Journal of Electrical Engineering & Technology Vol. 5, No. 3, pp. 389~399, 2010

A Cost/Worth Approach to Evaluate UPFC Impact on ATC

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Abstract – Available transfer capability (ATC) is a measure of the transfer capability remaining in a transmission system. Application of unified power flow controllers (UPFCs) could have positive impacts on the ATC of some paths while it might have a negative impact on the ATC of other paths.

This paper presents an approach to evaluate the impacts of UPFCs on the ATC from a cost/worth point of view. The UPFC application worth is considered as the maximum cost saving in enhancing the ATC of the paths due to the UPFC implementation. The cost saving is considered as the cost of optimal application of other system reinforcement alternatives (except for UPFC) to reach the same ATC level obtained by UPFC application.

UPFC application costs include the maximum cost of alleviating the probable negative impact on the ATC of some paths caused by implementing UPFCs. Optimal system reinforcement is used for systems with UPFCs to determine the aforementioned cost. The proposed method is applied to the IEEE-RTS and the results are evaluated through a sensitivity analysis. The cost/worth of UPFC application is also used to develop an index for optimal UPFC location and the results are compared with those of other indices. A comparison is finally made with the results obtained using an existing ATC allocation profit-based approach to determine UPFC application worth.

Keywords: Available transfer capability, ATC enhancement, Unified power flow controller, Power system reinforcement

1. Introduction

Unified power flow controllers (UPFCs) are one of the most versatile FACTS devices that have ever been used for the control and optimization of power flow in electrical power transmission systems [1]. A practical application of UPFCs is reported in [2]. Consisting of a series and a parallel inverter, UPFCs exchange active power and injects reactive power to manipulate electric power flow. The inverters can operate in various control modes to regulate different power system parameters, such as the magnitude and phase angel of bus voltages and the flow of transmission lines. The active and reactive injections of UPFCs are adjusted according to the control mode and the associated settings of the inverters [1].

Available transfer capability is defined as "*a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses*" [3]. As a power transfer path comprises of a pair of injection/extraction buses, the ATC associated with the paths is calculated by the independent system operator (ISO) and are posted on the Open Access Same-Time Information System (OASIS). Transmission system operators and planners are deploying various methods and techniques in the operation and planning of power systems to enhance ATC, hence permitting more utilization of power system facilities [4].

Various alternatives are available to enhance the ATC of the paths by reinforcing the power system, including: addition of UPFCs, generating units, and constructing new transmission lines.

UPFC application for ATC enhancement is studied in various works. A method is proposed in [5] to apply a UPFC to enhance ATC by increasing the transient stability margin of the power system. The optimal location of UPFCs to enhance the ATC is solved in [6] using Genetic Algorithm. Application of UPFCs and IPFCs to enhance ATC is studied in [7] using optimal power flow and it was shown that better ATC enhancement can be achieved by UPFC application.

The economic evaluation of UPFC impact on ATC has not as yet been well addressed. In particular, as UPFC implementation might degrade the ATC associated with certain paths, only a cost/worth assessment would provide a sound base for evaluating UPFC impact on ATC. A cost/worth assessment could also be used to determine whether UPFCs or other system reinforcement alternatives are economically feasible for ATC improvement. On the other hand, the cost/worth evaluation of UPFC impact on ATC can be determined using an approach to evaluate ATC modification cost/worth. However, the problem of deter-

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Received: March 3, 2010; Accepted: March 26, 2010

mining ATC modification cost/worth has not as yet been well addressed.

This paper presents an approach to evaluate the cost/worth of UPFC impacts on ATC. The approach considers the UPFC application worth as the maximum cost saving achieved in enhancing the ATC of the paths. The UPFC worth is, therefore, considered as the cost that should otherwise be incurred by applying the system reinforcement alternatives (in absence of UPFCs) to reach the same ATC level obtained by UPFC application. The set of system reinforcement alternatives includes new generating units, shunt capacitors, transformers and new transmission lines.

The UPFC application cost comprises of UPFC capital cost and the cost to compensate the probable negative impact of UPFCs for those paths whose ATC is reduced due to the UPFC application. The compensation cost is calculated based on the optimal application of the system reinforcement alternatives for the system with UPFCs to restore the ATC of the affected paths. A general mixed-integer non-linear optimization is used to calculate the system reinforcement cost. The UPFC application cost/worth is also used as the location index of merit to evaluate UPFC location and the results are compared with those obtained using other indices. The proposed approach is finally compared with an allocation profit-based approach to evaluate UPFC application worth.

This paper is arranged as follows: Section 2 presents the basic structure, operation and control of UPFCs. Section 3 presents the proposed approach to calculate UPFC application cost/worth. Optimal system reinforcement is fully described in section 4 to obtain leas cost application of other ATC enhancement alternatives. The proposed approach is applied to the IEEE-RTS in section 5. A sensitivity analysis is presented in section 6 to compare UPFC application and the application of the other alternatives. Several UPFC locations are compared in section 7 using existing and proposed location indices of merit. A comparison is made in section 8 between the proposed approach and the allocation-profit based approach to evaluate UPFC application worth. Concluding remarks are finally summarized in section 9.

2. UPFC Structure, Operation and Control

UPFCs consist of two identical inverters which are connected in parallel and series to the power system through their corresponding power transformers. Fig. 1 shows the structure of a typical UPFC installed on line Lx-y at bus Bx.

The UPFC parallel bus (PB) is directly connected to Bx and the transmission line is connected between By and the UPFC series bus (SB), and:

P_{SI} and Q_{SI} : active and reactive power injection of series inverter;

P_{PI} and Q_{PI} : active and reactive power injection of parallel inverter;

P_{SB} and Q_{SB} : active and reactive power of the transmission line Lx-y at SB;

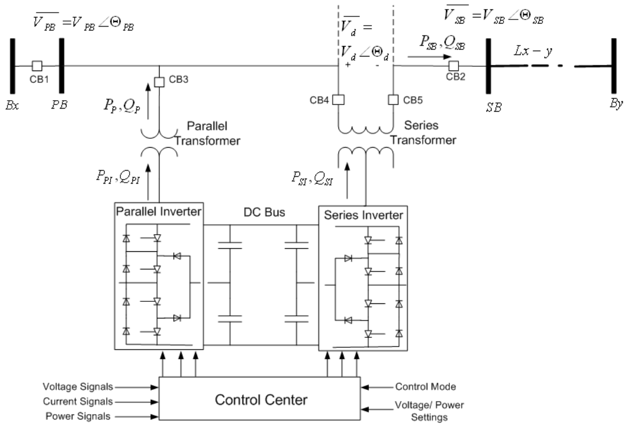

Fig. 1. Typical UPFC Structure.

P_P and Q_P : active and reactive power injected at bus PB;

V_{PB} and Θ_{PB} : magnitude and phase angle of PB voltage, $\overline{V_{PB}}$;

V_{SB} and Θ_{SB} : magnitude and phase angle of SB voltage, $\overline{V_{SB}}$;

$\overline{V_d}$: injected voltage by the series inverter with magnitude and phase angle of V_d and θ_d :

$$\overline{V_d} = \overline{V_{PB}} - \overline{V_{SB}} \tag{1}$$

The neglecting power loss of the inverters, the net active power exchange of the inverters, is zero:

$$P_{SI} + P_{PI} = 0 \tag{2}$$

UPFCs are equipped with a control unit which produces firing commands to the inverters according to the measured signals and control mode of the inverter such that the designated power system parameters are regulated at the associated settings. Control modes associated with the parallel and series inverters are explained hereafter.

2.1 Parallel Inverter

The parallel inverter can operate either as a constant reactive power source or as a voltage controller in the following control modes [1]:

1- Reactive Control Mode (RCM): in this mode, a constant positive or negative reactive power Q_P is injected to the power system at PB.

2- Voltage Control Mode (VCM): in this mode, the injected reactive power of the parallel inverter is automatically regulated to maintain the magnitude of the PB voltage, i.e. V_{PB} , at the associated settings.

2.2 Series Inverter

The control modes of the series inverter are as follows [1]:

1- Power Flow control Mode (PFM): in this mode, the UPFC regulates independently both the real and reactive flow of the transmission line, i.e. P_{SB} and Q_{SB}, at the associated settings. This control mode distinguishes the UPFC from other devices such as STATCOM and SSSC which manipulate the power flow.

2- Voltage Control Mode (VCM): in this mode, the magnitude and phase angle of the series inverter voltage are determined such that the magnitude and the phase angle of $\overline{V_{SB}}$ are regulated at the associated settings.

3- Voltage Injection Mode (VIM): in this mode, the magnitude and phase angle of the series inverter voltage are determined to maintain the voltage difference between PB and SB, i.e. $\overline{V_d}$ at the associated settings.

The parallel and series inverters can operate in each of the above control modes to modify the static and dynamic operation of a power system as well as the ATC associated with the transfer paths. In the rest of this paper, it is assumed that the parallel inverter operates in the RCM mode and series one operates in the VIM mode.

3. UPFC Cost/Worth Evaluation

For a transfer path with specified injection/extraction buses, ATC is mathematically defined as [3]:

$$ATC = TTC - TRM - ETC(including\ CBM) \qquad (3)$$

in which:

TTC is "*the amount of electric power transferred over the interconnected transmission network in a reliable manner*" [3];

TRM is "*the transmission transfer capability required to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system condition*" [3];

CBM is "*the amount of reserve transmission transfer capability to ensure access to generation from interconnected systems to meet generation reliability requirements*" [3] and ETC is the sum of existing transmission commitment (which includes retail customer service) of the path which include the CBM of the path.

Various methods have been developed to calculate the TTC and TRM, hence obtaining the ATC. The method presented in [10] is used in this paper to calculate the TTC, in which the TTC is determined such that the power system complies with N-1 security criterion, i.e.:

i) For pre-contingency power systems, all system parameters are within their normal operating limits;

ii) The system remains stable during the contingency;

iii) For post-contingency power systems, all system parameters are within permissible emergency limits, i.e. all bus voltages must be within 0.9 to 1.08 per-unit and the loading of the elements must not exceed 110% of their normal rating.

So, the TTC associated with a path is the amount of power that can be transferred from the injection bus to the extraction bus without violating N-1 security criterion.

We introduce the terms *"limiting contingency"* and *"limiting element"* in association with the TTC of a path. The limiting contingency is a contingency for which the emergency limits are violated if the power transfer of the path exceeds the TTC by 1 MW. Accordingly, the limiting element is an element whose parameters (voltage and/or loading) violate the emergency limits following the limiting contingency. In other words, the limiting contingency is the contingency which limits the TTC of the path and the limiting element is the element for which the loading or voltage limits the TTC of the path.

Using the method presented in [11], the TRM is considered simply as 8% of the TTC and the ATC is calculated as:

$$ATC = 0.92 \times TTC - ETC \qquad (4)$$

When a UPFC is applied to the system, the ATC of some paths, say path (i), is increased from ATC_i to ATC_i^U and for certain paths, say path (j), ATC is reduced from ATC_j to ATC_j^U.

An approach is required for an economic evaluation of the positive and genitive impact of UPFCs on ATC. An alternate cost-based approach is presented to calculate the cost/worth of ATC modification. In this approach, ATC modification worth is considered as the cost saving due to not using other alternatives to enhance ATC. The cost of ATC modification, on the other hand, is the cost of applying other alternatives to restore the degraded ATC of the paths. This approach is a general approach to evaluate the cost/worth of ATC modification.

For the case of UPFC application, the cost savings due to ATC enhancement for path (i) is the system reinforcement cost SRC_i for the base power system to enhance the ATC of path (i) to ATC_i^U. Taking into account all paths for which ATC is enhanced by UPFC application, UPFC application worth (UAW) is the maximum cost saving in ATC enhancement as:

$$UAW = Max\{SRC_i\ \forall i : ATC_i^U > ATC_i\}\ [\$] \qquad (5)$$

For path (j) whose ATC is reduced from ATC_j to ATC_j^U due to UPFC application, the cost to compensate the negative impact of UPFCs is the system reinforcement cost SRC_j for the power system with UPFCs to restore the ATC of path (j) to ATC_j. UPFC compensation cost (UCC) is the maximum reinforcement cost associated with the paths whose ATC is reduced by UPFC application as:

$$UCC = Max\{SRC_j \ \forall j : ATC_j^U < ATC_j\} \quad [\$] \qquad (6)$$

UPFC application cost (UAC) is composed of the UPFC capital cost (UIC) [5] and UCC:

$$UAC = UIC + UCC \qquad (7)$$

$$UIC = 0.003s^2 - 0.2691s + 188.22 \quad (\$/KVA) \qquad (8)$$

Where s is the capacity of the inverters in MVA.

A comparison between UAW and UAC would show if UPFC application is economically justified. The most important step to calculate the UPFC application cost/worth is to calculate the system reinforcement cost to modify the ATC which is explained in the next section.

4. Optimal System Reinforcement

The optimal system reinforcement is achieved using the following steps:

Step A- Modeling desired level of ATC;
Step B- Finding Limiting Contingencies;
Step C- Determining Reinforcement Candidates
Step D- Finding Optimal Reinforcement

The optimal reinforcement will incorporate one or more of the following system reinforcement alternatives:

- New Generating Unit(s);
- Shunt Reactive Compensator(s) including shunt compensator, synchronous condenser, STATCOM and Static Var Compensator (SVC);
- New Transmission Line(s);
- New Power Transformer(s);

Step A models the desired level of the ATC by adding an auxiliary power transaction at the path. Step B finds the limiting contingencies that must be considered to enhance ATC and exclude the remaining contingencies to reduce the computation burden. In Step C, the set of reinforcement candidates are generated according to the limiting contingencies.

The results of steps B and C are used in step D to find the optimal reinforcement to enhance ATC.

Step A-Modeling Desired Level of ATC

The desired ATC level for the path, ATC_{des}, is modeled by an auxiliary power transaction from the injection bus to the extraction bus of the path. Based on (4), the size of transaction, FTS, is set as:

$$FTS = [ATC_{des} + ETC]/0.92 - ETC \quad [\text{MW}] \qquad (9)$$

Step B- Find Limiting Contingencies

Having added the auxiliary transaction, all single contingencies are analyzed to verify if there is any violation of permissible emergency limits.

The contingencies which lead to the violation of the emergency limits are considered as limiting contingencies. In fact, the limiting contingencies are those which restrict the TTC of the path below the FTS. Based on (4) and (9), if the TTC of the path is equal to the FTS, then the ATC of the path would be ATC_{des}. A solution to the system reinforcement problem is one which removes the violation of permissible emergency limits in case of limiting contingencies. A total number of NLC limiting contingencies are identified which are used in the subsequent analyses.

Step C- Generating Reinforcement Candidates

An important step to determine the optimal system reinforcement is to generate reinforcement candidates. A large number of candidates has the advantage of giving more choices while poses a heavy computation burden. Fewer reinforcement candidates, on the other hand, lowers the computation burden and solution time while increasing the risk of finding a sub-optimal solution. A compromise, therefore, should be made between the optimality of the solution and the computation burden.

In the proposed method, a contingency-based approach is used to generate the reinforcement candidates. In this approach, for each limiting contingency, the candidates are generated:

1- To neutralize the limiting contingency by generating a redundant component for the component on outage. So, for each limiting contingency, a reinforcement candidate is also generated which has the same type, location and capacity as the component which is forced out;

2- To remove the violation of emergency limits of the limiting element(s), as presented in Table 1.

The capacity of the candidate generating unit and shunt compensators are determined by the optimization problem, as presented in Step D. However, the capacity of the candidate transmission lines and transformers are equal to that of the limiting element.

The reinforcement candidates are generated by analyzing the post contingency condition of the limiting contingencies.

Table 1. Reinforcement Candidates for Limiting Elements

Limiting Element	Reinforcement Candidate
	Type, Location
Gen. Unit	-Generating Unit, Parallel to the overloaded Unit
Trans. Line	-Transmission Line, parallel to the overloaded line
	-Generating Unit, at the receiving end of the overloaded line
Bus	-Shunt Compensator on the bus with under/over voltage
Transformer	- Transformer, parallel to the overloaded transformer
	-Generating Unit, at the LV side of the overloaded transformer

If multiple generating units or shunt compensators are generated for a specific bus, they can be aggregated into one generating unit or one shunt compensator, respectively. Based on a 20-year horizon, the application cost of each alternative is modeled as follows:

1-The application cost of the generating unit is 1000 \$/KW and the minimum capacity of the new generating unit is set to 125 MW;

2-The cost of the shunt compensator is 25 \$/kvar [7];

3-For transmission lines, the construction cost is 7000 \$/MVA/KM [8];

4- For power transformers, the application cost is 1000 \$/MVA [8].

Step D- Find Optimal Reinforcement

The problem which should be solved in this step is to find the least-cost system reinforcement subjected to the constraint on normal system operation and the post-contingency condition of the limiting contingencies.

The optimal system reinforcement is obtained such that the system reinforcement cost (SRC) is minimized:

$$Min \quad SRC = CAG + CAC + CAL + CAT \tag{10}$$

$$CAG = \sum_{AG=1}^{NAG} 1000 P_{AG} \tag{11}$$

$$CAC = \sum_{AC=1}^{NAC} 25 CQ_{AC} \tag{12}$$

$$CAL = \sum_{AL=1}^{NAL} \overline{UL}(AL) TLC \times TLS_{AL} \tag{13}$$

$$CAT = \sum_{ATR=1}^{NAT} \overline{UT}(ATR) TRC \times TRS_{ATR} \tag{14}$$

In which:

CAG: Cost of the added generating units; \$

CAC: Cost of the added shunt compensators; \$

CAL: Cost of the added transmission lines; \$

CAT: Cost of the added power transformers; \$

NAG: number of candidate generating units;

NAL: number of candidate transmission lines;

NAC: number of candidate shunt compensators;

NAT: number of candidate transformers;

P_{AG} : Active power generation of the candidate generating unit AG, MW;

CQ_{AC} : Absolute value of the reactive power of the compensator AC, Kvar;

$\overline{UL}$: vector of integer variables for which $\overline{UL}(AL)$ is one if the candidate transmission line AL with the capacity of TLS_{AL} is selected and, otherwise, gets zero;

TLC : cost of constructing lines; \$/MW.KM;

$\overline{UT}$: vector of integer variables for which $\overline{UT}(ATR)$ is one if the candidate transformer ATR with the capacity of TRS_{ATR} is selected and, otherwise, gets zero;

TRC : cost of power transformers \$;/MVA.

REC is minimized subject to the constraints on the normal operation of the power system:

$$P_{AG} \geq 125 \ MW \quad AG = 1,2,..,NAG \tag{15}$$

$$f(V, \delta, P, Q) = 0 \tag{16}$$

$$P_{\min} \leq P_g \leq P_{\max} \quad g = 1,2,..,NG \tag{17}$$

$$Q_{\min} \leq Q_g \leq Q_{\max} \quad g = 1,2,..,NG \tag{18}$$

$$0.95 \leq V_b \leq 1.05 \quad b = 1,2,..,NB \tag{19}$$

$$L_l \leq L_l^N \quad l = 1,2,...,NL \tag{20}$$

where:

$f(V, \delta, P, Q)$ is the power flow equation;

V, δ vectors of magnitude and angle of bus voltages;

P, Q vectors of bus active and reactive power injection;

P_g is the active power generation of generating unit g in MW with maximum and minimum limits of $P_{\max}$ and $P_{\min}$, respectively;

Q_g is the active power generation of the generating unit g in MW with maximum and minimum limits of $Q_{\max}$ and $Q_{\min}$, respectively;

V_b voltage magnitude for bus (b);

L_l loading of line (l) with normal rating L_l^N.

The voltages, active and reactive generation and loadings must also be within permissible emergency limits following the limiting contingencies.

This problem is, in essence, a sort of security based generation-transmission planning problem and various methods have already been proposed to solve the problem. A bender-decomposition approach is used in [12] to incorporate a system security assessment. The method presented in [13] is used in this paper to find optimal system reinforcement which uses line loading and generation shift factors to calculate post contingency line flows and bus voltages [14]:

$$0.9 P_{\min} \leq P_g + GASF(g, \overline{UL}, \overline{UT}, LC_j) \leq 1.1 P_{\max} \tag{21}$$

$$0.9 Q_{\min} \leq Q_g + GRSF(g, \overline{UL}, \overline{UT}, LC_j) \leq 1.1 Q_{\max} \tag{22}$$

$$0.9 \leq V_b + VSF(b, \overline{UL}, \overline{UT}, LC_j) \leq 1.08 \tag{23}$$

$$L_l + LSF(l, \overline{UL}, \overline{UT}, LC_j) \leq 1.1 L_l^N \tag{24}$$

in which:

$GASF(g, \overline{UL}, \overline{UT}, LC_j)$ is the amount of change in the active power generation of generating unit g, in MW, due to the limiting contingency LC_j when the set of selected candidate transmission lines and transformers are determined by vectors $\overline{UL}$ and $\overline{UT}$, respectively;

$GRSF(g,\overline{UL},\overline{UT},LC_j)$ is the amount of change in the reactive power generation of generating unit g, in MVar, due to the limiting contingency LC_j and the vectors $\overline{UL}$ and $\overline{UT}$;

$VSF(b,\overline{UL},\overline{UT},LC_j)$ is the amount of change in the voltage of bus b, in per-unit, due to the limiting contingency LC_j and vectors $\overline{UL}$ and $\overline{UT}$;

$LSF(l,\overline{UL},\overline{UT},LC_j)$ is the amount of change in the loading of transmission line l, in MVA, due to the limiting contingency LC_j and the vectors $\overline{UL}$ and $\overline{UT}$.

The number of shift factor that should be calculated for the system parameters is a function of $NAT \times NAL$. So, the less the number of candidate lines and transformers, the smaller the number of shift factors would be. The set of equations (6) to (20) forms a mixed-integer non-linear optimization problem which must be solved to give the optimum system reinforcement. Several techniques are available to solve non-linear optimization problem among them the branch and bound technique is used to solve the problem.

5. Method Application

The IEEE-Reliability Test System (IEEE-RTS) [15], shown in Fig. 2, is used to study UPFC application impacts on ATC in which the load and generation of the system are increased by 50 percents.

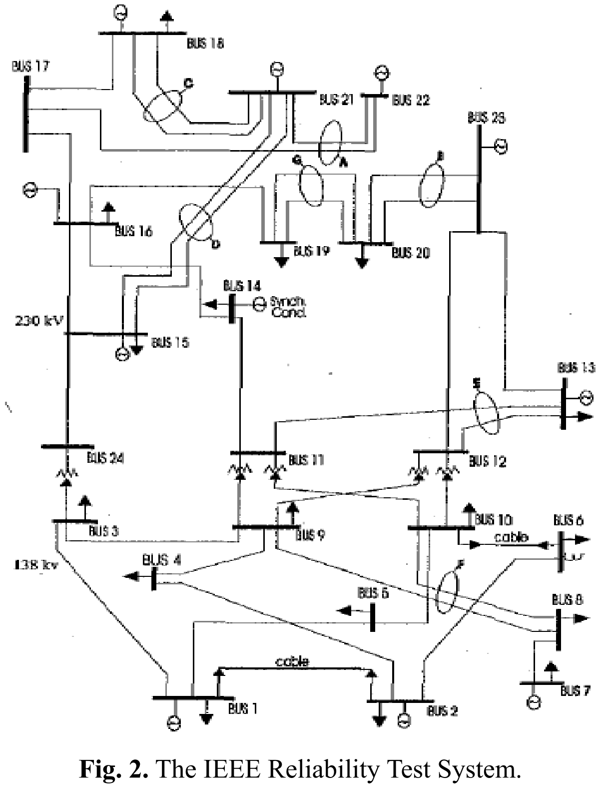

Fig. 2. The IEEE Reliability Test System.

A UPFC is installed on line L12-23 at bus B12 to increase the injection of this line at B12 from 175.98-j15.41 MVA to 213.64+j44.52 MVA, hence increasing the loading of L12-23 by 24%. The UPFC specifications [16] are presented in Table 2 in which X_{ST} and X_{PT} represent the reactance of series and parallel transformers, respectively.

The control mode and settings selected for the series and parallel inverters are presented in Table 3.

Seven transfer paths are introduced in the IEEE-RTS for which ETC and CBM are zero. ATC associated with the paths is calculated for the base system (without a UPFC) and the system with UPFCs using the described method. The results are presented in Table 4.

Comparing the ATC calculated for the base system with that obtained for UPFC application, it can be seen that:

1- UPFC application can considerably increase the ATC of the paths;
2- UPFC impact on ATC can be as large as 240.5% for path 6 or as small as 9.3% for path 1.

The limiting contingency and limiting contingency associated with the paths are presented in Table 4. For the base power system, the TTC of most paths is limited by outage of line L15-24 which leads to undervoltage in buses B3 and B24. For paths 1 and 5, however, the limiting outage has resulted in the overload in transmission lines L14-16 and L11-13, respectively.

Table 2. UPFC Specification

Component	Rating and Impedances
Inverters	10 KV, 200 MVA
Series Transformer	10/10 KV, 200 MVA, $X_{ST}=8\%$
Parallel Transformer	10/230 KV, 200 MVA, $X_{PT}=8\%$

Table 3. Control Mode and Settings of UPFC

Inverter	Control Mode	Controlled Parameter	Setting
Series Inv.	VIM	$V_d\angle\theta_d$	$0.0645\angle-73.6^\circ$
Parallel Inv.	RCM	Q_P	90 MVAR

Table 4. ATC of the Paths, without/with UPFC Application

Path No.	From/To	ATC (MW)		UPFC Impact (%)
		w/o UPFC	With UPFC	
1	B21/B13	276.92	302.68	9.3
2	B23/B13	320.16	494.04	54.3
3	B23/B14	168.36	220.8	31.1
4	B23/B9	37.72	102.12	170.7
5	B13/B14	197.8	225.4	14.0
6	B13/B9	38.64	131.56	240.5
7	B15/B3	3.68	11.04	200.0

Table 5. Limiting Contingency and Limiting Element of Paths

Path No.	Without UPFC		With UPFC	
	Limiting Contingency	Limiting Element(s)	Limiting Contingency	Limiting Element(s)
1	L15-24	L14-16	L15-24	L14-16
2	L15-24	B3, B24	L13-23	L23-12
3	L15-24	B3, B24	L14-16	B14, L11-14
4	L15-24	B3, B24	L15-24	B3, B24
5	L12-13	L11-13	L12-13	L11-13
6	L15-24	B3, B24	L15-24	B3, B24
7	L15-24	B3, B24	L15-24	B3, B24

UPFC application has provided sufficient reactive support at B3 and B24 such that, in the case of an outage of L15-24, undervoltage would happen for a greater TTC. So, the TTC of most paths has been improved considerably. However, for paths 1 and 5, the UPFC cannot do much to prevent the overloading of limiting transmission lines and, so, the amount of ATC enhancement achieved for these paths is small.

The ATC achieved for paths 1 to 7 by UPFC application, presented in Table 2, is used as the desired ATC to apply the proposed method. The results of steps A, B and C are presented in Table 6 in which the reinforcement candidates associated with each path are given in the last column. Candidate transmission lines (AL) and transformers (ATR) are followed by the number of buses they are connected to, and the capacity is presented in parentheses. For candidate generators (AG) and shunt compensators (AC), the number of the bus to which they connect is provided.

The optimal system reinforcement is found and the ATC of the reinforced system, i.e. ATC_{rein}, is also calculated. The results, as well as the SRC associated with the paths, are presented in Table 7.

It can be seen from Table 7 that:

1- For most paths, the SRC is smaller than 1000 K$;
2- For some paths, ATC enhancement is achieved only by applying shunt compensators;
3- The reactive power of the compensators has a negative sign which shows that the compensators inject reactive power to provide voltage support in the system;
4- For paths 1, 3 and 5, the ATC enhancement is achieved by adding some new transmission lines;
5- For paths 1 and 5, ATC_{rein} is greater than ATC_{des};
6- For paths 1, 3 and 5, the SRC is much greater than that of the other paths.

The SRC associated with each path is the amount that should be paid to enhance the ATC of the path to the level obtained by UPFC application. So, when UPFCs are applied, there is no need to pay the SRC and SRC can be considered as UPFC application worth for the path. For the power system, the maximum SRC of the paths is considered as the UPFC application worth. For the studied case, UPFC application worth is 207,760 K$ which is considerably high.

Table 6. Limiting Contingency and Reinforcement Candidates

Path No.	Limiting Contingency	Limiting Element(s)	Reinforcement Candidates (capacity)
1	L15-24, TR3-24	L14-16	AL15-24 (600 MVA), ATR3-24 (510 MVA), AL14-16(600MVA), AG14
2	G13(1), L15-24, L7-8	B13, B3, B24, B8	AL15-24 (600 MVA), ATR3-24 (510 MVA), AL7-8, AG13, AC3, AC8, AC13, AC24
3	L14-16, L15-24, TR3-24	B3, B24, B14, L11-14	AL14-16 (600MVA), AL15-24 (600 MVA), ATR3-24 (510 MVA), AL11-14 (600MVA), AG11, AC3, AC14, AC24
4	L15-24, TR3-24, L7-8	B3, B24, B8	AL15-24 (600 MVA), ATR3-24 (510 MVA), AL7-8 (600MVA), AC3, AC8, AC24
5	L11-13 L12-13 L14-16	L11-13, L12-13, B14, L11-14	AL11-13 (600 MVA), AL12-13 (600 MVA), AL14-16 (600 MVA), AL11-13.2 (600MVA), AL12-13.2 (600MVA), AL11-14 (600MVA), AG11, AC14
6	L15-24, TR3-24, L7-8	B3, B24, B8	AL15-24 (600 MVA), ATR3-24 (510 MVA), AL7-8 (600 MVA), AC3, AC8, AC24
7	L15-24, TR3-24,	B3, B24	AL15-24 (600 MVA), ATR3-24 (510 MVA), AC3, AC24

Table 7. Optimal System Reinforcements for the Paths

Path No.	ATC_{rein} (MW)	SRC (K$)	Optimal Reinforcement
1	321.08	170,520	AL14-16 (600 MVA)
2	494.04	865	AC13 (-14.9Mvar), AC8 (-6.5Mvar), AC3 (-13.2Mvar)
3	228.16	182,390	AL11-14 (600MVA), AC3 (-1.1 Mvar)
4	102.12	205	AC3 (-5.5 Mvar), AC8 (-2.7 Mvar)
5	237.36	207,760	AL11-13 (600 MVA)
6	131.56	245	AC3 (-6.3 Mvar), AC8 (-3.5 Mvar)
7	11.04	180	AC3 (-7.2 Mvar)

On the other hand, since for no path ATC is reduced due to the UPFC application, UCC is zero. Based on (8) and the UPFC specification in Table 2, UIC is 50,880 K$ and UAC is, then, 50,880 K$.

A comparison between the cost and worth of UPFC application will show the economic justification of UPFC application to enhance ATC. Comparing the UAC with the SRC of the paths in Table 7, it can be seen that:

1- The UAC is smaller than the SRC of the paths for which the enhancement is achieved solely by application of the shunt compensators;

2-The UAC is, however, comparable with the SRC associated with paths 1, 3 and 5 which incorporate the addition of new transmission lines;

3-The UAC is well below the UAW, so it can be concluded that UPFC application is an economically justified alternative to enhance ATC;

4- It can also be seen that the proposed approach can be used to determine the preferred alternative to enhance the ATC of the paths.

Although the proposed approach is applied in this paper to evaluate the cost/worth of UPFC impact on ATC, it can nevertheless be used to evaluate the impact of other devices, such as an SSSC, on ATC. The approach can, in particular, be used by power system planners to make decisions on reinforcing power systems.

6. Sensitivity Analysis

The considerable worth of UPFC application, which makes UPFC application an economically justified alternative, is due to the construction cost of new transmission lines for paths 1, 3 or 5. A sensitivity analysis is performed in this section to understand how TLC can affect the justification of UPFC application to enhance ATC.

Fig. 3 shows the variation of the SRC of paths 1, 3 and 5 with TLC. The UAC is also shown in Fig. 3.

It can be seen from Fig. 3 that the SRC of paths 1, 3 and 6 depend mainly on the construction cost of transmission lines. The maximum SRC of the paths, i.e. UAW, is always greater than the UAC, even where the TLC is as small as 2000 $/KM/KVA. So, it can be concluded that UPFC application is justified if otherwise the power system reinforcement requires construction of new transmission lines.

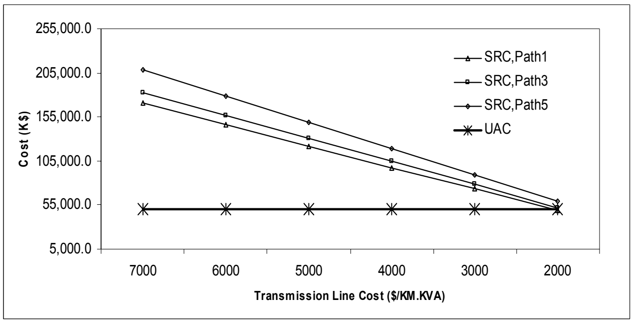

Fig. 3. Impact of TLC on SRC.

7. Evaluation of UPFC Location

While various objectives, such as power system loss, power system transfer capability, etc., have already been used to evaluate UPFC location, it is interesting to use UPFC application cost/worth to evaluate UPFC location.

Four candidate UPFC locations are selected as presented in Table 8.

Using the control mode and setting presented in Table 2, a UPFC is installed on each of the four candidate locations and the ATC associated with the paths are calculated, as presented in Table 9.

It can be seen that the ATC of the paths varies considerably when the UPFC location changes. In particular, the ATC of the paths for UPFC application in Loc. 1 are the same as the base power system (without a UPFC). This shows that UPFC application on Loc. 1 has no impact on the ATC of the paths. It can also be seen that for path 5, the ATC is reduced from the level obtained for the base power system when UPFCs are installed in Loc. 2 to loc. 4. This shows the deteriorating impact of UPFC application on ATC of the paths.

The proposed method is used to calculate the SRC such that the ATC of the paths, except for path 5, would be equal to those obtained for the four UPFC candidate locations. For path 5, since UPFC application has reduced ATC, the reinforcement is applied to the system with UPFCs such that the ATC would be equal to that obtained for the base system. Results are presented in Table 10. Note that the SRC associated with path 5 is considered as a UCC while that of the other paths is considered to calculate the UAW.

The active power loss (PL), total ATC of the paths, UAW and UCC associated with each candidate UPFC location is presented in Table 11.

In order to compare UPFC application in the candidate location, five different location index of merit (LIM) are defined as:

$$LIM1 = Total\ TTC \tag{25}$$

$$LIM2 = VRPL \tag{26}$$

$$LIM3 = UAW \tag{27}$$

$$LIM4 = -UCC \tag{28}$$

$$LIM5 = VRPL + UAW \tag{29}$$

Table 8. Candidate Points for UPFC Installation

Candidate Location	PB	SB
Loc. 1	B17	L22-17
Loc. 2	B11	L11-13
Loc. 3	B14	L11-14
Loc. 4	B12	L12-13

Table 9. ATC of the Paths for UPFC at Candidate Locations

Path No.	Loc. 1 ATC (MW)	Loc. 2 ATC (MW)	Loc. 3 ATC (MW)	Loc. 4 ATC (MW)
1	276.92	293.48	317.4	281.52
2	320.16	470.12	486.68	479.32
3	168.36	223.56	191.36	222.64
4	37.72	92.92	141.68	96.6
5	197.8	**172.04**	**192.28**	**185.84**
6	38.64	145.36	263.12	117.76
7	3.68	11.96	171.12	11.96

In which VRPL represents the value of reduced power loss due to UPFC application.

It can be seen that the defined LIMs cover various impacts of UPFC application on a power system. LIM1 represents the impact of UPFCs on the transfer capability of the system and is similar to the objective function used by [6] to find optimal UPFC location. LIM2 represents the UPFC application impact on power losses in the transmission system.

The power loss of the base power system (without UPFCs) is 43.68 MW. Assuming an electricity price of $80 per MWh, VRPL for a 20-year period is simply calculated as:

$$VRPL = (43.68 - PL) \times 80 \times 8760 \times 20 \quad [\$] \qquad (30)$$

LIM3 to LIM5 incorporate the UPFC application cost/worth to evaluate the candidate locations. LIM5, in particular, adds the UPFC application worth to the VRPL to evaluate the merit of the candidate. The value of the four LIM for the five UPFC locations are calculated and presented in Table 12 and for each LIM the greatest result is shown in bold.

It can be seen in Table 12 that the values obtained for LIM3 are even greater than those obtained for LIM2. This shows the importance of UAW over existing indices of merit. On the other hand, the values obtained for LIM4, i.e. negative of UCC, are smaller than those obtained for other indices. This shows that although UPFCs can pose a negative impact on ATC, the monetary value of this impact is not considerable compared with UAW or VRPL.

The order of merit of the candidate locations is obtained for the five LIM, as presented in Table 13.

It can be seen in Table 13 that the order given to the candidate locations depends mainly on the LIM. Although LIM2 and LIM 3 are in good agreement to select the best location, these indices do not give similar order to the other locations. It can also be seen that the order of merit of the locations obtained by LIM4 is of least similarity with that obtained for the other indices. This shows that adopting a cost-based or a worth-based approach for UPFC locating can totally change the results.

So, both the UPFC application worth and UPFC application cost could be used as indices to evaluate UPFC location and they can considerably change the merit of location candidates.

Table 10. SRC associated with the Paths for UPFC Locations

Path No.	Loc. 1 SRC (K$)	Loc. 2 SRC (K$)	Loc.3 SRC (K$)	Loc. 4 SRC (K$)
1	0	170,520	170,520	10.00
2	0	746.01	828.39	791.77
3	0	182,390	241.25	182,390
4	0	175.71	330.93	187.43
5	0	128.15	27.46	59.50
6	0	281.39	591.88	208.61
7	0	202.50	4095.00	202.50

Table 11. Power Loss, Total ATC and SRC for UPFC Locations

UPFC Location	PL (MW)	Total ATC (MW)	UAW (K$)	UCC (K$)
1	44.01	1043.28	0	0
2	43.95	1409.44	182390	128.15
3	43.67	1763.64	170520	27.46
4	43.62	1395.64	182390	59.50

Table 12. Value of LIMs for UPFC Locations

UPFC Loc.	LIM1 (MW)	LIM2 (M$)	LIM3 (M$)	LIM4 (M$)	LIM5 (K$)
1	1043.28	-4.625	0	0	-4.625
2	1409.44	-3.784	182.39	-0.128	178.605
3	**1763.64**	0.1401	17.052	**-0.027**	170.660
4	1395.64	**0.8409**	**18.239**	-0.0595	**183.230**

Table 13. Order of Merit of UPFC Locations

Order	LIM1	LIM2	LIM3	LIM4	LIM5
1	Loc. 3	Loc. 4	Loc. 4	Loc. 1	Loc. 4
2	Loc. 2	Loc. 3	Loc. 2	Loc. 3	Loc. 3
3	Loc. 4	Loc. 2	Loc. 3	Loc. 4	Loc. 2
4	Loc. 1	Loc. 1	Loc. 1	Loc.2	Loc. 1

8. Method Comparison

The proposed method to evaluate UPFC application cost/worth uses an approach for ATC modification cost/worth analysis which is based on calculating the system reinforcement cost to modify the ATC of the paths. This approach, in specific, does not consider the market value of the ATC of the paths.

Another approach that can be used to evaluate the ATC modification cost/worth is to evaluate the market value of modified ATC of the paths. In this approach, the ATC modification cost/worth is determined based on the change in ATC allocation profit due to ATC modification. For the study case, UPFC implementation profit (UIP) is calculated as:

$$UIP = EAP^{U} - EAP \qquad (31)$$

In which:

EAP represents the sum of expected ATC allocation profit of the paths before UPFC application and EAP^{U} is the total expected ATC allocation profit of the paths following UPFC application.

The method presented in [17] has been used to calculate ATC allocation profits considering the set of transmission requests presented in Table 14 with associated service prices and service curtailment costs. All the requests in Table

14 are assumed to be requests for reserving the non-recallable transfer capability for the 5th week of the year.

The results for ATC allocation for the systems with and without UPFCs are given in Table 15 in which for each path the amount of allocated requests and expected allocation profits are presented in MW and dollars, respectively.

According to Table 15, EAP and EAP^U are calculated as \$1585.7 and \$2562.57 respectively and UIP is then equal to \$976.67. A comparison of UAW and UIC calculated in Section 5 with UIP shows that:

1- There is a great difference between UIP and UAW. This means that the calculated worth of UPFC application varies considerably as the allocation profit-based approach is used.

2- UIC is much greater than UIP. This shows that UIP cannot cover even the capital cost of UPFC application. This result might be expected as UIP is calculated for just one week of the year while the UPFC impact on ATC can last for several years. The same reason has led to the great difference between UIP and UAW.

3- It can be shown that UIP depends mainly on the size, service price and curtailment cost of the requests. As these parameters are time-dependent, a comprehensive analysis of UIP requires a method which solves the long-term ATC allocation problem incorporating the uncertainty in the size, price and curtailment cost of the requests. The authors are working toward developing such methods.

So, it can be summarized that the proposed approach is the preferred tool to evaluate the cost/worth of UPFC application impact.

Table 14. Transmission Service Request

Request	Path	Size (MW)	Service Price ($/MWh)	Curtailment Cost ($/MWh)
TR1	1	310	3	40
TR2	2	500	5	50
TR3	3	220	5	50
TR4	4	110	7	70
TR5	5	230	6	60
TR6	6	150	4	40
TR7	7	15	4	40

Table 15. Results of Allocation Profit Approach

Request	Path	Without UPFC		With UPFC	
		Allcated	Profit	Allcated	Profit
TR1	1	123	335.79	162	451.98
TR2	2	70	315	89	404.95
TR3	3	56	246.4	73	328.5
TR4	4	17	110.67	55	361.9
TR5	5	96	524.16	124	699.36
TR6	6	15	50.4	81	288.36
TR7	7	1	3.28	8	27.52
Total		378	1585.7	592	2562.57

9. Conclusion

This paper has investigated the UPFC impact on ATC using a cost/worth approach. The approach uses a mixed-integer non-linear optimization problem to find the cost associated with system reinforcement to modify ATC and to obtain UPFC application cost/worth.

Using IEEE-RTS, it was observed that UPFC application can enhance ATC by 200%. The cost/worth of UPFC application was also evaluated and it was found that UPFC application worth could even exceed the UPFC application cost. A sensitivity analysis showed that in cases where ATC enhancement necessitates construction of new transmission lines, UPFC application is an economic alternative to enhance ATC.

The UPFC impact cost/worth has also been used as an index of merit to evaluate UPFC location and the results are compared with those obtained by other existing indices. It was concluded that UPFC application cost/worth can be used to evaluate UPFC location and can change the preferred UPFC location considerably.

A comparison has finally been made with an allocation profit-based approach to evaluate UPFC application cost/worth. It was concluded that the proposed method is the preferred tool to evaluate UPFC impact on ATC.

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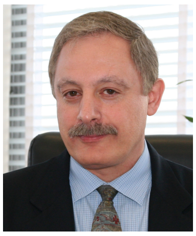

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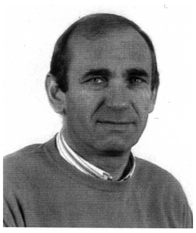

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