Double Branch Outage Modeling and Its Solution Using Differential Evolution Method

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***Abstract*—Power system operators need to check the system security by contingency analysis, which requires power flow solutions repeatedly. AC power flow is computationally slow even for a moderately sized system. Thus, fast and accurate outage models and approximated solutions have been developed. This paper adopts a single branch outage model to a double branch outage one. The final constrained optimization problem resulted from modeling is then solved by using differential evolution method. Simulation results for IEEE 30 and 118 bus test systems are presented and compared to those of full AC load flow in terms of solution accuracy.**

***Index Terms*—branch outage modeling, differential evolution, double branch outage, optimization, post outage state.**

I. Introduction

In the last two to three decades, electrical power systems have gone through restructuring process, which changed the nature of the system. One of the major challenges of the near future is the evolution of power system to the “smart networks”. With this new evolution idea, power system has been subjected to the several issues such as measuring, protection, communication issues as well as distributed generation facilities. New mobile consumers such as plug-in hybrid cars and new generation and storage elements such as solar cells and batteries have been introduced.

Outage of any components in a smart grid environment may cause significant problems in the system. Power system operators need to simulate the possible contingencies and take remedial actions in time. By simulating an outage, a power system operator can predict the post outage voltage magnitudes and post outage power flows. Full AC load flow, which is a time consuming process, can be used to determine the exact post-outage state. Because of high simulation cases required for a contingency analysis, fast and accurate models have been developed. DC power flow [1] is one of these methods, but it can’t handle reactive power and bus voltage magnitude calculations. Other methods [2]–[4] use linearized models but they do not provide enough accuracy.

A faster and more accurate model was developed in [5]. This model, formulates the branch outage problem as a local constrained optimization problem. Bus voltage magnitude values determined from the linearized reactive power equations are revised in a local optimization cycle. Since, the model uses only restricted group of network variables, it is fast and the results show that it provides better accuracy than the traditional methods [5]. Single branch outage simulation problem has been solved by Lagrange multiplier method [5], genetic algorithms [6], particle swarm optimization method [7], differential evolution method and harmony search method [8].

The number of single branch outages is the number of branches in the system at hand. However, the number of double branch outages is proportional to the square of the number of the branches [9]. Multiple branch outages have been simulated in [10], [11].

This paper presents the adoption of single branch outage modeling to double branch outage modeling and uses the differential evolution method to solive the final local constrained optimization problem. Differential evolution method was firstly introduced by Storn and Price [12], [13]. It is a stochastic direct search optimization method. Differential evolution is a population based algorithm and it has similar operators as those of the other evolutionary algorithms, such as crossover, mutation and selection. Differential evolution has been applied to several power system problems, such as, economic dispatch [14], power system planning [15], transient stability constrained optimal power flow [16], generation expansion planning [17], and unit commitment [18], etc.

The rest of the paper is organized as follows. In the second part, the proposed model for double branch outages is given. Differential evolution algorithm is given in the third part. The fourth part of the study gives simulation results for IEEE 30 and 118 bus test systems. The conclusion is provided in the last section.

II. Double Branch Outage Modeling

Single branch outage model in [5] is selected as the starting point of double branch outage modeling. Assume that the branches between buses i and j, and the branches between buses k and l are simultaneously outaged. The first branch outage is simulated by using fictitious source pairs Q_{si} and Q_{sj}, and the second branch outage is simulated by using fictitious source pairs Q_{sk} and Q_{sl}. The model for this simulation is shown in Fig. 1.

Constrained optimization problem representing a single branch outage was previously formulated for a bounded region in [5]. This study extends that formulation and defines a bounded region for a double branch outage as the union of individual bounded regions of the outaged branches.

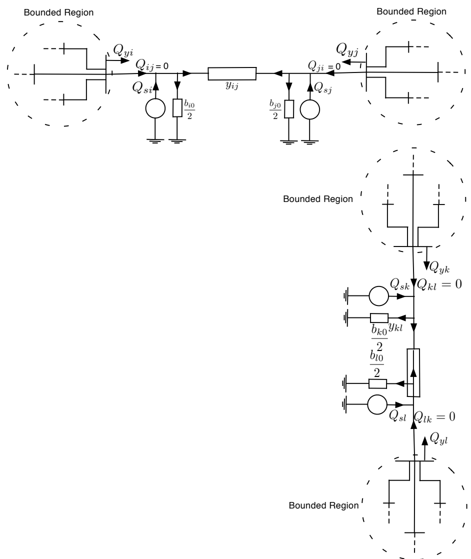

Fig. 1. Double branch outage modeling using fictitious sources

The steps of double branch outage modeling can be given as follows,

- Select two branches to be outaged and number them as: ij, and kl.
- Compute the bus voltage angles by using the linearized active power equations as shown below.

$$\delta_m = \delta_m + (X_{mi} - X_{mj}) \triangle P_n + (X_{mk} - X_{ml}) \triangle P_r \quad l = 2, 3, \cdots, \text{NB}$$

$$\triangle P_n = \frac{P_{ij}}{[1 - (\mathbf{X_{ii}} + \mathbf{X_{jj}} - \mathbf{2X_{ij}})/\mathbf{x_n}]} \qquad \triangle P_r = \frac{P_{kl}}{[1 - (\mathbf{X_{kk}} + \mathbf{X_{ll}} - \mathbf{2X_{kl}})/\mathbf{x_r}]} \tag{1}$$

  where, X_{ij} represents the ith row, jth column element of the bus susceptance matrix, X_{kl} represents the kth row, lth column element of the bus susceptance matrix, P_{ij} and P_{kl} are the pre-outage active power flows through the outaged branches, and x_n and x_r represent the reactance of the branches at hand.
- Calculate the loss reactive powers, represented as $\tilde{Q}_{Li} \cong \tilde{Q}_{Lj}$, $\tilde{Q}_{Lk} \cong \tilde{Q}_{Ll}$, for the optimization cycle.
- Minimize reactive power mismatches at buses i, j, k and l. This process is mathematically equivalent to the following constrained optimization problem.

$$\begin{aligned} \min_{wrt\ Q_{si}, Q_{sk}} \quad & \parallel Q_i - (\overline{Q}_{ij} + \overline{Q}_{Li}) + Q_{Di} \\ & Q_j - (-\overline{Q}_{ij} + \overline{Q}_{Li}) + Q_{Dj} \\ & Q_k - (\overline{Q}_{kl} + \overline{Q}_{Lk}) + Q_{Dk} \\ & Q_l - (-\overline{Q}_{kl} + \overline{Q}_{Li}) + Q_{Dl} \parallel \\ \text{subject to} \quad & g_q(V_b) = \triangle Q_b - B_b \triangle V_b = 0 \end{aligned} \tag{2}$$

where, $\parallel \cdot \parallel$ is the Euclidean norm of a vector. The constraint part of (II) is linearized reactive power equation for load buses, $\triangle Q_b$ is the reactive power mismatch vector in the bounded region, V_b is the load bus voltage magnitude vector in the bounded region and B_b is the bus susceptance matrix for the bounded region.

III. Differential Evolution Method

A. Differential Evolution Algorithm for Double Branch Outage Solution

Differential evolution (DE) algorithm for double branch outage problem is given as follows.

1) Run a power flow to obtain pre-outage bus voltage magnitudes.
2) Create matrix A, dimensions of which is $Np \times 2$, where Np represents the number of elements in a population. The elements of the first column of the initial matrix A are in between $Q_{ij} \pm \omega$ and the elements of the second column of the initial matrix A are in between $Q_{kl} \pm \omega$. Here ω is a user defined number, which limits the search space.
3) Let buses in the bounded region obtained for the first branch outage be named as; Bound1 and for the second branch outage be named as; Bound2. The union of these two sets Union can be found as follows:

$$\text{Union} = \text{Bound1} \cup \text{Bound2} \tag{3}$$

4) For every element of the first column of $\mathbf{A}$ matrix, perform the computations given below. Note that there are only two nonzero elements included in $\triangle \boldsymbol{Q}_1$.

$$\begin{aligned} \triangle \boldsymbol{Q}_1 &= [0, 0, \cdots, A_{(1,i)}, \cdots, A_{(1,j)}, \cdots, 0]^T \\ \triangle \boldsymbol{Q}_1 &= [0, 0, \cdots, A_{(1,i)}, \cdots, \overline{A}_{(1,i)}, \cdots, 0]^T \\ \overline{A}_{(1,i)} &= -A_{(1,i)} + 2Q_{L1i} \end{aligned} \tag{4}$$

$$\begin{aligned} \triangle \mathbf{V_{union}} &= \mathbf{B_{union}^{-1}} \triangle \mathbf{Q_1} \\ \mathbf{V_{union_{one}}} &= \mathbf{V_{union}} + \triangle \mathbf{V_{union}} \end{aligned} \tag{5}$$

Similarly, using the second column elements of matrix A, perform the following computations:

$$\begin{aligned} \triangle \boldsymbol{Q}_2 &= [0, 0, \cdots, A_{(2,k)}, \cdots, A_{(2,l)}, \cdots, 0]^T \\ \triangle \boldsymbol{Q}_2 &= [0, 0, \cdots, A_{(2,k)}, \cdots, \overline{A}_{(2,k)}, \cdots, 0]^T \\ \overline{A}_{(2,k)} &= -A_{(2,k)} + 2Q_{L2k} \end{aligned} \tag{6}$$

$$\begin{aligned} \triangle \mathbf{V_{union}} &= \mathbf{B_{union}^{-1}} \triangle \mathbf{Q_2} \\ \mathbf{V_{union_{two}}} &= \mathbf{V_{union_{one}}} + \triangle \mathbf{V_{union}} \end{aligned} \tag{7}$$

5) Compute the objective functions (mismatch vector) for the revised load bus voltage magnitudes.
6) Perform the following steps until a stopping criterion is reached.

- Add the weighted sum of elements of the second columnt of **A** to the third one. Do this for all elements in a population and form a new mutant matrix.

$$A_{i,:}^{'(G)} = A_{(r3,:)}^{(G)} + F(A_{(r1,:)}^{(G)} - A_{(r2,:)}^{G}) \quad (8)$$

where, $i \neq r_1 \neq r_2 \neq r_3$, and r_1, r_2 ve r_3 are random numbers between 1 and Np.
- Create trial matrix. Randomly select a number from 1 to N_p for all the elements in the population. If this number is equal to the population index or smaller than another random number q than the mutant element is in the trial (T) matrix otherwise the element from A matrix is in the trial matrix.
- For every element of the first column of $\mathbf{T}$ matrix, perform the computations given below.

$$\begin{aligned} \triangle \boldsymbol{Q}_1 &= [0, 0, \cdots, T_{(1,i)}, \cdots, T_{(1,j)}, \cdots, 0]^T \\ \triangle \boldsymbol{Q}_1 &= [0, 0, \cdots, T_{(1,i)}, \cdots, \overline{T_{(1,i)}}, \cdots, 0]^T \\ \overline{T_{(1,i)}} &= -T_{(1,i)} + 2Q_{L1i} \end{aligned} \quad (9)$$

$$\begin{aligned} \triangle \mathbf{V_{union}} &= \mathbf{B_{union}^{-1}} \triangle \mathbf{Q_1} \quad (10) \\ \mathbf{V_{union_{one}}} &= \mathbf{V_{union}} + \triangle \mathbf{V_{union}} \quad (11) \end{aligned}$$

Similarly, using the second column elements of T matrix perform the following computations,

$$\begin{aligned} \triangle \boldsymbol{Q}_2 &= [0, 0, \cdots, T_{(2,k)}, \cdots, T_{(2,l)}, \cdots, 0]^T \\ \triangle \boldsymbol{Q}_2 &= [0, 0, \cdots, T_{(2,k)}, \cdots, \overline{T_{(2,k)}}, \cdots, 0]^T \\ \overline{T_{(2,k)}} &= -T_{(2,k)} + 2Q_{L2k} \end{aligned} \quad (12)$$

$$\begin{aligned} \triangle \mathbf{V_{union}} &= \mathbf{B_{union}^{-1}} \triangle \mathbf{Q_2} \quad (13) \\ \mathbf{V_{union_{two}}} &= \mathbf{V_{union_{one}}} + \triangle \mathbf{V_{union}} \quad (14) \end{aligned}$$

- In the selection step the algorithm decides whether the trial elements will be included in the new generation or not. This is done by computing the objective function values by using the new voltage magnitude values.
- Compare the function values obtained by trial matrix and A matrix one by one and decide which elements are to be included in the next generation.

7) Algorithm stops if a predefined stopping criterion is met, otherwise go to the step 2.

IV. Tests and Results

DE algorithm developed for post outage voltage magnitude calculations is tested on the IEEE 30 and 118 bus test systems. Open source electrical power system package Matpower [20] and Matlab are used as tools. All simulations are run on a laptop, that has a 2.20 GHz Core Duo CPU, and 2.0 GB Memory.

Tests are conducted for the double branch outages, which do not create convergence problems, do not cause islanding problem and do result in load bus voltages less than 0.8 p.u. Total of 1214 double branch outage simulations were performed for IEEE 30 bus test system and 15312 double branch outage simulations were performed for IEEE 118 bus test system.

There are two different outage configurations from the point of the system topology.

1) The buses in the bounded regions are disjoint, that is there are no common buses included in the separate bounded regions defined in Fig. 1.
2) The buses in the bounded region are not disjoint, that is at least one branch is included in two different bounded regions of Fig.1.

On the other hand, there are 3 different outage cases for each of the two topologies, namely:

(a) Outaged branches are either power transmission lines or underground cables. None of the outaged branches include a tap changing transformer between the outaged bus pairs.
(b) One of the outaged branch is a transmission line/underground cable and the other one includes a transformer between the outaged bus pairs.
(c) Both of the outaged branches include a transformer between the outaged bus pairs.

The results for different outage configurations are illustrated in the following tables for the test systems. Simultaneous outages of lines $3-4$ and $21-22$ is a typical example for Case 1a in IEEE 30 bus test system. Simulation results for this line-line contingency are illustrated in Table (I). Note that, voltage magnitudes of the critical buses showing a percentage error higher than a threshold value 0.04% are reported in the table. In the following tables, Bus No. represents the bus number, $V_{(AC)}$ represents the bus voltage magnitudes computed by using full AC load flow, $V_{(DE)}$ represents the bus voltage magnitudes computed by the proposed DE based solution of local constrained optimization problem, and Error $\%$ represents the percentage difference between $V_{(AC)}$ and $V_{(DE)}$. Note that maximum percentage error for this representative line-line outage is less than 0.06%.

TABLE I
BUS VOLTAGE MAGNITUDES FOR SIMULTANEOUS OUTAGES OF LINE 3-4 AND LINE 21-22 IN IEEE-30 BUS TEST SYSTEM

Bus No	$V_{(AC)}$	$V_{(DE)}$	(Error) %
6	1.0343	1.0349	0.0594
7	1.0331	1.0336	0.0482
12	1.0525	1.0530	0.0425
14	1.0390	1.0394	0.0471
21	1.0334	1.0328	0.0571
22	1.0394	1.0400	0.0592
24	1.0281	1.0286	0.0459
28	1.0336	1.0340	0.0462
max. error	-	-	**0.0594**

Simultaneous outages of branch $6-9$ and branch $14-15$ is a representative example for Case 1b type outage in IEEE 30 bus test system. Table (II) gives the simulation results for this case. Voltage magnitudes of the critical buses showing a percentage error higher than a threshold value 0.3% are reported in the table. Note that the maximum percentage error for this representative transformer-line outage is less than 0.4%. There is not any case corresponding to 1(c) type outage in IEEE 30 bus test system.

TABLE II
BUS VOLTAGE MAGNITUDES FOR SIMULTANEOUS OUTAGES OF TRANSFORMER 6-9 AND LINE 14-15 IN IEEE-30 BUS TEST SYSTEM

Bus No	$V_{(AC)}$	$V_{(DE)}$	(Error) %
10	1.0410	1.0449	0.3737
17	1.0358	1.0391	0.3141
20	1.0255	1.0287	0.3118
21	1.0294	1.0331	0.3609
22	1.0303	1.0339	0.3518
maks. hata	-	-	**0.3737**

Simultaneous outages of branch $19-20$ and branch $16-17$ is a representative example for Case 2a type outage in IEEE 30 bus test system. Bus-10 has a direct connection to Bus-20 and to Bus-17. Therefore, Bus-10 is included both in the neighborhood of the first outaged branch and in the neighborhood of the second outaged branch. Voltage magnitudes of the critical buses showing a percentage error higher than a threshold value (0.1%) are reported in Table ((III). Note that the maximum percentage error for this representative line-line outage is less than 0.71%. In addition, the variance of the percentage errors are high when compared with those of the previous outages.

TABLE III
BUS VOLTAGE MAGNITUDES FOR SIMULTANEOUS OUTAGES OF LINE 19-20 AND LINE 16-17 IN IEEE-30 BUS TEST SYSTEM

Bus No	$V_{(AC)}$	$V_{(DE)}$	(Error) %
15	1.0282	1.0268	0.1354
16	1.0448	1.0469	0.2046
17	1.0464	1.0449	0.1391
18	1.0046	0.9998	0.4834
19	0.9941	0.9870	0.7098
20	1.0505	1.0528	0.2143
23	1.0244	1.0233	0.1038
max. error	-	-	**0.7098**

Simultaneous outages of transformer $4-12$ and line $10-22$ is a representative example for Case 2b type outage in IEEE 30 bus test system. Bus-6 has a direct connection to Bus-4 and to Bus-10. Therefore, Bus-6 is included both in the neighborhood of the first outaged branch and in the neighborhood of the second outaged branch. Voltage magnitudes of the critical buses showing a percentage error higher than a threshold value (0.5%) are reported in Table ((IV). Note that the maximum percentage error for this representative transformer-line outage is less than 1.0%. In addition, the percentage errors are generally high when compared with those of the previous outages.

Simultaneous outages of transformer 28-27 and transformer 6-10 is a representative example for Case 2c type outage in IEEE 30 bus test system. Bus-8 has a direct connection to Bus-28 and to Bus-6. Therefore, Bus-8 is included both in the neighborhood of the first outaged branch and in the neighborhood of second outaged branch. Moreover, one terminal of the second outaged transformer (Bus-6) is in the bounded region of the first outaged transformer. Therefore, this is one of the worst cases from the point of computational accuracy. Voltage magnitudes of the critical buses showing a percentage error higher than a threshold value (0.5%) are reported in Table ((V). The maximum percentage error for this representative transformer-transformer outage is less than 2.75%. The percentage errors are high as being one of the worst double outages in the system.

TABLE IV
BUS VOLTAGE MAGNITUDES FOR SIMULTANEOUS OUTAGES OF TRANSFORMER 4-12 AND LINE 10-22 IN IEEE-30 BUS TEST SYSTEM

Bus No	$V_{(AC)}$	$V_{(DE)}$	(Error) %
10	1.0467	1.0407	0.5781
16	1.0288	1.0223	0.6307
17	1.0351	1.0299	0.5048
19	1.0159	1.0108	0.5057
20	1.0229	1.0175	0.5283
21	1.0286	1.0195	0.8864
22	1.0273	1.0172	0.9832
23	1.0110	1.0053	0.5628
24	1.0156	1.0082	0.7198
25	1.0281	1.0209	0.6990
26	1.0106	1.0034	0.7127
27	1.0442	1.0372	0.6720
29	1.0248	1.0178	0.6851
30	1.0136	1.0066	0.6915
max. error	-	-	**0.9832**

TABLE V
BUS VOLTAGE MAGNITUDES FOR SIMULTANEOUS OUTAGES OF TRANSFORMER 28-27 AND TRANSFORMER 6-10 IN IEEE-30 BUS TEST SYSTEM

Bus No	$V_{(AC)}$	$V_{(DE)}$	(Error) %
21	1.0088	1.0141	0.5328
22	1.0078	1.0133	0.5503
23	0.9958	1.0013	0.5527
24	0.9737	0.9822	0.8662
25	0.9139	0.9286	1.6076
26	0.8942	0.9104	1.8183
27	0.8888	0.9049	1.8050
29	0.8656	0.8860	2.3620
30	0.8521	0.8755	2.7379
max. error	-	-	**2.7379**

Figures (2) and (3) show the highest voltage magnitude percentage errors for the entire possible simultaneous double branch outages in IEEE 30 Bus and 118 bus test systems, respectively. As can be seen from the figures, the maximum percentage errors are low for most of the simulated double branch outages. For IEEE 30 bus test system, mean value and the standard deviation of the highest voltage magnitude percentage error per simulation are found to be 0.873% and 1.792 respectively. For IEEE 118 bus test system, these values are found to be 0.425% and 0.674 respectively. Note that, the maximum percentage voltage magnitude error per double outage was decreased as the system size increased.

The number of critical double-branch outages giving maximum percentage errors greater than 5% is 20 and 42 for IEEE 30 bus test system and IEEE 118 bus test system,

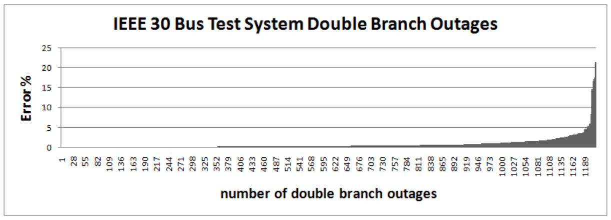

Fig. 2. Double Branch Outage simulations and their maximum errors in IEEE 30 bus test system

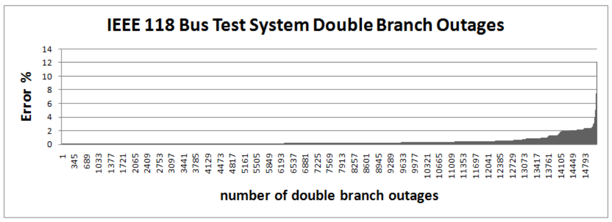

Fig. 3. Double Branch Outage simulations and their maximum errors in IEEE 118 bus test system

TABLE VII
CRITICAL DOUBLE BRANCH OUTAGES AND CORRESPONDING HIGH VOLTAGE MAGNITUDE ERRORS IN IEEE 118 BUS TEST SYSTEM

The first outaged branch	The second outaged branch	Error %
$23-24$	$22-23$	$5,00$
$16-17$	$8-5$	$5,13$
$8-5$	$30-17$	$5,15$
$34-43$	$38-37$	$5,39$
$14-15$	$8-5$	$5,62$
$100-106$	$105-106$	$5,67$
$23-32$	$22-23$	$5,78$
$44-45$	$38-65$	$5,78$
$53-54$	$49-51$	$6,13$
$22-23$	$26-30$	$6,34$
$34-43$	$38-65$	$6,58$
$22-23$	$23-25$	$7,12$
$56-58$	$49-51$	$7,49$
$8-5$	$3-5$	$8,19$
$49-51$	$51-58$	$8,55$
$11-12$	$11-13$	$8,66$
$38-65$	$38-37$	$9,49$
$12-14$	$8-5$	$9,63$
$12-16$	$8-5$	$10,42$
$8-5$	$11-13$	$11,32$
$30-38$	$38-37$	$12,13$

respectively. They correspond to 1.65% and 0.27% of entire outages in IEEE 30 bus test system and in IEEE 118 bus test system, respectively. Tables (VI) and (VII) illustrate those critical outages and corresponding maximum voltage magnitude percentage errors for the two test systems. Tables show the half number of the simulated double branch outages since, the other half is the symmetric branch outages. From a detailed analyze of the outages we can easily conclude that almost all the critical outages are Case-2 type outages. Among them, the followings give more severe results:

- One of the terminals of the outaged branch is included in the bounded region of the other outaged branch.
- There is a common bus between the terminals of the two outaged branches.

TABLE VI
CRITICAL DOUBLE BRANCH OUTAGES AND CORRESPONDING HIGH VOLTAGE MAGNITUDE ERRORS IN IEEE 30 BUS TEST SYSTEM

The first outaged branch	The second outaged branch	Error%
$4-6$	$6-8$	5.223
$9-10$	$6-10$	5.280
$15-23$	$28-27$	5.496
$9-10$	$28-27$	6.049
$12-15$	$12-14$	8.329
$6-28$	$6-8$	14.62
$6-28$	$28-27$	16.56
$6-28$	$8-28$	17.23
$10-21$	$10-22$	17.60
$8-28$	$28-27$	21.35

The highest maximum voltage magnitude error in IEEE 30 bus test system (see Table (VI)) is found for the simultaneous outage of line 8-28 and transformer 28-27. Bus-28 is the common terminal bus of the both outaged branches. Bounded regions for the two outaged branches are $\{6,8,27,28\}$ and $\{6,8,25,27,28,29,30\}$, respectively. Since, the first bounded region is a subset of the second one, no element other than elements in the second set is involved in the union set which is computed in the solution of double branch outages. In addition post-outage voltage magnitude of Bus-30 is found to be 0.86 p.u. which is low enough to create high computational errors for such an approximated modeling.

A similar case occurs for the simultaneous outage of lines $10-21$ and $10-22$. As in the previous case, this case also includes a common bus (Bus no: 10). Two bounded regions for this case are: $\{6,9,10,17,20,21,22\}$ and $\{6,9,10,17,20,21,22,24\}$ respectively. The first bounded region is again the subset of the second one. Similar to the previous case, the bus voltage magnitude for bus no: 21 is found to be 0.87 p.u. which is a low value to create high computational errors.

Another double line outage with high error is the outage of lines $6-28$ and $8-28$, which includes a common bus (Bus no: 28). Bounded regions for this double line outage are: $\{6,8,27,28\}$ and $\{2,4,6,7,8,9,10,27,28\}$ respectively. Similar to the previous cases, the first bounded region is again a subset of the second one. The bus voltage magnitude computed by full AC load flow is again a very low enough value: 0.86 p.u. (bus 30) to create the similar problems.

Line $6-28$ and transformer $28-27$ outage has bus 28 as a common bus. Bounded regions for this case are: $\{2,4,6,7,8,9,10,27,28\}$ and $\{6,8,25,27,28,29,30\}$ respectively. None of the bounded regions is a subset of the other in this case. However, bus voltage magnitude computed by AC load flow for bus 30 is 0.86 p.u.

If the other critical cases in Table (VI), are investigated, it can be seen that the outage of the line $15-23$ and transformer $28-27$ is different than the others as not including common branches in the separate bounded regions. However, bus voltage magnitude of Bus-30 is 0.82 and is low enough to create high computational errors because of high nonlinearities. On the other hand simultaneous outage of line $9-10$ and transformer $28-27$ is a special case. Bus-6 is included in the 3 of 4 bounded regions. Moreover, post-outage voltage magnitude of Bus-30 is again 0.82 as being the source of high errors.

The highest maximum voltage magnitude error in IEEE 118 bus test system (see Table (VII)) is found for the simultaneous outage of line $30-38$ and transformer $38-37$. Bus-38 is the common terminal bus of the both outaged branches. The bounded regions for the outaged branches can be found as $\{8,17,26,30,37,38,65\}$ and $\{30,33,34,35,37,38,39,40,65\}$. Four buses; namely Bus 30,37, 38 and 65 are included in both bounded regions.

Similarly, simultaneous outage of the line $11-13$ and transformer $8-5$ is one of the critical cases given in table (VII). The bounded regions are found as $\{4,5,11,12,13,14,15\}$ ve $\{3,4,5,6,8,9,11,30\}$. Buses 4,5 and 11 exists in both of two bounded regions. The highest error is obtained at bus 13, and the post-outage bus voltage magnitude for this bus is 0.90 p.u.

One other critical case is the simultaneous outage of the line $12-16$ and transformer $8-5$. The bounded regions for this case are $\{2,3,7,11,12,14,16,17,117\}$ and $\{3,4,5,6,8,9,11,30\}$ respectively. There are two critical buses included in both bounded regions. 0.93 p.u is the lowest post-outage bus voltage magnitude obtained using AC load flow. The remaining critical cases can be analyzed similarly.

V. Conclusion

This study has presented an extended version of an existing single branch outage model to account double-branch outages. A double branch outage phenomenon was first formulated as a local constrained optimization problem and was later solved by using differential evolution algorithm. The proposed formulation was finally tested on IEEE 30 bus test system and IEEE 118 bus test system.

Some sample simultaneous double branch outages representing the different configurations were simulated for IEEE 30 and 118 bus test systems and the results were compared with those of full AC load flow calculations in terms of accuracy. All the possible double contingency simulations for the test systems were evaluated from the point of maximum voltage magnitude percentage errors. Finally, critical double contingencies giving high computational errors were analyzed in detail. This analysis has shown that high computational errors were observed for the double contingencies where there is a common buses and/or for the double contingencies where there are one or more buses in the bounded region of the two outaged branches. Both of these two cases have resulted in unacceptable post-outage voltage magnitudes for one or more load buses in the system. These low bus voltage magnitudes caused high computational errors due to the high nonlinearities. Fortunately, although the computational errors were high for these critical contingencies, the proposed method did not fail to identify the insecure contingencies.

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