Available Transfer Capability Enhancement Using FACTS Devices

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***Abstract*—From the viewpoint of operational planning, this paper focuses on the evaluation of the impact of FACTS control on available transfer capability (ATC) enhancement. Technical merits of FACTS technology on ATC boosting are analyzed. An optimal power-flow-based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control. For better studying the capability of FACTS control, a power injection model of FACTS devices, which enables simulating the control of any FACTS devices, is employed. Studies based on the IEEE 118-bus system with all categories of FACTS devices demonstrate the effectiveness of FACTS control on ATC enhancement.**

***Index Terms*—Available transfer capability, electricity market, flexible ac transmission systems, optimal power-flow.**

I. Introduction

DEREGULATION of the electric industry throughout the world aims at creating competitive markets to trade electricity, which generates a host of new technical challenges to market participants and power system researchers. For transmission networks, one of the major consequences of the nondiscriminatory open-access requirement is a substantial increase of power transfers, which demand adequate available transfer capability (ATC) to ensure all economic transactions. Sufficient ATC should be guaranteed to support free market trading and maintain an economical and secure operation over a wide range of system conditions. However, tight restrictions on the construction of new facilities due to the increasingly difficult economic, environmental, and social problems, have led to a much more intensive shared use of the existing transmission facilities by utilities and independent power producers (IPPs). These concerns have motivated the development of strategies and methodologies to boost the ATC of the existing transmission networks. As a result, power suppliers will benefit from more market opportunities with less congestion and enhanced power system security; it will be more profitable for transmission owners with maximized use of existing transmission assets; and customers will also get improved services and reduced prices.

Aimed at this problem, various ATC enhancement approaches have been proposed, where adjusting terminal voltage of generators and taps changing of onload tap changer (OLTC), particularly rescheduling generator outputs, are considered as major control measures for ATC boosting [1], [2].

As discussed in the report of North American Electric Reliability Council (NERC)—*Available Transfer Capability Definition and Determination* [3], the ability of interconnected transmission network to reliably transfer power through prescribed interfaces may be restricted by thermal, voltage or stability limits. On the other hand, it is highly recognized that, with the capability of flexible power-flow control and rapid action, flexible ac transmission systems (FACTS) technology has a wide spectrum of impacts on the way the transmission system operates, in particular with respect to thermal, voltage, and stability constraints. From the perspective of steady-state system power-flow, circuits do not normally share power in proportion to their ratings, and in most situations, voltage profile cannot be smooth. Therefore, ATC values are always limited ultimately by heavily loaded circuits and/or nodes with relatively low voltage, with the increase of system loading. As stated in [4], FACTS concept makes it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate nodal voltage, thereby mitigating the critical situation. In addition, partly due to the physical constraints on circuit impedance and phase angle of nodal voltage, most high-voltage transmission lines are operating far below their thermal rating [5]. By the control of line reactance and voltage phase angle, FACTS technology enables line loading to increase flexibly, in some cases, all the way up to thermal limits. Therefore, theoretically it can offer an effective and promising alternative to conventional methods for ATC enhancement. To resolve the emerging power system problems in the late 1980s, the Electric Power Research Institute (EPRI) proposed that besides flexible power-flow control over designated transmission routes, another major objective of FACTS applications is to increase the power-transfer capability of transmission systems [4].

In a 1997 EPRI report—*FACTS Assessment Study to Increase the Arizona–California Transfer Capability* [6], the technical advantages of FACTS technology for increasing the ATC of Arizona–California interface are assessed based on power-flow, transient stability, and subsynchronous resonance mitigation. The result indicates that use of the FACTS devices could increase the ATC as much as 1000 MW. As stated in a California Energy Commission report [7], among all of the major FACTS devices, the unified powe-flow controller (UPFC) is the most beneficial one for increasing import capacity into San Diego Gas and Electric's (SDG&E)'s service area. According to another EPRI report [8], FACTS control can increase the capacity of individual corridors by up to 80%, simply by shifting power-flow

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from overloaded to underloaded transmission lines. In addition to that, by improving system stability through their rapid-response capability, FACTS controllers in widespread use can also increase the overall capacity of a large transmission network by 20% or more. Undoubtedly, it is very important and imperative to carry out studies on exploitation of FACTS technology to enhance the ATC.

Since comprehensive ATC evaluation and enhancement models that take into account stability aspects are still in the research and preliminary development stage, this paper only centers around steady-state ATC enhancement. An optimal power-flow (OPF)-based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control, where voltage limits and line thermal limits are considered. On the basis of the methodology proposed for improving ATC by the control of UPFC in [9], this paper focuses on quantitative evaluation of the impact of all categories of FACTS devices on ATC enhancement. For better studying the capability of FACTS control, a power injection model (PIM), which enables the implementation of the control of any FACTS device, is employed to derive the control parameters [10]. Finally, with the IEEE 118-bus system as a testing bed, case studies are conducted on all categories of FACTS devices. The results demonstrate the effectiveness of FACTS control on ATC enhancement.

II. Formulated ATC Enhancement Model

Based on the ATC evaluation model proposed in [11], the ATC enhancement problem is formulated to achieve the maximum power transfer by controlling the FACTS devices on interconnected lines, and meanwhile, increasing all of the complex loads D and generations G in current situation using a scalar loading factor λ_*, that is

$$\begin{aligned} P_{D^*} &= \lambda_* P_D, \qquad Q_{D^*} = \lambda_* Q_D \\ P_{G^*} &= \lambda_* P_G, \qquad Q_{G^*} = \lambda_* Q_G \end{aligned} \tag{1}$$

until a critical situation happens, that is, line thermal limits or nodal voltage limits are attained. Considering the focus of the paper, contingencies of power systems associated with ATC evaluation are not included in the model.

Basic elements of the formulated model are described as follows

A. Control Variables

As elucidated in [10], power injections of FACTS devices are taken as independent control variables. Taking UPFC as an example, it is able to control the active-, reactive power-flow and nodal voltage with its unique combination of shunt and series compensation. For a UPFC installed on line L, $I-J$, near bus I, it is usually represented by a shunt-connected reactive current source and a series inserted voltage source in the voltage source model (VSM), as shown in Fig. 1. Correspondingly, there are three independent power injections involved in the PIM, as shown in Fig. 2. One is $Q_{II(inj)}$ for regulating voltage, which is injected by the current source directly to bus I. The voltage source generates two independent power injections: an active power injection, $P_{I(inj)}$, and a reactive power injection, $Q_{IL(inj)}$, which flows along line L to bus I for active- and reactive power-flow control, respectively. The control vector is written as $\boldsymbol{C} = [P_{I(inj)}\ Q_{IL(inj)}\ Q_{II(inj)}]$. According to the derivation of the PIM in [12], the line flow control of FACTS devices can be considered as an additional controllable power-flow through the line, which is superimposed on the "natural" power-flow. Therefore, for power-flow control of the UPFC, the relationship between the power injections and the controlled power-flow can be expressed as the equations shown in Table I. It is to be noted that the power injections are only interim results. Once they are obtained, the original control parameters, including magnitude V_T and phase angle φ_T of the series inserted voltage, and magnitude of the current I_q, can be calculated according to the VSM of the UPFC.

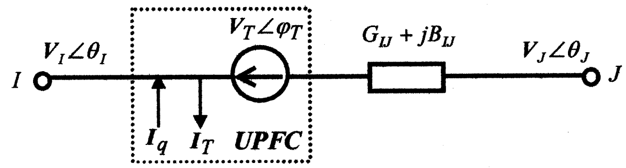

Fig. 1. Voltage source model of UPFC.

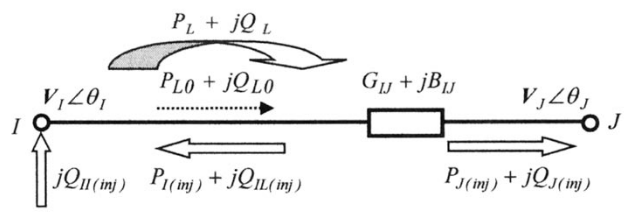

Fig. 2. Power injection model of UPFC for ATC enhancement.

Besides the UPFC as a unified controller, there are series controllers for active power-flow control and shunt controllers for voltage regulation. As the UPFC possesses the functions of both of them, control variables of shunt and series controllers can be extracted from the UPFC model, as shown in Table I, which have been described in detail in [10] where σ is the phase shifting angle of thyristor-controlled phase shifter (TCPS); and x_c represents controllable reactance of thyristor-controlled series capacitor (TCSC); and V_C denotes series-inserted voltage of static synchronous series compensator (SSSC); andI_S is the reactive current injected by static var compensator (SVC) and static synchronous compensator (STATCOM) [4].

B. Objective Function

The objective is to maximize the uncommitted active transfer capacity of the prescribed interface, which is represented by

$$\operatorname{Max} F = \sum_{h=1}^{H} (P_{h^*} - P_h) \tag{2}$$

where H is the number of tie lines across the interface, in which the active powers share the same prescribed direction; and P_h is the active power-flow of tie line h. Variables with subscript * represent those at the critical equilibrium point, while variables without subscript * denote those at the current operating point.

TABLE I
POWER-FLOW-CONTROL-RELATED INFORMATION OF FACTS DEVICES

Classification	Series Controller			Shunt Controller		Unified Controller
Steady-state functions	Active power flow control			Voltage regulation		Active power flow control Reactive power flow control Voltage regulation
Control variables	$P_{I(inj)}$			$Q_{II(inj)}$		$P_{I(inj)}, Q_{IL(inj)}, Q_{II(inj)}$
Relationship between control variables and controlled power flow	$P_L(X_L, P_{I(inj)}) = P_{L0}(X_L) - P_{I(inj)}$			$V_I = V_I(Q_{II(inj)})$		$P_L(X_L, P_{I(inj)}) = P_{L0}(X_L) - P_{I(inj)}$ $Q_L(X_L, Q_{II(inj)}) = Q_{L0}(X_L) - Q_{II(inj)}$ $V_I = V_I(Q_{II(inj)})$
FACTS devices	TCPS	TCSC	SSSC	SVC	STATCOM	UPFC
Control parameters	σ	x_c	V_C	I_S		V_T, φ_T, I_q

When applying the PIM of FACTS devices, the objective is further written as

$$\mathrm{Max}\, F(\boldsymbol{X}, \lambda_*, \boldsymbol{X}_*, \boldsymbol{C}_*) = \sum_{h=1}^{N_F} (P_{h^*}(\lambda_*, \boldsymbol{X}_*, \boldsymbol{C}_*) - P_h(\boldsymbol{X})) + \sum_{h=N_F+1}^{H} (P_{h^*}(\lambda_*, \boldsymbol{X}_*) - P_h(\boldsymbol{X})) \quad (3)$$

where N_F is the number of FACTS devices installed on the tie lines; and X is the state variables, including magnitudes and phase angles of nodal voltage, reactive output of generators performing nodal voltage control, as well as system fixed parameters.

C. Operating and Control Constraints

The constraints are categorized as follows.

1) Equality Constraints: As power-flow equations at the current operating points are ordinary, they are omitted here. To ensure that the system moves from the current equilibrium point to another one corresponding to the loading factor λ_*, the critical operating point is included into the constraints as follows.

For PQ node i, which has no connection with the FACTS devices, $i = 1, \ldots, N_1$

$$\lambda_*(P_{Gi} - P_{Di}) - V_{i^*} \sum_{j=1}^{N-1} V_{j^*}(G_{ij}\cos\theta_{ij^*} + B_{ij}\sin\theta_{ij^*}) = 0$$

$$\lambda_*(Q_{Gi} - Q_{Di}) - V_{i^*} \sum_{j=1}^{N-1} V_{j^*}(G_{ij}\sin\theta_{ij^*} - B_{ij}\cos\theta_{ij^*}) = 0.$$

For PV node i, which has no connection with the FACTS devices, $i = N_1 + 1, \ldots, N - 1$

$$\lambda_*(P_{Gi} - P_{Di}) - V_{i^*} \sum_{j=1}^{N-1} V_{j^*}(G_{ij}\cos\theta_{ij^*} + B_{ij}\sin\theta_{ij^*}) = 0. \quad (4)$$

Assuming FACTS device h installed on line $I_h - J_h$, $h = 1, \ldots, H_F$, for node I_h

$$\lambda_*(P_{GI_h} - P_{DI_h}) + P_{I_h(inj)^*} - V_{I_h^*} \sum_{j=1}^{N-1} V_{j^*}(G_{I_hj}\cos\theta_{I_hj^*} + B_{I_hj}\sin\theta_{I_hj^*}) = 0$$

$$\lambda_*(Q_{GI_h} - Q_{DI_h}) + Q_{I_hL_h(inj)^*} + Q_{I_hI_h(inj)^*} - V_{I_h^*} \sum_{j=1}^{N-1} V_{j^*}(G_{I_hj}\sin\theta_{I_hj^*} - B_{I_hj}\cos\theta_{I_hj^*}) = 0.$$

For node J_h

$$\lambda_*(P_{GJ_h} - P_{DJ_h}) - P_{I_h(inj)^*} - V_{J_h^*} \sum_{j=1}^{N-1} V_{j^*}(G_{J_hj}\cos\theta_{J_hj^*} + B_{J_hj}\sin\theta_{J_hj^*}) = 0$$

$$\lambda_*(Q_{GJ_h} - Q_{DJ_h}) + Q_{J_h(inj)^*} - V_{J_h^*} \sum_{j=1}^{N-1} V_{j^*}(G_{J_hj}\sin\theta_{J_hj^*} - B_{J_hj}\cos\theta_{J_hj^*}) = 0 \quad (5)$$

where

- N number of nodes;
- N_1 number of PQ nodes;
- $P_{I_h(inj)^*}$ active power injection of FACTS device h to the first node I_h;
- $Q_{I_hL_h(inj)^*}$ reactive power injection of FACTS device h through the line L_h to the first node I_h;
- $Q_{I_hI_h(inj)^*}$ reactive power injection of FACTS device h to the first node I_h directly;
- $Q_{J_h(inj)^*}$ reactive power injection of FACTS device h to the second node J_h.

2) Inequality Constraints: Nodal voltage limits: (for PQ node i, $i = 1, \ldots, N_1$)

$$V_{i,\min} \le V_i, V_{i^*} \le V_{i,\max}. \quad (6)$$

Line thermal limits (for line l, $l = 1, \ldots, M$)

$$\mathrm{TM}_l, \mathrm{TM}_{l^*} \le \mathrm{TM}_{l,\max}. \quad (7)$$

Generator capacity limits (for generator i, $i = 1, \ldots, N_G$)

$$P_{Gi,\min} \le P_{Gi}, P_{Gi^*} \le P_{Gi,\max},$$
$$Q_{Gi,\min} \le Q_{Gi}, Q_{Gi^*} \le Q_{Gi,\max} \quad (8)$$

where M is the number of lines, and N_G is the number of generators.

In order to obtain a realistic control scenario, capacity limits of the FACTS devices should also be taken into consideration. As analyzed and presented in detail in [10], the thermal rating of FACTS devices is considered as capacity limit.

The model can be rewritten as a more general optimization model

$$\begin{aligned} \text{Max} \quad & F(\boldsymbol{X}, \lambda_*, \boldsymbol{X}_*, \boldsymbol{C}_*) \\ \text{s.t.:} \quad & \boldsymbol{G}(\boldsymbol{X}) = 0 \\ & \boldsymbol{G}_*(\lambda_*, \boldsymbol{X}_*, \boldsymbol{C}_*) = 0 \\ & \boldsymbol{H}_{\min} \le \boldsymbol{H}(\boldsymbol{X}), \boldsymbol{H}_*(\lambda_*, \boldsymbol{X}_*, \boldsymbol{C}_*) \le \boldsymbol{H}_{\max} \end{aligned} \tag{9}$$

where $\boldsymbol{G}$ is the power-flow equations; and $\boldsymbol{H}$ is the operating constraints, including nodal voltage limits, circuit thermal limits, generator output limits, and capacity limits of FACTS devices.

III. Implementation

The program involves the development and integration of two main modules: FACTS control and an ac power-flow calculation.

Compared with the Simplex method for linear programming, the predictor-corrector primal-duel interior point linear programming (PCPDIPLP) is a powerful tool which enables the reduction of iteration numbers significantly, especially for practical problems which usually have enormous dimensions [13]. Therefore, the method is used to solve the ATC enhancement problem in this paper. The nonlinear objective and constraints must be piecewise linearized for using the LP algorithm to calculate incremental values of the control variables. An iterative procedure is needed to derive the control variables of FACTS devices and the loading factor for ATC maximization.

With the increase of the loading factor, systems ill condition will be aggravated, which may result in a long-time oscillation before convergence during power-flow calculation, sometimes even leading to an unsolvable system. Since it is widely recognized that the optimal multiplier Newton–Raphson (OMNR) method is an effective approach to deal with this problem, which has been well addressed in [14], it is applied here.

The overall procedure is sketched in Fig. 3, where ε is a given threshold value for convergence.

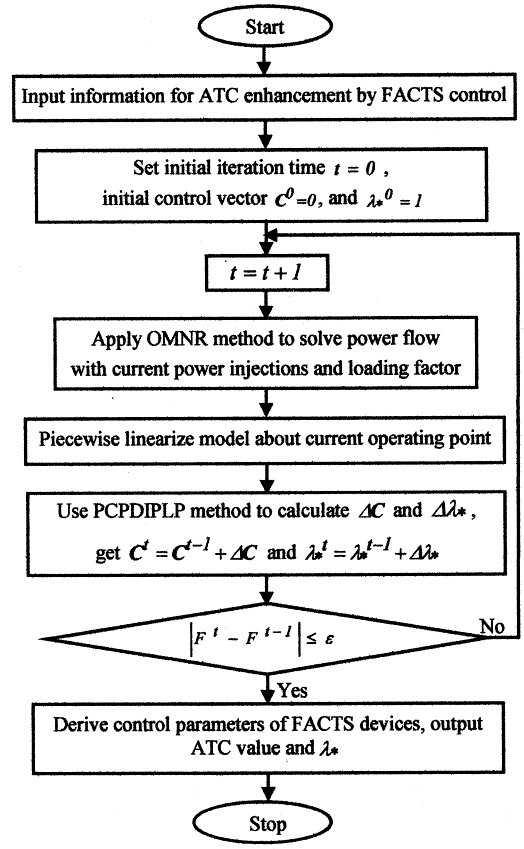

Fig. 3. Flowchart of proposed approach.

IV. Case Studies

In this section, the IEEE 118-bus system [15] is employed to evaluate the ability of FACTS devices on ATC enhancement. According to the network structure and the power-flow calculation results, the whole system is divided into two zones. The studied interface is illustrated in Fig. 4. In this study, the per-unit base is 100 MVA.

The following criteria and assumptions are applied.

- All nodal voltages are to be within the range 0.90 to 1.10 p.u. in normal and contingency situations.
- According to their voltage levels, line thermal limits are assumed and given in [11]. For better demonstration, thermal limits of some lines, such as lines 96, 108, and 116 are modified to cause an unbalanced power-flow sharing. Besides that, to achieve full potential of FACTS control, reactive loads of nodes 20 and 118 are reduced from 0.03 and 0.15 p.u. to −0.03 and 0.00 p.u., respectively.
- Under reasonable assumption, the generation limit of each unit is set as 180% of the current output.

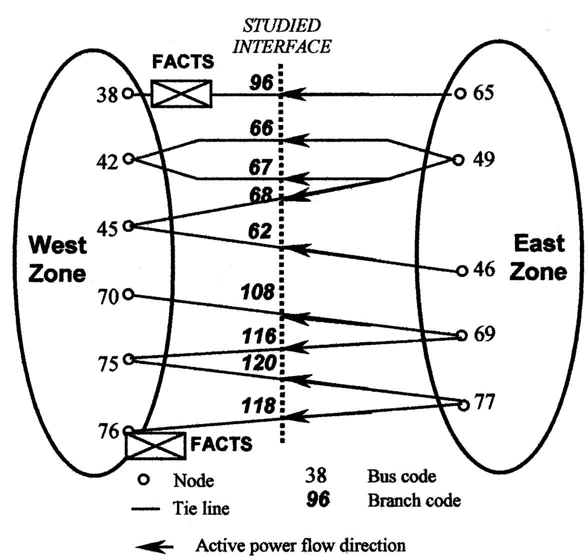

Fig. 4. Studied interface of IEEE 118-bus system.

power-flow results of the studied interface are set out in Table II, where nodes 42, 46, 49, 65, and 69 are all PV nodes. As a ratio between the apparent power of a line and the given thermal limit, thermal burden of the tie lines is also shown in Table II. It is indicated that the West-East transmission corridor is very important with a huge amount of active power transferred along.

TABLE II
POWER-FLOW RESULTS OF STUDIED INTERFACE IN CURRENT SCENARIO ($\lambda_* = 1.000$)

Branch (I - J)	96 (38-65)	66, 67 (42-49)	68 (45-49)	62 (45-46)	108 (69-70)	116 (69-75)	120 (75-77)	118 (76-77)
P_{IJ} (p.u.)	-1.8158	-0.6470	-0.4967	-0.3630	1.0815	1.1013	-0.3468	-0.6111
Q_{IJ} (p.u.)	-0.5615	0.0516	-0.0174	-0.0308	0.1678	0.1710	-0.0711	-0.1844
Thermal limit (p.u.)	3.00	2.00	2.00	2.00	4.00	4.00	2.00	2.00
Thermal burden (%)	63.35	33.92	25.72	18.44	27.36	27.86	17.89	33.34

Node	38	42	45	46	49	65	69	70	75	76	77
Voltage	0.963	0.985	0.987	1.005	1.025	1.005	1.035	0.983	0.971	0.946	1.005

TABLE III
RESULTS OF ATC ENHANCEMENT

Cases		Parameters of FACTS Devices (p.u.)		λ_*	ATC (MW)	Iteration	CPU time (s)
Without FACTS	Case 1	-		1.365	289.97	6	2
With FACTS Devices	Case 2	SVC (node 76)	I_S =0.304	1.553	447.76	7	3
	Case 3	TCPS (line 96)	σ =0.157	1.612	504.31	7	3
		SVC (node 76)	I_S =0.427				
	Case 4	UPFC (line 96)	V_T =0.691 , φ_T=1.094, I_q =6.156	1.783	675.96	13	8
		SVC (node 76)	I_S =1.537				

TABLE IV
POWER-FLOW RESULTS OF STUDIED INTERFACE IN CRITICAL SCENARIO WITHOUT FACTS (CASE 1, $\lambda_* = 1.365$)

Branch (I - J)	96 (38-65)	66, 67 (42-49)	68 (45-49)	62 (45-46)	108 (69-70)	116 (69-75)	120 (75-77)	118 (76-77)
P_{IJ} (p.u.)	-2.5595	-0.9123	-0.6832	-0.5092	1.5794	1.5869	-0.4535	-0.8136
Q_{IJ} (p.u.)	-0.5175	0.1905	-0.0436	-0.1427	0.2891	0.3656	-0.0956	-0.2515
Thermal burden (%)	87.04	46.60	34.23	26.44	40.14	40.71	23.17	42.58

Node	38	42	45	46	49	65	69	70	75	76	77
Voltage	0.938	0.985	0.964	1.005	1.025	1.005	1.035	0.964	0.938	0.900	0.987

A. ATC Evaluation Without FACTS Device (Case 1)

First, in case 1, the original ATC is calculated without any FACTS controller. The proposed method has been coded in Fortran and run on a Pentium III 1.0-GHz PC. The results are given in Table III. As all studies of FACTS control will be carried out on the interface, the power-flow results are given in Table IV. Thermal burden profiles of the tie lines and voltage profiles of the related buses in current and critical scenarios are depicted in Figs. 5 and 6, respectively. In this case, the ATC is restricted by voltage of node 76. Obviously, reactive power compensation on this node will be an effective measure to boost the ATC.

B. ATC Enhancement With Control of SVC (Case 2)

In order to mitigate the critical situation by voltage regulation, an SVC, as the most popular shunt controller, is applied on node 76 in case 2. The configuration is illustrated in Fig. 4. The results of case 2 are given in Table III. It is seen clearly that the ATC value is higher than the original ATC by 54.42%. power-flow results of the studied interface in the critical scenario in case 2 are given in Table V. The corresponding tie line thermal burden profile and voltage profile of the related nodes are also illustrated in Figs. 5 and 6. Scanning the thermal burden in the critical scenario reveals two major facts. One is that it is the thermal limit of branch 96 that prevents further increase of the ATC. The other is, the seriously unbalanced thermal burden profile means, when line 96 has reached its thermal limit, there is still plenty of space for intensive commitment of the remaining tie lines. Additionally, it is interesting to notice that voltage of node 76 is controlled to be at its lower boundary in the critical scenario, so as to obtain the largest available active power-flow of line 118. Thereby, the highest value of the ATC in case 2 can be achieved.

C. ATC Enhancement With Control of SVC + TCPS (Case 3)

For further ATC boosting on the basis of case 2, a viable solution is to alleviate the heavy load burden of line 96 by

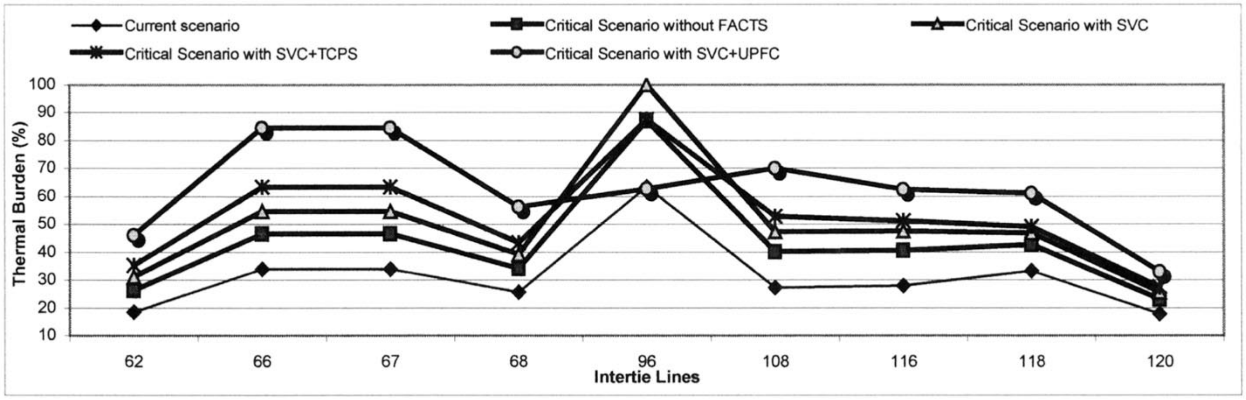

Fig. 5. Thermal burden profiles of studied interface.

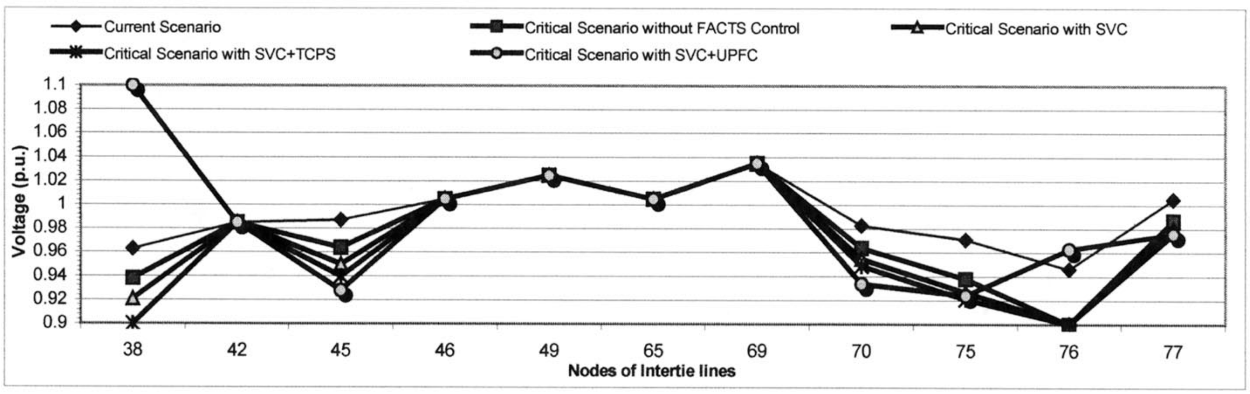

Fig. 6. Voltage profiles of studied interface.

TABLE V
POWER-FLOW RESULTS OF STUDIED INTERFACE IN CRITICAL SCENARIO WITH CONTROL OF SVC (CASE 2, $\lambda_* = 1.553$)

Branch (I - J)	96 (38-65)	66, 67 (42-49)	68 (45-49)	62 (45-46)	108 (69-70)	116 (69-75)	120 (75-77)	118 (76-77)
P_{IJ} (p.u.)	-2.9619	-1.0581	-0.7810	-0.5886	1.8592	1.8554	-0.5038	-0.9216
Q_{IJ} (p.u.)	-0.4764	0.2818	-0.0589	-0.2057	0.3515	0.4205	-0.0890	-0.1572
Thermal burden (%)	100.00	54.75	39.16	31.18	47.30	47.56	25.58	46.74

Node	38	42	45	46	49	65	69	70	75	76	77
Voltage	0.921	0.985	0.950	1.005	1.025	1.005	1.035	0.955	0.927	0.900	0.980

power-flow redistribution. Aimed at this, besides the SVC on node 76 as in case 2, a quadrature booster (QB)-type TCPS is applied on line 96. In case 3, ATC enhancement is conducted with control of the SVC and the TCPS, where the results are given in Table III. It is evident that with the control of the series controller, the ATC value sees a further boost of 56.55 MW, which is approximately 19.50% of the original ATC. Additionally, from iteration numbers and CPU times of the two cases, it is seen that efficiency of the methodology is quite satisfactory. power-flow results of the interface in the critical scenario are given in Table VI, where the corresponding thermal burden profile and voltage profile are also depicted in Figs. 5 and 6, respectively.

It is to be noted that in case 1, the ATC is restricted by voltage violation of node 76, while in case 2, further increase of transfer capability is prevented by thermal limit of line 96. These situations have been alleviated by the control of the SVC and the TCPS in case 3. These facts testified that with the ability to eliminate nodal voltage and thermal limit violation, FACTS control can be an effective method for ATC enhancement.

D. ATC Enhancement With Control of SVC + UPFC (Case 4)

As mentioned earlier, UPFC enables controlling line flow and regulating nodal voltage simultaneously. In order to further escalate the ATC by eliminating the critical voltage of node 38, the TCPS in case 3 is replaced with a UPFC on line 96 with the shunt part connected to node 38. Applying the SVC on node 76 and the UPFC on line 96 to control the power-flow in case 4, the results are given in Table III. power-flow results of the interface in the critical scenario are shown in Table VII. Comparing the ATC levels in case 3 and case 4, the considerable difference

TABLE VI
POWER-FLOW RESULTS OF STUDIED INTERFACE OF CRITICAL SCENARIO WITH CONTROL OF SVC AND TCPS (CASE 3, $\lambda_* = 1.612$)

Branch (I - J)	96 (38-65)	66, 67 (42-49)	68 (45-49)	62 (45-46)	108 (69-70)	116 (69-75)	120 (75-77)	118 (76-77)
P_{IJ} (p.u.)	-2.6210	-1.2058	-0.8660	-0.6640	2.0717	1.9988	-0.5443	-0.9758
Q_{IJ} (p.u.)	-0.1465	0.3866	-0.0605	-0.2440	0.3996	0.4505	-0.0829	-0.1144
Thermal burden (%)	87.50	63.31	43.41	35.37	52.75	51.22	27.53	49.13

Node	38	42	45	46	49	65	69	70	75	76	77
Voltage	0.900	0.985	0.940	1.005	1.025	1.005	1.035	0.949	0.921	0.900	0.976

TABLE VII
POWER-FLOW RESULTS OF STUDIED INTERFACE OF CRITICAL SCENARIO WITH CONTROL OF SVC AND UPFC (CASE 4, $\lambda_* = 1.783$)

Branch (I - J)	96 (38-65)	66, 67 (42-49)	68 (45-49)	62 (45-46)	108 (69-70)	116 (69-75)	120 (75-77)	118 (76-77)
P_{IJ} (p.u.)	-1.7206	-1.5470	-1.1243	-0.8959	2.7442	2.4682	-0.6611	-1.1614
Q_{IJ} (p.u.)	0.7534	0.6869	0.0396	-0.2274	0.5625	0.4053	-0.0166	0.3727
Thermal burden (%)	62.61	84.63	56.25	46.22	70.03	62.53	33.06	60.99

Node	38	42	45	46	49	65	69	70	75	76	77
Voltage	1.100	0.985	0.928	1.005	1.025	1.005	1.035	0.934	0.924	0.963	0.976

highlights the superior performance of the UPFC than the TCPS on ATC improvement. In this case, with the FACTS control to regulate the voltage of nodes 76 and 38, and to alleviate the heavy loading burden of line 96, the occurrence of a critical situation has been postponed. The maximum loading factor rises from 1.365 to 1.783. Consequently, the ATC value sees a considerable increase of 385.99 MW.

It is concluded that with the ability of flexible power-flow control, FACTS devices can enhance ATC to a great degree. Among them, as the most advanced and versatile FACTS devices with functions of supporting voltage and readjusting line flow simultaneously, UPFC can play an important and unique role in ATC boosting.

It can be further calculated that without the line-flow control of the UPFC to alleviate line thermal stress in the critical scenario in case 4, thermal burden of line 96 will attain 183.80%, which demonstrates the effect of the UPFC's series part on the ATC enhancement. From Fig. 6, it is observed that in this case, voltages of nodes 76 and 38 have to be lifted to relatively high values, so as to prevent neighboring nodes from violating the lower limit. In case 4, the critical voltage point has shifted from node 38 to node 74, which is 0.90 p.u. Meanwhile, line 41 bears the heaviest thermal burden, which is 99.94%.

V. CONCLUSIONS

To facilitate the electricity market operation and trade, sufficient transmission capability should be provided to satisfy the demand of increasing power transactions reliably. The conflict of this requirement and the restrictions on the transmission expansion in the unbundled power industry has motivated the development of methodologies to enhance the ATC of the existing transmission grids.

Based on operating limitations of the transmission system and control capabilities of FACTS technology, technical feasibility of applying FACTS devices to boost ATCs are analyzed and identified.

From the point of view of operational planning, the paper evaluated the impact of FACTS devices on ATC enhancement. An OPF-based ATC enhancement model is presented to achieve the maximum possible ATC value with FACTS control. Power injection model of FACTS devices is employed to simulate various FACTS control. With the IEEE 118-bus system as a testing bed, case studies have been conducted on all categories of FACTS devices, covering shunt controller, series controller, and unified controller. The results demonstrated that the use of FACTS devices, particularly the UPFC, which enables the balance of line flow and regulate node voltage simultaneously, can enhance the ATC substantially. The considerable difference between the ATC values with and without FACTS control supports the EPRI's proposal of FACTS applications for ATC enhancement quantitatively. In summary, FACTS technology can offer an effective and promising solution to boost the usable power-transfer capability, thereby improving transmission services of the present market-based power systems.

Finally, it is to be pointed out that the effect of FACTS devices on ATC enhancement is system dependent. For interfaces of the interconnected transmission network with relatively even load sharing and smooth voltage profile, efficient solutions have to rely on those transmission reinforcement-oriented strategies, such as upgrading transmission lines and facilities, construction of new lines, and so on.

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