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Optimal Power Flow Solution using Ant Lion Optimizer (ALO) under Generator Outages

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Abstract
This paper presents a meta-heuristic algorithm namely Ant Lion Optimizer (ALO) for solving optimal power flow problem in power systems under generator outages. Optimal power flow problem is a complex problem consists of equality and inequality constraints with different objective functions. The objective functions of the optimal power flow problem are to minimize the total fuel cost, minimize total active power loss, minimize the total voltage deviation and minimize the voltage stability index. The optimal solution of optimal power flow problem is drafted by obtaining optimal values for the decision variables. ALO allocates supreme values for the decision variables. The optimal values achieved by ALO shows this algorithm has merits in solving complex problem with diverse search space. The performance of ALO is investigated on a standard IEEE-30 bus system. The firmness and effectiveness of ALO is demonstrated under generator outages. The optimal values obtained by ALO minimize all objective functions of the optimal power flow problem.
Keywords - Ant Lion Optimizer, Generator outages, Optimal power flow.

1. Introduction

Optimal power flow (OPF) is well problem for power system engineer. The OPF problem has consists of equality and inequality constraints and different objective functions that have to be minimized or maximized depends the problem. Due to this combination, the OPF problem is framed as more complex, non-linear and multi-modal problem. The conventional methods such as Newton-Raphson method, linear programming, quadratic programming and interior point method are suffered to obtain global optimal value. Next to conventional methods, global optimization techniques are used for obtaining the best optimal solutions for OPF problem. Classical optimization techniques have some deficiencies in finding the global solution due to their inherent search space. Then to classical optimization techniques, meta-heuristics are designed by proper modification of variables, parameters, constraints and objective functions. The meta-heuristic techniques are designed from inspiration of nature ‘s behaviour. These techniques are developed for many several global optimization problems. The solution of OPF gives optimal values of generators, transformers, capacitors through which the objective functions are optimized. The objective functions considered are fuel cost, active power losses, improvement of voltage profile and enhancement of voltage stability. The obtained optimal values are used in minimizing the objective functions.

In this paper, a meta-heuristic algorithm Ant Lion Optimizer (ALO) is used to solve the OPF problem. The ALO algorithm is one of the meta- heuristics based on the hunting mechanism of ant lions in the nature proposed by Seyedali Mirjalili in 2015. The ALO algorithm consists of five steps: random walk of ants, building ant lion traps, entrapment of ants in the traps, catch the preys’, and re- building the traps. This method captured the interest of researchers, and it has been successfully used for finding the optimal solution of power system problems.

This paper is designed as follows: Section 1 starts with the introduction to OPF problem and ALO, Section 2 is formulated with the OPF problem consists of constraints and objective functions, Section 3 presents the methodology of ALO with pseudocode and flowchart, Section 4 discusses the results and discussion, Section 5 ends with conclusion.

2. Problem Formulation

The optimization problem can be mathematically represented as

$$\min F(x, u)$$

subjected to

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

F is objective function, x is a vector of dependent variables (control variables), u is a vector of independent variables (state variables), g_j is equality constraints, h_j is inequality constraints, m is the number of equality constraints, p is the number of inequality constraints.

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The dependent variables (control variables) x in power system can be represented as

$$x = [P_{G\,1}, V_{L\,1}, \dots V_{LNPQ}, Q_{G\,1}, \dots Q_{GNG}, S_{TL\,1}, \dots, S_{TLNTL}]$$

$P_{G\,1}$ is real power of slack bus (reference bus), V_L is voltage of load bus (PQ bus), Q_G is reactive power of generator bus (PV bus), S_{TL} is apparent power flow in transmission line, NPQ is number of load buses, NG is number of generator buses, NTL is number of transmission lines

The independent variables (decision variables) u in power system can be represented as

$$u = [P_{G\,2}, \dots P_{GNG}, V_{G\,1}, \dots, V_{GNG}, Q_{C\,1}, \dots Q_{CNC}, T_1, \dots T_{NT}]$$

P_G is output power of generator, V_G is the voltage of generator bus, Q_C is the injected reactive power of shunt compensator, T is tap settings of transformer, NC is the number of shunt compensators, NT is the numbers of transformers.

2.1. Equality constraints

$$P_{Gi} - P_{Di} - |V_i| \sum_{j=1}^{NB} |V_j| (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) = 0$$

$$Q_{Gi} - Q_{Di} - |V_i| \sum_{j=1}^{NB} |V_j| (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) = 0$$

P_{Gi} is generated active power at i^{th} bus, Q_{Gi} is generated reactive power at i^{th} bus, P_{Di} is active load demand at i^{th} bus, Q_{Di} is reactive load demand at i^{th} bus, G_{ij} is conductance between i^{th} bus and j^{th} bus, B_{ij} is susceptance between i^{th} bus and j^{th} bus, δ_{ij} is the phase difference between voltages of i^{th} bus and j^{th} bus, V_i is the voltage at i^{th} bus, V_j is the voltage at j^{th} bus.

2.2. Inequality constraints

Generators active power output,

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \qquad i = 1,2,..NG$$

Generator bus voltages,

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \qquad i = 1,2,..NG$$

Generator reactive power output,

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \qquad i = 1,2,..\ NG$$

Transformer tap settings,

$$T_i^{min} \le T_i \le T_i^{max} \qquad i = 1,2,..NT$$

Shunt VAR compensator,

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \qquad i = 1,2,..\ NC$$

Apparent power flow in transmission lines,

$$S_{Li} \le S_{Li}^{min} \qquad i = 1,2,..NTL$$

Voltage magnitude of load buses,

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \qquad i = 1,2,..NPQ$$

2.3. Objective Functions

2.3.1. TFC:

The objective function is to minimize the total generation fuel cost which is expressed as:

$$OF\_1 = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NPV} (a_i P_{Gi}^2 + b_i P_{Gi} + c_i)$$

F_i is fuel cost of i^{th} generator, a_i, b_i, c_i are the cost coefficients of i^{th} generator

2.3.2. TAPL:

The objective function is to minimize the total active power losses which are expressed as:

$$OF\_2 = P_{loss} = \sum_{i=1}^{NTL} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})$$

G_{ij} is conductance of transmission line, NTL is the number of transmission lines, δ_{ij} is the phase difference between voltages.

2.3.3. TVD:

The objective function is to minimize the total voltage deviations of load buses from specified voltage which is expressed as:

$$OF\_3 = VD = \sum_{i=1}^{NPQ} |(V_i - 1)|$$

2.3.4. VSI:

The objective function is to minimize the voltage stability index (L) value, thereby keep the system far away from voltage collapse. The objective function is expressed as:

$$OF_4 = \min(\max(L_n)) \qquad n = 1,2,3..,NPQ$$

3. Methodology

ALO is developed by Seyedali Mirjalili et.al, based on the hunting behaviour and prey. The hunting behaviour resembles the hunting mechanism used by antlions and the prey is insects mostly ants. Different sizes of cone shaped trench are created by antlions with their massive jaws. These trenches are designed in a circular shaped path by digging soil; thereby large open space is available at top end for the ants to fall which further cut down to point edge at the bottom end. Antlion hides at the bottom corner of the cone shaped pit where there is no chance for the prey (ants) to escape from it. Whenever the prey (ants) is fall into the trap, it is realised by the antlion and tries to snap them. The size of the traps made by the antlions depends on the level of hungry or moon shape. Antlions make large traps when they are more hungry or at the full moon day.

The pseudo code for ALO is given below:
Initialize the population of ants and antlions
Calculate the fitness value
Find the best optimal (elite)
While the end criterion is not satisfied
For each ant
Select using Roulette wheel
Update minimum (c) and maximum (d) vector

$$v_{min}{}^{t} = v_{min}{}^{t}/I$$
$$v_{max}{}^{t} = v_{max}{}^{t}/I$$

I is a ratio, I=$10^{c}\ t/t_{max}$,
c is present iteration constant,
t is current iteration,
t_{max} is max of iteration,
$v_{min}{}^{t}$ is min of all variables at t,

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$v_{max}{}^{t}$ is max of all variables at t.
Create a random walk and normalize it.

$$A(t) = [0, cs(2r(st_1) - 1, .., cs(2r(st_n) - 1)]$$

cs is the cumulative sum,
n is the maximum number of iterations,
$st_1 \ldots st_n$ is the step of random walk,
r(t) is a stochastic function defined as
r(t) = 1 if rand > 0.5 and r(t) = 0
if rand ≤ 0.5, rand is a random number generated with uniform distribution in (0,1)
The normalized equation is

$$A_i^t = \frac{(A_i^t - v_{min,i}) * (v_{max,i} - v_{min,i}^t)}{v_{max,i}^t - v_{min,i}} + v_{min,i}$$

$v_{min,i}$ is the minimum random walk for variable i, $v_{max,i}$ is the maximum random walk for variable i, $v_{min,i}{}^{t}$ is the minimum of the i^{th} variable in repetition t, $v_{max,i}{}^{t}$ is the maximum of the i^{th} variable in repetition t.
Update ant position

$$ant_i^t = \frac{RW_{AL}^t + RW_E^t}{2}$$

$RW_{AL}{}^{t}$ is the random walk around antlion,
$RW_E{}^{t}$ is the random walk around elite
End for
Calculate the fitness for all ants
Replace the antlion with ant if the ant is better than the antlion in view of fitness value

$$AL_j^t = A_j^t \; if \; f(A_i^t) > f(AL_j^t)$$

$AL_j{}^{t}$ inidicates position of antlion j, $A_j{}^{t}$ is the position of ant j in the current iteration t
Update the elite if fitness of antlion is better than the fitness of Elite
End while
Return Elite

The flow chart of ALO is given in figure 1:

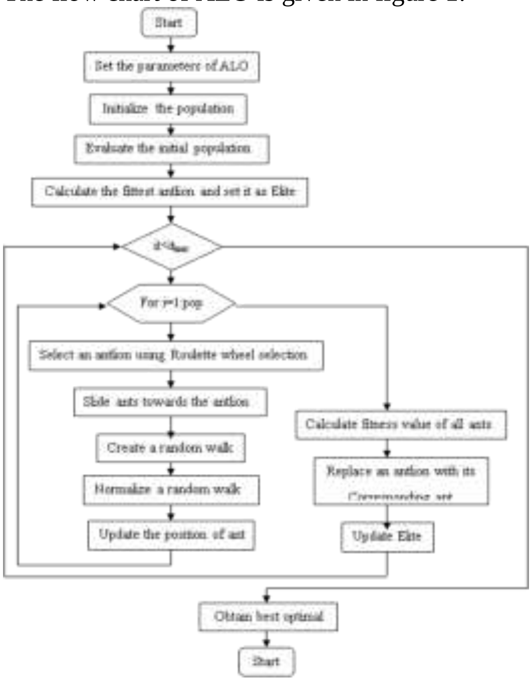

Figure 1. Flow chart of ALO

4. Results and Discussions

Meta-heuristic algorithm is applied for IEEE-30 bus system in Windows 10 64-bit operating system having AMD RYZEN 5 processor with 8 GB RAM. The results are obtained using MATPOWER 7.0 in MATLAB 2016. A maximum number of iterations are set as 200. A number of search agents are taken as 50 and 25 individual runs have conducted to obtain best optimal value for each objective function.

IEEE-30 bus system consists of 30 bus with 6 generators, 21 fixed loads, 41 branches. The total generation capacity is 435 MW out of which the actual generation is 287.2 MW. The load connected to the system is 283.4 MW with losses of 3.82 MW. The six generators (G1, G2, G3, G4, G5, G6) are connected at bus no 1, 2, 3, 5, 8, 11, 13. The G1 is connected to slack bus is very crucial in generation. Without G1, the total generation capacity is 235 MW which is less than the connected load of 283.4 MW. Thus, G1 is always connected with system for convergence of the system. The minimum and maximum MW for generators is G1 is [50,200], G2 is [20, 80], G3 is [15, 30], G4 is [10, 35], G5 is [10, 30], G6 is [12, 40]. The best values of objective functions under generator outages are given in Table 1. The optimal values obtained by using ALO are lesser than without ALO. When generator G2 is outage the objective function TFC is more than the remaining generator's outages. TAPL is higher if the outage generator is G3. During G4 is outage, TVD and VSI is high. The comparison of objective function values with and without ALO is shown in figure 2.

Table 1. Objective function values with and without ALO

GO	Without ALO	With ALO	Without ALO	With ALO
OF	TFC		TAPL	
G2	931.2419	930.2583	4.6254	4.4187
G3	876.7882	876.0657	6.7048	6.5201
G4	820.0691	818.3729	5.1001	4.661
G5	816.0316	815.4286	4.537	4.3671
G6	815.5545	814.9811	4.3326	4.1787
NGO	802.7629	802.1894	3.8188	3.6435
OF	TVD		VSI	
G2	1.908	0.497	0.1276	0.1246
G3	1.7705	0.5094	0.1294	0.125
G4	1.5716	0.527	0.1331	0.1259
G5	1.7895	0.5189	0.1288	0.1249
G6	1.8913	0.5088	0.1278	0.1251
NGO	1.8859	0.5115	0.1279	0.1246

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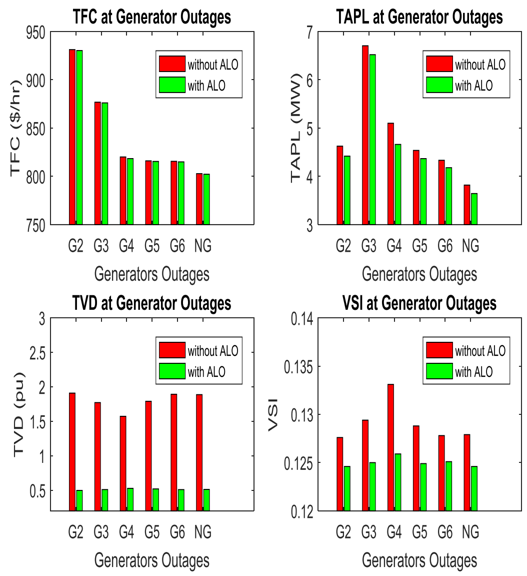

Figure 2. TFC, TAPL, TVD, VSI values with and without ALO

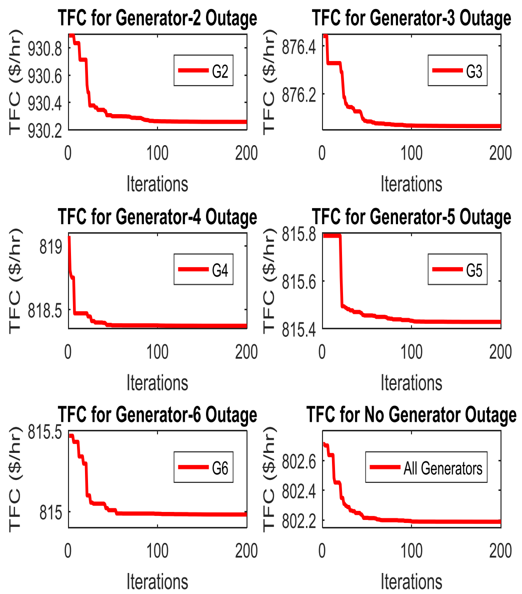

Figure 3. TFC – Convergence Curves

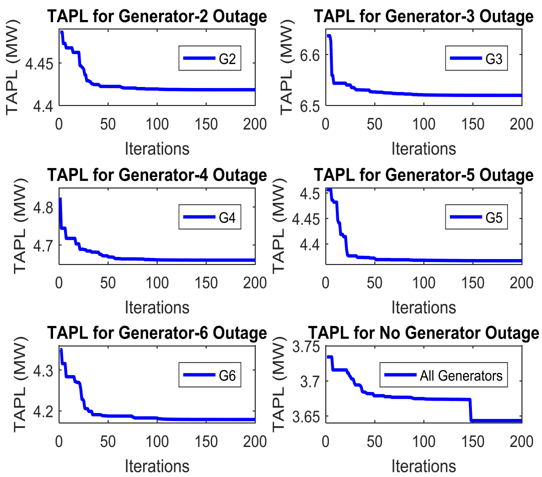

Figure 4. TAPL – Convergence Curves

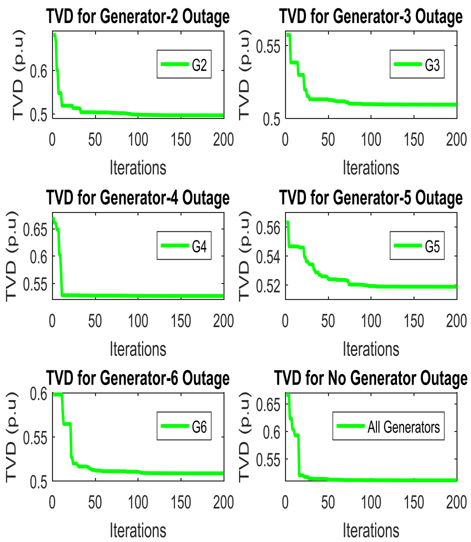

Figure 5. TVD – Convergence Curves

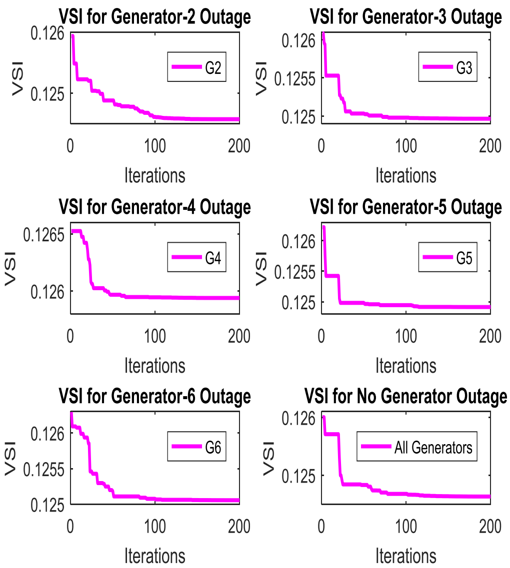

Figure 6. VSI – Convergence Curves

The convergence characteristics for objective function-TFC using ALO under generator outages is shown in figure 3.

The convergence characteristics for objective function-TAPL using ALO under generator outages is shown in figure 4.

The convergence characteristics for objective function-TVD using ALO under generator outages is shown in figure 5.

The convergence characteristics for objective function-VSI using ALO under generator outages is shown in figure 6. The optimal values of different objective functions (TFC, TAPL, TVD, VSI) under different generator outages using ALO are tabulated in Table 2.

Active power generated at different generators under each generator outages (except generator outage at slack bus) are formulated in Table 3.

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The outage generator is G2, the active power generated at G1 is 133 MW, G2 is 0 MW, G3 is 50 MW, G4 is 35 MW, G5 is 30 MW, G6 is 40 MW.

The outage generator is G3, the active power generated at G1 is 105 MW, G2 is 80 MW, G3 is 0 MW, G4 is 35 MW, G5 is 30 MW, G6 is 40 MW.

The outage generator is G4, the active power generated at G1 is 91 MW, G2 is 80 MW, G3 is 48 MW, G4 is 0 MW, G5 is 30 MW, G6 is 38 MW.

The outage generator is G5, the active power generated at G1 is 89 MW, G2 is 80 MW, G3 is 48 MW, G4 is 35 MW, G5 is 0 MW, G6 is 36 MW. T

he outage generator is G6, the active power generated at G1 is 93 MW, G2 is 80 MW, G3 is 49 MW, G4 is 35 MW, G5 is 30 MW, G6 is 0 MW.

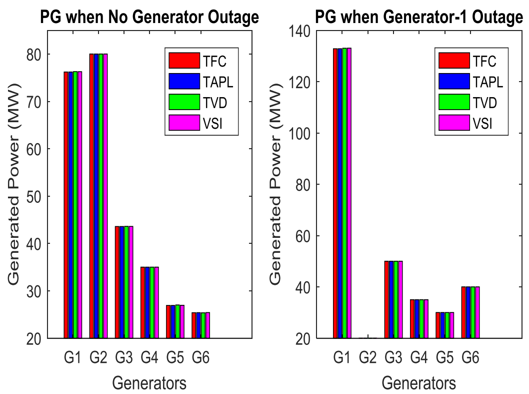
If no generator outage, the active power generated at G1 is 76 MW, G2 is 80 MW, G3 is 43 MW, G4 is 35 MW, G5 is 27 MW, G6 is 25 MW. The generated power of the outage generator is 0 MW and the power generated by remaining generators reaches its maximum MW except the generator G1 at slack bus. The generator G1, varies its generation value to balance the system. The generated power of G1 (132 MW) is high when the generator G2 is outage. The power generated by G1 is minimum (76 MW) when all generators are connected with in the system. The power generation for different objective functions- TFC, TAPL, TVD, VSI at different generators under each generator outages are shown in figure 7.

Table 2. Values of objective function at generator outages

GO	OF	TFC	TAPL	TVD	VSI
G2	TFC	**930.2583**	930.2780	931.2214	931.3472
	TAPL	4.4193	**4.4187**	4.6211	4.6480
	TVD	1.9971	2.0149	**0.4970**	1.9552
	VSI	0.1263	0.1264	0.1461	**0.1246**
G3	TFC	**876.0657**	876.0808	876.8340	877.3985
	TAPL	6.5286	**6.5201**	6.7160	6.8536
	TVD	1.8885	1.9319	**0.5094**	1.8664
	VSI	0.1276	0.1271	0.1478	**0.1250**
G4	TFC	**818.3729**	818.3816	818.9248	820.7238
	TAPL	4.6662	**4.6610**	4.8096	5.2685
	TVD	1.6931	1.6021	**0.5270**	1.6021
	VSI	0.1306	0.1314	0.1479	**0.1259**
G5	TFC	**815.4286**	815.4791	816.2267	816.2397
	TAPL	4.3803	**4.3671**	4.5878	4.5896
	TVD	2.0210	2.0032	**0.5189**	1.8569
	VSI	0.1260	0.1262	0.1462	**0.1249**
G6	TFC	**814.9811**	814.9927	815.8494	817.0760
	TAPL	4.1860	**4.1787**	4.4084	4.7203
	TVD	2.0654	2.0842	**0.5088**	1.7452
	VSI	0.1252	0.1251	0.1461	**0.1251**
No GO	TFC	**802.1894**	802.2392	802.9081	802.7071
	TAPL	3.6599	**3.6435**	3.8580	3.8034
	TVD	2.0457	2.0475	**0.5115**	1.9905
	VSI	0.1256	0.1256	0.1474	**0.1246**

Table 3. Power generation at different generators under outages

Generators	Outage Generator- G2			
OFs	TFC	TAPL	TVD	VSI
PG1	132.8143	132.8189	133.0211	133.048
PG2	0	0	0	0
PG3	50	49.9998	50	50
PG4	35	34.9999	35	35
PG5	30	29.9999	30	30
PG6	40	39.9999	40	40
Generators	Outage Generator- G3			
OFs	TFC	TAPL	TVD	VSI
PG1	104.9287	104.9201	105.1161	105.2538
PG2	80	80	80	80
PG3	0	0	0	0
PG4	35	35	35	35
PG5	30	30	30	29.9999
PG6	40	40	39.9999	39.9998
Generators	Outage Generator- G4			
OFs	TFC	TAPL	TVD	VSI
PG1	91.0754	91.0796	91.2238	91.3967
PG2	80	79.9999	79.9999	80
PG3	48.808	48.8065	48.8585	48.9117
PG4	0	0	0	0
PG5	30	29.9997	29.9998	30
PG6	38.1827	38.1751	38.1274	38.3601
Generators	Outage Generator- G5			
OFs	TFC	TAPL	TVD	VSI
PG1	88.8687	88.8527	89.0241	88.9397
PG2	80	80	80	80
PG3	48.016	48.0136	48.0859	48.0489
PG4	35	35	34.9999	35
PG5	0	0	0	0
PG6	35.8956	35.9008	35.8778	36.001
Generators	Outage Generator- G6			
OFs	TFC	TAPL	TVD	VSI
PG1	93.1713	93.1639	93.3552	93.5787
PG2	80	80	80	80
PG3	49.4147	49.4148	49.4534	49.5416
PG4	35	35	34.9999	35
PG5	30	30	29.9999	30
PG6	0	0	0	0
Generators	All Generators ON			
OFs	TFC	TAPL	TVD	VSI
PG1	76.1979	76.1976	76.2783	76.2632
PG2	79.9999	80	80	80
PG3	43.5767	43.578	43.6104	43.5939
PG4	34.9998	35	34.9999	35
PG5	26.9076	26.9102	27.0114	26.9411
PG6	25.3779	25.3876	25.358	25.4051



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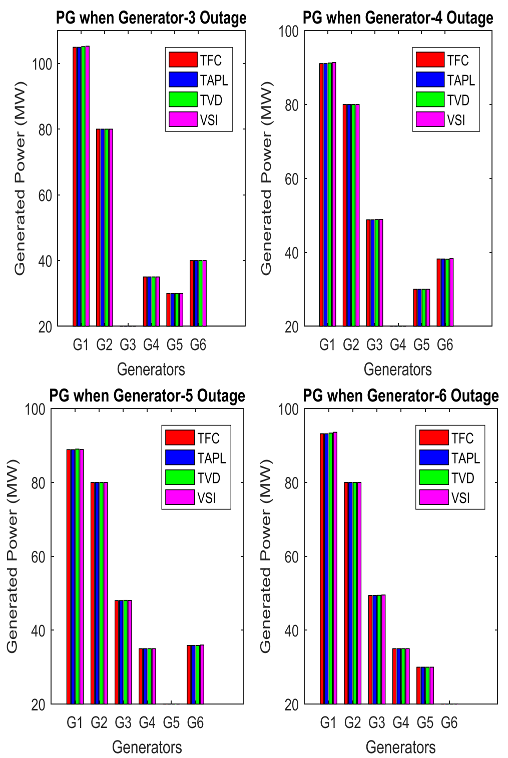
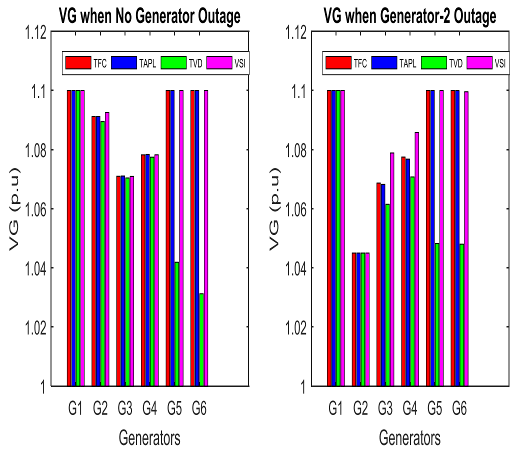


Figure 7. Power generations for different generator outages.

Table 4. Voltage magnitudes at different generators under outages

GO	Outage Generator- G2			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.1
VG2	1.045	1.045	1.045	1.045
VG3	1.0687	1.0682	1.0615	1.0788
VG4	1.0775	1.0768	1.0707	1.0858
VG5	1.1	1.1	1.0482	1.1
VG6	1.1	1.1	1.048	1.0996
GO	Outage Generator- G3			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.1
VG2	1.0876	1.0876	1.0856	1.0905
VG3	1.01	1.01	1.01	1.01
VG4	1.0746	1.0746	1.0739	1.0706
VG5	1.1	1.1	1.0776	1.1
VG6	1.1	1.1	1.0434	1.1
GO	Outage Generator- G4			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.0999
VG2	1.0896	1.0896	1.0879	1.0943
VG3	1.0696	1.0696	1.0693	1.0696
VG4	1.01	1.01	1.01	1.01
VG5	1.1	1.1	1.0974	1.1
VG6	1.1	1.1	1.0442	1.1
GO	Outage Generator- G5			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.1
VG2	1.0902	1.09	1.0885	1.0918
VG3	1.07	1.0701	1.0699	1.0713
VG4	1.0748	1.075	1.0753	1.0766
VG5	1.082	1.082	1.082	1.082
VG6	1.1	1.1	1.0602	1.1
GO	Outage Generator- G6			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.1
VG2	1.0903	1.0901	1.0896	1.093
VG3	1.0708	1.0708	1.071	1.0723
VG4	1.0754	1.0755	1.0757	1.0772
VG5	1.1	1.1	1.0822	1.1
VG6	1.071	1.071	1.071	1.071
GO	All Generators ON			
OF	TFC	TAPL	TVD	VSI
VG1	1.1	1.1	1.1	1.1
VG2	1.0912	1.0912	1.0895	1.0926
VG3	1.071	1.0711	1.0704	1.0709
VG4	1.0782	1.0784	1.0774	1.0782
VG5	1.1	1.1	1.0419	1.1
VG6	1.1	1.1	1.0312	1.1

The magnitudes of voltages generated at each generator for different objective functions under every generator are indexed in Table 4. The minimum and maximum voltage magnitudes are 0.95 pu and 1.1 pu. When particular generator is outage, the generated voltage magnitude reaches its maximum value of generator's voltage magnitude. Generator G2 is outage, the generator's voltage magnitude is 1.045 pu. The generator's voltage magnitude is 1.01 pu if the outage generator is G3. When the generator G4 is outage, the generator's voltage magnitude is 1.01 pu. The generator's voltage magnitude is 1.082 when the outage generator is G5. When the generator G6 is outage, the generator's voltage magnitude reaches to 1.071 pu. The voltage magnitude of generator G1 is 1.1 pu. The magnitudes of voltage generated at each generator for different objective functions- TFC, TAPL, TVD, VSI at under each generator outages are shown in figure 8.



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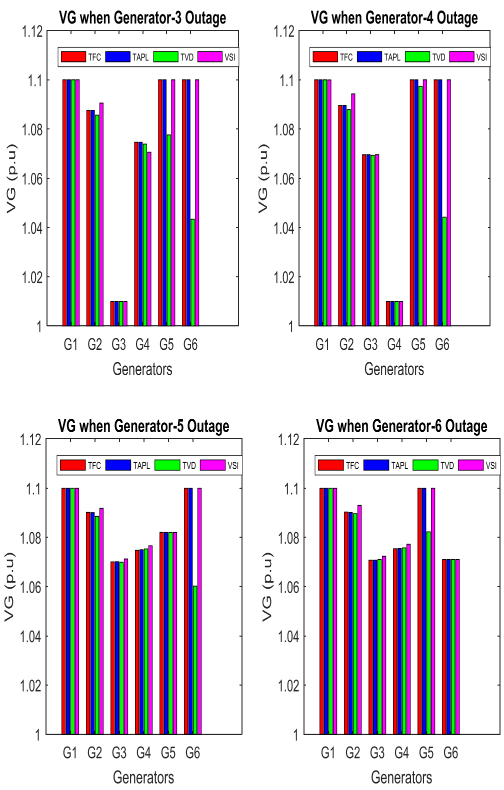

Figure 8. Voltage magnitudes for different generator outages.

5. Conclusion

The solution to optimal power flow problem using meta-heuristic algorithm ALO is presented in this paper. The optimal values for OPF problem is obtained by using ALO. The best value given by ALO is very close to the mean value. In order to validate the effectiveness and performance of ALO, the experiments are carried on a standard IEEE-30 bus system. The results are compared with and without using ALO. Under different generator outages, the percentage decrease for TFC is 0.07% to 0.2%, TAPL is 2.7% to 8.6%, TVD is 66% to 74%, VSI is 2.1 % to 5.5% is achieved by using ALO for getting solution to OPF problem. The simulated results have shown that ALO has superior performance in optimizing the objective functions.

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