Real World Optimal UPFC Placement and its Impact on Reliability

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Abstract: - UPFC allows simultaneous control of active power flow, reactive power flow, and voltage magnitude at the UPFC terminals. These characteristics give UPFC the capability to enhance the performance of the power system during various operating conditions. In this paper, a Genetic Algorithm (GA) is used to find the optimal location and the optimal UPFC settings to enhance the transmission lines overloading issue. Additionally the outage cost of the power system is used to verify the impact of the optimized UPFC on reliability. The application of this procedure is proposed on a real world 110-kV sub transmission network with operating conditions of the present year and the year 2020. The results show a network with improved overloading issue while maintaining the same level of reliability in terms of outage costs.

Key-Words: - Genetic Algorithm (GA), Outage Cost, Optimal location, Optimal setting, Reliability, Unified Power Flow Controller (UPFC)

1. Introduction

Unified Power Flow Controller (UPFC) is considered as a powerful device of the Flexible Alternating Current Transmission Systems (FACTS) family, where it has both a shunt and a series controller inside its frame. Therefore UPFC has the ability to do both of Static VAR Compensator (SVC) and Static Synchronous Series Compensator (SSSC) performance simultaneously [1]. Alternatively, the controller may be set to control one or more of these parameters in any combination or to control none of them [2]. UPFC allows not only the combined application of phase angle control with controllable series reactive compensations and voltage regulation, but also the real-time transition from one selected compensation mode into another one to damp oscillations and to handle particular system contingencies more effectively [3]. Furthermore the utilization of UPFC technologies can have positive impacts on power system transmission reliability performance [4].

Series reactive compensation could be replaced by phase-angle control or vice versa to achieve the required criteria [5]. This may become especially important when relatively large numbers of FACTS devices will be used in interconnected power systems, and control compatibility and coordination may have to be maintained in the face of equipment failures and system changes [6]. UPFC also provide considerable operating flexibility by its inherent adaptability to power system expansions and changes without any hard-ware alterations [7].

Loading conditions, configuration of the system and the current operating point of the system are the main factors which define the normal operation of the power network [8]. All the previous factors affect the reliability of the system and the trajectory of the system performance [9]. This paper concerns with increasing loadability of the grid and violation of bus voltage profile. Load increasing studies on the system can be applied at different cases and aspects. UPFC in optimal placement can restore the system operating condition to steady state point. Also the impact of the optimal location of an UPFC within a real world 110-kV-sub transmission power system on reliability is analyzed and the actual benefit is emphasized. The reliability calculation is based on the normal configuration of the system with increased loading pattern. Since the consideration of substations in composite reliability analysis is of high importance [10], the substations are included in this analysis.

2. Problem Formulation

2.1 GA and Fitness Function

The normal operation of a power network depends on many factors as the loading conditions, the configuration of the system and the current operating point of the system. All the previous factors affect the stability and the performance of the system.

Some of these indices will be used to show power line overloadings and bus voltage violations. After determining the performance indices, GA technique is applied to find the optimal location and parameters settings of UPFC. Installations of UPFCs in such can eliminate or minimize the overloading of lines and the bus voltage violations while increasing the loadability. Therefore the task is finding the optimal location and
the optimal parameters setting of a UPFC in the power network to eliminate or minimize the overloaded lines and the bus voltage violations. The main general description of the optimized equation is

Min Fitness \( F_i(X,U) \) \( (1) \)

with subject to:

\[ G_i(X,U) = 0.0 \quad , \quad H_i(X,U) \leq 0.0 \] \( (2) \)

where \( F_i(X,U) \) represents the fitness function to be minimized; \( G_i(X,U) \) represents the vector of the equality constraints corresponding to active and reactive power balance equations; \( H_i(X,U) \) represents the vector of the inequality constraints corresponding to UPFC parameter bounds limits, active and reactive power generation limits, bus voltage limits and phase angles limits; \( X \) represents the vector of the state of the power system consisting of voltage magnitude and phase angles. \( U \) represents the vector of considered optimizable control variables, the location of UPFC and its parameters setting.

The fitness function depends on some performance indices. These fitness function and the performance indices will be changed according the scope zone of interest in the optimization process:

\[ F(X,U) = \sum_{V(BV)} + \sum_{L(OL)} \] \( (3) \)

\[ V(BV) = \begin{cases} \log \left( \frac{V_{\text{nominal}} - V_i}{V_i} \right) & \text{if } 0.95 \leq V_i \leq 1.05 \\ 0 & \text{otherwise} \end{cases} \]

\[ L(OL) = \begin{cases} \log \left( \frac{S_i}{S_{\text{max rate}}} \right) & \text{if } S_i \leq S_{i,\text{max rate}} \\ 0 & \text{otherwise} \end{cases} \]

where

- \( V(BV) \) the Bus Voltage Violation function
- \( V_i \) the voltage magnitude for each bus
- \( V_{\text{nominal}} \) the bus nominal voltage for each bus
- \( \Psi_{V(BV)} \) the weight which is determined in order to have a certain weight value for the various percentage of voltage difference, also used to adjust the slope of the logarithm
- \( Q \) the coefficient which is used to penalize more or less voltage variations
- \( nbb \) the number of the buses in the system
- \( L(OL) \) the Over Loaded Line function
- \( S_i \) the current apparent power of line \( j \)
- \( S_{i,\text{max rate}} \) the apparent power rating of line \( j \)
- \( \Psi_{L(OL)} \) the weight which is used in order to have a certain weight value for the various percentage of line loading, also used to adjust the slope of the logarithm

\( R \) the coefficient is used to penalize overloads and \( ntl \) the number of lines in the system

Additionally some simulations the log relations can be replaced with linear relations, according to the penalty of overloading and voltage violations values.

2.2 UPFC Modeling for Power Flow

The equivalent circuit of an UPFC, shown in Figure 1, is attached with power system equations, and programmed in Matlab for results output. It consists of two synchronous voltage sources (SVS), which are simultaneous coordinated together to achieve the required performance mode [11].

![Fig. 1. UPFC equivalent circuit](image)

The active and reactive power equations for bus \( k \) and \( m \) can be combined with (4) and (5) to get:

\[ P_{rk} = V_{rk} V_k (G_{km} \cos(\delta_k - \theta_k) + B_{km} \sin(\delta_k - \theta_k)) \]

\[ + V_{rk} V_m (G_{km} \cos(\delta_k - \theta_m) + B_{km} \sin(\delta_k - \theta_m)) + V_{rk}^2 G_{km} \]

\[ Q_{rk} = V_{rk} V_k (G_{km} \sin(\delta_k - \theta_k) - B_{km} \cos(\delta_k - \theta_k)) \]

\[ + V_{rk} V_m (G_{km} \sin(\delta_k - \theta_m) - B_{km} \cos(\delta_k - \theta_m)) - V_{rk}^2 B_{km} \]

\[ P_{km} = -V_{rk}^2 G_{km} + V_{rk} V_k (G_{km} \cos(\delta_k - \theta_k) + B_{km} \sin(\delta_k - \theta_k)) + V_{rk} V_m (G_{km} \sin(\delta_k - \theta_k) - B_{km} \cos(\delta_k - \theta_k)) \]

where

- \( V_k \) and \( V_m \) the voltage magnitudes at bus \( k \) and bus \( m \)
- \( \theta_k \) and \( \theta_m \) the voltage angles at bus \( k \) and bus \( m \)
- \( G_{km} \) and \( B_{km} \) the series SVS active and reactive powers
- \( G_{rk} \) and \( B_{rk} \) the shunt SVS active and reactive powers
- \( G_{kk} \) and \( B_{kk} \) the conductance elements, related to lines between buses \( k \) and \( m \)
- \( G_{kk} \), \( B_{kk} \), \( G_{mk} \), \( B_{mk} \) the susceptance elements, related to lines between buses \( k \) and \( m \)
- \( G_{rk} \), \( B_{rk} \), \( G_{rk} \), \( B_{rk} \) the susceptances and conductances for shunt and series SVS.
constraints, which are equality constraints as the active and reactive power balance equations at each bus in the network. Also the inequality constraints as the generation power limits, bus voltage limits, power line limits and UPFC parameters constraint are included.

2.3 Performance Ranking Index
For applying UPFC installation, the optimal locations and optimal parameters setting \((V_{dR}, V_{oR})\) will be adjusted by the designed Genetics Algorithm (GA) which will be shown later. The installations of UPFC will be performed on the system during the normal operation while increasing the loading pattern. For each operating condition the following performance indices will be used:

- \(K_{(LOLN)}\): the index which indicates the Lines Over Loaded Number
- \(\Gamma_{(VBVN)}\): the index which indicates the Buses Voltage Violation Number and
- Performance Index \(\mathcal{F} = K_{(LOLN)} + \Gamma_{(VBVN)}\)

where \(\mathcal{F}\) is zero for the case that there is no overloading on power lines or no violations in bus voltage.

2.4 Reliability Analysis
The sub transmission reliability calculation is based on the frequency and duration approach [12] and it is performed with an AC-load flow from NEPLAN [13], including first and second order faults. The UPFC is integrated in the 110-kV-sub transmission grid based on the UPFC model in [14] with two additional circuit breakers. The failure rate and repair time of the UPFC are 0.02 f/yr and 60 hours respectively from [4]. All generators in the grid are assumed to be ideal in the sense of reliability.

The single line diagram of the 110-kV-sub transmission grid in Figure 3 has been extended with four different substation types from [15]. The exact substation type of each node, including the number of modeled HV/MV-transformers (equal to the number of loads), can be found in Figure 3 and Table 1. Outage costs and the Outage Cost Function (OCF) from [16], based on the expected energy not delivered, are used to quantify the benefit of the UPFC in the grid. These outage costs, listed in Table 1, do not consider the ability of switching at medium voltage substations but the outage costs consider congestion management in terms of load shedding. The used reliability data - only long independent outages and common mode faults are considered in the calculation - for each modeled component is listed in Table 2. Disconnectors are assumed to have no outages. The considered time dependent overload capability (OLC) of the overhead lines and cables is additionally listed in Table 2.

### Table (1) OCF, Substation type (ST) for each load point; D: Double busbar, S: Single busbar, H: upper H-connection and B: Block-connection

<table>
<thead>
<tr>
<th>Bus, ST</th>
<th>OCF = k.x+d</th>
<th>Bus, ST</th>
<th>OCF = k.x+d</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>d</td>
<td>k</td>
<td>d</td>
</tr>
<tr>
<td>€/kW</td>
<td>€/kWh</td>
<td>€/kW</td>
<td>€/kWh</td>
</tr>
<tr>
<td>1, D</td>
<td>0.92</td>
<td>13, H</td>
<td>2.28</td>
</tr>
<tr>
<td>2, D</td>
<td>2.90</td>
<td>14, H</td>
<td>2.28</td>
</tr>
<tr>
<td>3, D</td>
<td>2.28</td>
<td>15, S</td>
<td>2.28</td>
</tr>
<tr>
<td>4, D</td>
<td>1.88</td>
<td>16, B</td>
<td>2.28</td>
</tr>
<tr>
<td>5, D</td>
<td>1.88</td>
<td>17, S</td>
<td>1.88</td>
</tr>
<tr>
<td>6, D</td>
<td>0.92</td>
<td>18, S</td>
<td>1.88</td>
</tr>
<tr>
<td>7, D</td>
<td>0.66</td>
<td>19, H</td>
<td>1.88</td>
</tr>
<tr>
<td>8, D</td>
<td>2.90</td>
<td>20, H</td>
<td>1.88</td>
</tr>
<tr>
<td>9, S</td>
<td>0.92</td>
<td>21, H</td>
<td>1.88</td>
</tr>
<tr>
<td>10, H</td>
<td>1.38</td>
<td>22, S</td>
<td>2.28</td>
</tr>
<tr>
<td>11, H</td>
<td>1.38</td>
<td>23, H</td>
<td>2.28</td>
</tr>
<tr>
<td>12, H</td>
<td>1.38</td>
<td>24, S</td>
<td>2.28</td>
</tr>
</tbody>
</table>

### Table (2) Reliability Component Data of the grid; \(\mu\) … average repair time for long independent outages; \(\lambda\) … average failure rate for long independent outages

<table>
<thead>
<tr>
<th>Component 110 kV</th>
<th>(\mu)</th>
<th>(\lambda)</th>
<th>OLC in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h/a km</td>
<td>1/a</td>
<td>11 min</td>
</tr>
<tr>
<td>Circuit Breaker</td>
<td>100</td>
<td>3.36E-03</td>
<td>100</td>
</tr>
<tr>
<td>Busbar</td>
<td>200</td>
<td>6.80E-03</td>
<td>100</td>
</tr>
<tr>
<td>Transformer 110/20</td>
<td>300</td>
<td>3.00E-03</td>
<td>150</td>
</tr>
<tr>
<td>Overhead Line</td>
<td>48</td>
<td>4.00E-04</td>
<td>120</td>
</tr>
<tr>
<td>Cable</td>
<td>336</td>
<td>1.00E-03</td>
<td>120</td>
</tr>
</tbody>
</table>

3. Proposed Genetics Algorithm
In the GA, the individuals are coded to a chromosome that contains variables of the problem. The configuration of chromosome in order to optimal location of the UPFC consists of two types of parameters: location of UPFC and parameters setting \((V_{dR}, V_{oR})\) as decoupled model parameters of UPFC. In Figure 2, the chromosome for the proposed algorithm is shown.

Fig. 2  Chromosome of proposed GA

- The first set of chromosomes (first chromosome) in the individual represents the locations of UPFCs devices in the network. This set contains the indices of the lines where the UPFCs should be located.
- The second set (starting from the end of the first set) represents the value of \(V_{dR}\) for the series SVS. The range for this set is randomly generated within the working range \([0.001, 0.3]\).
- At last, the third set (starting form the end of the second set) represents the value of $V_{vR}$ for the shunt $SV$. The range for this set is randomly generated within the range $[0.8, 1.2]$.

A genetic algorithm is governed by three factors: mutation rate, crossover rate and population size. The GA is a search process which can be applied to constrained problems [17]; the constraints may be included into the fitness function. In this algorithm optimization issues that must be performed on the objective function and all equality and inequality constraints including the UPFC equations [18], were all explained in the pervious sections. The architecture of the GA implementation can be segregated into the following three constituent phases, namely: Initial population generation, fitness evaluation and genetic operations.

4. Simulation Results

4.1 Scope of the Simulations Files
Matlab Codes for GA (with the main GA file, the fitness function file and the constraints file) and a modified power flow algorithm to include UPFC were developed. Programmed M-files are incorporated to include the updates for each individual in each population for adjusting the algorithm according to the required indices and terms. This procedure is proposed to be applied on a real world 110-kV-sub transmission grid; the data for this system is available in [19].

4.2 Application Results
The data, configuration, loading and generation patterns of the real world network are available in [19]. Also the configuration of the network is depicted in Figure 3. The load and generation data is provided through Helsinki University of Technology. The data was measured hourly for twelve months in 2006. The applications of UPFC for this network will be studied until year 2020 using the load forecasting coefficient which is available for the year 2020.

To show the high effectiveness of the UPFC installation, the design of the UPFC will be applied for the worst case which is the highest loading value at each bus, for all the buses at the same time. This procedure will be applied for present loading pattern and also for worst case of year 2020. Increasing load patterns will be performed with two procedures, the first one is multiplying all the entire loads in the system by increasing with a specified percentage factor. The second one is multiplying all the entire loads in the system by its individual forecasted load coefficient for the considered year 2020. Estimating loadability of a power transmission network has practical importance in power system operations and planning.

Increasing the loadability of the system will be indicated during the analysis to measure the utilization of the network after the UPFC installation. The simulation results show that UPFC can be used to enhance loadability in some cases at the power system even with one; two or more lines are overloaded. $Y_1$ will penalize the value of overall overloading for all lines of the system and $Y_2$ will penalize the value of overall voltage violations for all buses of the system. The calculations for $Y_1$ and $Y_2$ will depend on the terms in equation (3).

The results show that the UPFC can significantly improve the performance of power systems with optimal location and optimal parameter settings. Placing UPFC in the system eliminates all of the overloaded lines. The algorithm is able to reach the solution space eliminating the overloaded lines and at the same moment keeping the voltage profile constraint. Increasing of transmission system loadability of a power system as an index to evaluate the impact of UPFC in power system is achieved in some cases with respect to the line flow limits and the bus voltage magnitude limits.

4.3 Reliability Study Results
To verify the effect of the optimal UPFC location and settings on reliability with different loading scenarios, the annualized expected outage costs are calculated with the load duration approach [13] using the load and
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5. Conclusion

The results show that the UPFC can significantly improve the performance of power systems with optimal location and optimal parameter settings. Placing UPFC in the system eliminates all of the overloaded lines. While the algorithm is able to reach the solution space to eliminate the overloaded lines, keeping the voltage profile within its limits. Increasing of transmission system loadability of power system as an index to evaluate the impact of UPFC in power system is achieved in most of cases with respect to the line flow limits and the bus voltage magnitude limits. The increased loadability in the real world 110-kV-sub transmission grid forced by the optimal location and optimal settings of a single UPFC leads to a slight decrease (0.01 %) of the expected annualized outage
costs. Although the UPFC is an additional device with certain reliability data it has no significant impact on the expected outage cost in this real world study.

6. References


[13] BCP Busarelo, Cott and Partner AG, NEPLAN ® Version 5.3.51, Bahnhofstrasse 40, CH - 8703, Erlenbach, Switzerland


7. BIOGRAPHIES

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