Application of Series and Shunt Compensation to Turkish National Power Transmission System to Improve System Loadability

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Abstract: **The purpose of this paper is to outline the effects of series and shunt compensation on transmission lines. In this study, load flow analysis is applied to the 380-154-66 kV voltage levels of Turkish power transmission system. The goal of using series compensation is to increase the available transfer capability, whereas the reason of using shunt compensation is to increase the voltage profile of the system. The location of such compensation devices is an important question. Placing reactive power sources at suitable points improves system's voltage profile and increases system loadability. This paper presents a method to place compensation devices using load flow equations and the singularity of load flow Jacobian matrix. The method is applied to power transmission system of Turkiye to determine the lines and buses where series and shunt compensation will be applied. Thyristor Controlled Series Compensation (TCSC) is used to increase the available transfer capacity.**

Keywords: Series and Shunt Compensation, Load Flow, TCSC.

1. Introduction

The demand placed on transmission network has grown in recent years and will go on growing. Due to the problems associated with constructing new transmission lines, it is important to examine the other possible options of increasing the transmission capability on present sites and making maximum use of existing transmission systems [1]. Thus, in this study apply both series and shunt compensation techniques to Turkish power system to increase transmission capacity.

An electric transmission system must provide power transmission within voltage limits at safe and high quality conditions. By industrial development, demand of electrical energy has become harder to provide acceptable voltage profile in power system. Therefore voltage stability and voltage collapse studies have become increasingly important.

Voltage collapse is a type of system instability, and it is defined as the ability of power system to keep bus voltages at acceptable steady state values following a disturbance and under normal operating conditions. Main reason of voltage instability is an insufficient injection of reactive power to the system. Consequently, sufficient amount of reactive power reserve must be placed at suitable points [2].

The load flow analysis involves the calculation of load flows and voltages of network for specified terminal and bus conditions [3].

This paper uses power flow analysis and the singularity of load flow Jacobian matrix to locate series and shunt compensation devices on Turkish power transmission system.

2. Series and Shunt Compensation

Load flow through a (lossless) ac transmission line is a function of line impedance, the magnitude of sending and receiving end voltages, and phase angle between the two end voltages [4].

$$P = \frac{V_R \cdot V_S}{X_L} Sin\delta \qquad (1)$$

where, V_R (V_S) is receiving (sending) end voltage magnitude, X_L is line reactance, and δ is angle between sending and receiving end voltages.

Series and shunt compensation are applied to electric power transmission system to confirm transmission effectively. The transmittable power can be increased by series compensation. Series compensation decreases the line total reactance by adding series capacitor. In Fig.1 a two-machine system with ideal series compensation is shown.

With series compensation the total line reactance becomes,

$$X = X_L - X_C$$
$$X = (1-s)X_L \qquad (2)$$

Here, X is equal to the net reactance of line after series compensation, X_L is line reactance, and s is the compensation degree, which is given as

$$s = \frac{X_C}{X_L} \qquad (3)$$

The compensation changes with the series capacitor value between 0 and 1 [4].

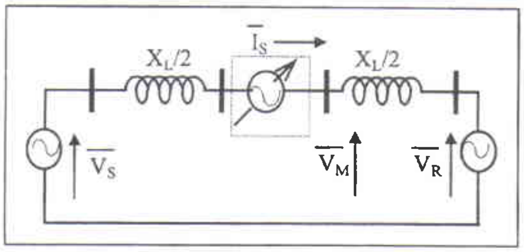

Figure 1. *Simple two-machine power system with ideal series compensation [4].*

Series compensation provides the following features:

1) Improves the power system transient stability,
2) Decreases reactive losses,
3) Improves transmission system voltage regulation.

The middle point of transmission line is the best point to place series capacitor to increase the power transmission capacity to its maximum value [5].

Transmittable power can also be increased by shunt compensation. In Fig.2 a two-machine system with shunt compensation is shown.

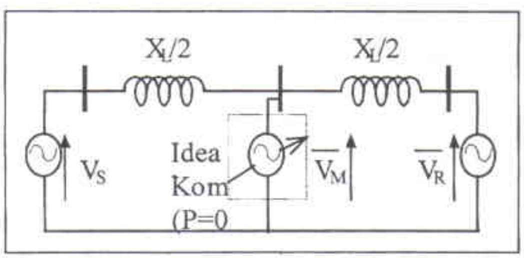

Figure 2. *A Simple two-machine power system with shunt compensation [4].*

For an ideal system,

$$V_M\angle\delta/2 = V_S\angle 0° = V_R\angle\delta = V \qquad (4)$$

The transmittable power is:

$$P = \frac{2 \cdot V^2}{X_L} Sin(\delta/2) \qquad (5)$$

A shunt compensation system ideally performs the following functions:

1) It helps produce a substantially flat voltage profile at all levels of power transmission,
2) It improves stability by increasing the maximum transmissible power,
3) It provides an economical means for meeting the reactive power requirements of transmission [6].

3. Analysis Technique

The power system operating environment of today has substantially increased the difficulty of maintaining an acceptable system voltage profile. Problems associated with the steady state stability and voltage collapse of electric power systems have become increasingly important [7]. Voltage collapse is a serious concern to the electric utility industry. It is common to associate steady-state stability with the ability of the transmission system to transport real power to necessary locations within the system.

Load flow analysis is used for static voltage stability studies. In large systems by using load flow analysis the relationship between active power, voltage and reactive power can be determined for each bus. The values of critical voltage and power can be calculated.

Voltage collapse point is determined by the help of load flow Jacobian [8,9]. It is generally known that the system proximity to voltage collapse can be seen either from the eigenvalues of reduced or full Jacobian of load flow. The full Jacobian matrix, whose elements give the sensitivity between power flow and bus voltage change, is [10].

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \qquad (6)$$

At the voltage collapse point determinant of Jacobian matrix is equal to zero due to one eigenvalue being zero. The point of collapse technique calculates the left eigenvector corresponding to this zero eigenvalue. This eigenvector shows the most sensitive state variable [11]. The right eigenvector associated to the zero eigenvalue points to the area(s) most prone to instability. The right and left zero eigenvectors can be used to identify the bus(es) most prone to instability and state variables which affect the system most. This idea is used to find the optimal location and compensation device to use [11].

The TCSC is well suited for a flexible AC Transmission system (FACTS). TCSC is needed for applications that required sophisticated fast control of series compensation [12]. A simplified steady state model of TCSC is shown in Fig.3.

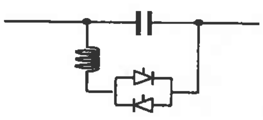

Figure 3. *TCSC System [12].*

The capacitor bank is provided with a thyristor controlled inductor.

The inductor circulates current pulses with the line current. This is because to boost the capacitive voltage beyond the level that would be obtained by the line current alone [12]. Each thyristor is triggered once per cycle and has a conduction internal that is shorter than half a cycle of the rated main frequency. The reasons for the use of TCSC are given below.

- Voltage instability,
- Installations where SSR (Sub-Synchronous Resonance) is a concern,
- Power oscillation damping,
- Load flow control [12].

4. Application

Load flow is applied to Turkish power transmission system consisting of 380-154-66 kV voltage levels with 605 ac buses. Out of these buses 551 are load buses and 55 are generation buses. The system has 54 voltage regulation transformers. For load flow analysis, *pflow* program [13] is used with 1997 data of lines, generations, and loads in IEEE Common format [14].

The system is loaded up to the voltage collapse point by the use of point of collapse technique. It is realized that the system can be loaded with % 3.74 loading factor. The system consists of 48 weak buses whose voltages are between 0.8 and 0.9 pu. Then right and left eigenvector corresponding to the smallest eigenvalue of Jacobian matrix are determined and the maximum values of these vectors for voltage, reactive power, and active power variables are given in Tables 1, 2, and 3 respectively. Having obtained the sensitive buses we apply series compensation and display the results first, then we apply shunt compensation and show the results.

Table 1. *The maximum values of right eigenvector concerning voltage variables.*

3134 Van	1
3112 Engil	0.99196
3113 Erciş	0.96553
3102 Adilcevaz	0.94674
3131 Tatvan	0.91818

Table 2. *The maximum value of left eigenvector concerning reactive power variables.*

3112 Engil	1
3134 Vanl	0.98812
3131 Tatvan	0.95819
3102 Adilcevaz	0.95778
3113 Erciş	0.9503

Table 3. *The maximum value of left eigenvector concerning active power variables.*

3134 Van	1
3112 Engil	0.95052
3113 Erciş	0.89881
3102 Adilcevaz	0.83107
3131 Tatvan	0.80146

Right eigenvector gives information about the most sensitive buses in terms of voltage. These specified bus voltages are lower than other bus voltages in the system. Table 2 shows the five most sensitive buses in terms of reactive power and Table 3 shows the five most sensitive buses in terms of active power.

4.1. Series Compensation

We use TCSC to increase maximum loading point. Using the information on Table 3 series compensation is applied to the lines connect to those sensitive buses, which are shown Table 4. The degree of series compensation is 0.12, that is 12 percent of the line reactance. From Table 4, it can be seen that the loading factor is at most %4.42. This is because the system had a bad voltage profile on the sensitive region. Increasing current on those lines aggravated voltage drop, thus voltage collapse.

Table 4. *Application of series compensation with eigenvector information.*

Bus name	Bus name	s	L.F(%)	X_C(pu)
3134 Van	3113 Erciş	%12	4.42	0.167
3134 Van	3112 Engil	%12	4.06	0.065
3112 Engil	3131 Tatvan	%12	3.72	0.176
3112 Engil	3134 Van	%12	4.06	0.065
3113 Erciş	3134 Van	%12	4.42	0.169
3113 Erciş	2901 Ağrı	%12	4.36	0.189
3113 Erciş	3102 Adilcevaz	%12	4.11	0.106
3131 Tatvan	3102 Adilcevaz	%12	4.09	0.108

Table 5 shows the effect of series compensation applied on random lines selected from the Turkish transmission system to see whether it was possible to improve the loading factor beyond the value obtained above. As expected, the loading factor is not greater than the obtained value because the later is based on a theory and is supposed to be the best.

Table 5. *Application of series compensation using random lines*

Bus name	Bus name	s	L.F(%)	Xc(pu)
1806 Manisa	1801 Akhisar	%12	3.74	0.095
1806 Manisa	1810 Turgutlu	%12	3.74	0.072
5025 Bornova	1807 Morsan	%12	3.74	0.041
3131 Tatvan	3110 Dodan	%12	4.03	0.015
2005 AntSB	2006 A.Kemer	%12	3.74	0.078
2739 Karabu	2736 Çatalca	%12	3.748	0.548

The voltage profile before and after series compensation on line between Van and Erciş is shown in Fig.4 [14]. As seen from the figure the collapse point is delayed but the amount is not satisfactory.

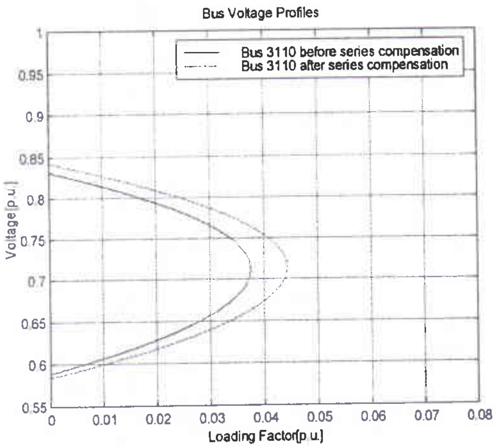

Figure 4. *Voltage Profiles with and without Series Compensation*

4.2. Shunt Compensation

With the information obtained from the eigenvectors reactive power compensation is applied at 3112 Engil, 3134Van, 3131Tatvan, 3102 Adilcevaz, 3113 Erciş buses for amount of 1 MVAr, 3 MVAr, and 5 MVAr. The change of loading factor for each compensation is summarized in Table 6 [15].

For 5 MVAr compensation at 3112 Engil, 3134 Van, 3131 Tatvan, 3102 Adilcevaz, and 3113 Erciş buses loading factor is found to be % 7.0669. Voltage profiles before and after compensation are given in Fig.5 for bus 3110 [15].

Compared to series compensation we see that the effect of shunt compensation on this particular system is more pronounced. This is expected because the system had voltage problem.

Table. 6. Application of Shunt Compensation

Bus name	Reactive power support	Loading factor (%)
3112 Engil	**1MVAR**	**4.01563**
3134 Van	1MVAR	4.01235
3131 Tatvan	1MVAR	4.00513
3102 Adilcevaz	1MVAR	4.00463
3113 Erciş	1MVAr	4.00255
3112 Engil	**3MVAR**	**4.54615**
3134 Van	3MVAR	4.53614
3131 Tatvan	3MVAR	4.52014
3102 Adilcevaz	3MVAR	4.5164
3113 Erciş	3MVAR	4.50998
3112 Engil	**5MVAR**	**5.06017**
3134 Van	5MVAR	5.04325
3131 Tatvan	5MVAR	5.02548
3102 Adilcevaz	5MVAR	5.01569
3113 Erciş	5MVAR	5.00468

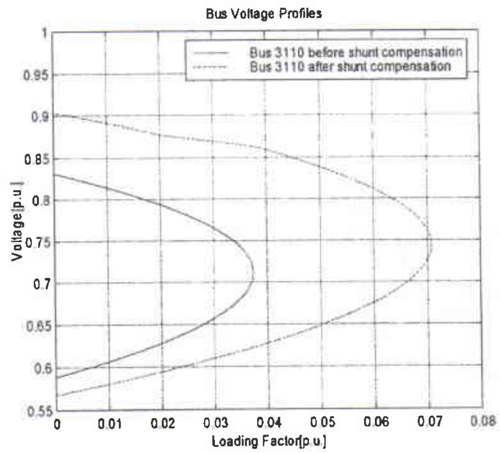

Figure 5. *Voltage Profiles with and without Shunt Compensation*

5. Conclusion

In recent years environment and cost problems have delayed the construction of both generation facilities and new transmission lines. For this purpose, in this paper a study is conducted to increase the transmission capacity of electrical power system of Turkiye by using series compensation.

The paper demonstrates that power flow combined with eigenvalue-vectors analysis of power system is a useful tool for choosing the most efficient type and location of compensation devices. As illustrated the compensation is the most effective where the theory indicates.

After the series compensation this loading factor is increased to % 4.42. Series compensation is applied on different lines but the best solution as expected is

% 4.42. This loading factor is obtained from the lines obtained by the use of point of collapse technique. But, the change in loading factor is too small. This is because the voltages of the buses that series compensation is implemented is below 0.9 pu. After the shunt compensation at five buses loading factor is increased % 7.0669. The transmittable power, as demonstrated, is increased by the series and shunt compensation. The series compensation is the most effective method to maximize available transmission capacity.

In the present system the change in loading factor is not satisfactory. According to energy demands from the system construction of new transmission lines and generation facilities are needed. Voltages of weak buses need to be increased to 1 pu for a reliable operation.

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