Available Transfer Capability Enhancement Using Series FACTS Devices in a Designed Multi-Machine Power System

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***Abstract*—Series FACTS devices have been successfully used for many years in order to enhance the stability and loadability of high voltage transmission networks. The principle is to compensate the inductive voltage drop in the line by an inserted capacitive voltage or in other words to reduce the effective reactance of the transmission line to enhance Available Transfer Capability (ATC) in the network. ATC accurately reflects the physical realities of the transmission network, all system conditions, uses, and limits in a consistent manner. It depends on other parameters namely Total Transfer Capability (TTC), Capacity Benefit Margin (CBM), Transmission Reliability Margin (TRM), and Existing Transmission Commitments (ETC) that are described in this study thoroughly. This paper investigates the optimized use of FACTS devices and mainly Thyristor Controlled Series Capacitor (TCSC) to improve ATC and maximize Total Transfer Capability generally defined as the maximum power transfer transaction between a specific power-seller and a power-buyer in a two area designed power system. The case study has been implemented on a 13-bus multi-machine test system using PowerWorld Simulator version 12.0. Furthermore, static linear analysis methods have been taken into account in calculating ATC and the impact on various factors has been defined clearly.**

***Index Terms*—Available Transfer Capability, Thyristor-Controlled Series Capacitor, Total Transfer Capability, Thermal Limits, Optimal Placement.**

I. Introduction

The electric power industry has encountered major changes during its evolution. In recent years the load has increased significantly mainly due to the growing amount of individual power suppliers and rivals among electric power firms which is continuing on. Besides, some new conditions have emerged constraining the physical development of the power transmission networks. These major drawbacks are environmental issues, economical matters constructing new transmission lines, and ground availability concerns especially in densely-populated areas and regions consisting of distribution networks. Thus, for the optimized usage of present transmission lines there is a necessity to increase the power transfer capability in transmission lines, control the power flow in transmission grids, enhance the reliability of the power grid, and improve the efficiency of available facilities. These facts indicate the importance of utilizing devices that enhance power transmission, security, reliability, and controllability of the power system known as Flexible Alternating Current Transmission System (FACTS).

This group of controllers are revolutionizing the way electric power is transmitted by rapidly and smoothly controlling power system quantities. They are designed to overcome the constraints mentioned in a fast and intelligent way so that the electric power regulators and investors goals are met without them having to undertake major system additions. According to FACTS IEEE definition; they are Alternating current transmission systems incorporating power-electronic based and other static controllers to enhance controllability and increase power transfer capability. Furthermore, FACTS controller is a power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters [1]. From the time this technology has been established numerous FACTS devices have been introduced in which each have their own impact on the load flow equation parameters affecting the power system [2], but the most common ones implemented in the power grids are: Static VAR Compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC), Phase Angle Regulator (PAR), and Unified Power Flow Controller (UPFC) [3]. In this paper the optimized usage of TCSC in a designed multi-machine power system is studied, improving the stability and loadability of the power transmission network.

II. Thyristor-Controlled Series Capacitor

A. Series Compensation

Series FACTS devices and TCSC have been successfully used for many years in order to enhance the stability and loadability of the power transmission network. The principle is to compensate the inductive voltage drop in the line by an inserted capacitive voltage or in other words to reduce the effective reactance of the transmission line increasing the current and consequently the power flow in the line under operation. The series capacitors also contribute to an improvement in voltage profiles and enhance the transient stability [4]. Fig. 1 illustrates a model of transmission line with a TCSC connected between buses i and j. The transmission line is represented by its lumped π-equivalent parameters connected between the two buses. During the

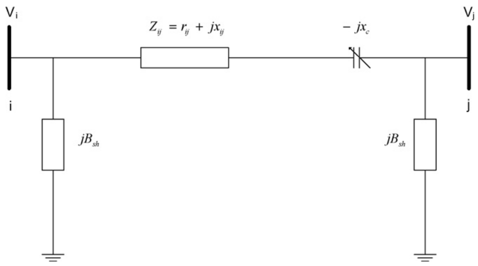

Fig.1. Model of Transmission Line with TCSC

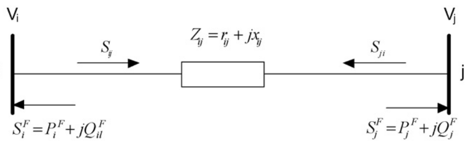

Fig. 2. TCSC Power Injection Model

steady state, TCSC can be considered as a static reactance $-jX_c$. The controllable reactance "X_c" is directly used as the control variable to be implemented in the power flow equation.

B. Power Injection Model (PIM)

There are two standard models for FACTS devices; the dynamic model of a FACTS device is the Voltage Source Model (VSM), based on a shunt and a serial voltage source with internal admittances, for static applications and load-flow calculations the Power Injection Model (PIM) has been introduced [5-9]. The injection model describes FACTS as devices that inject a certain amount of active and reactive power to a node, so that a FACTS device is represented as PQ elements. The advantages of the PIM are that it does not destroy the symmetrical structure of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical tools [5-8]. Among various types of FACTS devices, TCSC as mentioned in section II.A has the capability to control power flow and it is the most widely used series FACTS device, also in this study.

The PIM model of the TCSC incorporated within the transmission line is shown in Fig. 2. The real and reactive power injections due to the series capacitor of TCSC at buses *i* and *j* are given by (1) to (4) [8,9]:

$$P_i^F = V_i^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos(\delta_i - \delta_j) + \Delta B_{ij} \sin(\delta_i - \delta_j)\right] \quad (1)$$

$$Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j \left[\Delta G_{ij} \sin(\delta_i - \delta_j) - \Delta B_{ij} \cos(\delta_i - \delta_j)\right] \quad (2)$$

$$P_j^F = V_j^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos(\delta_i - \delta_j) - \Delta B_{ij} \sin(\delta_i - \delta_j)\right] \quad (3)$$

$$Q_j^F = -V_j^2 \Delta B_{ij} + V_i V_j \left[\Delta G_{ij} \sin(\delta_i - \delta_j) + \Delta B_{ij} \cos(\delta_i - \delta_j)\right] \quad (4)$$

where:

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)[r_{ij}^2 + (x_{ij} - x_c)^2]} \quad (5)$$

$$\Delta B_{ij} = -\frac{x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)[r_{ij}^2 + (x_{ij} - x_c)^2]} \quad (6)$$

The model introduced is extensively used in OPF calculations. Furthermore, the maximum series compensation implementing TCSC is limited to 70% of the uncompensated lines reactance where TCSC is located in [1,9].

The impact of TCSC on the network's admittance matrix and the changes in the i-j transmission line admittance before and after placing TCSC is indicated as below:

$$\Delta y_{ij} = y'_{ij} - y_{ij} = (g'_{ij} + jb'_{ij}) - (g_{ij} + jb_{ij}) \quad (7)$$

where:

$$g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}} \quad , \quad b_{ij} = -\frac{x_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}} \quad (8)$$

$$g'_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}} \quad , \quad b'_{ij} = -\frac{x_{ij} + x_c}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}} \quad (9)$$

When TCSC is installed between buses i and j, the new network's admittance Y'_{bus} will be formed as shown in (10):

$$Y'_{bus} = Y_{bus} + \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & \Delta y_{ij} & 0 & \cdots & 0 & -\Delta y_{ij} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & -\Delta y_{ij} & 0 & \cdots & 0 & \Delta y_{ij} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

Taking into account the different lines TCSC has to be installed and its compensation degree, the above formulation in calculating Y_{bus} is revised at every iteration.

III. AVAILABLE TRANSFER CAPABILITY

A. Definition

A key concept in the restructuring of the electric power systems is the ability to accurately and rapidly quantify the capabilities of the transmission system. For this purpose, Available Transfer Capability (ATC) and its dependant parameters have been introduced. ATC 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 [10]. It accurately reflects the physical realities of the transmission network, all system conditions, uses, and limits in a consistent manner.

ATC depends on other parameters namely Total Transfer Capability (TTC), Capacity Benefit Margin (CBM), Transmission Reliability Margin (TRM), and Existing Transmission Commitments (ETC) which need to be determined in order to reach an accurate value in calculating ATC. "Total Transfer Capability" is the fundamental parameter in calculating ATC. It is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of the specific set of defined system conditions. "Transmission Reliability Margin" is the amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. The "Capacity Benefit Margin" is the amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements [10]. Finally, "Existing Transmission Commitments" indicates the overall amount of power flowing in the interconnected transmission lines between specified areas during OPF execution in a given case; it can also be named as "Existing Power Flows".

B. Proposed ATC Computation

Mathematically, ATC is defined as the TTC less the TRM, less the sum of ETC (which includes retail customer service) and the CBM [10-13]:

$$ATC = TTC - TRM - CBM - ETC \tag{11}$$

The ATC between two areas provides an indication of the amount of additional electric power that can be transferred from one area to another for a specific duration and set of conditions.

In this case study which has been implemented on a 13-bus multi-machine test system, optimized use of TCSC is investigated in order to improve ATC and to come into an approximate estimation of its value based on other relevant parameters and mainly TTC. Thus, Total Transfer Capability will be generally defined as the maximum power transfer transaction between a specific power-seller and a power-buyer in the two area designed power system, considering the limitations by the physical and electrical characteristics of the power system including thermal, voltage, and stability constraints [10,11]. Therefore, the TTC can be evaluated by determining the most restrictive of those limitations for a specific duration and set of conditions:
TTC= Minimum of {Thermal limit, Voltage limit, Stability limit} as indicated in [10].

In this study voltage limits is of minor importance and doesn't constrain power transactions between the two areas, due to the reason that the test system has been constructed of short transmission lines less than fifty kilometers. In fact, the main constraint in this type of power systems is the transmission line's thermal limitations. Therefore, in the designed 13-bus power system according to TTC= minimum of {thermal limits, voltage limits, transient stability limits} and its definition: the maximum power transfer transaction of the transmission lines between the two areas utilizing series FACTS devices, TTC is estimated considering thermal MVA limits as its major bound. Consequently, the case studies simulation and its results confirm the importance of this limiting factor in evaluating TTC.

Furthermore, both TRM and CBM which account for the reliability of the system can be typically assumed as fixed values. TRM is assumed as a fixed percentage of TTC which is 5% under normal operating conditions [11,13] and CBM is assumed to be zero according to [12-14]. Hence, the ATC can be approximated as follows:

$$ATC = 0.95\ TTC - ETC \tag{12}$$

The foregoing illustrates that ATC is determined by load flow study results and transmission limits which reduces the complexity of the ATC calculations. In the following sections these parameters will be determined and utilized in (12) estimating the ATC values as their outcome.

IV. CASE STUDY

A. Description of The 13-Bus Power System

This section represents our designed 13-bus multi-machine power system as the test system of this study, which has been designed and assessed utilizing PowerWorld Simulator version 12.0. The designed power system's overall information has been given in Table I. This system is divided into two areas of which the left area is the generation area (seller) and the right area is the sink (buyer). In fact, the reason of this division is due to the high amount of power the left area generates, and provides part of the right areas consumed power through eight transmission lines interconnecting the two areas (lines 1 to 8). Table II clarifies the two areas condition comparatively.

The main goal of this simulation is to determine the

TABLE I
13- BUS TEST SYSTEM DATA

Buses	Generator			Load			Transmission Lines	Power Loss		Area	Slack Bus Number
	Units	MW	Mvar	Units	MW	Mvar		MW	Mvar		
13	10	1890	263	12	1870	228	22	20	35	2	7

TABLE II
13- BUS POWER SYSTEM AREA CONDITIONS

Area	Generation (MW)	Load (MW)	Loss (MW)	Buses
Left	1150	450	5	6
Right	740	1420	15	7

optimal placement of the TCSC in the designed power system in order to enhance the ATC from the left area (seller) to the right area (buyer). Taking into account this fact that the power is dispatched from the left to the right area through the eight transmission lines, the most appropriate place to install the compensating series device is one of these eight lines. Consequently, the increase in power transmission in these lines and from the seller to the buyer will define the best case and the most suitable line to install TCSC. ATC improvement is defined by taking into consideration the network's topology and its constraints, mainly known as thermal limits discussed in section III.B. Thus, it is not feasible to increase the series compensation degree 'k' to any desired rate because of the mentioned constraints.

In this simulation a TCSC with a definite compensation degree is installed on each line (one of the eight transmission lines between the two areas) representing eight cases, enabling the calculation of TTC, ETC, and ATC in each case respectively; providing us with the optimal placement of this series FACTS device. In each of these eight cases TCSC will be placed in the transmission lines with three different compensation statuses forming 24 scenarios:

- compensation degree of 25%
- compensation degree of 50%
- maximum compensation degree for each case

B. Base Case

The single line diagram of this designed system is depicted in Fig. 3, considered as the base case and without any FACTS device installed on it. Base values are assumed to be 100 MVA and 138 kV. In this case as it can be observed by the pie charts on the lines between each two buses, all of the transmission lines operate under their thermal limit value 100 MVA. The buses comprehensive attributes are listed in Table III. Bus 7 is the slack bus and the direction of the power transaction between the buses can be inferred according to the voltage phase difference among two buses and the transmission lines between them. Consequently, the buses located in the left area of the test system (1, 2, 6, 10, 12, 13) are leading in phase in respect to buses situated in the right

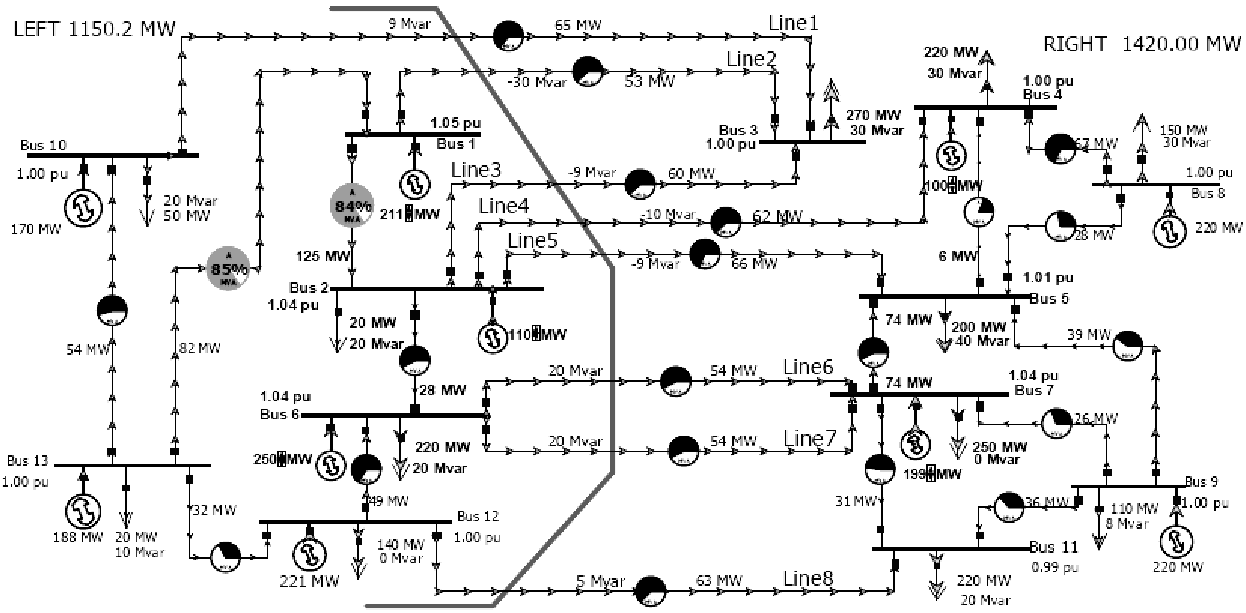

Fig. 3. 13-bus power system

TABLE III
BUSES SPECIFICATIONS

Name	Area	Type	V (p.u.)	V (kV)	Angle (deg.)	Load		Generation	
						MW	Mvar	MW	Mvar
Bus 1	Left	138	1.05	144.9	-64.35	0	0	210.78	10.19
Bus 2	Left	138	1.04	143.52	-68.33	20	20	110.4	56.35
Bus 3	Right	138	1.00015	138.02	-75.1	270	30	0	0
Bus 4	Right	138	1	138	-74.88	220	30	100.49	21.74
Bus 5	Right	138	1.00718	138.991	-74.68	200	40	0	0
Bus 6	Left	138	1.04	143.52	-69.23	220	20	250.19	20.5
Bus 7	Right	138	1.04	143.52	-72.49	250	0	199.17	199.55
Bus 8	Right	138	1	138	-70.18	150	30	220	13.85
Bus 9	Right	138	1	138	-68.36	110	8	220	-15.82
Bus 10	Left	138	1	138	-67.64	50	20	170	17.89
Bus 11	Right	138	0.99114	136.777	-74.16	220	20	0	0
Bus 12	Left	138	1	138	-65.48	140	0	220.81	-35.15
Bus 13	Left	138	1	138	-63.22	20	10	188	-26.2

area (3, 4, 5, 7, 8, 9, 11). Hence, the power is dispatched from the left area to the right and all the eight lines 1 to 8 dispatch power from the left area to the right area. In the designed system, the per unit value of the buses voltage has to be in the permissible bounds, so that the system wouldn't encounter overvoltage or voltage collapse maintaining the power quality in its suitable amount. The standard voltage variation is in the range of 94% to 106% of its nominal value [15], of which in all of the scenarios has been maintained.

Table IV shows the positive and negative sequence electrical parameters for each of the specified eight transmission lines in the base case (lines 1 to 8 in Fig. 3) with $S_b = 100^{MVA}$, $Z_b = 190.44^{\Omega}$, and $V_b = 138^{kV}$. Installing a series capacitor in each of these lines only affects the reactance (X) of the line, so that it decreases the line's reactance causing an increase in the specified line's power transaction. The results of installing TCSC on each line will be discussed in the following section.

V. Results and Discussion

The series FACTS device is placed in lines 1 to 8 of the power system at each time (named case 1, case 2, …, case 8) with three different compensation degree rates and the maximum ATC improvement in these lines has been achieved, indicating the optimal placement and maximum compensation degree of the TCSC in the 13-bus multi-machine power system. In all these cases TCSC placement in the lines didn't change the buses voltages and had minor impact on it, since all of the transmission lines are less than fifty kilometers long and series capacitors insert an capacitive voltage or in other words reduce the effective reactance of the transmission line mainly influencing real power (P) than reactive power(Q). On the other hand, in transmission lines shorter than 100 kilometers ($l<100^{km}$) the factor which receives attention is the thermal limit and voltage and stability constraints are not of a major importance and don't cause any specific limitation for the power grid. The fact is that only in distances with $l>250^{km}$ the voltage's magnitude encounters major changes and will be much more important than the thermal constraint. Therefore, TCSC placement in the base case system's lines only changes the voltage's phase due to the change in the power transfer rate between the buses and the voltage magnitude remains constant. In addition, TTC is estimated according to Thermal limitations discussed in section III.B.

TABLE IV
Electrical Parameters of Lines 1 to 8

Line No.	R (pu)	X (pu)	B (pu)
1	0.02	0.20	0.03
2	0.02	0.10	0.03
3	0.03	0.21	0.04
4	0.03	0.20	0.04
5	0.02	0.18	0.03
6	0.04	0.10	0.05
7	0.04	0.10	0.05
8	0.02	0.24	0.03

The comprehensive results calculated for each case at its maximum compensation degree can be derived from Table V. They hold the principle results of the simulation, TCSC installations, and ATC calculations for the eight cases discussed, including the base case. In this table, in each specific case e.g. case x (number of each case identifies the line TCSC is installed on), based on the amount of power transferred by each of the eight lines from left to right, ETC_x is derived indicating the sum of power flowing in the lines between the two area at case x (x= 1, 2, …, 8). Consequently, according to (12), TTC definition, and the assumptions made in section III.B; ATC is estimated. In fact, TTC is approximated as the sum of the diagonal entries "a_{11}, a_{22}, a_{33}, a_{44}, a_{55}, a_{66}, a_{77}, a_{88}" of the 8×8 power transmission matrix excluding the base case. Since this amount of MW is the most reached installing the series FACTS device with its maximum compensation degree (refer to Table V) and in a reliable manner while meeting all of the specific set of defined system conditions including system constraints mainly thermal limits of the lines (max. 100% is equivalent to 100^{MW}), it's TTC values are also implemented in calculating ATC for 25% and 50% compensation degree. The TTC amount estimated based on the above details is 719.1^{MW} and following TRM= 36^{MW}.

Table V works as a reference consisting of all the data required to indicate the optimal placement of the series FACTS device in the lines between the two areas. In this status, TCSC is installed with its maximum compensation

TABLE V
Results Obtained of TCSC Installation With Maximum Compensation Degree in Lines Between Two Areas

Transmission Line No.	Power Transmission (MW)									TTC
	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	
1	64.6	98.3	58.3	61.1	63.1	65.6	64.7	64.7	66.8	98.3
2	53.7	41.6	87.7	43.5	48.2	57	55.9	55.9	54.1	87.7
3	60.4	56.6	54.8	99.6	51.3	54.5	59.2	59.2	58.8	99.6
4	61.5	59.8	58	51.9	98.9	54.4	60.3	60.3	59.8	98.9
5	66	67.3	68.2	58.4	57.4	98.5	64.2	64.2	63.9	98.5
6	53.5	53.9	58.9	48.1	48.2	47	68.2	46.4	46.6	68.2
7	53.5	53.9	58.9	48.1	48.2	47	46.4	68.2	46.6	68.2
8	62.6	64.3	62.7	61.4	61.4	61.4	61.5	61.5	99.7	99.7
ETC	475.8	495.7	507.6	472.1	476.7	485.5	480.4	480.4	496.3	-
Power Loss (MW)	7	8.6	9	8.4	8.2	7.8	9.7	9.7	8.3	-
Compensation Degree (k)	-	56%	62%	51%	51%	50%	63%	63%	60%	-
ATC	207.3	187.4	175.5	211	206.4	197.6	202.7	202.7	186.8	-
ATC Enhancement	-	9.6%	15.3%	-1.8%	0.4%	4.7%	2.2%	2.2%	9.9%	-

degree in each case as it doesn't overload the line located on. The outcome of the TCSC placement in different lines (cases) indicates remarkable enhancement in ATC in respect of the base case, so that the most impact is with case 2, showing 15.3% enhancement in comparison to the base case. Also, cases 8 and 1 go through an ATC improvement of 9.9% and 9.6% respectively, which conclude a better usage of the transmission lines available capacity. In cases 6 and 7, the amount of MW transmitted in lines 6 and 7 during their 100% thermal capacity operation increases lesser in comparison to the other cases, reaching 68.2^{MW} out of 100^{MVA}. This points out the large amount of Mvar flowing in these lines in respect of other cases and other diagonal entries of the 8×8 power transmission matrix. By observing the ATC of these two cases it can be inferred that lines 6 and 7 are not suitable for installing TCSC. In fact, the best lines for placing it are 2 and 8 respectively, whereas they enhance ATC 15.3% and 9.9% with the compensation degree of 62% and 60% respectively. Furthermore, a comparison among the sum of the electric power loss in the lines between the two areas in cases 2 and 8 with cases 5 and 6 indicates the advantage of installing TCSC in lines 2 and 8.

Fig. 4 depicts the ETC of each case with the line number TCSC is installed on in three different compensation degrees. In fact, it is a comparison between the figures acquired in Table V with 25% and 50% compensation, tracing the changes in them in order to find the suitable line to place TCSC with its best compensation degree. According to ATC formulation in section III.B as much as the ETC_x is higher, ATC_x will be lesser in amount indicating a more efficient utilization of the lines available capacity. The chart defines lines 2, 8, and 1 as the most suitable lines to place TCSC in respectively. Accordingly, maximum compensation degree has more improvement on ATC, which can be seen in the chart obviously. Line 2 with ETC= 507.6^{MW} transfers the highest amount of power from the left area to the right, confronting with the utmost amount of ATC enhancement (ATC= 175.5^{MW}). Therefore, installing TCSC on line 2 with its maximum compensation degree of 62% utilizes the lines available capacity more efficiently, confirming this line as the optimal location installing TCSC on, in the 13-bus multi-machine power system.

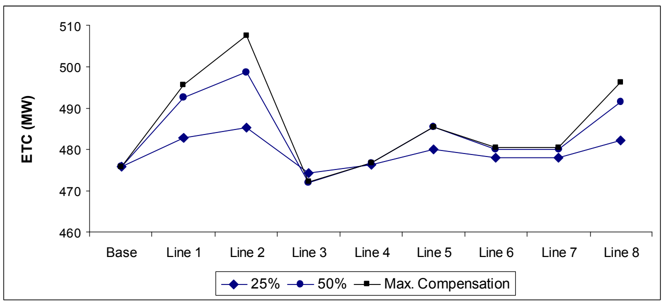

Fig. 4. Power transfer between two areas with the installation of TCSC in three compensation status

VI. Conclusion

ATC Enhancement is an important issue in restructuring the electrical power systems. Furthermore, Optimum utilization of the transmission lines available capacity indicates the necessity of implementing series FACTS devices in the power grid. In the present paper, the impacts of TCSC on ATC improvement are investigated. The case study has been implemented on a reliable designed 13-bus multi-machine power system. From the numerical results, it can be seen that TCSC increases TTC causing the ATC to improve, and leading to better utilization of transmission grids. Moreover, the results show a maximum 15.3% improvement in ATC by installing TCSC and indicate the optimal placement of it in the designed power system. Since series FACTS devices have many other uses such as improving power system angle and voltage stability in long transmission lines etc., the optimal placement of them in the power grid may be a practical solution decreasing new transmission lines structural investments and expansion planning issues.

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