7	6.7	0.95-1.05
25	1	0	0	0.95-1.05
26	1	3.5	2.3	0.95-1.05
27	2	0	0	0.95-1.1
28	1	0	0	0.95-1.05
29	1	2.4	0.9	0.95-1.05
30	1	22	1.9	0.95-1.05

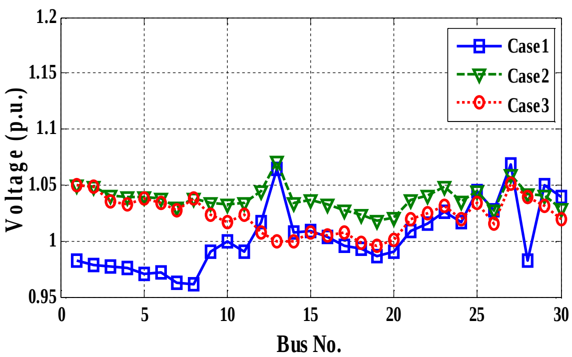

Fig. 5. Comparison of voltage profiles for all cases (test system 1-considering P)

Table 2. Optimal location and size of STATCOM (test system 1-considering P)

		Case1	Case2	Case3
Total cost $/hr		576.89	573.84	583.24
Minimum Voltage Magnitude (p.u.)		0.961 at bus 8	1.018 at bus 19	0.996 at bus 19
Maximum Voltage Magnitude (p.u.)		1.069 at bus 27	1.071 at bus 13	1.051 at bus 27
Mean voltage		1.0034	1.0380	1.0358
Total active power loss(MW)		2.861	2.243	2.770
Total reactive power loss(MVAr)		13.33	7.77	9.55
No. of STATCOM bus		-	8	8
STATCOM characteristics	Q(MVAr)	-	33.92	46.68
	V_{vr}(p.u.)	-	1.0707	1.083
	δ_{vr}(deg)	-	-3.529	-3.753

Table 3. Some selected results for test system 1 (considering P)

Line outage	STATCOM bus	Cost ($/hr)		Loss (MW)	
		with	w/o	with	w/o
1-2	8	575.07	577.95	2.522	3.090
2-6	8	575.39	578.19	2.622	3.141
6-8	8	575.65	Infeasible	2.716	Infeasible
12-13	8	583.24	Infeasible	2.770	Infeasible

For example, the first row of Table 3 shows the outage of line 1-2 with/without STATCOM installation. In this particular case, bus no. 8 is the best location of STATCOM and as it is expected, STATCOM improves total cost and loss of the overall system. Looking at Table 3, it can be seen that there are two lines whose outages lead to infeasible solutions without STATCOM. Fortunately, in both cases installation of STATCOM on bus no. 8 helps to reach feasible solution which is a critical aspect in contingency analysis. Revisiting IEEE 30 bus system it can be concluded that bus 8, which has large amount of load and somewhat far from generators, seems to be the deep point of the power system. On the other hand, the proposed algorithm seeks for deep point of system, considering contingency related parameters such as outages duration, number, sensitivity and cost to obtain best location of STATCOM to first prevent infeasible solutions and then reduce the overall cost and loss of power system. According to this fact that STATCOM is a reactive power source, when this device is used in the network, generators reactive power should be redispatched. Therefore, reactive power costs should be considered in generators cost functions.

Furthermore the proposed algorithm is used for such a case in which both the active and reactive power costs are considered (both terms of (2)) and its results are given in Table 4. In comparison with Table 2, it is obvious that STATCOM is more effective in cost reduction when reactive power costs is considered in generators cost functions. The voltage profiles of cases 1-3 for such an objective function are shown in Fig. 6. Table 5 shows the results due to selective line outages. It could be seen that the economical location of STATCOM is bus no. 10. However, it should be considered when the line 6-8 is interrupted, while the STATCOM has been located in bus no. 10 there will be no feasible optimal power flow solution which satisfies problem security constraints. So if this line outage probability is negligible (P_l~0) then STATCOM can be placed in bus no. 10, this lead to reduce total cost and total power loss. Otherwise, STATCOM should be located in bus no. 8.

Table 4. Optimal location and size of STATCOM (test system 1-considering P & Q)

		Case1	Case2	Case3
Total cost $/hr		623.01	581.77	592.92
Minimum Voltage Magnitude (p.u.)		0.984 at bus 19	0.977 at bus 19	0.970 at bus 19
Maximum Voltage Magnitude (p.u.)		1.069 at bus 27	1.050 at bus 1	1.051 at bus 27
Mean voltage		1.0098	1.0111	1.0070
Total active power loss(MW)		2.534	2.441	2.918
Total reactive power loss(MVAr)		9.49	8.63	10.56
No. of STATCOM bus		-	8	8
STATCOM characteristics	Q(MVAr)	-	51.47	51.85
	V_{vr}(p.u.)	-	1.0838	1.0813
	δ_{vr}(deg)	-	-3.429	-3.627

4.2. Test system 2

In second case study, Azarbaijan regional power system of Iran, illustrated in Fig. 7, is selected to prove effectiveness of the proposed method. It consists of 48 branches, 6 generators and 27 buses. In addition, the load is assumed to be constant. The system data are given in Table 6. Other system data are available in [18].

Table 5. Some selected results for test system 1 (considering P & Q)

Line outage	STATCOM bus	Cost ($/hr)		Loss (MW)	
		with	w/o	with	w/o
1-2	10	584.17	624.62	3.279	2.811
2-6	10	584.28	623.24	3.309	2.813
6-8	8	588.74	infeasible	3.042	infeasible
6-8	10	infeasible	infeasible	infeasible	infeasible
12-13	10	591.58	infeasible	3.541	infeasible
12-13	8	592.92	infeasible	2.918	infeasible

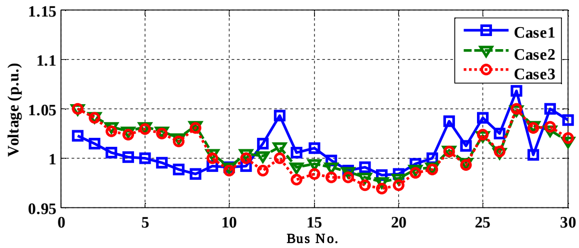

Fig. 6. Comparison of voltage profiles for all cases (test system 1-considering P & Q)

Again, it is concerned to install a single STATCOM and parameter values of BF-PSO algorithm are set similar to previous example. Since there is not valid data for reactive power generation costs, only active power is considered in this test system.

Table 7 has summarized the results of each case of suggested system. The optimal cost and loss of objective function in the case 1 has been calculated as 57358.55 $/hr and 23.86 MW, respectively. Also, optimal cost and loss in the case 2 has been calculated 57288.38 $/hr and 21.905 MW, respectively. In this case the best location of STATCOM is bus 13 with 127.94 MVAr capacity.

Voltage profile of cases 1 and 2 are shown in Fig. 8. STATCOM has relatively improved power losses, voltage profile and total cost in case 2. Again, for more clearance of evaluation of case 3, some selected results are shown in Table 8 and outages of some selected lines have been verified with/without STATCOM installation. For example, first row of Table 8 shows the outage of line 1-5 with/without STATCOM installation. In this case, bus no. 13 is the best location of STATCOM and as it is expected, STATCOM improves total cost and loss of overall system. Through benchmarking of single contingency installation. In this particular case, bus no. 13 is the best location of STATCOM.

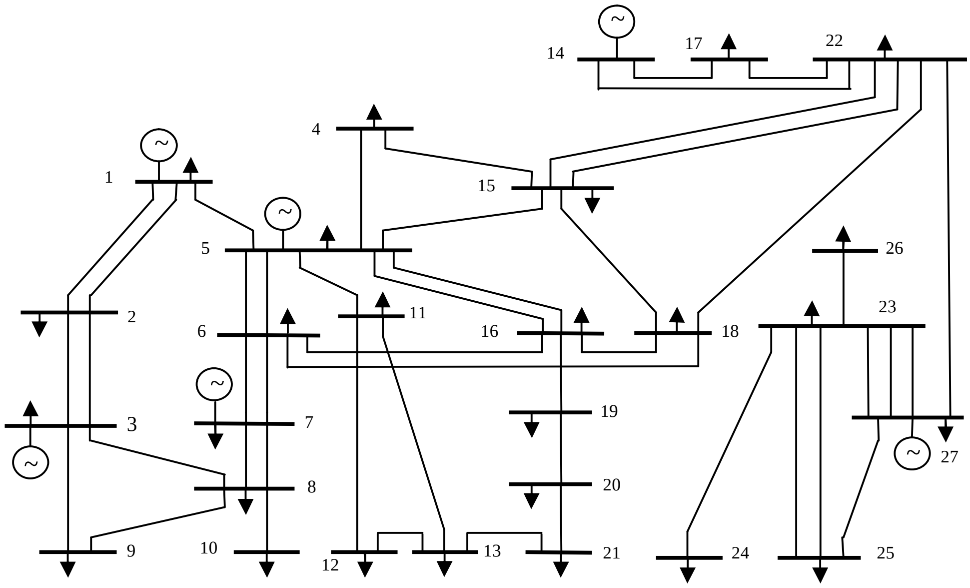

Fig. 7. Azarbaijan test system [19]

Table 6. Azarbaijan test system bus data (Type1 means load bus & Type2 means generator bus) [18]

Bus No.	Type	P_d (MW)	Q_d (MVar)	Voltage constraints (p.u.)
1	2	75.21	-29.63	0.9-1.1
2	1	239.54	32.19	0.9-1.1
3	2	2	1.07	0.9-1.1
4	1	64.9	21.69	0.9-1.1
5	3	131.58	88.6	0.9-1.1
6	1	86.94	28.24	0.9-1.1
7	2	211.26	131.95	0.9-1.1
8	1	94.58	70.96	0.9-1.1
9	1	112.88	20.7	0.9-1.1
10	1	59.30	-13	0.9-1.1
11	1	61.12	-151.07	0.9-1.1
12	1	0	84.67	0.9-1.1
13	1	60.80	61.20	0.9-1.1
14	2	0	0	0.9-1.1
15	1	85.29	74.42	0.9-1.1
16	1	180.79	141.39	0.9-1.1
17	1	20	9.2	0.9-1.1
18	1	146.68	100.24	0.9-1.1
19	1	79.92	23.06	0.9-1.1
20	1	39.8	24.42	0.9-1.1
21	1	1.3	1.20	0.9-1.1
22	1	59.96	66.82	0.9-1.1
23	1	76.5	45.81	0.9-1.1
24	1	20	0	0.9-1.1
25	1	75.84	-19.07	0.9-1.1
26	1	69.08	43.91	0.9-1.1
27	2	2.5	0.83	0.9-1.1

As it is expected, STATCOM improves total cost and loss of overall system.

Table 7. Optimal location and size of STATCOM (test system 2-considering P)

		Case1	Case2	Case3
Total cost ($/hr)		57358.55	57288.38	57828.62
Minimum Voltage Magnitude (p.u.)		0.931 at bus 12	1.018 at bus 12	1.019 at bus 12
Maximum Voltage Magnitude (p.u.)		1.100 at bus 1	1.100 at bus 1	1.100 at bus 1
Mean voltage		1.0590	1.0803	1.0226
Total active power loss (MW)		23.860	21.905	34.518
Total reactive power loss (MVAr)		167.78	151.45	209.41
No. of STATCOM bus		-	13	13
STATCOM characteristics	Q(MVAr)	-	127.94	128.73
	V_{vr}(p.u.)	-	1.2127	1.2126
	δ_{vr}(deg)	-	-5.056	-5.055

Table 8. Some selected results for test system 2 (considering P).

Interrupted line	STATCOM bus	Cost ($/hr)		Loss(MW)	
		with	w/o	with	w/o
1-5	13	57828.62	57905.20	34.51	36.62
3-9	13	57399.48	57471.63	24.90	26.90
13-21	12	57292.87	57362.92	22.03	23.98
20-21	20	57339.17	57363.86	23.32	24.01
12-13	13	57325.26	57380.87	22.94	24.49
19-20	20	57317.85	57505.03	22.73	23.92

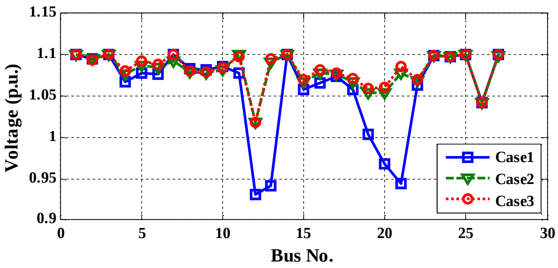

Fig. 8. Comparison of voltage profiles for all cases (test system 2-considering P)

Through benchmarking of single-contingency analysis, it was proved there is no infeasible solutions in this case study. Moreover, outage of each line leads to different buses to install STATCOM. Consequently, the proposed algorithm including BF-PSO seeks for the best location of STATCOM, considering contingency related parameters such as outages duration, number, sensitivity and cost to obtain best location of STATCOM to mitigate the overall cost and loss of power system, where is bus no. 13 with 128.73 MVAr capacity and is shown in Table 7. The last column of Table 7 is related to the worst line outage *i.e.* line 1-5 (see Table 8). Voltage profile of case 3 has been depicted in Fig. 8.

5. CONCLUSIONS

In this paper, a useful combinational algorithm has been introduced for STATCOM installation to overcome contingency related problems. Various constraints have been taken appropriately into account. BF-PSO coordinated with optimal power flow was selected to solve this combinational optimization problem. IEEE 30 bus standard system and Iran regional practical system were selected to show the validity of the suggested method. Each case study has been considered in various operational modes; with and without STATCOM to show its effect on system performance improvement. Also, line outages were considered and the results for the worst outage conditions were obtained. In addition, according to simulation results, considering reactive power generation cost in the total cost function was effective on STATCOM generation. Simulation results show that applying the proposed algorithm on two case studies caused to firstly preventing infeasible power flow solutions without load-shedding and then reducing power losses and the overall cost and also improving voltage profiles.

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