DETERMINATION OF LOCATION OF FACTS DEVICES USING FUZZY DECISION MAKING

Mustafa Bagriyanik **Hasan Dag**

Istanbul Technical University
Electrical and Electronics Faculty
Department of Electrical Engineering
Maslak 80626, Istanbul, Turkey
bagriy@ elk.itu.edu.tr, dag@elk.itu.edu.tr

Abstract - **This paper presents a method to place FACTS devices, especially thyristor controlled series capacitor (TCSC), in transmission lines using fuzzy decision making method. The indices used for making a decision are those TCSC affects the most. Amount of increase in operation limit boundary, amount of voltage drop, level of short circuit current, and the amplitude of line reactance etc., are some of the indices that can be used when making a fuzzy decision. The method is applied to some standard test cases and the results are provided.**

Keywords: FACTS, Series Compensation, TCSC, Fuzzy Decision Making, Fuzzy Sets.

I. INTRODUCTION

Transmission line thermal limits, transient stability constraints, and voltage stability are some of the factors that limit transmission system capacity. Due to both economical and environmental concerns it is usually hard to build new transmission lines. Thus, the existing transmission lines need be used with full capacity or be loaded up to thermal limits assuming the latter comes after voltage stability and dynamic stability limits. Flexible AC Transmission Systems (FACTS) devices are used to increase system loading, to increase system dynamic stability, and voltage stability [1-3]. Depending on the aim of the use, the issue of locating these devices becomes important. If care is not taken, placement of FACTS devices may do harm rather than improvement [4]. The placement issue can be resolved by trial and error depending on the purpose of placement, if there is a single criterion only. However, in case of multiple criteria a decision needs be made.

The growing number of publications on applications of fuzzy-set-based approaches to power systems indicates its potential role in solving power system problems [5,6].

This paper uses fuzzy decision making method to place series compensation devices on transmission lines of power systems. When making a decision one can use any number of criteria. Some of the criteria that can be used, but not limited to, are reactive power loss index [7], magnitude of line reactance, singular values (or eigenvalues) of either full or reduced Jacobian of load flow [8], static or dynamic voltage collapse proximity indicators [8,9], and maximum loadability index [10]. If the goal of placing a series compensation device, or any FACTS device for that matter, on a power system is to improve transient stability of the system, an index can be devised and used with others when using fuzzy decision making. However, the magnitude of line reactance is already related to transient stability, since the reduced line reactance provides greater power transfer between two buses in a network [3].

Series compensation has the following effects:

- it increases maximum power that can be transmitted on a line
- it reduces reactive power loss (I^2X)
- it reduces line reactance
- it improves power system stability
- it improves voltage regulation of transmission line [3].

The criteria we use are the indicators of and/or related to total reactive power loss, maximum transmittable power, and voltage stability. These indices are explained in detail in section II.

II. INDICES

It is generally agreed that series compensation is the most effective way of enhancing power transfer capability of a (long) transmission line. Power between two buses of a lossless transmission line is given by

$$P_{ij} = \frac{V_i V_j}{X_{ij}} Sin\delta_{ij} \qquad (1)$$

where, V_i and δ_i is the i^{th} bus voltage magnitude and angle, V_j and δ_j is the j^{th} bus voltage magnitude and angle, X_{ij} is line reactance. From (1) it is clear that the power flow between buses i and j can be increased by a reduction of line reactance, and transient stability can be controlled by varying reactance and power angle.

II.1. Reactive Power Loss Sensitivity Index

Application of series compensation has a big effect on reactive power losses in the system especially in the compensated line. This fact can be utilized in devising an index. A reactive power loss sensitivity index (RPLSI) in each line was designed in [7]. The index is basically the rate of change in reactive power loss with respect to line reactance. By the use of RPLSI the most suitable line, from the reactive power losses reduction point of view, for the series compensation can be found.

The reactive power loss equation of the k^{th} line, between buses i and j can be written as,

$$Q_{L-k} = B_k(V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)) \qquad (2)$$

and the total reactive power loss of all the lines of system is

$$Q_L = \sum_{k=1}^{nl} B_k(V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)) \quad (3)$$

where, nl is the total number of lines and B_k is line susceptance.

The sensitivity of the reactive power loss with respect reactance of the k^{th} line is

$$\frac{\partial Q_L}{\partial X_k} = \frac{R_k^2 - X_k^2}{(R_k^2 + X_k^2)^2}(V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)) \qquad (4)$$

This equation can be used as reactive power loss index to determine a location for series compensation devices.

The variation of the total reactive power loss of the 6-bus test system of Ward and Hale [11] is given in Fig. 1. The test system itself is given in appendix A. It can be seen from Figure 1 that the reactive power losses vary about linearly with respect to degree of the line compensation, hence RPLSI is a suitable index to use.

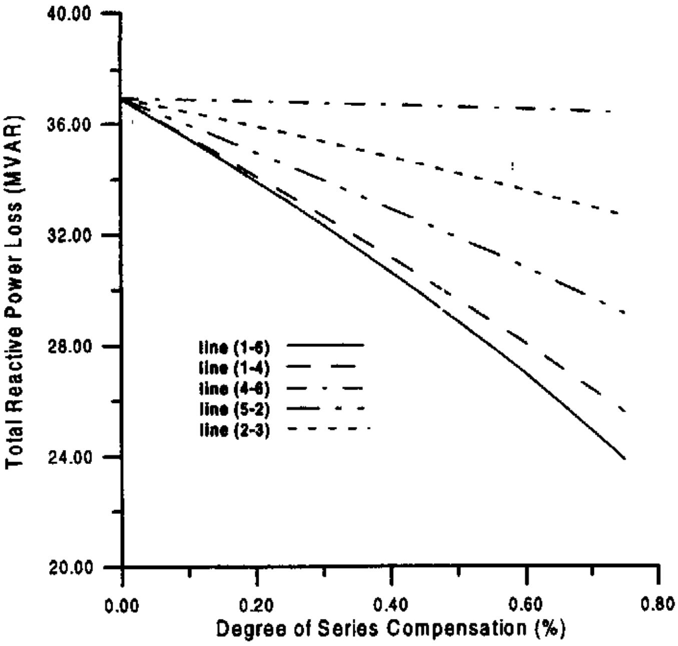

Fig. 1. *Total reactive power loss versus degree of compensation.*

II.2. Amplitude of line reactance

We use the magnitude of line reactances when making a fuzzy decision. The reason of considering line reactances is to see the effect of series compensation on transient stability, since controlling the reactance enable us to control the power transfer between two busses, hence transient stability.

II.3. Eigenvalue of load flow Jacobian

It is generally known that the system proximity to voltage collapse can be seen either from the eigenvalues of reduced or from full Jacobian of load flow. The full Jacobian matrix, whose elements give the sensitivity between power flow and bus voltage changes, is,

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \qquad (5)$$

and the reduced Jacobian matrix is

$$J_R = \left[\left(\frac{\partial Q}{\partial V}\right) - \left(\frac{\partial Q}{\partial \delta}\right)\left(\frac{\partial P}{\partial \delta}\right)^{-1}\left(\frac{\partial P}{\partial V}\right)\right] \qquad (6)$$

The closer the minimum eigenvalue of the (reduced) Jacobian to zero, the closer the system to voltage collapse [8,12]. The series compensation affects the voltage stability of the system and thus, the eigenvalues can be used as indicators of the proximity of the system to instability [8].

We obtain an ordering of lines in terms of their effect on minium eigenvalue by compensating each line one by one, say 30 percent. The line that places the minimum eigenvalue furthest from the origin has the biggest effect on voltage stability. The variations of eigenvalues are smooth. That is, they do not make any jumps when the entries of the matrix are changed. If the smallest eigenvalue moves away from the origin as a result of a change in the matrix entries so do the rest [13]. Fig. 2 and 3 show the variation of minimum eigenvalue with respect to degree of compensation for full and reduced Jacobian respectively for the 6-bus test system. Both figures indicate that the lines connected to generation buses directly affect the minimum eigenvalue the most. Similar behaviour was observed on IEEE-14 and 30 bus test systems.

III. FUZZY DECISION MAKING

In this study, an approach is proposed in applying fuzzy decision making to obtain final ordering of series compensation location. Fuzzy decision making allows user to possess different purposes while still assuming that the overall purpose is to reach a common, acceptable decision.

Decision making is defined to include any choice or selection alternatives. Applications of fuzzy sets within the field of decision making consist of extensions or fuzzifications of the classical theories of the decision making.

A decision making problem can be classed to different classes according to the number of decision makers. Since we consider three indices as decision makers to determine which line is convenient as location, we apply multi-person fuzzy decision making method, which is explained in detail in [14], to our problem.

In a decision making problem the set of alternatives, X, is

$$X = \{x_1, x_2, \cdots, x_m\} \qquad (7)$$

where m is number of alternatives. The preference orderings on this set of alternatives made by decision makers, P, is

$$P = \{P_1, P_2, \cdots, P_n\} \qquad (8)$$

where n is number of decision makers.

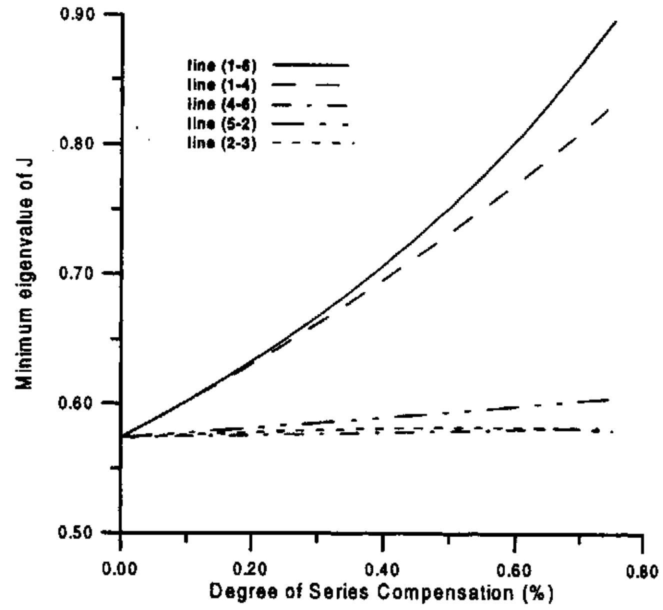

Fig. 2. *The variation of minimum eigenvalue of full Jacobian with respect to degree of compensation.*

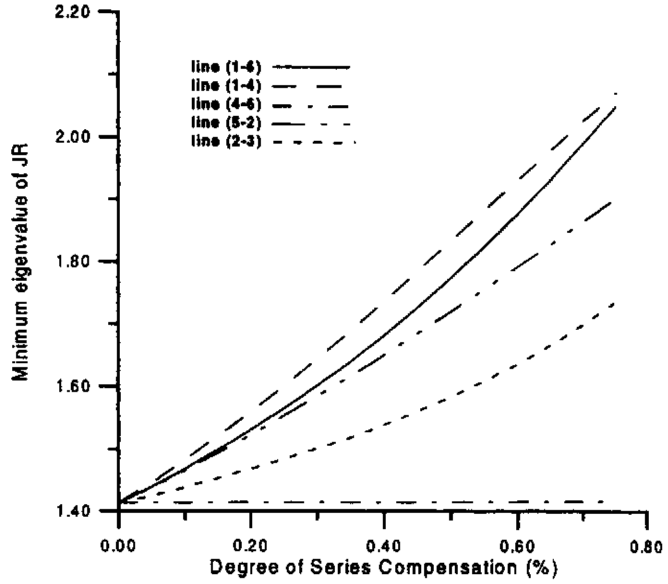

Fig. 3. *The variation of minimum eigenvalue of reduced Jacobian with respect to degree of compensation.*

In applied method, a fuzzy social preference relationship (S) can be obtained by using a membership grade function, μ_s,

$$\mu_s(x_i, x_j) = \frac{N(x_i, x_j)}{n} \qquad (9)$$

where, $N(x_i,x_j)$ is the number of decision indices preferring line-i to line-j, and n is the total number of decision indices. This membership grade indicates the degree of group preference of alternative x_i, over alternative x_j. In other words, by using this function, the relative popularity of alternative x_i (line i) over x_j (line j) can be computed.

After the fuzzy relationship S is defined, the α-cuts of this fuzzy relation is obtained. Hence, the resolution form of S is the union of the crisp relation S_α,

$$S = \bigcup_{\alpha} \alpha S_\alpha \tag{10}$$

Each value α essentially represents the level of agreement between the preference orderings concerning the particular crisp ordering S_α.

In the process of obtaining a final total crisp ordering, first, the total orderings O_α, which are compatible with the pairs in the crisp relation S_α for the maximum α-cut, are formed. If the number of elements of O_α is not single, the agreement level is decreased to the next α-cut value and the classes of crisp total orderings are intersected. This procedure is continued until a single crisp total ordering is achieved. In this process, any pairs (x_i, x_j) that lead to an intransitivity are removed. The final crisp ordering represents the group decision. The corresponding largest value of α-cut level represents the maximized agreement level of the group [14].

IV. APPLICATION

In this study, a fuzzy decision making method for series compensation is applied to two test systems: Ward-Hale 6-bus and IEEE 14-bus systems [15]. The 6-bus test system has two generators and four load buses. Generator buses are numbered as 1 and 2. In the IEEE 14-bus test system 1-3, 6, and 8 are the generator buses and the rest are load buses. For each test systems, 3 different orderings of lines for insertion of the FACTS device, TCSC, are obtained.

The first ordering of lines is obtained using RPLSI, the second ordering is obtained by listing the lines according to the magnitude of line reactances in descending order. Finally, the third one is obtained based on the line number most affecting the minimum eigenvalue of reduced Jacobian of load flow for 30 percent series compensation. After three orderings are obtained, each of them is considered as a preference index, and by using fuzzy decision making, the final decision ordering is obtained. For both test systems, all of the lines are considered as candidate locations to install compensation devices.

For both test systems, the orderings with respect to indices are given in the first three columns of Table 1 and 2. The last column of the tables give the line orderings based on fuzzy decision making. When making a fuzzy decision we have three decision makers: placement of series compensation device for reducing total reactive loses (line ordering with respect to RPLSI), for increasing transient stability (line ordering with respect to magnitude of line reactance), and for increasing voltage stability of system (line ordering with respect to eigenvalues).

V. CONCLUSION

A fuzzy decision making method is used to place a FACTS device, TCSC on a power system. Fuzzy decision making tries to find a good compromise among all preferences. This method can be used to maximize the useful effects of TCSC, or any other FACTS device.

Table 1. *Final ordering of lines for series compensation using fuzzy decision making for 6-bus test system.*

RPLSI	Reactance Ordering	Eigenvalue of J_R	Fuzzy Decision
(1-4)	(2-3)	(1-4)	(1-4)
(1-6)	(5-2)	(1-6)	(1-6)
(5-2	(1-6)	(5-2)	(5-2)
(2-3)	(4-6)	(2-3)	(2-3)
(4-6)	(1-4)	(4-6)	(4-6)

Table 2. *Final ordering of lines for series compensation using fuzzy decision making for 14-bus test system.*

RPLSI	Reactance Ordering	Eigenvalue of J_R	Fuzzy Decision
(1-2)	(13-14)	(6-11)	(6-11)
(1-5)	(9-14)	(7-8)	(13-14)
(2-3)	(6-12)	(13-14)	(1-5)
(4-5)	(1-5)	(7-9)	(7-8)
(2-4)	(12-13)	(6-13)	(9-14)
(2-5)	(6-11)	(10-11)	(6-12)
(7-9)	(2-3)	(6-12)	(2-3)
(3-4)	(10-11)	(3-4)	(2-4)
(7-8	(2-4)	(9-14)	(7-9)
(6-13)	(7-8)	(2-4)	(2-5)
(9-14)	(2-5)	(2-5)	(6-13)
(6-11)	(3-4)	(9-10)	(10-11)
(6-12)	(6-13)	(4-5)	(3-4)
(9-10)	(7-9)	(1-5)	(9-10)
(13-14)	(9-10)	(12-13)	(12-13)
(10-11)	(1-2)	(2-3)	(1-2)
(12-13)	(4-5)	(1-2)	(4-5)

VI. REFERENCES

[1] L. Guygyi, "Solid state control of AC power transmission", *EPRI Workshop on Flexible AC Transmission System*, Cincinnati, Ohio, November 1990.

[2] N.G. Hingorani, "FACTS- Flexible AC transmission systems", *Proc. 5th International Conference on AC and DC Power Transmission*, London, September, 1991, pp. 1-7.

[3] P.M. Anderson, R.G. Farmer, *"Series Compensation of Power Systems"*, PBLSH Inc., 1996.

[4] F. Alvarado et. al, "Impact of network topology on steady state control interactions among series FACTS devices", *EPRI Conference on the Future of Power Delivery*, April 9-11, Washington DC, 1996.

[5] J.A. Momoh, X.W. Ma, K. Tomsovic, "Overview and Literature Survey of Fuzzy Set Theory in Power Systems", *IEEE Trans. on Power Systems*, Vol. 10, No. 3, August 1995, pp. 1676-1690.

[6] M. Bagriyanik, S. Seker, F.G. Bagriyanik, "Fuzzy Decision Making Approach to Reactive Power Compensation Location", *Proc. 16th IASTED International Conference Modelling, Identification and Control*, Innsbruck, Austria, February 1997, pp.249-252.

[7] A.A. Mutlu, E.B. Makram, "Analysis of Series Compensation from Different Aspects", *Proceedings of the 1998 IEEE SOUTHEASTCON Conference*, Orlando, FL, USA, pp. 100-104.

[8] P. Kundur, *"Power System Stability And Control"*, Mc Graw-Hill, Inc., 1994.

[9] A.Mohamed, G.B. Jasmon, "Neural Network Approach to Dynamic Voltage Stability Prediction", *Electric Machines and Power Systems*, Vol. 25, No. 5, June 1997, pp. 509-523.

[10] R. Rajaraman, F. Alvarado, A. Maniaci, R. Camfield, S. Jalali, "Determination of Location and Amount of Series Compensation to Increase Power Transfer Capability", *IEEE Trans. on Power Systems*, Vol. 13, No. 2, May 1998, pp.294-300.

[11] J. B. Ward and H. W. Hale, "Digital computer solution of power flow problems", *AIEE Trans.*, Vol. 80, Pt. III, 1956.

[12] I. Dobson, "Observations on the geometry of saddle node bifurcations and voltage collapse in electrical power systems", *IEEE Transactions on Circuits and Systems-I*, Vol. 39, No.2, March 1992, pp. 240-243.

[13] G. H. Golub and C. F. Van Loan, *"Matrix Computation"*, Johns Hopkins., 2nd edition, 1989.

[14] G. J. Klir, T.A. Folger, *"Fuzzy Sets Uncertainty And Information"*, Prentice-Hall International, Inc., 1988.

[15] M.A. Pai, *"Computer Techniques in Power System Analysis"*, TATA McGraw-Hill Publishing Company Limited, Third Reprint, 1984.

VII. APPENDIX A

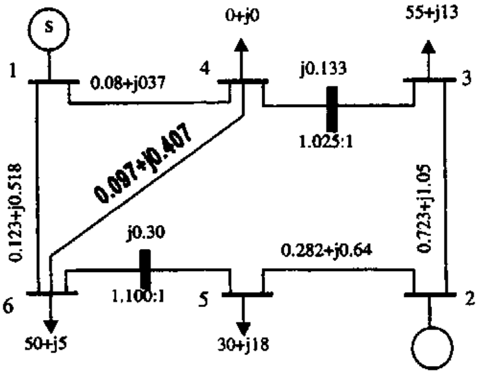

Fig A.1. *Ward-Hale 6-bus test system.*