Total Transfer Capability Considering FACTS and Security Constraints

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***Abstract*—This paper presents a discussion of the effects of Flexible AC Transmission System (FACTS) devices on Total Transfer Capability (TTC). TTC indicates the power transfer capability among different systems or different subsystems. FACTS devices can redistribute load flow and regulate bus voltages. Development and use of methods for proper implementation of FACTS can help improve TTC to a certain extent. TTC is limited not only by the violation of system thermal and voltage limits, but also restricted by transient stability limits. In this paper, an algorithm to incorporate stability constraints to calculate TTC is proposed. Based on this algorithm, a software package with Graphical User Interface (GUI) is developed to facilitate comprehensive and flexible analysis of TTC. The WSCC-9 bus system is used as the test system to demonstrate the methodology.**

***Index Terms*—Total transfer capability, Flexible AC Transmission System, Static Var Compensator, Thyristor Controlled Series Compensator, Transient stability.**

I. INTRODUCTION

Total Transfer Capability (TTC) is the largest value of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of specified constraints. TTC is the key component for calculating Available Transfer Capability (ATC). The relationship of TTC and ATC is described in NERC report [1]: ATC equals TTC less the sum of the Transmission Reliability Margin (TRM), Existing Transmission Commitments (ETS) and Capacity Benefit Margin (CBM).

In a power system, the circuits normally do not share power in proportion to their ratings, and in most situations, smooth voltage profile cannot be achieved. The TTC is ultimately limited by heavily loaded circuits and nodes with relatively low voltage [2]. The use of Flexible AC Transmission System (FACTS) has potential impact on TTC. FACTS technology can control circuit reactance, voltage magnitude and phase angle and therefore redistribute load flow and regulate nodal voltages. Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are the two main commercially available FACTS devices [3]. TCSC has a series of capacitor banks shunted by thyristor-controlled reactor. The firing control of the thyristors can change the apparent reactance smoothly and rapidly [4]. SVC is a shunt compensation component which is a shunt connected static var generator or absorber whose output is adjusted to exchange capacitive to inductive current so as to maintain and control specific parameters (typically bus voltage) of the electrical power system [3]

There are a number of methods and algorithms for computing TTC. Only three of them are practical for large realistic applications [5]. These are

1) Security Constrained Optimal Power Flow (SCOPF) method.
2) Continuation Power Flow (CPF) method [6, 7].
3) Repeated Power Flow (RPF) method.

SCOPF method needs to calculate a large number of OPFs under different postulated system conditions. It is obviously a time consuming approach. The CPF method, whose implementation involves parameterization, predictor, corrector and step-size control, is mathematically complicated. The RPF method, which repeatedly solves power flow equations at a succession of points along the specified load/generation increment, is used in this paper for TTC calculation. Compared with SCOPF and CPF, the implementation of RPF is much easier and it also provides part of V-P, V-Q curves, which facilitates the potential analysis of voltage stability [8].

The TTC is a function of thermal, voltage and transient stability limits of the system. All three limits restrict the value of TTC. The previous work on calculating TTC considers only the first two constraints, i.e. thermal limit and voltage magnitude limit [5][6][7][8]. The results without considering transient stability limit are prone to be somewhat optimistic and could not represent the actual system performance. Following those values in operation may lead to system instability in case of contingencies. In this paper, we establish an algorithm that incorporates all three constraints to calculate the TTC. Therefore this approach is expected to yield more realistic results.

II. FORMULATION OF THE PROBLEM

A. TTC without TCSC and SVC

RPF formulation for TTC without TCSC and SVC (base case) is expressed as follows:

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$$Max\ \ P_{tie-lines} = f(P_{G_i(i\in Source)}, P_{D_j(j\in Sink)}, Q_{D_j(j\in Sink)})$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) = 0 \tag{1}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) = 0 \tag{2}$$

$$|U_i|_{\min} \le |U_i| \le |U_i|_{\max} \tag{3}$$

$$|S_{ij}| \le |S_{ij}|_{\max} \tag{4}$$

$$|\delta_{Gi}(t) - \delta_{Gj}(t)| \le \delta_{G\max} \tag{5}$$

where:

P_D : the total real power load on all load buses.

$P_{tie-lines}$: the summation of real power flow on tie lines

P_{Gi}, Q_{Gi} : real and reactive power generation at bus i

P_{Di}, Q_{Di} : real and reactive load at bus i

n : number of system buses

$|U_i|$: voltage magnitude at bus i

G_{ij}, B_{ij} : real and imaginary part of the ij^th^ element of bus admittance matrix.

δ_{ij} : voltage angle differnece between bus i and bus j

S_{ij} : apparent power flow in line ij

$|U_i|_{\min}$: lower limit of voltage magnitude at bus i

$|U_i|_{\max}$: upper limit of voltage magnitud at bus I

$|S_{ij}|_{\max}$: thermal limit of line ij

$\delta_{Gi}(t)$: rotor angle of generator i.

$\delta_{G\max}$: maximum secure relative swing angle.

In the process of calculation, P_{Gi}, P_{Di} and Q_{Di} are changed in following ways[7]

$$P_{Gi} = P_{G1}^{0}(1 + \lambda k_{Gi}) \tag{6}$$

$$P_{Di} = P_{D1}^{0}(1 + \lambda k_{Di}) \tag{7}$$

$$Q_{Di} = Q_{D1}^{0}(1 + \lambda k_{Di}) \tag{8}$$

where

P_{G1}^{0} : base case real power generation at bus i

P_{D1}^{0}, Q_{D1}^{0} : base case real and reactive load at bus i

λ : increment factor in bus load or generation

k_{Gi}, k_{Di} : constants specifying the rate of change in generation and load

According to (6)~(8), we can increase the apparent load with constant power factor at each bus in the sink area and increase injected real power at each generator bus in the source area in successive steps until one or more limits are reached.

B. TTC with TCSC

When TCSC is installed in a transmission line, the reactance of the line can be adjusted. Normally the adjustment range is 0.5X to 1.5X, where X is the reactance of the original line. The formulation of TTC can be expressed as below:

$$Max\ \ P_{tie-lines} = f(P_{G_i(i\in Source)}, P_{D_j(j\in Sink)}, Q_{D_j(j\in Sink)})$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij-TCSC}\cos\delta_{ij} + B_{ij\_TCSC}\sin\delta_{ij}) = 0 \tag{9}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij-TCSC}\sin\delta_{ij} - B_{ij-TCSC}\cos\delta_{ij}) = 0 \tag{10}$$

$$|U_i|_{\min} \le |U_i| \le |U_i|_{\max} \tag{11}$$

$$|S_{ij}| \le |S_{ij}|_{\max} \tag{12}$$

$$-0.5X \le X_{TCSC} \le 0.5X \tag{13}$$

$$|\delta_{Gi}(t) - \delta_{Gj}(t)| \le \delta_{G\max} \tag{14}$$

where:

$G_{ij-TCSC}$, B_{ij_TCSC} : real and iamginary part of the ijth element of bus admittance matrix when TCSC is installed.

X_{TCSC} : reactance of TCSC

X : origianl reactnace of the line where TCSC is installed

C. TTC with SVC

SVC is a shunt compensation component. When it is installed in the transmission line, it can be treated as a PV bus with zero generation of real power[9]. The formulation of TTC using RPF can be represented as follows:

$$Max\ \ P_{tie-lines} = f(P_{G_i(i\in Source)}, P_{D_j(j\in Sink)}, Q_{D_j(j\in Sink)})$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij-SVC}\cos\delta_{ij} + B_{ij\_SVC}\sin\delta_{ij}) = 0 \tag{15}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j|(G_{ij-SVC}\sin\delta_{ij} - B_{ij-SVC}\cos\delta_{ij}) = 0 \tag{16}$$

$$|U_i|_{\min} \le |U_i| \le |U_i|_{\max} \tag{17}$$

$$|S_{ij}| \le |S_{ij}|_{\max} \tag{18}$$

$$P_{SVC} = 0 \tag{19}$$

$$|\delta_{Gi}(t) - \delta_{Gj}(t)| \le \delta_{G\max} \tag{20}$$

where:

G_{ij-SVC}, B_{ij_SVC} : real and iamginary part of the ijth element of bus admittance matrix when SVC is installed.

P_{SVC} : real power output of the additional PV bus representing the SVC

D. Security Constraint Model

Among the three constraints in TTC calculation, thermal and voltage magnitude limits are easier to implement.

However, transient stability constraint needs special procedure to deal with.

Power system stability considers the dynamic behavior of the power system after a contingency [10]. Power system stability denotes a condition in which various synchronous machines of the system remain "in synchronism" or "in step" with each other [11]. Therefore, the security assessment can be conducted by checking generator rotor angles in the n-1 contingency scenario. In this paper, swing equation model is used to handle stability analysis directly. A typical swing-equation model includes second-order differential equations associated with generator buses and algebraic equations for other buses. For generator buses, we have:

$$M_i \ddot{\delta}_{Gi} + D_i \dot{\delta}_{Gi} = P_{mi} - P_{gi} \qquad i=1,\ldots,n \tag{21}$$

where δ_{Gi} : the generator rotor angle.

P_{mi} : the mechanical power input

P_{gi} : the electrical power input

n : the number of generators

M_i : the ith-generator's inertia coefficient

D_i : the ith-generator's damping coefficient

Mechanical power P_{mi} is equal to the prefault electrical power, which can be obtained by power flow calculation. Electric power output is given as (22):

$$P_{gi} = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos\left(\theta_{ij} - \delta_{Gi} + \delta_{Gj}\right) \qquad i=1,\ldots,n \tag{22}$$

where Y_{ij} is the reduced bus admittance matrix.

In this paper, fixed typical fault clearing time is used in stability analysis. The transient stability criterion is that within a certain period after the occurrence of fault, the difference of any two rotor angles does not exceed the maximum secure relative swing angle, which is set as 180°.

III. METHODOLOGY AND IMPLEMENTATION

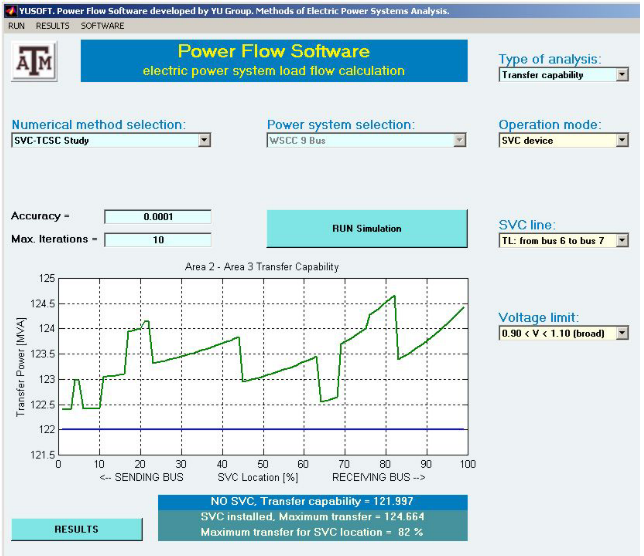
A. General Procedure

The methodology suggested in this paper includes both steady state and dynamic security constraints. The general procedure to calculate TTC with TCSC/SVC can be described as follows:

1) If TCSC is installed, set initial TCSC=-0.5X. If SVC is installed, set initial position, normally at one line end.
2) Select the base case and solve the power flow.
3) Use RPF to make a step increase in generation and load.
4) Estabilish and solve the power flow problem according to the modified system condition; conduct stability assessment under the current condition.
5) Check the power flow solution to see whether thermal limit or voltage limit are violated. Check stability assessment result to see whether security limit is violated. If none of these limits are violated, go to step 3). Otherwise go to step 6).
6) Take opposite step of RPF to eleminate all violations in minimum steps. Compute the TTC level.
7) If TCSC is installed, increase the reactance of TCSC by a specified increment, go to step 2) until the reactance of TCSC reaches 0.5X. If SVC is installed, move the SVC location along the line in a certain step until the end of the line is reached. The maximum values of the TTC associated with each TCSC reactance or SVC location are the fianl results.

B. Software Package

Based on the above procedure, a user-friendly software package is developed. The full software functionality is controlled by Graphical User Interface (GUI), which facilitates effective and flexible analysis for various system conditions. Different test systems, analysis types, operation modes and corresponding system conditions can be easily chosen. Both graphic and numerical outputs are available for assessment. Graphic output results include the relation of TTC and value of TCSC applied, relation of TTC and position of SVC installed, and swing curves of generator phase angles. One snapshot of the interface is shown in Fig. 1.



YUSOFT. Power Flow Software developed by YU Group. Methods of Electric Power Systems Analysis.

Power Flow Software
electric power system load flow calculation

Type of analysis: Transfer capability

Numerical method selection: SVC-TCSC Study

Power system selection: WSCC 9 Bus

Operation mode: SVC device

Accuracy = 0.0001

Max. Iterations = 10

SVC line: TL: from bus 6 to bus 7

Voltage limit: 0.90 < V < 1.10 (broad)

NO SVC, Transfer capability = 121.997
SVC installed, Maximum transfer = 124.664
Maximum transfer for SVC location = 82 %

Fig. 1. GUI of the software package

IV. CASE STUDY

A. Test System

The WSCC-9 bus system (shown in Fig. 2) is used as the test. Three areas are identified for TTC analysis, in which we focus on the transfer capability from Area-2 to Area-3

The transmission line parameters are shown in Fig. 2 too. The base case system loads are listed in Table I.

Fixed thermal limits for transmission lines are set as in Table II. Transformers are assumed to have infinite thermal limit.

Protective zone II tripping time is used as typical fault clearing time for n-1 contingency stability analysis.

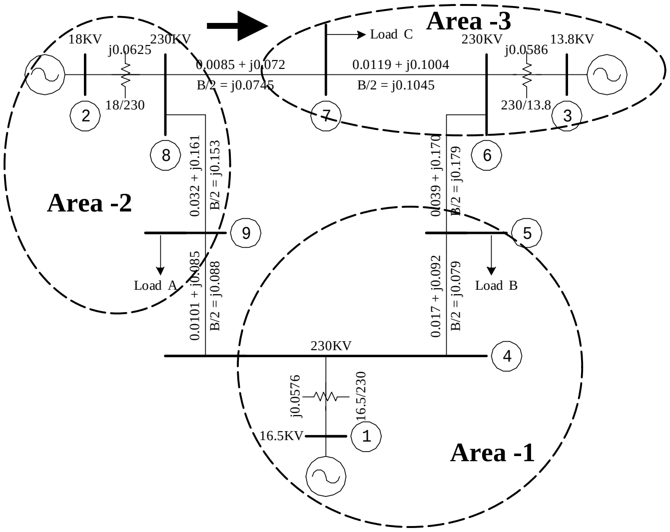


Fig. 2. WSCC-9 bus system

TABLE I
BASE CASE LOAD

Load A	Load B	Load C
90MW	100MW	125MW

TABLE II
TRANSMISSION LINE THERMAL LIMITS

Line	4-5	5-6	6-7	7-8	8-9	9-4
Thermal limit (MVA)	50	115	70	150	150	80

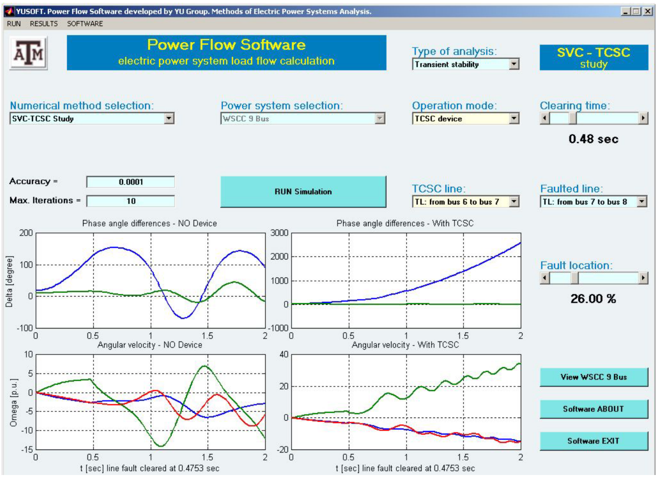
B. *Impact of FACTS devices on Stability*

FACTS devices are designed and installed to enhance system stability to some extent. However, this may not be true in all cases. In this section we demonstrate the negative influence of SVC and TCSC devices on power system stability in some particular cases. The location of SVC is set at 50% of transmission line under consideration and TCSC factor is set to -0.5X. The base case system load is applied.

1) Effect of TCSC

Fig. 3 presents an example of negative influence of TCSC devices.

Two lines observed in this case are line 6-7 where SVC is installed and line 7-8 where the fault was applied. Fault clearing time that roughly corresponds to zone II tripping is selected as 0.48 sec. This corresponds to the delayed clearing from the remote end of the line 7-8 and gives greater influence of the system on the right-hand side of the fault. Since SVC is installed in line 6-7 and increases right-hand side fault infeed, the system is more prone to instability.


YUSOFT. Power Flow Software developed by YU Group. Methods of Electric Power Systems Analysis.

Type of analysis: Transient stability

Numerical method selection: SVC-TCSC Study

Power system selection: WSCC 9 Bus

Operation mode: TCSC device

Clearing time: 0.48 sec

Accuracy = 0.0001

Max. Iterations = 10

TCSC line: TL: from bus 6 to bus 7

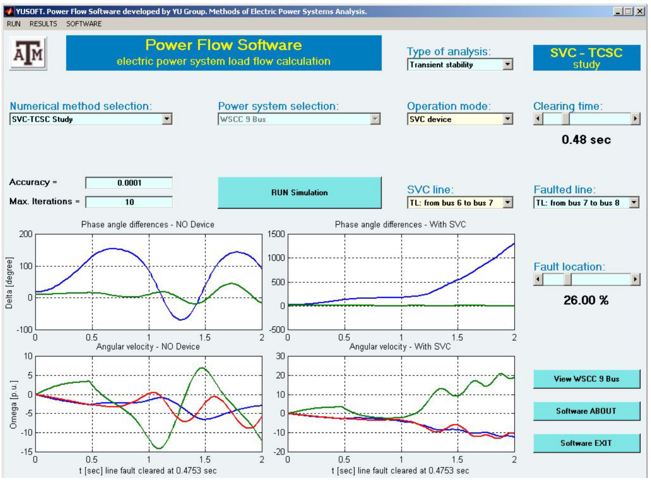
Faulted line: TL: from bus 7 to bus 8

Fault location: 26.00 %

Fig. 3. Negative influence of TCSC on system stability illustration

2) Effect of SVC

The same fault and protection scenario is selected for SVC device as 1). In this case, the influence of SVC device proved to have negative impact on the system transient stability too. It is illustrated in Fig. 4.


YUSOFT. Power Flow Software developed by YU Group. Methods of Electric Power Systems Analysis.

Type of analysis: Transient stability

Numerical method selection: SVC-TCSC Study

Power system selection: WSCC 9 Bus

Operation mode: SVC device

Clearing time: 0.48 sec

Accuracy = 0.0001

Max. Iterations = 10

SVC line: TL: from bus 6 to bus 7

Faulted line: TL: from bus 7 to bus 8

Fault location: 26.00 %

Fig. 4. Negative influence of SVC on system stability illustration

Another example that TCSC has greater impact on the system stability than SVC can be observed in comparison of the above two cases. In fact, in both cases, both TCSC and SVC cause system instability, but the magnitude of generator oscillations increased in the case when TCSC was applied.

C. *TTC Analysis*

Two sets of voltage limit, the broad one and the narrow one, are applied to analysis. The loose one is expected to allow the thermal limit violation to occur and we call it “thermal limit dominant” case. The narrow one, on the other hand, makes voltage magnitude violation normally happen and we call it “voltage limit dominant” case.

1) Effect of TCSC

Case-1: Voltage Limit 0.90<|V|<1.10

Table III gives two sets of results, one of which does not include stability constraint and the other does. Without considering stability constraint, the base case transfer capability is 122.0MVA and the installation of TCSC improves the transfer capability. The maximum improvement (16.1%) occurs when TCSC is installed on line 8-9.

TABLE III
EFFECT OF TCSC ON TTC (THERMAL LIMIT DOMINANT)

TCSC Installed on	Without considering stability		Considering stability	
	Transfer Capability	Violation	Transfer Capability	Violation
Null	122.0	Thermal: 8-9	102.3	Stability: 7-8
4-5	122.6	Thermal: 8-9	102.9	Stability: 7-8
5-6	140.7	Thermal: 8-9	102.9	Stability: 7-8
6-7	123.2	Thermal: 8-9	104.8	Stability: 7-8
7-8	128.7	Thermal: 8-9	104.1	Stability: 7-8
8-9	141.6	Thermal: 8-9	105.4	Stability: 8-9
4-9	123.1	Thermal: 8-9	102.9	Stability: 8-9

On the other hand, when considering stability constraint, the base case transfer capability is decreased to 102.3MVA. Stability violations occurred in all other cases and there is not much improvement for TTC by installing TCSC in these cases.

Without consideration of stability, TCSC could have significant effect on increasing the transfer capability, and this matches the conclusion from reference [8]. However, that conclusion may not always be true when stability limit is incorporated.

Case-2: Voltage Limit $0.95<|V|<1.05$

Without considering stability constraint, this case would be a “pure” voltage limit dominant case. Table IV shows the results. The base-case TTC is the same for both conditions. This is because for either condition, the voltage limit always hits first. After installing TCSC, the transfer capability increases. When TCSC is installed in different lines, the effect varies. That also matches the conclusion in [8]. When considering stability constraint, either voltage limit or transient stability limit might hit for TCC calculation. This demonstrates the importance of taking the stability into account in TTC calculation. When TCSC is installed in line 4-9, which is connected to the bus-9 with voltage violation, the effect is significant. The case where TCSC is installed in line 5-6 also gives good effect. That is because the installation of TCSC in that line changes the power flow with positive effect on the transfer capability.

TABLE IV
EFFECT OF TCSC ON TTC (VOLTAGE LIMIT DOMINANT)

TCSC Installed on	Without considering stability		Considering stability	
	Transfer Capability	Violation	Transfer Capability	Violation
Null	96.5	Voltage: 9	96.5	Voltage: 9
4-5	97.4	Voltage: 9	97.4	Voltage: 9
5-6	121.3	Voltage: 9	102.9	Stability: 7-8
6-7	103.8	Voltage: 9	103.8	Voltage: 9
7-8	107.9	Voltage: 9	104.1	Stability: 7-8
8-9	102.8	Voltage: 9	102.8	Voltage: 9
4-9	120.8	Voltage: 9	102.9	Stability: 8-9

2) Effect of SVC

Case-1: Voltage Limit $0.90<|V|<1.10$

Table V shows the results of the effect of SVC on TTC. When considering stability constraints, the base case TTC decreased 16.2% from 122.0MVA to 102.3MVA. After installing SVC, no obvious improvement is found from the results in Table V. Therefore, the SVC cannot improve the transfer capability in thermal limit dominant cases. Stability limit further confines the TTC.

TABLE V
EFFECT OF SVC ON TTC (THERMAL LIMIT DOMINANT)

TCSC Installed on	Without considering stability		Considering stability	
	Transfer Capability	Violation	Transfer Capability	Violation
Null	122.0	Thermal: 8-9	102.3	Stability: 7-8
4-5	123.3	Thermal: 8-9	102.3	Stability: 7-8
5-6	123.3	Thermal: 8-9	102.3	Stability: 7-8
6-7	124.7	Thermal: 8-9	102.3	Stability: 7-8
7-8	122.4	Thermal: 8-9	104.8	Stability: 8-9
8-9	122.4	Thermal: 8-9	102.3	Stability: 8-9
4-9	122.4	Thermal: 8-9	102.3	Stability: 7-8

Case-2: Voltage Limit $0.95<|V|<1.05$

Transfer capability without SVC decreases due to the narrow voltage limit margin. In both conditions the voltage limits are hit for base case TTC. The installation of SVC can fairly improve the TTC from Table VI.

TABLE VI
EFFECT OF SVC ON TTC (VOLTAGE LIMIT DOMINANT)

TCSC Installed on	Without considering stability		Considering stability	
	Transfer Capability	Violation	Transfer Capability	Violation
Null	96.5	Voltage 9	96.5	Voltage 9
4-5	123.3	Thermal: 8-9	102.3	Stability: 7-8
5-6	116.2	Voltage 9	102.3	Stability: 7-8
6-7	110.6	Voltage 9	102.3	Stability: 7-8
7-8	122.4	Thermal: 8-9	104.8	Stability: 7-8
8-9	122.4	Thermal: 8-9	102.3	Stability: 8-9
4-9	122.4	Thermal: 8-9	102.3	Stability: 7-8

In this case, either thermal limit or voltage limit might be hit when stability constraint is not taken into account. When stability is considered, however, the stability limit becomes the bottleneck except for the base case.

3) Comparison of Results

Table VII summarizes the TTC results with the most significant improvements under various conditions.

TABLE VII
COMPARISON OF THE EFFECT OF TCSC AND SVC ON TTC

	Without considering stability		Considering stability	
	$0.90<\|V\|<1.1$	$0.95<\|V\|<1.05$	$0.9<\|V\|<1.1$	$0.95<\|V\|<1.05$
TTC (base case)	122.0	96.5	102.3	96.5
TTC with TCSC	141.6	121.3	105.4	104.1
Improvement	16.1%	25.7%	3.0%	7.9%
TTC with SVC	124.7	123.3	104.8	104.8
Improvement	2.2%	27.8%	2.4%	8.6%

From Table VII, it is observed that when transient stability is not considered, TCSC and SVC improve TTC significantly for voltage limit dominant cases while only TCSC improves TTC for thermal limit dominant cases. On the other hand, when stability constraint is considered the improvement drops.

V. CONCLUSIONS AND FUTURE WORK

A comprehensive approach for TTC calculation is established with consideration of thermal, voltage and transient stability limits. Based on this approach, both steady state and dynamic security assessments are included in the process of obtaining total transfer capability. The studies reported indicate that TTC without considering transient stability limits is prone to give optimistic results.

The FACTS devices have both positive and negative effects on system stability depending on their location. In order to evaluate the effects of FACTS devices on TTC, all critical factors need to be taken into account simultaneously.

Fault conditions such as fault location and fault duration time are major factors in determining the system stability. In this paper, fixed fault location and fault duration time are used for stability analysis. However, a fault condition varies greatly based on the nature of fault and protection device/scheme applied. Therefore, probabilistic stability analysis is expected to give more realistic results in TTC calculations.

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VII. BIOGRAPHIES

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