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Double branch outage modeling and simulation: Bounded network approach

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ABSTRACT

Energy management system operators perform regular outage simulations in order to ensure secure operation of power systems. AC power flow based outage simulations are not preferred because of insufficient computational speed. Hence several outage models and computational methods providing acceptable accuracy have been developed. On the other hand, double branch outages are critical rare events which can result in cascading outages and system collapse. This paper presents a double branch outage model and formulation of the phenomena as a constrained optimization problem. Optimization problem is then solved by using differential evolution method and particle swarm optimization algorithm. The proposed algorithm is applied to IEEE test systems. Computational accuracies of differential evolution based solutions and particle swarm optimization based solutions are discussed for IEEE 30 Bus Test System and IEEE 118 Bus Test System applications. IEEE 14 Bus Test System, IEEE 30 Bus Test System, IEEE 57 Bus Test System, IEEE 118 Bus Test System and IEEE 300 Bus Test System simulation results are compared to AC load flows in terms of computational speed. Finally the performance of the proposed method is analyzed for different outage configurations.

Introduction

Electric power systems have gone to restructuring process during the last two decades. One of the major challenges of the near future is the evolution to "smarter networks". With this new evolution idea, measurement, control, protection and communication tasks have been improved and distributed generation facilities have been extended.

Since the outage of the components in this smart environment can cause significant problems, power system operators need to pre-simulate all possible contingencies. Those simulations provide the estimation of post outage voltage magnitudes and power flows by which they take the remedial actions on time. This can be achieved by resolving the AC load flow problem separately for each outage [1].

However it is a time-consuming process even for a moderate power system comprising hundreds of components. Therefore fast and accurate models have been developed for contingency analysis. DC load flow [2] was fast enough but it could not handle reactive power flows. Other methods [3–5] suffered from insufficient accuracy due to using linearized models. On the other hand, Taylor series based methods required large number of iterations to converge [6].

Power injection and solution by sensitivity matrices were used in [7,8]. Simulation results of [7] showed that the proposed method did not provide accurate results for voltage magnitudes and reactive power flows. [8] was not fast enough for real time operation. One recent paper solved the line outage problem using piecewise linear estimates [9]. A faster and more accurate model was developed in [10] where the line outage phenomena was simulated by inserting two fictitious sources, and post outage state calculation was formulated as a local constrained optimization problem. Bus voltage magnitudes were initially determined solving linearized reactive power equations and they were later improved by a local optimization process. Since, the model used only limited number of network variables, it was fast enough for real time applications providing better accuracy than the traditional methods [10]. Single branch outage problem was later solved by genetic algorithms [11], by particle swarm optimization method [12], by differential evolution method and by harmony search method [13].

The number of outages in a contingency analysis is proportional with the number of branches for single branch outages whereas it

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is proportional with the square of the number of branches for double branch outages [14]. Computation speed, therefore, becomes more important for double branch outages. Multiple line outages were simulated in [8]. However, there were only a few ”non-problematic” examples given for IEEE 118 Bus Test system.

Double branch outage modeling was initially proposed in [15], and solved by using differential evolution method. Later, it was solved by harmony search method [16]. This paper presents modeling of double branch outages by extending our previous work, formulating the process as a local constrained optimization problem and solution of the problem by differential evolution (DE) method and by particle swarm optimization (PSO) method. The validity of the proposed formulation is tested on IEEE 30 Bus Test System and on IEEE 118 Bus Test System. Post-outage voltage magnitudes calculated using the proposed formulation are compared with those of conventional full AC load flow results from the point of computational accuracy. Critical busses and outage types giving high computational bus voltage magnitude errors are identified and the reasons are criticized. Finally, comparisons are performed from the point of solution speed for several IEEE test systems.

The rest of the paper is organized as follows. In the second section, double line outage model is introduced. Adaptation of DE algorithm and PSO algorithm for double branch outage problem is briefly explained in the third section. Fourth section of the study illustrates the simulation results for several IEEE test systems. Fifth section concludes the paper.

Double branch outage simulation

Single branch outage model introduced in [10] was selected as a starting point of modeling double branch outages. Assume that the branch between busses i and j, and the branch between busses k and l are simultaneously outaged. The first branch outage and the second branch outage are simulated using fictitious pairs $Q_{si} - Q_{sj}$, and $Q_{sk} - Q_{sl}$ respectively. Double branch outage simulation is shown in Fig. 1.

The proposed double branch outage model is formulated for the union of the individual (marginal) bounded regions of the outaged branches. That is, it enforces all fictitious source reactive powers to circulate in the bounded region. Consequently, load bus voltage magnitudes of the busses in this union region are the parameters those will be optimized during the optimization cycle. Optimization cycle aims to minimize the additional reactive power flows between the bounded region and the remaining part of the network; that is, enforces all reactive power of the fictitious sources to circulate in the bounded region.

The steps of double branch outage solution can be given as follows [15],

- Select two lines to be outaged and assign them as: ij and kl.
- Compute bus voltage phase angles using the linearized active power equations as shown below.

$$\begin{aligned}
&\delta_m = \delta_m + (X_{mi} - X_{mj}) \triangle P_n + (X_{mk} - X_{ml}) \triangle P_r \\
&m = 2, 3, \cdots, \mathrm{NB} \\
&\triangle P_n = \frac{P_{ij}}{[1 - (X_{ii} + X_{jj} - 2X_{ij})/x_n]} \\
&\triangle P_r = \frac{P_{kl}}{[1 - (X_{kk} + X_{ll} - 2X_{kl})/x_r]}
\end{aligned} \tag{1}$$

where, X_{ij} represents the ith row, jth column entry of the bus susceptance matrix, P_{ij} and P_{kl} are the pre-outage active powers flowing through the outaged branches, and x_n and x_r represent the reactances of the branches.

- Calculate the loss reactive power components, $\widetilde{Q}_{Li} \cong \widetilde{Q}_{Lj}$, $\widetilde{Q}_{Lk} \cong \widetilde{Q}_{Ll}$, those will be used during the optimization.
- Minimize reactive power mismatches at busses i, j, k and l. This process is mathematically formulated by the following constrained optimization problem.

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

where, $\| \cdot \|$ is the Euclidean norm of the reactive power mismatch vector. Equality constraints of (2) are linearized reactive power equations for the load busses, $\triangle \boldsymbol{Q}$ is the reactive power mismatch vector, $\boldsymbol{V}$ is the load bus voltage magnitude vector and $\boldsymbol{B}$ is the bus susceptance matrix. The subscript b signifies the variables included in the bounded region.

DE and PSO algorithms for double branch outage problem solution

DE was first introduced by Storn and Price [17,18] and is a stochastic direct search optimization method. It is a population-based solution algorithm and uses the conventional operators of evolutionary algorithms. DE has been applied to several power system problems, such as, economic dispatch problem [19], power system planning [20], transient stability constrained optimal power flow [21], generation expansion planning [22], and unit commitment [23].

PSO was first introduced by Kennedy and Eberhart [24], mimicking the swarm behaviors of fish schools and birds. It was widely used in power system applications; such as, economic dispatch problem [25,26], transmission network expansion problem [27], and optimal load flow problem [28].

DE and PSO based solution procedure of double branch outage problem consists of two main stages. The first one includes the common steps for both methods; whereas the second one includes the individual steps of the methods.

Common steps of PSO and DE based double branch outage problem solution

1. Perform a power flow and determine pre-outage (base case) bus voltage magnitudes.
2. Create a random matrix, $\boldsymbol{A}$ whose dimensions is $Np \times 2$. The first column and the second column entries of $\boldsymbol{A}$ are in the range of $[Q_{ij} - \omega \quad Q_{ij} + \omega]$ and $[Q_{kl} - \omega \quad Q_{kl} - \omega]$ respectively. ω is a user defined parameter corresponding to half of the initial solution range.
3. Let the set of busses included in the bounded regions of the first outaged branch and the second outaged branch named as; BR_1 and BR_2, respectively. The set of the busses included either in BR_1 or in BR_2 will constitute the bounded region of double branch outage:

$$BR = BR_1 \cup BR_2 \tag{3}$$

4. Perform the following computations for each entry of the first column of $\boldsymbol{A}$.

$$\begin{aligned}
&\triangle \boldsymbol{Q_1} = [0, \ldots, A_{(1,i)}, \ldots, A_{(1,j)}, \ldots, 0]^T \\
&\triangle \boldsymbol{Q_1} = [0, \ldots, A_{(1,i)}, \ldots, \overline{A}_{(1,i)}, \ldots, 0]^T \\
&\overline{A}_{(1,i)} = -A_{(1,i)} + 2Q_{L1i}
\end{aligned} \tag{4}$$