Power System Security by Corrective Switching

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Abstract

Limit violations may occur by power systems operation, such as: voltage level at buses, loadings of transmission lines and power transformers, etc. If violations are detected in the supervision process, corrective measures may be carried out in order to eliminate them or to reduce their intensity. Loading shedding is an extreme solution and should only be adopted as the last control action. It is possible to control constraints in electrical systems by changing the network topology, using a technique named Corrective Switching, which requires no additional costs. The main problem of finding a switching variant to eliminate overloads in transmission links is the large number of switching variants to be analyzed. This paper presents firstly a methodology based on Relief Functions to estimate currents in overloaded branches by means of few calculations. At last, results obtained by simulation in a real network will be presented.

1. Introduction

Power Systems with high degrees of security, quality and reliability is the objective of all planning Engineers. However, the higher these degrees, the higher will be required investment. In a competitive environment, where investment costs must be carefully analyzed, it is necessary to prioritize financial resources and find creative ideas to postpone investments corresponding to the construction of electrical reinforcements.

Eventually, limit violations may occur by the operation of power systems, such as voltage level at buses, loadings of transmission lines and power transformers. If violations are detected, corrective measures may be carried out in order to mitigate them. Because of increasingly requirements on quality and continuity imposed by the regulatory agencies to power utilities, loading shedding is an extreme solution and should only be adopted as the last control action. In order to avoid load restrictions, it is possible to adopt control measures, such as active and reactive power rescheduling, phase shifters adjustments or even voltage control at generator units. These measures require in general increase of costs. Another way for controlling constraints in electrical systems may occur by changing the network topology, using a technique named Corrective Switching.

The technique of Corrective Switching dates from the late 70’s and consists in a tool for controlling power flow in electrical networks, changing its topology. According to this methodology, the control tools are on/off of switching of transmission lines, transformers or shunt elements, substation buses coupling or splitting or yet rearrangement of branches connected to the bus-bars. It has been proved that, this way it is possible to change the state of power systems, influencing the distribution of power flow, the technical losses, the short-circuit level, and the voltage profile at the system buses. The main advantage of this control technique compared with the former ones is the economy, because its implementation depends on the operation of existing elements in the system, exclusively. Simulation in real networks show that overloads up to 30% may be eliminated by Corrective Switching. The idea of this methodology can be viewed by Fig. 1, where it’s possible to analyze two situations: in Fig. 1a, buses B21 and B22 are interconnected by a circuit breaker. In Fig. 1b, the network topology is changed by opening the circuit breaker that connects these buses.

Over the past 30 years, some Corrective Switching algorithms were proposed with different applications: the objective of [1]-[4], [6]-[9] was eliminate overloads in transmission lines; Solve voltage problems in substations buses was the objective of [6]-[7], [9]; Increasing power system security was proposed by [5] and [8]. Furthermore, these algorithms were also different in a couple of the proposed switching variants: switching on/off of transmission lines and transformers was proposed by [1]; switching shunt elements; changing-over connections of branches and loads in substations bus-bars as proposed by [3]-[4], [6]-[9].
If all N transmission elements of a power system may change its operational condition, the number of possible arrangements is $2^N$. Considering also the possibility of changing the interconnection of these elements in substations bus-bars, the search space to be analyzed in order to obtain a feasible solution would be very broad, leading to a discrete multi-variable problem. Thus, most developed algorithms over the years consider different approaches to reduce the search space, such as: switching only in substations and transmission lines electrically close to the overloaded branch; discard combinations of variants belonging to different switching nodes; list of more probable effective arrangements for eliminating overloads in a specific branch, assigned off-line.

Planning Engineers should propose the electrical reinforcements for proper system operation at all loading horizons. When the available resources are not enough, it is necessary to indicate the priority of the improvements and evaluate alternatives to mitigate the impact of the excluded ones, according to financial criteria. Moreover, in areas with higher load density it is usual to adopt the reliability criterion (n-1) for meshed networks. Nevertheless, because of the increasing demand for energy by some contingency situations or even simultaneous outages this criterion may not be attended. To overcome these inconvenient, corrective switching actions may be used as a strategy for delaying investments in transmission links. This technique was developed for the operation of electrical systems. However, it is possible to expand their concepts in order to include it in the planning environmental. Recent simulations show that the incorporation of new bus-bars in existing substations resulted in important resources, since this hypothesis would provide the substation by new planning variants with the possibility to eliminate operating constraint violations. Exploring these new possibilities, including switching measures (reconfiguration of the connections of branches and loads), may eventually permit to find planning variants with lower costs.

The major obstacle to use switching measures by the on-line operation was the huge number of switching variants, even in smaller networks. The first developed algorithms were based on different forms of load flow linearization and network reduction. The following works showed the non-linear nature of most switching actions. Later, by the proposition of relief functions, it was possible overcome the major difficulties of calculation and got a fast and appropriate answer from switching influence in a network. Considering the relief functions success, it is possible to develop similar functions for planning variants, as well as switching variants involving bus coupling.

2. Linearization by backyard injection

First Corrective Switching application was in power system operation. Some linearizations of the equations that describe power system behavior have been proposed in order to enable a fast identification of the higher effective variants. Then, it has been developed in [3] a methodology based on current injection, named backyard injection. For presenting the technique of injection, consider, as an example, the process of splitting and coupling two bus-bars in a substation, as illustrated in Fig. 2.

![Diagram of switching measures by superposition of base case and backyard injection](image)

Figure 2b illustrates how a switching measure can be simulated, starting from the base case and applying backyard injection, using superposition. Figure 2c presents m transmission lines connected to two buses S and N. Adding backyard injection (Fig. 2b), it results in splitting the bus-bars. The coupling between bus-bars S and N is obtained starting from the base case (Fig. 2a). After subtracting backyard injection (Fig. 2b), it results in the system with interconnected bus-bars. The main computational effort is calculating voltage and currents from backyard injection by solving (1):

$$
\begin{pmatrix}
0 \\
0 \\
-\Delta I \\
\end{pmatrix} =
\begin{pmatrix}
-1 & \ldots & \ldots & 1 \\
0 & \ldots & \ldots & 0 \\
0 & \ldots & \ldots & 0 \\
\end{pmatrix}
\begin{pmatrix}
\Delta V_S \\
\Delta V_N \\
\end{pmatrix} +
\begin{pmatrix}
\Delta V_L \\
\end{pmatrix}
$$

In (1), $\Delta V_i$ refers to current variation between S and N buses; $\Delta V_L$ corresponds to i-th nodal admittance matrix element; $\Delta V_L$ is voltage variation in all system buses.

All $\Delta V_L$ elements belong to the nodal admittance matrix. All loads and injections as constant active and reactive power were discarded. The additional condition that voltage at slack node remains constant ($\Delta V_L = 0)$ is also modeled in (1). In case of opening the two buses, $\Delta I$ is the switching current through Buses S and N shifted by 180°.

It is noteworthy that the procedure for opening transmission lines and substations bus-bars, based on backyard injection, with application in power system operations, has already been developed and is detailed in [3]-[4], [6]-[7]. A model for bus-bars coupling using backyard injection has been detailed in [10]. Another way for modeling bus-bars coupling is using short-circuit theory. This procedure will be developed in next section. It finds adequate application in networks, whose supervisory system is able to carry out on-line generalized short-circuit calculations.

3. Bus coupling by short-circuit theory

For coupling buses S and N in Fig. 2, switching current $\Delta I$ is unknown. So, (1) must be divided by $\Delta I$, resulting in (2):
Considering:

\[ \begin{bmatrix}
0 \\
0 \\
\vdots \\
1
\end{bmatrix} =
\begin{bmatrix} -1 & y_{12} & \cdots & y_{1N} \\
0 & y_{22} & \cdots & y_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
0 & y_{N2} & \cdots & y_{NN}\end{bmatrix}
\begin{bmatrix} \Delta V_{CPSN}^1 / \Delta \lambda \\
\Delta V_{CPSN}^2 / \Delta \lambda \\
\vdots \\
\Delta V_{CPSN}^N / \Delta \lambda \end{bmatrix}
\] (2)

In (2) \( \Delta V_{CPSN}^i \) represents voltage variation at i-th node caused by coupling between nodes S and N. It is not necessary to solve (2); its solution can be obtained using short-circuit theory. A three-phase short-circuit at node S can be presented by (3):

\[ \begin{bmatrix}
L_I \\
L_S \\
L_N
\end{bmatrix} =
\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1S} & \cdots & y_{1N} \\
y_{21} & y_{22} & \cdots & y_{2S} & \cdots & y_{2N} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
y_{N1} & y_{N2} & \cdots & y_{NS} & \cdots & y_{NN}\end{bmatrix}
\begin{bmatrix} \Delta V_{CPSN}^1 / \Delta \lambda \\
\Delta V_{CPSN}^2 / \Delta \lambda \\
\vdots \\
\Delta V_{CPSN}^N / \Delta \lambda \end{bmatrix}
\] (3)

Applying superposition to (7) and (11), it results in (12). Combination of (2) and (12) leads to (13):

\[ \begin{bmatrix} \Delta V_{CPSN}^1 / \Delta \lambda \\
\Delta V_{CPSN}^2 / \Delta \lambda \\
\vdots \\
\Delta V_{CPSN}^N / \Delta \lambda \end{bmatrix} =
\begin{bmatrix} -V_{bc}^S / L_S^P - V_{bc}^N / L_N^P \\
-\Delta V_{CPSN}^I / L_N^P \\
\vdots \\
-\Delta V_{CPSN}^I / L_N^P \end{bmatrix}
\] (13)

Thus, all voltage in power system buses can be calculated after bus coupling. Next step consists in calculating currents in all branches of the system.
4. Effect of bus splitting according to relief function methodology

Initially, it will be presented the methodology showed in [4], [6]-[7], using relief functions developed by sensibility analysis for estimating branch loading, previously overloaded, after bus splitting in a substation. After, it will be presented new relief functions.

4.1 Bus Splitting using Previous Relief Function

The first method to show a reduction in the number of switching variants in a substation is detailed in [2], and is kept in [3]-[4], [6]-[7]. It was shown in [2] that even in bulk power systems, just a few substations are feasible to mitigate overloads on a specific branch. These substations are known as switching nodes and can be obtained by rerouting the overload. Switching nodes are that ones where a substantial part of the rerouted overload flows.

Figure 3 shows power flow in a system with an overloaded branch A-B. In this figure, $P_{\text{rat}}$ corresponds to the rated power of the branch, $\Delta P_{ov}$ means the branch overload. A switching node S with coupled bus-bars is also illustrated.

For (22) and (23), $P_{ov}$ refers to estimated loading of overloaded branch, after opening circuit breaker; $P$ means loading of overloaded branch on base case; $F_r$ is the relief function showed in [5]; $P_s$ represents the switching power; $\Delta P_{re}$ is the part of rerouted overload flowing through the switching node S; $\Delta P_{re}^S$ is the part of $\Delta P_{re}$ flowing through the circuit breaker.

The following conditions must be satisfied by a relief function:

- If the realization of a switching variant results in $\Delta P_{re}^S$ in opposition to $P_s$, it will contribute to a relief of the overload. This variant is named relief variant;
- For a switching variant, if $P_s$, $\Delta P_{ov}$, $\Delta P_{re}$ and $\Delta P_{re}^S$ are approximately equal, the realization of that one reduces the loading of overloaded branch to a value close to rated power of this element;
- Variants with very small $\Delta P_{re}^S$ must have a very large switching power $P_s$, in order to cause an appreciable relief.

Therefore, for eliminating overloads on branches, it is necessary to search variants that produce an estimated loading up to 100% of rated power of these elements. These variants are ranked in a priority list according to decreasing switching powers, $P_s$, among all variants with corresponding estimated loading less or equal 100%. Thus, the first switching variant to be tested is the one with lower $P_s$. This procedure reduces the possibility of other branches become overloaded, also eliminating superfluous calculation of load flow. Thus, the goal to be reached by using relief functions is the estimating of branch loading with minimum number of calculation, avoiding superfluous computational effort, if one considers the huge number of switching variants in real networks.

4.2 Bus Splitting using a new Relief Function

The relief function showed in [6] results in reasonable good estimates of branch loading after realization of a switching variant. However, searching for improvement of estimates, two other relief functions based also on heuristic calculations in real networks has been developed. They are presented in (24) and (25).

For (22) and (23), $P_{ov}$ refers to estimated loading of overloaded branch, after opening circuit breaker; $P$ means loading of overloaded branch on base case; $F_r$ is the relief function showed in [5]; $P_s$ represents the switching power; $\Delta P_{re}$ is the part of rerouted overload flowing through the switching node S; $\Delta P_{re}^S$ is the part of $\Delta P_{re}$ flowing through the circuit breaker.

5. Effect of bus-bars coupling according to relief function methodology

Using short-circuit theory, according to section 3, it is possible to estimate the branch loading after bus-bars coupling in a substation. Although the effect of splitting may be estimated by
heuristic relief function methodology, as presented in previous section, the goal here is derive a method that simulates even splitting or coupling of bus-bars. Thus, a model for bus coupling using relief functions is proposed next.

A relief function for bus coupling can be obtained by using similar ideas as adopted for bus splitting. Figure 4 resembles Fig. 3 excepted for replacing active powers by complex currents, with addition of a bus N, connected to bus S by an opened circuit breaker.

![Fig. 4 – System for simulating power rerouting with opened buses](image)

Since circuit breaker that interconnects buses S and N is opened, developing a relief function based on power is not possible. Thus, the adopted variables will be voltages in base case and in overload rerouting one. However, conclusion extracted from bus opening can be expanded for coupling:

- For a current reduction in the branch overloaded A-B, coupling between buses S and N must reduce voltage difference between these buses;
- In bus splitting, \( P_s = -\Delta P_{s}^{\text{re}} = P_{N}^{\text{re}} - P_s \) results in a loading reduction of branch A-B. For coupling, if \( V_{SN} = -\Delta V_{SN}^{\text{re}} = V_{SN}^{r} - V_{SN} \), then loading of branch A-B will be reduced.

A relief function derivation for bus-bar coupling starts from the application of nodal analysis to network in Fig. 5, governed by (28).

\[
L_{s} - \Delta L_{s}^{\text{re}} = L_{s}^{\text{re}} - L_{s}
\]

Dividing the result of subtraction between (28) and (29) by \( I^{\text{re}} \), it results in (30).

\[
0 - \Delta L_{s}^{\text{re}} = \Delta L_{s}^{\text{re}}
\]

Rewriting (30) in terms of \( Z \) matrix, one obtains (31). Considering no change slack bus voltage, in (30) and (31) \( \Delta L_{s}^{\text{re}} \) is unknown instead of \( \Delta V_{SN}^{\text{re}} \).

![Fig. 5 – Network with an overloaded branch](image)

![Fig. 6 – Overload rerouting in a branch by current injection](image)
\[
\begin{bmatrix}
\Delta V_{BC} / l_{BC} \\
\Delta V_{CD} / l_{CD} \\
\Delta V_{DE} / l_{DE} \\
\Delta V_{EF} / l_{EF} \\
\Delta V_{FG} / l_{FG} \\
\Delta V_{GH} / l_{GH} \\
\Delta V_{HI} / l_{HI} \\
\Delta V_{IJ} / l_{IJ}
\end{bmatrix}
\begin{bmatrix}
Z_{BC} & Z_{CD} & Z_{DE} & Z_{EF} & Z_{FG} & Z_{GH} & Z_{HI} & Z_{IJ}
\end{bmatrix}
\begin{bmatrix}
1 \cdots 1 \cdots 1 \cdots 1 \cdots 1 \cdots 1 \cdots 1 \cdots 1
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\] (30)

Using short-circuit theory, it is possible obtain (35) from the subtraction between (33) and (34).

\[
\begin{align*}
\Delta V_{A} &= (Z_{AA} - Z_{AB}) I_{EF} \\
\Delta V_{B} &= (Z_{AB} - Z_{BB}) I_{EF} \\
\Delta V_{AB} &= (Z_{AB} + Z_{BA} - 2Z_{AB}) I_{EF}
\end{align*}
\] (35)

The impedance \(Z_{AB}^{th}\) corresponds to the parallel between \(Z_{AB}^{th}\) (impedance between A and B buses without branch A-B) and \(Z_{AB}\) (impedance of branch A-B). Current \(I^{re}\) can be determined by applying a current divider in network of Fig. 6, whose result is presented in (36).

\[
I^{re} = \frac{Z_{AB}^{th}}{Z_{AB}} (I_{bc}^{re} - L_{bc}^{re}) \Rightarrow I^{re} = -\frac{\Delta V^{re}_{AB}}{Z_{AB}^{th}}
\] (36)

Once \(I^{re}\) is known, it is possible to obtain voltage variations in all network buses using overload rerouting. Starting from (30), it is possible to obtain (37) and (38), which will be used to estimate currents in all network branches caused by coupling between bus-bars S and N.

For calculating the estimated current in remaining branches of the network after coupling buses S and N, it is necessary to substitute (42) in (41) to obtain (45).

\[
\Delta L^{CPSN} = -\frac{Z_{SN}^0}{Z_{SN}} \left( Z_{SN}^0 + Z_{NS} - Z_{SN} - Z_{NS} \right) \cdot \frac{V_{bc}^0}{Z_{SN}^0}
\] (45)

Using (44) and (45), it is possible to calculate currents in all network branches applying (46).

\[
\Delta L^{CPSN} = L^{re}_{ramo} + \Delta L^{CPSN} \Rightarrow L^{CPSN}_{ramo} = L^{re}_{ramo} + \frac{\Delta L^{CPSN}}{Z_{ramo}}
\] (46)

6. Simulations

Simulations will be presented in two parts. First one will show results for bus coupling using relief function and short-circuit theory. In second part, results for bus-bar splitting will be shown using previous relief function and the ones developed in this work. For a better understanding, it is important an explanation about the following figures. The abcissa are the estimated loading for variants. The ordinates are the corresponding values from exact load flow calculations. The figures are divided into four regions. Points in region B correspond to overly pessimistic estimates. Relief variants would be falsely rejected by these estimates. In contrast, overly optimistic variants correspond to points in region A. Such estimates would result in superfluous load flow calculations. All the other points in figures correspond to well-estimated variants.

6.1 Bus-bar coupling simulation

To evaluate the effectiveness of the proposed linear method, Fig. 7 shows results for estimated loading of network branches by using relief functions compared to the ones obtained by an exact load flow calculations. Although the last one has been
more exact, since it incorporates non-linear calculations, obtained results using backyard injection were faster than the one and well-estimated too, since no points exist in regions A and B.

In Table 1, results are presented, just for overloaded branches, for estimated currents by changing network topology, using linearization by short-circuit currents and relief function. Both methods guide to good results comparing to exact load flow calculations.

<table>
<thead>
<tr>
<th>Short-circuit (A)</th>
<th>Relief function (A)</th>
<th>Load flow (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>470.3677</td>
<td>470.3657</td>
<td>467.0891</td>
</tr>
<tr>
<td>117.5885</td>
<td>117.5849</td>
<td>115.8659</td>
</tr>
<tr>
<td>365.3848</td>
<td>365.3857</td>
<td>362.1843</td>
</tr>
<tr>
<td>366.0792</td>
<td>366.08</td>
<td>362.1843</td>
</tr>
<tr>
<td>590.3233</td>
<td>590.1853</td>
<td>588.7395</td>
</tr>
<tr>
<td>594.8653</td>
<td>594.5197</td>
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</tr>
<tr>
<td>591.9565</td>
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<td>588.7395</td>
</tr>
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<td>593.8737</td>
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</tr>
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<td>223.7986</td>
<td>220.7109</td>
</tr>
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<td>594.2214</td>
<td>593.9735</td>
<td>588.7395</td>
</tr>
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<td>588.7395</td>
</tr>
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<td>195.3036</td>
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</tr>
<tr>
<td>595.1035</td>
<td>595.0894</td>
<td>588.7395</td>
</tr>
</tbody>
</table>

### 6.2 Bus-bar splitting simulation

This section presents a comparison between relief function developed in [6] and the ones presented in section 4.2. The analyzed network is the same used for bus-bar coupling. Figure 8 shows estimated branch loading obtained by (23). It can be viewed that there are points in region B.

Figure 9 shows estimated branch loading obtained by (24). There are points in region B too. Comparing results obtained by (23) and (24), estimated loading of branches are better for (23).

Figure 10 shows estimated branch loading obtained by (25). In this case, there are no points in region B.
Comparing results obtained by (23), (24) and (25), points estimated by the last one are closer to load flow calculations than the others, so this relief function produce a better estimative. Both processes, bus-bar splitting and bus-bar coupling were developed by linear calculations However, while for bus-bar splitting equations were obtained by using an heuristic process, for bus-bar coupling, there was an analytical derivation of the proposed equation, becoming more exact results. Another important consideration is for developing bus coupling equations, reactive power was incorporated in the analysis, once the currents were adopted to have real and imaginary parts.

7. Conclusions

Corrective switching is undoubtedly a powerful tool for influencing load flow in power systems operation. In this area, it is important a method that provides fast results based on estimates. So, method developed in [3], [4], [6] and [7] was improved, incorporating bus coupling by short-circuit theory and relief functions, both considering reactive power effects. It was also developed new relief functions for bus-bar splitting with better results than [6]. A suggestion for future researches is the development of a new method for bus splitting, including reactive power and current analysis instead of active power for estimating branch loading.

References