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# Post-Outage State Estimations for Outage Management

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**Abstract:** Real time outage information is required to the utility operators for outage management process. In addition to some basic information regarding the outage, post-outage system status will help to improve the response to outages and management of system reliability. This paper presents particle swarm optimization based reactive power estimations for branch outages. Post outage voltage magnitudes and reactive power flows results for IEEE 14 and IEEE 30 bus systems are given. Simulation results show that post outage voltage magnitudes and reactive power flows can be computed with a reasonable accuracy.

*Keywords:* power flow; outage management, branch outage; optimization problem; particle swarm optimization; heuristic methods

## 1. INTRODUCTION

Outage management is one of the vital tasks of smart grid environment. One of the aims of outage management is to assign and coordinate the necessary resources as well as to apply several switching actions to restore the required power as quickly as possible. Effective way of fast restoration requires information regarding the post outage status of the system. This study is therefore devoted to the estimation of post outage voltage magnitude and reactive power flow estimation following an outage of a branch in a power system.

Line outage studies are not only the basic tools of security analysis but also interest of smart grids of the near future. Electric energy management system operators need to simulate effects of the outages of the power system components. This must be performed in real time in order to take the remedial actions in time as well as to apply the best switching strategy to restore the required power. AC load flow based outage analyses are not fast enough even for a moderate size system due to the large number of contingencies. Therefore, approximated models and fast solution algorithms are needed for practical applications. DC load flow was found to be fast and accurate enough for active power flow estimations (See Wood and Wollenberg (1996)). However, it was impossible to handle reactive power flows and voltage magnitudes. AC load flow was later proposed for this purpose (See Lee and Chen (1992), Ilic and Phadke (1986), Taylor and Maahs (1991)).

For voltage magnitudes and reactive power flows, the methods mentioned above have large computational errors because of the linearized network model implementations. One of the recent papers formulates line outage as a local constrained optimization problem in Ozdemir et al. (2003) and the problem is solved by Lagrangian function approach. The optimization is formulated for a bounded network consisting sending and receiving ends of the outaged branch and their first order neighboring busses. This approach brought some advantages in computational efficiency. Later, the problem was solved by genetic algorithms (See Ozdemir et al. (2005)).

Optimization problems can be solved either by gradient based analytical methods such as the steepest descent method, conjugate gradient method, etc., or evolutionary based algorithms such as, genetic algorithms, particle swarm optimization, ant colony optimization, simulated annealing, differential evolution method etc. In this paper particle swarm optimization is preferred to solve the local optimization problem. Matlab oriented cost free power systems package Matpower (See Zimmermann et al. (2009)) is used as a simulation tool.

Particle swarm optimization is one of the evolutionary techniques, and has been widely used in power system applications, such as economic dispatch problem (See Pancholi and Swarup (2004)), state estimation problem (See Naka et al. (2003)), optimal load flow problem (See Abido (2002)), etc. in recent years. It is based on social behaviors of birds, fishes or any other populations that have swarming behavior.

The organization of the paper is as follows. Line outage modeling and formulation of the problem is introduced in the second section of the paper. In the third section, basics of particle swarm optimization method are given together with its implementation to line outage problem. Section four presents post outage voltage magnitude and reactive

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power flow estimations and associated errors for IEEE 14 Bus, and IEEE 30 Bus test systems. Finally, section five is devoted to the conclusions.

## 2. BRANCH OUTAGE MODELING

An interconnected power system transmission line's $\pi$ equivalent, connecting two busses and the associated reactive power flows are given in Fig. 1.

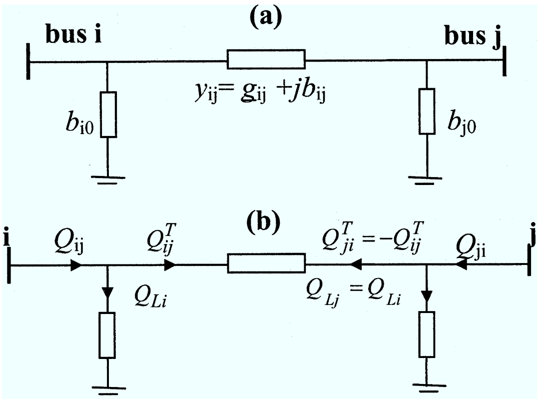

Fig. 1. Transmission line and reactive power flow model. a) $\pi$ equivalent of a transmission line. b) reactive power flows.

Reactive power flowing through the line $ij$, transferred reactive power, and reactive power loss are represented by $Q_{ij}$, $Q^T_{ij}$, and $Q_{Li}$ respectively. These reactive powers can be expressed in terms of system variables as follows.

$$Q_{ij} = -[V_i^2 - V_iV_jcos\delta_{ji}]b_{ij} + V_iV_jg_{ij}\sin\delta_{ji} \\ - V_i^2\frac{b_{i0}}{2} \tag{1}$$

$$Q^T_{ij} = -[V_i^2 - V_j^2]\frac{b_{ij}}{2} + V_iV_jg_{ij}sin\delta ji \tag{2}$$

$$Q_{Li} = -[V_i^2 + V_j^2 - 2V_iV_j\cos\delta ji]\frac{b_{ij}}{2} \\ - (V_i^2 + V_j^2)\frac{b_{i0}}{4} \tag{3}$$

Pre-outage and actual outage states of a transmission line are shown in Figures 2.a and 2.b respectively. A line outage is simulated using fictitious sources as shown in Fig. 2.c (See Ozdemir et al. (2003)).

Local constrained optimization is solved in the bounded network which is composed of the first order neighbours of the outaged buses. Only load bus voltage magnitudes in this bounded region are taken into consideration during the computation process of the optimization problem.

The procedure for the existing method is as follows.

(1) Select an outage of a branch, connected between busses i and j, and number it as k.
(2) Calculate bus voltage phase angles using linearized MW flows (see Wood and Wollenberg (1996) for details).

$$\delta_l = \delta_l - (X_{li} - X_{lj}) \triangle P_k, \\ l = 2, 3, \cdots, \text{NB} \tag{4}$$

$$\triangle P_k = \frac{P_{ij}}{1 - \frac{(X_{ii}+X_{jj}-2X_{ij})}{x_k}} \tag{5}$$

where, $X$ represents the inverse of the bus susceptance matrix, $P_{ij}$ is the pre-outage active power flow through the line, and $x_k$ represents the reactance of the line at hand. If the voltage magnitudes are calculated, then the calculation of the busses included in the bounded network would suffice.

(3) Calculate the reactive power transfer $\overline{Q}_{ij}^T$between the busses. This power includes the increment due to the change in bus voltage phase angles.
(4) Minimize the reactive power mismatches of busses i and j. This process is mathematically equivalent to the following constrained optimization problem.

$$\min_{wrt\ Q_{si},Q_{sj}} \| Q_i - (\overline{Q}_{ij} + \overline{Q}_{Li}) + Q_{Di} \\ Q_j - (-\overline{Q}_{ij} + \overline{Q}_{Li}) + Q_{Dj} \| \tag{6}$$

$$\text{subject to} \quad g_q(V_b) = \triangle Q_b - B_b \triangle V_b = 0$$

where, $\| \cdot \|$ is the Euclidean norm of a vector. Equation (6) is linear reactive power equation for load busses, $\triangle Q$ is reactive power mismatch vector, $V$ is bus voltage magnitude vector and $B$ is bus susceptance matrix. It should be stated that only two elements of $\triangle Q$ vector are nonzero and they are represented as shown below.

$$[\triangle Q] : [\triangle Q]_i = -[\triangle Q]_j = Q_{si} - Q_{ij} \tag{7}$$

On the other hand, we use subscript b to denote the bounded region where the optimization process is done.

For the case of a transformer with tap t, these values are given as follows.

$$[\triangle Q]_k = \begin{cases} [\triangle Q]_i & = Q_{si} - Q^T_{ij} \\ [\triangle Q]_j & = \frac{tV_j}{-2V_i+tV_j}[\triangle Q]_i \\ [\triangle Q]_k & = 0 \quad \text{for} \quad k \neq i, j \end{cases} \tag{8}$$

## 3. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is biologically inspired from the behaviors of the bird flocks and fish schools

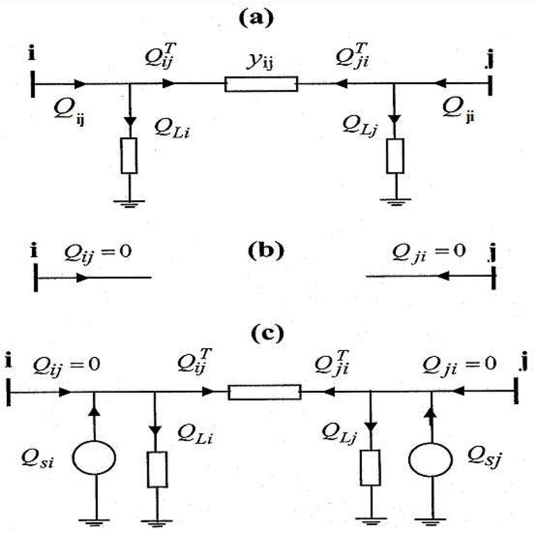

Fig. 2. Line outage modeling. a) pre-outage b) actual outage c) simulated post outage.

first by Kennedy and Eberhart in 1995 (See Kennedy and Eberhart (1995)).

In particle swarm optimization, population is called swarm and each individual in the swarm is called particle. A particle $i$, in iteration $k$ has two attributes; position and velocity. Random initialization of the swarm positions can be performed as follows,

$$x_0^i = x_{min} + \text{rand}(x_{max} - x_{min}) \tag{9}$$

where, $x_{max}$, $x_{min}$ show the maximum and the minimum positions that a variable can take, rand is a random number between 0 and 1, and $x_0^i$ represents the position of a variable in the $i^{th}$ iteration. Swarm size is generally 15-30 times the number of variables. Random initialization of the velocity vector is shown below:

$$v_0^i = v_{min} + \text{rand}(v_{max} - v_{min}) \tag{10}$$

where, $v_{max}$, $v_{min}$ show the maximum and the minimum velocities.

In each iteration velocity and position vectors are updated according to (11) and (12) respectively.

$$v_{k+1}^i = wv_k^i + c_1\text{rand}(\text{best}_i - x_k^i) + c_2\text{rand}(\text{best}_k^g - x_k^i) \tag{11}$$

$$x_{k+1}^i = x_k^i + v_{k+1}^i \tag{12}$$

where, $w$ is the inertial constant, $\text{best}_i$ and $\text{best}_k^g$ are the personal best and global best positions respectively. $c_1$ and $c_2$ are learning factors.

Finally the algorithm terminates if a predetermined stopping criterion is met, otherwise the process restarts. The flowchart of the pso algorithm is given in Fig. 3.

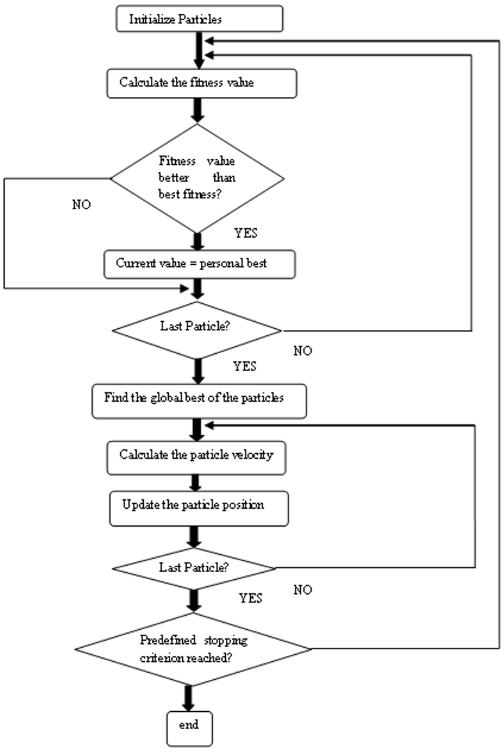

Fig. 3. Flowchart of pso algorithm

*Application of Particle Swarm Optimization to Branch Outage Problem* The steps of particle swarm optimization algorithm to solve branch outage problem can be summarized as follows:

1. Run a base case load flow and obtain the initial voltage magnitudes of the load buses included in the bounded region.
2. Create initial swarm $Q_{si-initial}$ elements of which are between $Q_{ij}^T -$ limit and $Q_{ij}^T +$ limit.
3. Determine $\triangle Q$ vectors either by using (7) or by using (8) and update load bus voltage magnitudes after solving second equation of (6).
4. Evaluate the objective function given by the first part of equation (6) for all particles in the swarm. Find personal and global bests of the particles.
5. Calculate the new velocity and new position values for all particles using (11) and (12).
6. If a predetermined stopping criterion is met stop, otherwise go to step 2.

## 4. TEST RESULTS

PSO based solution of line outage problem is tested on IEEE 14 Bus, and IEEE 30 bus test systems. Matlab based open-source software Matpower (See Zimmermann et al. (2009)) is used as a solution tool. Post outage voltage magnitudes and reactive power flows for the test systems are calculated both with full AC power flow method and with PSO based branch outage simulation. Programs for simulating the outages are written in Matlab. Outages of heavily loaded lines and transformers are selected as the sample cases because of the limited space.

In all simulations, program parameters are chosen as follows:

$w_{max} = 0.9$,
$w_{min} = 0.4$,
$N_p = 15$,
$c1 = 2$, $c_2 = 2$.

Tables 1-4 illustrate the simulation results for several test systems. In the tables $V_{AC}$ repesents the post-outage voltage magnitude of a specific bus calculated by using full AC load flow where, $V_{PSO}$ symbolizes the post-outage voltage magnitude of a specific bus calculated by using PSO method. $Err\%$ represents the percentage error of the specific bus voltage magnitude, and is computed as follows.

$$Err\% = 100 \times |\frac{V_{AC} - V_{PSO}}{V_{AC}}| \tag{13}$$

On the other hand $Q_{PF}$ represents the post outage reactive power flow computed by AC load flow, $Q_{PSO}$ represents the post outage reactive power flow computed by PSO method. $Q_E$ represents the reactive power error and is computed as follows.

$$Q_E = |Q_{PF} - Q_{PSO}| \tag{14}$$

For IEEE 14 bus test system two outages are simulated. The first one is the outage of the line connected between bus-7 and bus-9 whose pre-outage reactive power flow is 5.77 MVar. The second one is the outage of the transformer connected between bus 5 and bus 6 whose pre-outage reactive power flow is 12.42 MVar. Table 1 shows post outage voltage magnitudes for the outage of a line connected between buses 7 and 9 and for the outage of a transformer connected between buses 5 and 6. Maximum percentage voltage magnitude errors for the outage of the line and for the outage of the transformer are found to be 0.60 and 0.87 respectively. They are shown bold in table.

Table 1. Two Representative Outages and Corresponding Post-Outage Voltage Magnitude Calculations for IEEE 14 Bus Test System

| | **Outage of Line 7-9** | | | **Outage of Tr. 5-6** | | |
|---|---|---|---|---|---|---|
| **Bus No** | $V_{AC}$ | $V_{PSO}$ | **Err(%)** | $V_{AC}$ | $V_{PSO}$ | **Err(%)** |
| **1** | 1.0600 | 1.0600 | 0.00 | 1.0600 | 1.0600 | 0.00 |
| **2** | 1.0450 | 1.0450 | 0.00 | 1.0450 | 1.0450 | 0.00 |
| **3** | 1.0100 | 1.0100 | 0.00 | 1.0100 | 1.0100 | 0.00 |
| **4** | 1.0169 | 1.0178 | 0.08 | 1.0181 | 1.0269 | **0.87** |
| **5** | 1.0174 | 1.0196 | 0.21 | 1.0272 | 1.0350 | 0.76 |
| **6** | 1.0700 | 1.0700 | 0.00 | 1.0700 | 1.0700 | 0.00 |
| **7** | 1.0671 | 1.0699 | 0.26 | 1.0656 | 1.0658 | 0.01 |
| **8** | 1.0900 | 1.0900 | 0.00 | 1.0900 | 1.0900 | 0.00 |
| **9** | 1.0291 | 1.0353 | **0.60** | 1.0682 | 1.0601 | 0.76 |
| **10** | 1.0282 | 1.0338 | 0.54 | 1.0614 | 1.0545 | 0.65 |
| **11** | 1.0446 | 1.0480 | 0.32 | 1.0623 | 1.0587 | 0.34 |
| **12** | 1.0535 | 1.0539 | 0.04 | 1.0543 | 1.0555 | 0.11 |
| **13** | 1.0459 | 1.0472 | 0.13 | 1.0525 | 1.0510 | 0.14 |
| **14** | 1.0179 | 1.0225 | 0.45 | 1.0422 | 1.0382 | 0.39 |

Calculated post-outage reactive power flows for the two representative outages of IEEE 14 Bus test system are illustrated in Table 2. Maximum reactive power flow errors are found to be 2.66 MVar and 8.17 MVar for the outage of the line connected between bus 7 and bus 9 and for the outage of the transfomer connected between bus 5 and bus 6, respectively. Even though the reactive power flow errors are high, they are less than the ones reported in the literature. These high computational errors are thought to be originated due to the size of the sample system and are expected to decrease for greater ones.

Table 2. Two Representative Outages and Corresponding Post-Outage Reactive Power Flows for IEEE 14 Bus Test System

| | **Outage of Line 7-9** | | | **Outage of Tr. 5-6** | | |
|---|---|---|---|---|---|---|
| **Line** | $Q_{PF}$ | $Q_{PSO}$ | $Q_E$ | $Q_{PF}$ | $Q_{PSO}$ | $Q_E$ |
| 1-2 | $-20.26$ | $-20.21$ | 0.05 | $-21.47$ | $-21.03$ | 0.44 |
| 1-5 | 4.73 | 3.76 | 0.97 | 0.41 | $-3.01$ | 3.42 |
| 2-3 | 3.62 | 3.63 | 0.01 | 3.31 | 3.34 | 0.03 |
| 2-4 | $-0.78$ | $-1.27$ | 0.49 | $-3.04$ | $-7.68$ | 4.64 |
| 2-5 | 1.99 | 0.80 | 1.19 | $-2.37$ | $-6.27$ | 3.90 |
| 3-4 | 5.19 | 4.69 | 0.50 | 3.14 | $-1.06$ | 4.20 |
| 4-5 | 14.82 | 12.16 | **2.66** | 11.79 | 15.22 | 3.43 |
| 4-7 | $-13.55$ | $-14.52$ | 0.97 | $-9.15$ | $-4.56$ | 4.59 |
| 4-9 | 6.12 | 5.34 | 0.78 | $-0.61$ | 2.86 | 3.47 |
| 5-6 | 13.17 | 14.31 | 1.14 | 0.00 | 42.72 | |
| 6-11 | 5.99 | 4.01 | 1.98 | 14.14 | 14.86 | 0.72 |
| 6-12 | 2.64 | 2.43 | 0.21 | 4.39 | 4.10 | 0.29 |
| 6-13 | 8.58 | 7.43 | 1.15 | 12.35 | 12.90 | 0.55 |
| 7-8 | $-13.90$ | $-12.24$ | 1.66 | $-14.73$ | $-14.66$ | 0.07 |
| 7-9 | 0.00 | 47.39 | | $-0.93$ | 7.24 | **8.17** |
| 9-10 | 2.46 | 3.40 | 0.94 | $-3.51$ | $-4.42$ | 0.91 |
| 9-14 | 2.55 | 3.38 | 0.83 | $-1.61$ | $-2.64$ | 1.03 |
| 10-11 | $-3.35$ | $-1.20$ | 2.15 | $-10.15$ | $-11.04$ | 0.89 |
| 12-13 | 0.85 | 0.52 | 0.33 | 2.70 | 2.82 | 0.12 |
| 13-14 | 2.95 | 1.96 | 0.99 | 9.04 | 9.06 | 0.02 |

Two outages are simulated for IEEE 30 bus test system. The first one is the outage of the line connected between bus 4 and bus 6 whose pre-outage reactive power flow is $-33.14$ MVar. The second one is the outage of the transformer connected between bus 5 and bus 6 whose pre-outage reactive power flow is 22.85 MVar. Table 3 shows the post outage voltage magnitudes for those representative outages. Maximum percentage voltage magnitude errors for the outage of the line and for the outage of the transformer are 0.52 and 0.63 respectively.

Table 3. Two Representative Outages and Corresponding Post-Outage Voltage Magnitude Calculations for IEEE 30 Bus Test System

| | **Outage of Line 4-6** | | | **Outage of Tr. 4-12** | | |
|---|---|---|---|---|---|---|
| **Bus No** | $V_{AC}$ | $V_{PSO}$ | **Err(%)** | $V_{AC}$ | $V_{PSO}$ | **Err(%)** |
| 1 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 2 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 3 | 1.0233 | 1.0223 | 0.09 | 1.0419 | 1.0454 | 0.34 |
| 4 | 1.0165 | 1.0155 | 0.09 | 1.0396 | 1.0439 | 0.42 |
| 5 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 6 | 1.0399 | 1.0411 | 0.12 | 1.0381 | 1.0408 | 0.26 |
| 7 | 1.0364 | 1.0373 | 0.09 | 1.0355 | 1.0371 | 0.15 |
| 8 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 9 | 1.0507 | 1.0532 | 0.24 | 1.0498 | 1.0482 | 0.15 |
| 10 | 1.0449 | 1.0499 | 0.48 | 1.0462 | 1.0398 | 0.62 |
| 11 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 12 | 1.0526 | 1.0507 | 0.17 | 1.0252 | 1.0220 | 0.31 |
| 13 | 1.0500 | 1.0500 | 0.00 | 1.0500 | 1.0500 | 0.00 |
| 14 | 1.0392 | 1.0376 | 0.15 | 1.0131 | 1.0109 | 0.21 |
| 15 | 1.0339 | 1.0347 | 0.07 | 1.0150 | 1.0109 | 0.41 |
| 16 | 1.0397 | 1.0427 | 0.29 | 1.0288 | 1.0222 | **0.63** |
| 17 | 1.0387 | 1.0427 | 0.39 | 1.0348 | 1.0292 | 0.53 |
| 18 | 1.0253 | 1.0279 | 0.25 | 1.0136 | 1.0089 | 0.47 |
| 19 | 1.0235 | 1.0270 | 0.34 | 1.0161 | 1.0109 | 0.51 |
| 20 | 1.0280 | 1.0320 | 0.38 | 1.0229 | 1.0173 | 0.54 |
| 21 | 1.0329 | 1.0379 | 0.48 | 1.0334 | 1.0272 | 0.60 |
| 22 | 1.0336 | 1.0385 | 0.47 | 1.0338 | 1.0277 | 0.59 |
| 23 | 1.0260 | 1.0282 | 0.22 | 1.0133 | 1.0091 | 0.42 |
| 24 | 1.0243 | 1.0280 | 0.37 | 1.0198 | 1.0150 | 0.46 |
| 25 | 1.0285 | 1.0334 | 0.47 | 1.0306 | 1.0252 | 0.53 |
| 26 | 1.0110 | 1.0160 | 0.49 | 1.0132 | 1.0077 | 0.54 |
| 27 | 1.0400 | 1.0452 | 0.50 | 1.0457 | 1.0399 | 0.56 |
| 28 | 1.0376 | 1.0386 | 0.10 | 1.0357 | 1.0378 | 0.20 |
| 29 | 1.0205 | 1.0257 | 0.52 | 1.0264 | 1.0205 | 0.57 |
| 30 | 1.0092 | 1.0145 | **0.52** | 1.0152 | 1.0093 | 0.58 |

In table 4, post outage reactive power flows, for the two representative outages in IEEE 30 Bus test system are given. Maximum reactive power flow errors are calculated to be 2.38 MVar and 5.70 MVar for the outage of the line connected between bus 4 and bus 6 and for the outage of the transfomer connected between bus 4 and bus 12, respectively. These errors are smaller than the ones computed for IEEE 14 Bus test system.

## 5. CONCLUSIONS

The aim of the study is to provide relevant information for an improved line outage management. Post outage bus voltage magnitude and reactive power flow calculations by PSO method has been introduced. Local constrained optimization problem representing the line outage phenomena has been solved by PSO. Efficiency of the proposed solution algorithm was tested on IEEE 14 Bus and IEEE

Table 4. Two Representative Outages and Corresponding Post-Outage Reactive Power Flows for IEEE 30 Bus Test System

| | **Outage of Line 4-6** | | | **Outage of Tr. 4-12** | | |
|---|---|---|---|---|---|---|
| **Line** | $Q_{PF}$ | $Q_{PSO}$ | $Q_E$ | $Q_{PF}$ | $Q_{PSO}$ | $Q_E$ |
| 1-2 | −39.12 | −38.55 | 0.57 | −34.82 | −34.723 | 0.10 |
| 1-3 | 3.50 | 3.87 | 0.37 | −10.94 | −12.80 | 1.86 |
| 2-4 | 13.72 | 13.59 | 0.13 | −6.23 | −8.20 | 1.97 |
| 3-4 | 3.38 | 2.70 | 0.68 | −13.56 | −15.22 | 1.66 |
| 2-5 | −15.43 | −15.46 | 0.03 | −14.42 | −14.43 | 0.01 |
| 2-6 | −16.59 | −17.12 | 0.53 | −10.34 | −11.74 | 1.40 |
| 4-6 | 0.00 | −121.87 | | −19.68 | −17.33 | 2.35 |
| 5-7 | 10.54 | 10.23 | 0.31 | 15.70 | 14.59 | 1.11 |
| 6-7 | −3.20 | −3.15 | 0.05 | −7.64 | −6.55 | 1.09 |
| 6-8 | −31.24 | −29.15 | 2.09 | −35.97 | −30.27 | **5.70** |
| 6-9 | 6.55 | 5.89 | 0.66 | 7.23 | 9.57 | 2.34 |
| 6-10 | 5.64 | 4.91 | 0.73 | 6.21 | 8.08 | 1.87 |
| 9-11 | 0.45 | 1.73 | 1.28 | 0.01 | −0.80 | 0.81 |
| 9-10 | 5.79 | 3.41 | **2.38** | 4.59 | 9.22 | 4.63 |
| 4-12 | 18.92 | 19.26 | 0.34 | 0.00 | 52.75 | |
| 12-13 | 2.03 | 0.64 | 1.39 | −18.07 | −20.37 | 2.30 |
| 12-14 | 1.05 | 1.00 | 0.05 | 2.77 | 2.65 | 0.12 |
| 12-15 | 2.67 | 1.48 | 1.19 | 5.89 | 6.76 | 0.87 |
| 12-16 | −0.32 | −1.89 | 1.57 | 1.91 | 3.48 | 1.57 |
| 14-15 | −0.76 | −0.96 | 0.20 | 1.10 | 1.39 | 0.29 |
| 16-17 | −2.56 | −2.82 | 0.26 | −0.01 | −0.40 | 0.39 |
| 15-18 | −0.80 | −1.21 | 0.41 | 1.66 | 1.97 | 0.31 |
| 18-19 | −1.91 | −2.21 | 0.30 | 0.74 | 1.06 | 0.32 |
| 19-20 | −5.37 | −5.66 | 0.29 | −2.69 | −2.27 | 0.42 |
| 10-20 | 6.22 | 6.49 | 0.27 | 4.15 | 3.66 | 0.49 |
| 10-17 | 8.68 | 9.40 | 0.72 | 6.40 | 5.22 | 1.18 |
| 10-21 | 9.81 | 9.93 | 0.12 | 9.64 | 9.32 | 0.32 |
| 10-22 | 4.48 | 4.56 | 0.08 | 4.34 | 4.13 | 0.21 |
| 21-22 | −1.61 | −1.49 | 0.12 | −1.84 | −2.16 | 0.32 |
| 15-23 | −0.56 | −0.90 | 0.34 | 2.76 | 2.89 | 0.13 |
| 22-24 | 2.77 | 3.04 | 0.27 | 2.36 | 1.69 | 0.67 |
| 23-24 | −2.33 | −2.53 | 0.20 | 1.12 | 1.30 | 0.18 |
| 24-25 | −2.21 | −2.27 | 0.06 | 0.66 | 0.80 | 0.14 |
| 25-26 | 2.37 | 2.36 | 0.01 | 2.36 | 2.36 | 0.00 |
| 25-27 | −4.60 | −4.62 | 0.02 | −1.86 | −1.65 | 0.21 |
| 28-27 | 9.05 | 7.90 | 1.15 | 7.56 | 9.82 | 2.26 |
| 27-29 | 1.66 | 1.66 | 0.00 | 1.66 | 1.66 | 0.00 |
| 27-30 | 1.65 | 1.65 | 0.00 | 1.65 | 1.65 | 0.00 |
| 29-30 | 0.60 | 0.60 | 0.00 | 0.60 | 0.60 | 0.00 |
| 8-28 | 4.03 | 3.67 | 0.36 | 4.44 | 3.48 | 0.96 |
| 6-28 | −0.85 | −0.64 | 0.21 | −2.57 | −1.78 | 0.79 |

30 Bus Test systems. Bus voltage magnitude and reactive power flow calculations are compared with of the full AC load flow results from the point of calculation accuracy. The results have shown that the problem can effectively be solved by PSO with reasonable accuracies. However, solutions speeds are still need to be improved by parallel implementation of the proposed evolutionary algorithm.

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