Abstract: The power system operation and its security management has become one of the typical tasks to system operator under competitive market environment. The economic efficiency of energy market is mainly dependent on strategic bidding of the market participants and network capability to drive market driven schedule. In order to avoid congestion state and its consequences, the traditional approaches for security management have been replacing by modern technologies like flexible ac transmission system devices, distributed generation etc. This paper addressing the congestion relief approach using unified power flow controller (UPFC). The location and its parameters are optimized with an objective of social welfare maximization. The results on IEEE 30-bus test system are validating the proposed deterministic approach based on contingency ranking for optimal location of UPFC in deregulated power systems.

Key words: Deregulated Power System, Congestion Management, Unified Power Flow Controller, Contingency Ranking.

1. Introduction

The traditional approach of power system generation scheduling has been changed in different ways in the present deregulated environment. The dispatch of competitive electricity market driven schedule becomes one of the typical operational tasks to the system operator in addition to the general security and reliability concerns. The preventive and corrective actions for transmission security margin have also been changed tremendously with the market gamming. Due to geographical and economic issues, the transmission system expansion becomes difficult to implementation. Under these circumstances, the planning and control actions should validate the adoption and integration of emerging technologies as a long-term solution to satisfy the system operational constraints as well as economic issues. One of the factors which influence the market economics greatly is transmission congestion and has been addressing by the many researches at present. Different techniques and studies have been used to resolve this problem.

According to Ashwani Kumar et al. [1], the existing congestion management (CM) approaches have been categorized in to four major groups i.e. sensitivity factors based, auction based, pricing based approaches and re-dispatch & willingness to pay approach. Many researchers have been focused on the emerging technologies like flexible ac transmission system (FACTS) devices to explore their impact on various congestion relief approaches. Naresh Acharya et al. [2], [3], S.K.Joshi et al. [4], Srinivasa Rao Pudi et al. [5] and Seyed Abbas Taher et al. [6] have addressed the influence of TCSC on market economics under congestion state. You Shi et al. [7] present FACTS validation for CM instead of re-dispatch in hybrid market environment. Sudipta et al. [8] adopt optimal re-scheduling of generators to obtain minimum absolute mismatch to the actual schedule. J. Sridevi et al. [9] explore the FACTS devices impact on zonal congestion management.

From all these works, FACTS can be a promising solution to the CM as well as system security. In this paper, the effect of unified power flow controller (UPFC) on a voluntary pool based day-ahead (DAEM) energy market economics under congestion state is presented. Based on the impact of UPFC on critical loading margin enhancement under N-1 contingency, its optimal location is determined. Finally with the suitable parameter control of UPFC, the economic loss which will incur due to congestion management actions can overcome.

The rest of the paper is organized as follows: Section 2 reviews the UPFC steady state modeling and Section 3 presents the proposed approach for UPFC location. Section 4 addresses the single-sided auction based DAEM settlement and in Section 5, congestion...
relief with UPFC is presented. The numerical results of case studies on IEEE 30-bus test system are presented in Section 6. Finally, Section 7 concludes the paper.

2. Static Modeling of UPFC

Since UPFC can be used for many technical issues or application in the system hence its modeling is depended on the particular application. Seungwon An et al. [10] has developed an ideal transformer model of UPFC suitable for sensitivity approach to identify its optimal location. Bhowmick et al. [11] has proposed an indirect UPFC model to enhance reusability of Newton power-flow codes. Similarly Alomoush [12] has proposed a model of lossless UPFC-embedded transmission lines including the effect of line charging susceptance. The most popular model is power injection (PIM) and it can be found in Palma-Behnke et al. [13], Jun-Yong Liu et al. [14], H.C. Leung et al. [15], K. S. Verma et al. [16], Wei Shao et al [17], Sun-Ho Kim et al [18], Hongbo Sun et al [19], Jung-Uk Lim et al [20], Ying Xiao et al [21], are some of the works which has adopted PIM approach.

Some other specific models can be found in literature. A novel approach of setting for the state variables of an UPFC by incorporation of a UPFC model into the Newton–Raphson power flow algorithm has been presented by Arnim Herbig et al. [22]. Kwang M. Son et a. [23] present Newton-type current injection model. C. R. Foerte-Esquivel et al. [24] present a comprehensive Newton-Raphson UPFC Model for the Quadratic Power Flow Solution of Practical Power Networks. Saeed Arabi et al. [25] was introduced power flow representation of UPFC using auxiliary capacitors. Marcos Pereira et al. [26] present current based model considering the current in the series converter as a variable.

For better exploration on decoupled modeling of UPFC [20], [21], its application for congestion relief can be understood with the following example. From the Fig. 1, the line connected between buses $i$ to bus $j$ is subjected congestion state. If that line is integrated with UPFC as shown in Fig. 2, the decoupled model and its required power injections at buses $i$ and $j$ are given in Fig. 3. The model modified the bus $i$ as PQ bus and bus $j$ as PV bus. If power direction is from bus $j$ to $i$, then bus $j$ should become PQ bus and bus $i$ should become PV bus. The observable thing is, if the injected power is further increased to 50 MW, then the power flow will also further decreased to 50 MW in the line. So the required power control can easily be possible through this modeling.
Baskaran et al. [32] use genetic algorithm (GA) to find optimal choice and allocation of FACTS devices to minimize economics saving cost and Vilmair E. Wirmond et al. [33] use OPF and GA for optimal location of TCPST to minimize overload in the transmission system.

Similarly, some of the works focused on technical benefits with FACTS application. Ying Xiao et al. [34], N. Schnurr et al. [35], Harinder Sawhney et al. [36] and P. Gopi Krishna et al. [37] for available transfer capability (ATC) enhancement, Wang Feng et al. [38] for total transmission capacity enhancement, Ya-Chin Chang et al. [39] for transmission system loadability enhancement, P.S.Venkataramu et al. [40] for voltage stability margin enhancement, Chonhoe Kim et al. [41] for transient stability enhancement, A. Rajabi-Ghahnavieh et al. [42] for system reliability, A.V.Naresh babu et al. [43], M.H.Haque et al. [44] and Ch. Chengaiah et al. [45] for load flow control are some of the examples of FACTS application in deregulated environment.

As a long-term solution for technical issues in the system, this paper has been proposed a novel approach for UPFC location in the network. To validate UPFC function clearly during the abnormalities, the (N-1) line contingency (i.e. also only the lines which are not incident to any generator bus in the network) has been imposed in the network. Based on the reduced critical loading margin [46], the line was opted as a best location for UPFC installation.

The power extraction (i.e. reduced generation level) at bus-\(i\) and insertion (i.e. reduced load level) at bus-\(j\) should be equal for lossless UPFC operation. The reactive power generated at bus-\(i\) is to maintain the desired voltage by PV bus model. In order to maintain constant power factor at bus-\(j\), not only real power but also reactive should be adjust properly.

**4. Day-Ahead Energy Market Modeling**

The day-ahead energy market and with mandatory pool operation has been considered in this work. All the generator buses are treated as generation companies (GENCOs) and load buses as distribution companies (DISCOs) and the entire transmission network as a single entity (TRANSCO) and is functioned under independent system operator (ISO) regulatory body. Single-sided auction mechanism [47] has been considered in the market model. The objective function is to minimize the generation cost at unconstrained case. The bids submitted by any GENCO will arrange in a sequence from lower to higher cost. The intersecting point of forecasted demand and aggregated supply curve will give the market clearing price (MCP). The market cleared quantity (MCQ) for any GENCO can be obtained from its bid curve at this MCP as explained in case studies. If this schedule is not subjected to any operational constraints, then that market settlement will be the perfect market equilibrium point.

Mathematically, the DA market objective function is as follows:

\[
\min \left( \sum_{i=1}^{NG} C_{G_i}(P_{G_i}) - \sum_{i=1}^{ND} C_{D_i}(P_{D_i}) \right)
\]  

(1)

In single sided auction market model, only GENCOs will submit bids and then the objective function will become as:

\[
\min \left( \sum_{i=1}^{NG} C_{G_i}(P_{G_i}) \right)
\]  

(2)

As explained in [48], the perfect competitive energy market can also simulate as a traditional economic load dispatch problem [49]. Under this assumption, the generation schedule at any bus and market clearing price can obtained using equations (3) and (4) respectively.

\[
MCP = \frac{P_D + \sum b_i}{\sum_1^{i=NG} \frac{1}{2a_i}}
\]  

(3)

\[
P_{G_i} = \frac{MCP - b_i}{2a_i}
\]  

(4)

The equality and inequality constraints to the objective function of equation (2) are as follows:

\[
\Delta P_i = \sum_{j=1}^{NB} |V_j| |V_j| |\delta_j - \delta_j - \theta_j| \cos (\delta_i - \delta_j - \theta_j)
\]  

(5)

\[
\Delta Q_i = \sum_{j=1}^{NB} |V_j| |V_j| |\delta_j - \delta_j - \theta_j| \sin (\delta_i - \delta_j - \theta_j)
\]  

(6)

**5. Congestion Relief using UPFC**

The solution of the system can be obtained using Newton-Raphson method. The network loading and its
security level can easily understand with performance index [49] which can calculate using equation (7). The higher value of $PI$ indicates overloading of one or more lines.

$$PI = \sum \left( \frac{f_a}{f_{a,\text{max}}} \right)^{2\alpha}$$  \hspace{1cm} (7)

As explained Section 2.2, the UPFC has been installed at its optimal interface between bus-$i$ to bus-$j$. The residual powers at these buses modify with UPFC control factors as follows:

$$\Delta P_i = P_{G,i} - P_{\text{upfc}}$$  \hspace{1cm} (8)

$$\Delta P_j = P_{G,j} - (P_{D,j} - P_{\text{upfc}})$$  \hspace{1cm} (9)

$$\Delta Q_j = Q_{G,j} - (Q_{D,j} - Q_{\text{upfc}})$$  \hspace{1cm} (10)

$$P_{\text{upfc}} + jQ_{\text{upfc}} = \tau (P_{D,j} + jQ_{D,j})$$  \hspace{1cm} (11)

where $\tau(0 \leq \tau \leq 1)$ is the UPFC control parameter which will adjust up to congestion problem overcome by the network.

6. Case Studies

(A) Contingency Analysis for Optimal Location

The IEEE-30 bus system data can be found in [50, 51]. The base load on the system is 283.4 MW and it is shared among all the generators in proportional to their maximum generation limit. By performing NR load flow, the system suffers with 4.040 MW loss and all the lines are under their MVA ratings. In order to identify the severe line outage, the (N-1) line contingency has been performed at base case and the corresponding system performance index (SPI), real power loss (Loss), and minimum voltage bus with its magnitude among all the buses are given in Table 1 and Table 2 based on SPI values in two categories like severe and normal respectively. The results of incredible contingencies (not solvable cases) of line numbers 13, 16 and 34 are not listed.

All the lines listed in Table 1 are suitable for UPFC location since they are having significant impact on system loadability. In the second steps, among these lines the first 10 lines are considered to investigate their impact on (CLM) or maximum loading capability (MLC). For each contingency, the reduced MCL from base case i.e. reduced security margin (RSM) and critical bus which constrained to NR method fails to convergence as well as its voltage magnitude have been given in Table 3.
Table 3
Impact of severe line outages on CLM

<table>
<thead>
<tr>
<th>Line #</th>
<th>CLM</th>
<th>RSM</th>
<th>Critical Bus</th>
<th>Veri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>2.899</td>
<td>-</td>
<td>30</td>
<td>0.562</td>
</tr>
<tr>
<td>36</td>
<td>1.485</td>
<td>1.414</td>
<td>30</td>
<td>0.539</td>
</tr>
<tr>
<td>25</td>
<td>2.596</td>
<td>0.303</td>
<td>20</td>
<td>0.586</td>
</tr>
<tr>
<td>5</td>
<td>2.625</td>
<td>0.274</td>
<td>30</td>
<td>0.621</td>
</tr>
<tr>
<td>14</td>
<td>2.438</td>
<td>0.461</td>
<td>30</td>
<td>0.565</td>
</tr>
<tr>
<td>24</td>
<td>2.865</td>
<td>0.034</td>
<td>30</td>
<td>0.566</td>
</tr>
<tr>
<td>38</td>
<td>1.928</td>
<td>0.971</td>
<td>30</td>
<td>0.566</td>
</tr>
<tr>
<td>9</td>
<td>2.918</td>
<td>-0.019</td>
<td>30</td>
<td>0.568</td>
</tr>
<tr>
<td>40</td>
<td>2.808</td>
<td>0.091</td>
<td>30</td>
<td>0.574</td>
</tr>
<tr>
<td>37</td>
<td>2.115</td>
<td>0.784</td>
<td>29</td>
<td>0.531</td>
</tr>
<tr>
<td>18</td>
<td>2.688</td>
<td>0.211</td>
<td>30</td>
<td>0.561</td>
</tr>
</tbody>
</table>

From results, the high reduced CLM has happened for the contingency of line 36, 38 and 37. Hence, these three lines are considered most suitable locations for UPFC installation. Under these contingencies, the buses 30 and 29 are subjected to voltage instability hence these locations can opt for shunt compensation devices like SVC, STATCOM and TCVR etc.

(B) Simulation of Day-Ahead Energy market
The cost curve coefficients and maximum generation capacities of each generator are given in Table 4. Since the market settlement is only based on incremental costs hence, the initial cost has been neglected. Similarly the minimum generation limits are also omitted to avoid mandatory participation of the producers in market.

For the base case load of 283.4 MW, the market has been cleared at 4.3724 $/MWh and for this MCP, the production cost is 949.62 $/h. The load flow has been performed with the market driven schedule $P_{G,i}$ and the results are framed in Table 4. The system is subjected to congestion with line # 10 overloaded to 110.01%. The SPI and losses are 2.189 and 4.577 MW respectively.

Table 4
Cost curve coefficients and Market schedule

<table>
<thead>
<tr>
<th>Gen #</th>
<th>$a_i$</th>
<th>$b_i$</th>
<th>$P_{G_{max}}$</th>
<th>$P_{G,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>2</td>
<td>80</td>
<td>78.383</td>
</tr>
<tr>
<td>2</td>
<td>0.0175</td>
<td>1.75</td>
<td>80</td>
<td>78.383</td>
</tr>
<tr>
<td>5</td>
<td>0.0625</td>
<td>1</td>
<td>50</td>
<td>27.947</td>
</tr>
<tr>
<td>8</td>
<td>0.00834</td>
<td>3.25</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>11</td>
<td>0.025</td>
<td>3</td>
<td>30</td>
<td>29.868</td>
</tr>
<tr>
<td>13</td>
<td>0.025</td>
<td>3</td>
<td>40</td>
<td>29.868</td>
</tr>
</tbody>
</table>

(C) UPFC Function at Stressed Conditions
The best suitable locations of UPFC have been tested in this section. At first, UPFC has been inserter in line 36 i.e. connected between buses 28 to 27. As explained in section 2, the UPFC configuration is formulated by modifying bus-28 as a PV bus and bus-27 remains as a PQ bus. The reactive power limits for PV bus are considered as -15MVAr to 50MVAr. The severe contingencies are imposed one after one with UPFC in line 36 and the corresponding changes in SPI, losses, voltage at critical bus given in Table 5. As compared with base case results i.e., Table 1, all the parameters are changed significantly. The voltage profile at all buses is illustrated in figure 4.

Table 5
Severe line outage contingencies with UPFC

<table>
<thead>
<tr>
<th>Line #</th>
<th>Loss</th>
<th>SPI</th>
<th>Vmin</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>4.6587</td>
<td>0.8066</td>
<td>0.9893</td>
<td>30</td>
</tr>
<tr>
<td>36</td>
<td>6.3830</td>
<td>6.5186</td>
<td>0.9734</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>5.1294</td>
<td>2.5966</td>
<td>0.9881</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>10.0983</td>
<td>2.1424</td>
<td>0.9700</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>5.3073</td>
<td>1.7926</td>
<td>0.9889</td>
<td>30</td>
</tr>
<tr>
<td>24</td>
<td>4.9431</td>
<td>1.6393</td>
<td>0.9892</td>
<td>30</td>
</tr>
<tr>
<td>38</td>
<td>5.0473</td>
<td>1.4245</td>
<td>0.9637</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>6.6273</td>
<td>1.4265</td>
<td>0.9758</td>
<td>30</td>
</tr>
<tr>
<td>37</td>
<td>4.7055</td>
<td>1.3891</td>
<td>0.9890</td>
<td>30</td>
</tr>
<tr>
<td>18</td>
<td>5.3164</td>
<td>1.2460</td>
<td>0.9930</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>4.7201</td>
<td>1.1887</td>
<td>0.9890</td>
<td>30</td>
</tr>
<tr>
<td>28</td>
<td>5.0061</td>
<td>1.1749</td>
<td>0.9883</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>4.6130</td>
<td>1.1262</td>
<td>0.9897</td>
<td>30</td>
</tr>
<tr>
<td>26</td>
<td>4.8149</td>
<td>1.0068</td>
<td>0.9895</td>
<td>30</td>
</tr>
</tbody>
</table>

(D) Congestion Relief by UPFC
In addition to the line 36, the lines 37 and 38 are also considered here. When UPFC is in line #37, bus-29 and for line #38, bus-28 are considered as PV buses. As UPFC control parameter $\tau$ changes, the congestion
relief in the form of decrement in SPI and %loading in line #10 as well as transmission losses can observe in figures 5, 6 and 7 respectively.

7. Conclusions

The literature survey provides the basic understand on deregulated power system security problems which can change the physical and financial flows significantly in the network. In order to optimize the security level under competency, the optimal location of UPFC has been proposed based on a novel approach, i.e. reduced critical loading margin under (N-1) contingency condition. The control strategy of UPFC for security management in the competitive energy market has been addressed. Under congestion state, without deviating from market driven schedule, the UPFC parameters have been optimized. In some inevitable situations, the congestion management problem can be solvable with re-dispatch or load curtailment which causes to change power flows and economics of the market. The comparative study of this concept with UPFC will be the content of future work.

References


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