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Optimal Location and sizing of TCSC for Improvement of Static Voltage Stability

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Abstract— **Voltage instability in power system is a major issue in electrical power system operation. Voltage instability occurs due to deficit of reactive power at load buses during some contingency or under increased loading condition. Flexible AC Transmission System (FACTS) devices can improve the voltage stability with reduction of losses and generation cost. Though Thyristor Controlled Series Compensator (TCSC) is a series device, it can improve voltage stability with improved power transfer capability of the transmission line. Like other FACTS devices, TCSC is also costly. Hence it is important to find its optimal location and size for improvement of voltage stability. Here Line Stability Index (LSI) is considered to find the optimal location of TCSC in the system. LSI provides the information about the stability condition of a power system and its proximity to voltage collapse. The analysis has been demonstrated on a standard IEEE 6-bus system with some modification in load data using Power World Simulator.**

Index Terms— **FACTS Devices, Line Stability Index (LSI), Power World Simulator, TCSC, Voltage Stability**

I. Introduction

In recent years, due to restructuring of the electricity industry, increasing load demands, some economic and environmental constraints power systems are being operated closer to their stability limits, which may sometimes leads to voltage collapse. Maintaining a stable and secure operation of a power system is therefore a very important and challenging issue. Voltage stability is the ability of a power system to maintain acceptable voltages at all the load buses of the system under normal conditions and also following a disturbance [1].

Many analysis are carried out on voltage stability, they are either static analysis or dynamic analysis. The dynamic analysis emphasizes on large disturbance or transient stability occurrence, while static analysis is considered as a small signal phenomenon, load increasing and line outage. Voltage collapse is a relatively slow process thus being primarily considered as a small signal phenomenon. So Voltage stability determination have been developed on static analysis techniques based on the power flow model since they are simple, fast and convenient to use [2].

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The major factors affecting voltage stability of a power system are its generators reactive power limit, voltage control limits, characteristics of connected loads, reactive power compensation devices characteristics and their actions. Several methods have been used for static voltage stability analysis such as the P-V and Q-V curves, modal analysis, artificial neural networks etc. Line stability index (LSI) provides important information about the proximity of the system to voltage collapse and also used to identify the critical line of the system [3-5].

Voltage instability [3] can be avoided by: (a) appropriate load shedding on the consumer network; (b) on load tap changers; (c) reactive compensation (series and/or shunt). An effective solution to improve the voltage profile and voltage stability of power system with reactive power compensation is to place an appropriate Flexible AC transmission system (FACTS) controller [6] in the system. FACTS controllers are solid state converters which use reliable high speed thyristor based control elements and have the capability of controlling and improving the various electrical parameters in transmission network i.e. power transmission capacity, voltage profile, minimization of transmission losses, power system stability etc. FACTS controllers are costly. To obtain maximum benefits from these controllers, the choice of type of controller and its optimal location and size is also a challenging issue [7].

Thyristor controlled series capacitor (TCSC) is a series FACTS device. It is a series capacitor, connected with thyristor controlled inductor in parallel so that variable reactance of the capacitor can be achieved. As other FACTS devices, TCSC is also a costly device and hence it is important to place it at optimal location and to find its optimal size [10], so that maximum benefits from it may be achieved. Sequential quadratic programming, mixed integer programming and line stability index have been proposed for optimal location and sizing of TCSC for voltage stability enhancement. In this paper line stability index is used for optimally locate a TCSC in the system.

II. Mathematical Model of TCSC

Thyristor controlled series compensator is one of the most important device of FACTS controllers' family. TCSC is in use for many years to increase line power transfer and to enhance stability. TCSC can enhance the power system stability by effectively controlling the line power flows. Controlling the power flows in the system helps in reducing the flows in heavily loaded lines, resulting in increased system loadability and improved stability of the power system.[8]

The TCSC can serve as the capacitive or inductive compensation respectively by modifying the resistance of the transmission line. In this study, the reactance of the transmission line is adjusted by TCSC directly. The rated value of the TCSC is a function of the reactance of the transmission line, where the TCSC is located.

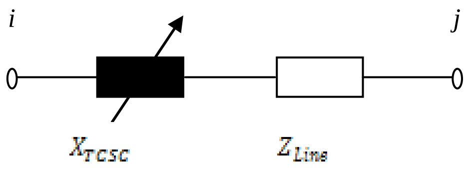

Fig. 1. Mathematical Model of TCSC

$$Z_{ij} = Z_{Line} + jX_{TCSC}$$
$$X_{ij} = X_{Line} + X_{TCSC}$$
$$X_{TCSC} = r_{TCSC} \times X_{Line}$$

Where, X_{Line} = Reactance of transmission line.

X_{TCSC} = Reactance of TCSC.

r_{TCSC} = Coefficient which represents the compensation of degree of TCSC.

To avoid overcompensation, the working range of TCSC is between -0.7× X_{Line} and 0.2× X_{Line} [9].

$$r_{TCSC(min)} = -0.7, r_{TCSC(max)} = 0.2$$

III. LINE STABILITY INDEX (LSI)

The line stability index determines the critical line and provides a measure to proximity to the voltage collapse point of the system [10]. In an interconnected system, the value of line stability index that is closed to one indicates the line has reached its instability limit.

In any power system, the voltage stability analysis is carried out for two purposes: (a) to determine how much any system is close to its instability limit, and (b) which is the critical line or weak bus in a power system.

A. Derivation of LSI:

Moghavvemi [12], derived a voltage stability criterion based on a power transmission concept in a single line. An interconnected system is reduced to a single line network and then applied to assess the overall system stability. Utilizing the same concept but using it for each line of the network a stability criterion is developed. Consider a single line of interconnected network shown in Fig. 2. The line is connected to the other lines forming a grid network. Any of the lines from that network can be represented with the following parameters as shown in the Fig. 2.

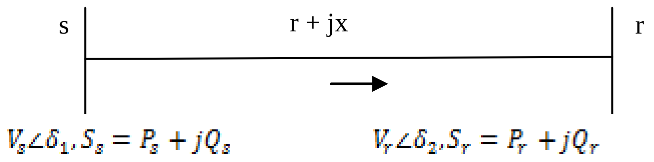

Fig. 2. Typical one line diagram of transmission line

Utilizing the concept of power flow in the line and analyzing with 'π' model representation, the power flow at the receiving and sending end can be expressed as

$$S_r = \frac{|V_s||V_r|}{Z}\angle(\theta - \delta_1 + \delta_2) - \frac{|V_r|^2}{Z}\angle\theta$$
$$S_s = \frac{|V_s|^2}{Z}\angle\theta - \frac{|V_s||V_r|}{Z}\angle(\theta + \delta_1 - \delta_2)$$

From these power equations one can separate real and reactive power,

$$P_r = \frac{V_s V_r}{Z}\cos(\theta - \delta_1 + \delta_2) - \frac{V_r^{\,2}}{Z}\cos\theta$$
$$Q_r = \frac{V_s V_r}{Z}\sin(\theta - \delta_1 + \delta_2) - \frac{V_r^{\,2}}{Z}\sin\theta$$

Putting, $\delta_1 - \delta_2 = \delta$ into equation 4 and solving it for V_r

$$V_r = \frac{V_s\sin(\theta - \delta) \pm \{[V_s\sin(\theta - \delta)]^2 - 4\,ZQ_r\sin\theta\}^{0.5}}{2\sin\theta}$$

Now, for $Z\sin\theta = x$, we have

$$V_r = \frac{V_s\sin(\theta - \delta) \pm \{[V_s\sin(\theta - \delta)]^2 - 4xQ_r\}^{0.5}}{2\sin\theta}$$

To obtain real values of Vr in terms of Q, the equation must have real roots. Thus the following conditions, which can be used as a stability criterion, need to be satisfied:

$$\{[V_s\sin(\theta - \delta)]^2 - 4xQ_r\} \geq 0$$

Or

$$\frac{4x\,Q_r}{[V_s\sin(\theta - \delta)]^2} = L_{mn} \leq 1.00$$

L_{mn} is termed the stability index of the line. The stability criterion is used to find the stability index for each line connected between two busbars in an interconnected network. Based on the stability indices of lines, voltage collapse can be accurately predicted. As long as the stability index L_{mn} remains less than 1, the system is stable and when this index exceeds the value 1, the whole system loses its stability and voltage collapse occurs. Thus the proposed method can be used in voltage collapse prediction.

IV. Simulation and Discussion

Effectiveness of TCSC in the system is analyzed on a 6 bus test system (modification in standard IEEE 6-bus system) using power world simulator. Its simulation gives the direct power flow analysis. This test system is consist of 6 buses, three generators, three loads and eleven transmission lines, data is given in APPENDIX (shown in Fig.3). In this paper, data of load flow taken from power world simulator results and LSI values have been computed for base case and various line outages. The line providing highest value of LSI is considered as the most severe line voltage from the view point of voltage stability.

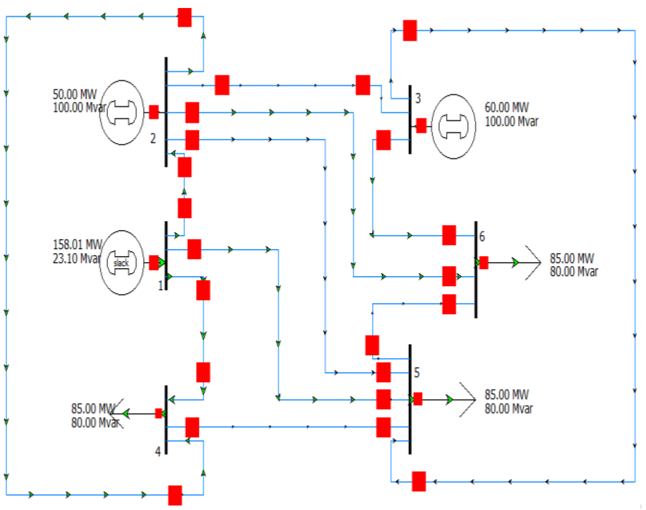

Fig. 3. 6 Bus Test System in Power World Simulator

A. *Without Compensation Voltage Stability Analysis (Locate TCSC)*

From the given data, the model of the test system is made in power world simulator and check the power flow. With normal operating condition, LSI values for all eleven lines are computed. This normal condition is termed as the base case here.

Then after different line outage contingencies are considered and the power flow is analyzed. Again the LSI values of each line for these cases are computed. The line outage providing highest value of LSI is considered as the most critical line from the viewpoint of voltage stability.

Here, the Table I show the lines which are having the maximum LSI values for different cases.

From the table we can see that line 3-5 is having high LSI values in all the cases considered. So, lines 3-5 can be considered as the most critical lines of the system.

TABLE I. Lines Having Maximum LSI Values

No.	**Case**	**Lines with maximum LSI value**		
		Rank I	**Rank II**	**Rank III**
1	Base Case	**3-5**	2-5	2-4
2	Outage of line 1-2	**3-5**	2-4	2-5
3	Outage of line 1-4	2-4	1-5	**3-5**
4	Outage of line 1-5	**3-5**	2-5	1-4
5	Outage of line 2-3	**3-5**	3-6	2-5
6	Outage of line 2-4	1-4	4-5	**3-5**
7	Outage of line 2-5	**3-5**	2-4	1-5
8	Outage of line 2-6	2-5	**3-5**	4-5
9	Outage of line 3-5	2-5	1-5	3-6
10	Outage of line 3-6	2-6	**3-5**	5-6
11	Outage of line 4-5	**3-5**	2-5	2-4
12	Outage of line 5-6	**3-5**	2-5	2-4

Ideally it can be considered that we should provide the compensation on transmission line connecting bus no. 3 and 5.

B. *Calculation of Compensation Value (Size of TCSC)*

Here compensating device TCSC changes the reactance of the line and change the power flow in the system. For the purpose of improvement in voltage stability, proper value of the TCSC reactance is required to be selected.

New reactance of the line is,

$$X = X_{LINE} + X_{TCSC}$$

$$X_{TCSC} = rX_{LINE}$$

To get the required reactance value of TCSC here trial and error method is applied. The voltage at all the buses with different value of r is shown in Table II.[(a),(b)]

TABLE II. Bus Voltage Values for Different r

BUS	Bus voltages in pu					
	Base	r=-0.03	r=-0.035	r= -0.05	r= -0.1	r= -0.2
1	1.05	1.05	**1.05**	1.05	1.05	1.05
2	1.0403	1.04337	**1.04339**	1.04334	1.0432	1.0428
3	1.04302	1.05616	**1.05624**	1.056	1.05521	1.05339
4	0.97347	0.97379	**0.97379**	0.97379	0.97381	0.97375
5	0.97208	0.96265	**0.96259**	0.96277	0.9634	0.9646
6	0.9737	0.98134	**0.98139**	0.98126	0.98084	0.9798

(a)

(b)

BUS	Bus voltages in pu r=-0.3	r=-0.4	r= -0.5	r= -0.6	r= -0.7
1	1.05	1.05	1.05	1.05	1.05
2	1.04238	1.04193	1.04143	1.04089	1.0403
3	1.05149	1.04948	1.04738	1.0452	1.04302
4	0.97372	0.97367	0.97362	0.97355	0.97347
5	0.96592	0.96734	0.96886	0.97045	0.97208
6	0.97872	0.97757	0.97634	0.97505	0.9737

From Table II it is seen that for r = -0.035, bus voltage at almost all the buses is improved than in the base case. So TCSC having capacitive reactance of 0.0091 pu can be used.

C. With Compensation Voltage Stability Analysis

In this analysis, first of all reactance of compensating device TCSC is added to the actual reactance of line between bus 3 and 5 (critical bus of the system). Then the same analysis of the obtained system is carried out. For base case and for different line outage contingency LSI of each line is to be found out.

Now, maximum LSI for each case with compensation and without compensation is compared. Comparison of these both systems is shown in TABLE III

TABLE III. COMPARISON OF LSI IN WITH AND WITHOUT COMPENSATION SYSTEM

Rank	**Case**	**Maximum LSI Values** With TCSC	**without TCSC**
	Base case	0.32061	0.32742
1	Line 3-6 outage	0.79953	0.49520
2	Line 2-4 outage	0.45910	0.46021
3	Line 1-5 outage	0.39406	0.40401
4	Line 1-4 outage	0.38917	0.38952
5	Line 2-5 outage	0.37400	0.38245
6	Line 5-6 outage	0.35460	0.36326
7	Line 1-2 outage	0.35343	0.36019
8	Line 2-3 outage	0.34003	0.34712
9	Line 4-5 outage	0.32450	0.33254
10	Line 2-6 outage	0.31272	0.31350

From this comparison it is seen that except one case (line 3-6 outage) LSI value after compensation is lesser than before compensation. Thus for all cases (except outage of line 3-6) of line outage, TCSC of capacitive reactance 0.0091 pu at line between bus 3 and bus 5 improves voltage stability of the system.

V. CONCLUSION

In this paper TCSC at proper location and rating is used to improve voltage stability of the system. Voltage stability analysis is done with power flow and LSI calculation. This paper has identified that TCSC optimum location for one contingency may not be optimum for other contingencies and more than one TCSC are required to improve the voltage stability of a power system under various contingencies.

FUTURE SCOPE

Optimal location and size of TCSC can be decided using some Artificial Intelligent Techniques like Genetic Algorithm, Particle Swarm Optimization etc. These techniques give better results than conventional optimization methods.

APPENDIX

6 BUS TEST SYSTEM DATA
(BASE MVA=100)

Table A Demand data of six bus system

Bus Number	Type	Real Power Demand P_d (pu)	Reactive Power Demand Q_d (pu)	Base KV	V_{max} (pu)	V_{min} (pu)
1	Slack	0	0	230	1.05	1.05
2	PV	0	0	230	1.05	1.05
3	PV	0	0	230	1.07	1.07
4	PQ	0.85	0.8	230	1.05	0.95
5	PQ	0.85	0.8	230	1.05	0.95
6	PQ	0.85	0.8	230	1.05	0.95

Table B Generator Data of six bus system

Bus No.	Real Power Generation P_g (pu)	Reactive Power Generation Q_g (pu)	Reactive power Generation Limit Q_{max} (pu)	Q_{min} (pu)	P_{max} (pu)	P_{min} (pu)
1	0	0	1.0	-1.0	200	50
2	0.5	0	1.0	-1.0	150	37.5
3	0.6	0	1.0	-1.0	180	45

Table C Branch Data of six bus system

Bus Number	Line resistance R(pu)	Line reactance X(pu)	Line charging admittance B(pu)
1-2	0.1	0.2	0.04
1-4	0.05	0.2	0.04
1-5	0.08	0.3	0.06
2-3	0.05	0.25	0.06
2-4	0.05	0.1	0.06
2-5	0.1	0.3	0.04
2-6	0.07	0.2	0.05
3-5	0.12	0.26	0.05
3-6	0.02	0.1	0.02
4-5	0.2	0.4	0.08
5-6	0.1	0.3	0.06

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