Graph Theory Assisted Corrective Strategies for Overload Alleviation under Contingencies

Summary of the Synopsis

by

Manoj Kumar Maharana

Department of Electrical Engineering

Indian Institute of Technology Madras, India

November, 2009
1. Introduction

Electric power systems are subjected to various types of disturbances during their operation. The incidence of unexpected contingencies result in overloads in one or more transmission lines and forces the system to emergency operating state. Power system equipments are protected by automatic devices (relays) that can cause equipment to be switched out, if the system operating limits are violated. This can cause further deterioration of the overall health of the system if the overloaded lines are also tripped. If this process of cascading failure continues, the entire system or large part of the system may get disturbed, which is referred as system blackout. When disturbance occurs, corrective control strategies are required to stop the splitting of the power system and minimize the impact of the disturbances. Some of the basic techniques used to correct the systems are i) generator rescheduling, ii) load shedding, iii) line switching, etc.

Alleviation of contingency initiated transmission line overload is a critical problem in power system operation. Under emergency conditions system operator has to take quick decisions without considering the optimal operating point. A fast identification of participating generators, loads and suitable corrective strategies with local optimization concept are essential for secure and reliable operation of power system.

2. Motivation

The disturbance (outage) stresses the power system equipments and overloads the transmission lines. Minimum number of control action is essential for secure operation of power system. The direct methods for line overload alleviation are generation rescheduling and load shedding schemes [1, 2]. The mathematical calculation for entire system is computationally expensive and time consuming. Expert systems based on ANN configuration have been developed to alleviate line overloads [3]. Development and training of the expert system required large amount of data patterns and seldom the result obtained are not feasible.
due to random nature of contingency. Overload mitigation by line switching techniques [4-6] consider line overloads and do not give any consideration to bus voltages after line switching.

The zones are identified based on real and reactive transmission congestion distribution factor to alleviate line overloads [7]. Identification technique of participating generators [8, 9] and rescheduling their output based on local optimization approach [10] to alleviate line overloads have been used. Generator rescheduling based on relative electrical distance approach [11], reduction of participating generator and rescheduling was used for congestion management [12]. In some cases, closer values of generator sensitivity factors may result in critical situations, in which selection of participating generators become indistinct for overload alleviation. Selections of participating loads for curtailment also encounter the same problem.

The indistinct nature of sensitivity based participating generator identification approach and overloads alleviation, without considering bus voltage limit violation, motivates the need for an efficient, minimum computational based identification and reliable sub-optimal solution for power system operation after disturbance. Furthermore, graph theoretic techniques i.e. Direct Acyclic Graph (DAG) based on power flow tracing approach, were found to be more suitable for identification of the participating generators and loads. A number of power flow tracing based identification methods for variety of application have been presented [13-15].

3. Objectives and Scope

The main objectives of the study are the following.

1. Identification of the participating generators and loads of a power system to activate remedial control action during emergency operation.

2. Selection of appropriate corrective strategies by generator rescheduling and/or load shedding to avoid cascading outages.
A fast identification of the participating generators, loads and proper control actions are essential for secure and reliable operation of power system. This study is restricted to N-1 contingencies, covering both generators and transmission lines. The selection of contingency cases was considered randomly. Restoration and voltage collapse are out of scope of this work. For this work only active power rescheduling and both active and reactive load shedding has been considered.

4. Description of the research work

Alleviation of line overload is the suitable corrective strategy to avoid network contingencies. The overload alleviation problem can be solved by non-decomposed or decomposed approach. In the non-decomposed approach, the single optimization problem is solved with security constraints. This requires excessive computational storage and time. The decomposed approach is usually preferred keeping in view of the time and computational requirements. The graph theoretic approach is utilized to decompose the problem into two groups and the sub-problems are solved separately considering the base case operating point as reference, thereby improvements in computational time and storage. The basic block diagram of the proposed corrective strategy for contingency is shown in Fig. 1.

![Fig. 1 Basic block diagram of the proposed corrective strategy](image)

The pre and post contingency direct acyclic graph (DAG) are constructed with the help of generator areas (GA) (block 1-4). The identified Generator Decrease (GD) and
Generator Increase (GI) optimization problems are solved by particle swarm optimization (PSO) method (block 5). PSO is one of the evolutionary computation techniques [16] that can generate high quality solution within shorter calculation time and has stable convergence characteristics than other stochastic methods. The generator rescheduling (GR)/load shedding (LS) results obtained from PSO are the corrective strategies (block 6) which would bring back the system from abnormal operating state to normal operating state.

4.1 Graph theoretic modeling

A graph is a set of nodes and a set of edges. An acyclic graph is a graph with no path that starts and ends at the same node. There are no cycles in direct acyclic graph (DAG); i.e. if there is a path from node ‘a’ to node ‘b’, then there is no way back to node ‘a’ [17]. Graph theory organizes the buses and branches of the network into a homogeneous group according to the concept of ‘reach of a generator’ (ROG), ‘generator area’ (GA) and ‘links’. The homogeneous group developed using generator areas is called DAG and it is used to identify the participating generators and loads. The construction of ROG and GA are explained in Fig. 2(a) and (b) respectively.

4.1.1 Reach of a generator (ROG)

ROG is defined as the set of buses which are reached by power produced by that generator. Power from a generator reaches a particular bus if it is possible to find a path through the network from the generator to the bus for which the direction of travel is always consistent.

4.1.2 Generator area (GA)

The generator area is defined as a set of contiguous buses supplied by the same generator. Unconnected set of buses supplied by the same generator are treated as separate generator area.
4.1.3 Link

The link is defined as one or more branches connecting the different generator areas. Furthermore, the flow in a link is always from a generator area of rank $N$ to generator area of rank $M$ where $M$ is strictly greater than $N$.

(a) Reach of a generator (ROG)

(b) Generator area (GA)

Fig. 2 Construction of reach of a generator and generator area

4.2 Participating generator identification

Construct the pre and post contingency GA and DAG. The occurrence of contingency may change the occupied buses in the generator areas of DAG. Depending on the changes encountered in the post-contingency DAG with respect to the base case, the GD and GI groups are identified as follows.

4.2.1 Line outage case

Due to outage of line ‘$x$-$y$’, if bus ‘$x$’ is in the generator area ‘$k$’ in the pre-contingency DAG, then after contingency;

(i) if bus ‘$x$’ moves from generator area ‘$k$’ to generator area ‘$p$’, then the $k^{th}$ generator area and the generator areas injecting power to the ‘$x$-$y$’ line are identified as GD group. The
generator area ‘p’ and generator areas receiving power through outage line ‘x-y’ are declared as GI group.

(ii) If bus ‘x’ retains in generator area ‘k’ even after contingency, then the generator areas injecting power to the contingency line ‘x-y’ are identified as GD group. The generator areas receiving powers through outage line are declared as GI group.

(iii) Similarly there is a possibility for bus ‘y’ to move from generator area ‘m’ to generator area ‘n’, or retain in generator area ‘m’ itself. In such situations, the bus ‘y’ acquired by generator area (generator area ‘m’) and other generator areas receiving powers through ‘x-y’ line are identified as GI group.

(iv) The buses which remain unaltered in the generator areas are not considered in GD/GI group.

4.2.2 Generator outage case

The generator ‘p’ is connected to bus ‘x’ and bus ‘x’ was in generator area ‘p’ in the pre-contingency DAG. After the outage of generator ‘p’, the generator areas which are supplying power to the loads coming under the pre-contingency generator area ‘p’ are considered as generator increase (GI) group. In generator outage case, there is no generator decrease (GD) group.

4.3 Mathematical modeling

The mathematical modelling of generator rescheduling/load shedding optimization problem for the GD and GI groups are provided as follows.

4.3.1 Modeling of generator decrease (GD) group

The reduction of generation with respect to load can be modeled as classical economic load dispatch problem with line-flow and voltage limits as constraints. The objective is to minimize the total cost of generation $F_t$ given by
\[ F_t = \sum_{i=1}^{NG} (a_i P_{gi} + b_i P_{gi} + c_i) \]  

(1)

where \( NG \) is the number of GD group generators; \( a_i, b_i, c_i \) are the cost coefficient of the \( i^{th} \) generator and \( P_{gi} \) is the active power generated by \( i^{th} \) generator. The equality constraints are the load flow equations given by

\[
g(x) = 0 \approx \begin{bmatrix} \sum_{j \in \text{all}} G_{ij} v_i^2 - v_i v_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] = 0 \\ \sum_{j \in \text{all}} B_{ij} v_i^2 + v_i v_j [B_{ij} \cos(\theta_i - \theta_j) - G_{ij} \sin(\theta_i - \theta_j)] = 0 \end{bmatrix} \]

(2)

where \( P_i, Q_i \) are net real and reactive power injection at bus \( i \), \( G_{ij} \) and \( B_{ij} \) are real and imaginary part of \((i, j)^{th}\) element of bus admittance matrix, \( v_i, v_j \) are the bus voltages and \( \theta_i, \theta_j \) are the phase angles of \( i^{th} \) and \( j^{th} \) bus respectively. The fitness function \( F_t^* \) used in PSO and inequality constraints are provided as follows

\[
F_t^* = F_t + K_1 \sum_{i=1}^{NB} (v_i - v_i^{Lim})^2 + K_2 \sum_{j=1}^{NL} (S_{ij} - S_{ij}^{max})^2 + K_3 (P_{Slack} - P_{Lim}^{Slack})^2
\]

(3)

\[
h(x) \leq 0 \equiv \begin{bmatrix} P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} \\ v_i^{\min} \leq v_i \leq v_i^{\max} \\ S_{ij} \leq S_{ij}^{\max} \end{bmatrix}
\]

(4)

where \( NB \) is the number of buses, \( NL \) is the number of lines in the group. The penalty coefficients \( K_1, K_2 \) and \( K_3 \) are calculated as follows.

\[
K_1 = \frac{F_t}{(v^{\max})^2}, \quad K_2 = \frac{F_t}{(S_{ij}^{\max})^2}, \quad K_3 = \frac{F_t}{(P_{Slack}^{\max})^2}
\]

(5)

4.3.2 Modeling of generator increase (GI) group

In GI group, the aim is to increase the generation within its limit so as to meet the demand. If the above is not possible, resort to load shedding. The objective is to alleviate overloads in the overloaded lines (\( OVLines \)) given by
\[ L_t = \min_{ij \in \text{\textit{OVL}}} \left( S_{ij} - (S_{ij}^{\max} \times S_f) \right)^2 \]  

(6)

where \( S_{ij} \) is the MVA flow of \((i, j)\)th line and \( S_f \) is the factor of safety (generally 0.9 to 0.95).

The equality constraints are the load flow equations given by

\[
\begin{bmatrix}
\sum_{j \in \text{all}} G_{ij} v_i^2 - v_i v_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] = 0 \\
\sum_{j \in \text{all}} B_{ij} v_i^2 + v_i v_j [B_{ij} \cos(\theta_i - \theta_j) - G_{ij} \sin(\theta_i - \theta_j)] = 0
\end{bmatrix}
\]

(7)

where \( P_i, Q_i \) are net real and reactive power injection at bus \( i \); \( G_{ij} \) and \( B_{ij} \) are real and imaginary part of \((i, j)\)th element of bus admittance matrix; \( v_i, v_j \) are the bus voltages and \( \theta_i, \theta_j \) are the phase angles of \( i \)th and \( j \)th bus respectively. The fitness function \( F_t^* \) used in PSO and inequality constraints are provided as follows

\[
F_t^* = L_t + K_1 \sum_{i=1}^{NB} (v_i - v_i^{\text{Lim}})^2
\]

(8)

\[
h(x) \leq 0 \approx \begin{cases}
P_{g i}^{\text{min}} \leq P_{g i} \leq P_{g i}^{\text{max}} \\
Q_{g i}^{\text{min}} \leq Q_{g i} \leq Q_{g i}^{\text{max}} \\
v_i^{\text{min}} \leq v_i \leq v_i^{\text{max}}
\end{cases}
\]

(9)

The participating loads are reduced by a factor called load reduction factors (LRF) and defined as follows.

\[ \text{LRF} = \frac{\sum_{i \neq j} P_{ij} - \sum_{i \neq j} P_{ij}^{\text{base}}}{\text{Total Group Load}} \]

(10)

\[ \text{Modified load} = (1 - \text{LRF}) \times \text{Initial MVA load at the bus.} \]

(11)

where

\[ P_{ij} \quad \text{= the amount of real power injected to bus ‘}j\text{’ from bus ‘}i\text{’ after contingency} \]

\[ P_{ij}^{\text{base}} \quad \text{= base case power injected to bus ‘}j\text{’ from bus ‘}i\text{’} \]

\[ \text{Total Group Load} \quad \text{= Total MVA load in the generator increase Group.} \]
5. Results

To verify the effectiveness of the proposed corrective strategy, simulation was carried out for various IEEE standard systems (14, 30 and 118) and New England 39 bus system. The algorithm was implemented using MATLAB® 7.0 with a 2.66 GHz Pentium IV, 512 MB RAM personal computer. The upper and lower limits of load bus voltages were taken as 1.1 pu and 0.95 pu respectively. Line loading limits (MVA limits) of 125% of base case were considered. In PSO, a population size of 10, number of iterations limited to 50, parameters $c_1 = 2.0$, $c_2 = 2.1$, $w_{\text{max}} = 0.9$, $w_{\text{min}} = 0.4$ were considered. For each test case, 50 independent trials were carried out; and the results of best cases are tabulated. An acceptable variation from ±1% to ±10% is observed in few worst cases among the 50 trials.

The IEEE 30 bus system results are provided here to illustrate the working of the proposed approach. Outage of line 4-12 case, lines 1-2 and 2-6 overload alleviation case and generator G11 outage case are considered. The IEEE 30 bus system indicating different GA and base-case DAG based on graph theoretic approach is shown in Fig. 3 (a) and (b) respectively.
5.1 Corrective strategies for line 4-12 outage of IEEE 30 bus system

The DAG for outage of line 4-12 is shown in Fig. 4, where the GD and GI groups are identified by graph theoretic approach. The overloaded lines due to contingency are tabulated in Table 1.

Overload alleviation is achieved by rescheduling generators 1, 2, 8, 11, 13 and load shedding at the load buses 12, 14-19, 23 and 24 respectively. The results of the corrective strategy for outage of line 4-12 is shown in Table 1.

![Fig. 4 DAG after outage of line 4-12](image)

<table>
<thead>
<tr>
<th>Line 4-12 out (A) Max Cap.</th>
<th>(B) Contingency Flows</th>
<th>Generation schedule</th>
<th>Bus Load schedule</th>
<th>(C) Post cont. Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pre-contingency)</td>
<td>(Post Cont.)</td>
<td>(Pre-contingency)</td>
<td>(Post Cont.)</td>
<td>(Pre-contingency)</td>
</tr>
<tr>
<td>MVA</td>
<td>Bus</td>
<td>MW</td>
<td>MW</td>
<td>MW</td>
</tr>
<tr>
<td>4-6 48.23 62.68</td>
<td>1*</td>
<td>138.69</td>
<td>107.58</td>
<td>25.14</td>
</tr>
<tr>
<td>6-9 20.86 30.13</td>
<td>2*</td>
<td>57.56</td>
<td>59.17</td>
<td>2.68</td>
</tr>
<tr>
<td>6-10 14.79 20.34</td>
<td>5</td>
<td>24.56</td>
<td>24.56</td>
<td>7.77</td>
</tr>
<tr>
<td>9-10 41.15 47.67</td>
<td>8*</td>
<td>35.00</td>
<td>34.43</td>
<td>6.14</td>
</tr>
<tr>
<td>12-13 23.38 28.34</td>
<td>11*</td>
<td>17.93</td>
<td>22.33</td>
<td>13.48</td>
</tr>
<tr>
<td>16-17 5.11 9.56</td>
<td>13*</td>
<td>16.91</td>
<td>18.69</td>
<td>6.40</td>
</tr>
<tr>
<td>18-19 3.57 4.49</td>
<td>15*</td>
<td>8.57</td>
<td>4.69</td>
<td>0.78</td>
</tr>
<tr>
<td>19-20 9.09 13.77</td>
<td>16*</td>
<td>3.94</td>
<td>2.28</td>
<td>6.61</td>
</tr>
<tr>
<td>10-20 12.19 16.44</td>
<td>17*</td>
<td>10.71</td>
<td>6.21</td>
<td>9.05</td>
</tr>
<tr>
<td>10-17 8.56 18.92</td>
<td>18*</td>
<td>3.33</td>
<td>1.93</td>
<td>8.28</td>
</tr>
<tr>
<td>22-24 8.98 9.85</td>
<td>19*</td>
<td>10.09</td>
<td>5.85</td>
<td>8.16</td>
</tr>
<tr>
<td>23-24 3.19 5.91</td>
<td>20</td>
<td>2.31</td>
<td>2.31</td>
<td>1.12</td>
</tr>
<tr>
<td>24-25 1.88 5.46</td>
<td>21</td>
<td>20.77</td>
<td>20.77</td>
<td>1.18</td>
</tr>
<tr>
<td>25-27 4.32 8.28</td>
<td>23*</td>
<td>3.57</td>
<td>2.07</td>
<td>4.14</td>
</tr>
<tr>
<td>6-28 16.33 17.03</td>
<td>26</td>
<td>4.18</td>
<td>4.18</td>
<td>13.14</td>
</tr>
</tbody>
</table>

The '*' indicates the alteration of generation and loads as corrective control action at that bus.

It can be observed from Table 1 that the line flows after the occurrence of contingency (Column B) exceeds the MVA limits (Column A). The post-contingency flows (Column C) are within the MVA limits (Column A) after the corrective strategy as observed from Table 1.
5.2 Overload alleviation for line 1-2 and 2-6 of IEEE 30 bus system

The overload alleviation result for the line 1-2 and 2-6 of IEEE 30 bus system reported in [12] has been compared with the proposed DAG based participating generator identification approach result. The line overload alleviated by rescheduling the generators 1, 2, 5, 8 and 11 are given in Table 2.

Table 2: Comparison results for overload alleviation of line 1-2 and 2-6

<table>
<thead>
<tr>
<th>Generator Number</th>
<th>Gen. Limit (MW)</th>
<th>Base case Generation (MW)</th>
<th>Generator Rescheduling ΔP in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reference [12]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proposed Approach</td>
</tr>
<tr>
<td>1</td>
<td>150.00</td>
<td>138.69</td>
<td>-59.00</td>
</tr>
<tr>
<td>2</td>
<td>80.00</td>
<td>57.56</td>
<td>19.90</td>
</tr>
<tr>
<td>5</td>
<td>50.00</td>
<td>24.56</td>
<td>13.00</td>
</tr>
<tr>
<td>8</td>
<td>55.00</td>
<td>35.00</td>
<td>6.00</td>
</tr>
<tr>
<td>11</td>
<td>40.00</td>
<td>17.93</td>
<td>6.50</td>
</tr>
<tr>
<td>13</td>
<td>40.00</td>
<td>16.91</td>
<td>7.00</td>
</tr>
</tbody>
</table>

Total generation reschedule in MW 111.40

Table 3: Flow change through the lines after generator rescheduling

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Limit</th>
<th>Before Reschedule (MVA)</th>
<th>After Rescheduling (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference [12]</td>
<td>Proposed Approach</td>
<td></td>
</tr>
<tr>
<td>1-2</td>
<td>130.00</td>
<td>170.04</td>
<td>129.00</td>
</tr>
<tr>
<td>2-6</td>
<td>65.00</td>
<td>66.79</td>
<td>60.00</td>
</tr>
</tbody>
</table>

Table 3 provides the power flow results before and after the corrective strategy.

5.3 Corrective strategies for generator G_{11} outage of IEEE 30 bus system

Fig. 5(a) and (b) illustrate the base-case and the generator G_{11} outage case DAG indicating GI group.
The outage of generator $G_{11}$ alters the buses of the pre and post contingency generator areas.

The corrective strategy results for outage of generator $G_{11}$ is given in Table 4.

<table>
<thead>
<tr>
<th>Lines</th>
<th>Pre-contingency</th>
<th>Post-contingency</th>
<th>Pre-contingency</th>
<th>Post-contingency</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-9</td>
<td>138.69</td>
<td>131.36</td>
<td>10</td>
<td>10.14</td>
</tr>
<tr>
<td>12-16</td>
<td>57.56</td>
<td>66.40</td>
<td>10</td>
<td>6.14</td>
</tr>
<tr>
<td>14-15</td>
<td>24.56</td>
<td>24.56</td>
<td>17</td>
<td>10.71</td>
</tr>
<tr>
<td>16-17</td>
<td>35.00</td>
<td>37.90</td>
<td>19</td>
<td>10.09</td>
</tr>
<tr>
<td>18-19</td>
<td>17.93</td>
<td>--</td>
<td>21</td>
<td>20.77</td>
</tr>
<tr>
<td>21-22</td>
<td>16.91</td>
<td>16.91</td>
<td>24</td>
<td>10.98</td>
</tr>
<tr>
<td>23-24</td>
<td>13.86</td>
<td>13.86</td>
<td>26</td>
<td>4.19</td>
</tr>
</tbody>
</table>

The '*' indicates the alteration of generation and loads as corrective control action at that bus.

From Table 4 it is observed that the overloading of lines are removed by rescheduling generators 1, 2, 8 and load shedding at the load buses 17, 19, 21, 24 and 26 respectively. The post-contingency flows (Column C) are within the MVA limits (Column A) after the control strategy.

5.4 Observation

From the above results of three case studies, it is observed that the proposed graph theory assisted corrective strategy method can alleviate the line overloads due to contingency, thereby preventing the cascading outages.

6. Conclusions

Application of graph theory assisted corrective strategy for power system under contingencies has provided the following important conclusions.

Participating generators and loads are identified by Direct Acyclic Graph (DAG). In graph theory approach, the mathematical computation is relatively less compared to other sensitivity based methods. The number of participating generators as obtained by graph theory approach is relatively few compared to other sensitivity methods. Apart from identification, the DAG provides the information about the contribution from generators to
loads. In the decomposition approach, the rescheduling of minimum number of generators are effective and the computational storage and time required is less. This provides a quicker control under emergency condition. The concept of local optimization is utilized i.e. a fewer buses are processed for local optimization, irrespective of the size of the network, which facilitates the operator to arrive at a good sub-optimal solution quickly.

7. References


8. List of Publications based on the research work

Journal Publications


Conference Proceedings


3. Manoj Kumar Maharana and K. S. Swarup, “Particle Swarm Optimization based Corrective Strategy to Alleviate Overloads in Power System”, World Congress on Nature and Biologically Inspired Computing (NaBIC-09), December 09-11, Coimbatore, India.