직렬형 FACTS 기기 위치 선정을 위한 감도 해석

호세 로델 도사노 송화창* 장병훈 이병준
군산대 전자정보공학부 한전 전력연구원 고려대 전기공학과

Sensitivity Analysis for Determination of Series FACTS Location

Jose Rodel Dosano Hwachang Song* Byunghoon Chang Byongjun Lee
Kunsan National University KEPRI Korea University

Abstract - This paper discusses sensitivity analysis for determining adequate locations of series-type FACTS devices. The main objective of FACTS reinforcement is to alleviate line over-loadings against violation of thermal limits after disturbances. This paper, to obtain the information concerning series-type FACTS locations, proposes a formulation for the sensitivity of the PI (Performance Index) with respect to the variation of the branch parameters, and applies to 5-bus test system to show the effectiveness of the sensitivity.

1. Introduction

FACTS devices can be used for several power system performance enhancements such as the improvement of static security, dynamic stability and damping, available transfer capability, etc. The effectiveness of FACTS controllers is mainly dependent on their proper placement for the selected purpose. This paper focuses on reinforcement of series-type FACTS devices.

The variable-series compensation of transmission lines is likely to result in [1]: i) enhanced base-power flow and loadability of the compensated line; ii) minimized losses in the compensated line from the enhanced power flow, and iii) enhanced responsive of power flow in the compensated line from the outage of other lines in the system. Therefore it is advantageous to install series FACTS devices in key transmission paths to manage line congestions and enhance system security.

To determine adequate location of series FACTS devices, in [2], Singh et al. proposed a sensitivity of the performance index (PI) [3], which evaluates severity of contingencies in terms of line overloading. The formulation to obtain this sensitivity is based on DC power flow and a certain distribution factor indicating how much line loadings in other liens are changed when active power flow on a selected line is changed. In [4], for location of UPFC (Unified Power Flow Controllers), Song et al. utilized not only the line flow PI but also voltage PI and calculated their sensitivity with respect to line flows using the Marquardt method.

In this paper, we introduce a new formulation for the PI sensitivity with respect to the change of line susceptances based on AC power flow. Using this formulation, we can easily obtain the PI sensitivity because it only demands one backward and forward substitution of the pre-factorized power flow Jacobian. An illustrative example is provided using 5-bus test system, to show the effectiveness of the sensitivity from the proposed formulation for decision making of series-type FACTS location.

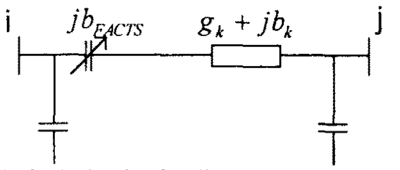
2. Performance Index Sensitivity

The severity of line overloading under normal and contingent cases can be described by real power line flow performance index [3], as given below:

$$PI = \sum_{m=1}^{n_l} \frac{w_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \qquad (1)$$

where n_l is the number of branches in the system, and P_{lm} and P_{lm}^{max} are the real power flow and the rated capacity of line m. In (1), n represents the exponent and wm denotes the weighting coefficient of line m.

As shown in Fig. 1, assume that a series-type FACTS device is installed in the selected line i-j, and the device acts in a line-compensation mode. Then the net line susceptance can be controlled and hence line loading of the line and the power transmission pattern in the system can be also changed. If a severe contingency is given in terms of line overloading, the places that can dramatically reduce the PI can be considered as proper FACTS locations. To obtain this information, thus, we use the PI sensitivity with respect to the change of bus susceptance (i.e., b_k in Fig. 1) in this paper.



<Fig. 1> Equivalent circuit of a line compensated by a FACTS device

The PI sensitivity in line k is defined as:

$$\frac{\partial PI}{\partial b_k} = \sum_{m=1}^{n_l} w_m P_{lm}^3 \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{dP_{lm}}{db_k} \qquad (2)$$

where dP_{lm}/db_k denotes the sensitivity of active power flow in line m with respect to b_k. However, it cannot be directly obtained because P_{lm} is not an explicit function of b_k. To solve this difficulty, this paper employs the chain rule with respect to $\underline{\delta}$ and $\underline{V}$, which are the vectors for voltage angles and magnitudes, yielding:

$$\frac{\partial P_{lm}}{\partial b_k} = \frac{dP_{lm}}{d\underline{\delta}} \cdot \frac{d\underline{\delta}}{db_k} + \frac{dP_{lm}}{d\underline{V}} \cdot \frac{d\underline{V}}{db_k} \qquad (3)$$

where $dP_{lm}/d\underline{\delta}$ and $dP_{lm}/d\underline{V}$ corresponds to the derivative vectors of P_{lm} with respect to $\underline{\delta}$ and $\underline{V}$, respectively. In (3), $d\underline{\delta}/db_k$ and $d\underline{V}/db_k$ are the sensitivity vectors of $\underline{\delta}$ and $\underline{V}$, with respect to b_k, and they can be calculated as follows:

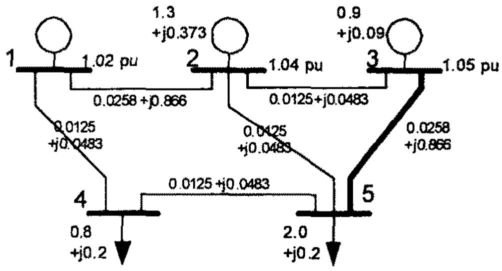
$$\begin{bmatrix} \partial\underline{\delta}/\partial b_k \\ \partial\underline{V}/\partial b_k \end{bmatrix} = -J_{pflow}^{-1} \begin{bmatrix} \partial\underline{P}_{Ti}/\partial b_k \\ \partial\underline{Q}_{Ti}/\partial b_k \end{bmatrix}$$

$$J_{pflow} \equiv \begin{bmatrix} \partial\underline{P}_{Ti}/\partial\underline{\delta} & \partial\underline{P}_{Ti}/\partial\underline{V} \\ \partial\underline{Q}_{Ti}/\partial\underline{\delta} & \partial\underline{Q}_{Ti}/\partial\underline{V} \end{bmatrix} \qquad (4)$$

where J_{pflow} denotes the power flow Jacobian. In (4), $\underline{P}_{Ti}$ and $\underline{Q}_{Ti}$ are the function vectors for active and reactive power flow injection, respectively. From (2), (3) and (4), it can be known that the PI sensitivity can be obtained by the Jacobian inverse, and that it only needs one backward and forward substitution of the pre-decomposed power flow Jacobian, because the sensitivity analysis is performed after power flow calculation.

3. Case Study

In this study, 5-bus test system was simulated with a base case where line parameters, generation and load information is shown in Fig. 2. Based on the study results, the severe line contingencies were identified and the key transmission paths or installing FACTS devices were chosen.



<Fig. 2> One-line diagram of 5-bus system

Table 1 shows the lines flows and the PI index of the normal and six line contingent cases. The severest contingency is the outage of line 1-4 in terms of line overloading, and the outage of line 3-5 is the second severest one. Line 2-5 is overloaded for all the cases. Thus, there should be a measure to transfer the line loading on line 2-5 so that the real power congestion problem in line 2-5 can be minimized. Thus, series compensation on line 2-5 and/or 3-5with FACTS devices can be options for that purpose.

With (2) and (3), the PI sensitivities for all the cases were obtained as shown in Table 2. From Table 2, it can be seen that the PI sensitivities for compensation of line 3-5 are most high negative for all the cases except for the outage of line 3-5, and that those for line 2-5 have the second largest values. Thus, if we need to select onelocation for series FACTS controllers, then the place should be on line 3-5. Table 3 illustrates the line flows and the PI after compensation of line 3-5 by reducing the corresponding line reactive by 0.4 [pu]. After this compensation, the maximum PI is reduced from 6.2555 to 1.1960 for all the contingencies but line 3-5. Thus steady-state security related to line overloading is quite improved through this compensation.

The installation of series FACTS devices on either line 2-5 or 3-5 can assure system security even if the worst case N-1 contingency takes place. Installation of series FACTS device on these lines might be the appropriate choice. This finding can be verified using the PI flow value equal to 6.255 and 2.5141 for line 2-5 and line 3-5 respectivelyin Table 1. Evaluating the 5-bus test system with series compensation in line 2-5 was also verified applying the N-1 contingencies. For a given wide range of series FACTS device capacity installed in line 2-5, it can minimize line congestions, but on the severe contingency it fails to minimize overloading especially on line 2-5. In addition, the line reactance of line 2-5 is very small, so the range of series compensation should be limited.

Installation of series FACTS device in line 3-5 gives the system wider control of system security level. The series reactance value of line 3-5 is 0.866 [pu], in which wide variation of line reactance can be manipulated assuming that series FACTS device installed has enough capacity to maintain system security. Even for the worst case N-1 system contingency, series compensatorlocated on this line can enhance system security.

4. Conclusions

This paper proposes a method for determining adequate locatio ns of series-type FACTS devices using the PI sensitivity with r espect to the change of line susceptances based on AC power flo w. The formulation for the PI sensitivity is simple, so the sensiti vity can easily obtained using one backward and forward substit ution of the pre-decomposed power flow Jacobian. The proposed method is applied to 5-bus test system in case study and the res ults show that the PI sensitivity provides the proper locations of FACTS controllers. The presented methodology can be further us ed in a bulk power system to identify the most effective location of series FACTS devices to improve system performance in term s of line loading.

[References]

[1] R.M. Mathur and R.K. Varma, "Thyristor-Based FACTS Con trollers for Electrical transmission System", 277-312, 2002

[2] S.N. Singh, "Location of FACTS Devices for Enhancing Powe rSystems' Security", IEEE Trans. Power Syst., 58-60 January 2001

[3] G. C. Ejebe and B. F. Wollenberg, "Automatic Contingency S election," IEEE Trans. on Power Apparatus and Systems, vol. 98, no. 1, Jan./Feb. 1979, pp. 92-104.

[4] S.-H. Song, J.-U. Lim, S.-I. Moon, "Installation and Operation of FACTS devices for Enhancing Steady-state Security," Elect ric Power Systems Research, vol. 70, 2004, pp. 7-15.

<Table 1> Line flows and PI indices for the normal and contingent cases (before compensation)

Outage of line	*Line flows*						
	1-2	1-4	2-3	2-5	3-5	4-5	PI flow
1-2		66.24 + j22.06	70.35 + j1.69	200.35 + j33.45	19.06 + j7.69	14.36 + j 0.18	1.9955
1-4	72.11 + j18.57		66.51 + j2.84	267.24 + j69.82	22.96 + j11.58	80.0 + j20	6.2555
2-3	3.55 + j2.20	68.57 + j23.15		126.44 + j51.09	90.0 + j31.37	12.08 + j0.73	0.4139
2-5	95.44 + j48.02	170.76 + j116.3	31.72 + j16.17		121.57 + j83.26	85.47 + j76.56	1.4540
3-5	7.81 + j1.88	75.05 + j24	89.05 + j4.05	211.23 + j39.37		5.72 + j1.14	2.5141
4-5	15 + j.99	80.88 + j23.27	71.25 + j1.41	186.19 + j30.87	18.14 + j7.24		1.5319
Base case	6.99 + j1.95	73.03 + j20.39	70.8 + j1.55	193.80 + j84.29	18.6 + j 7.63	7.68 + j2.27	1.7655

<Table 2> PI sensitivities for the normal and contingent cases

Outage of line	*Line i-j*					
	1-2	1-4	2-3	2-5	3-5	4-5
1-2		-281.0450	1257.9600	-83838.2700	-109291.3213	6.2711
1-4	0.0000		3776.9810	-280425.0443	-333955.4639	-4564.9503
2-3	-6241.1655	-550.9367		-12703.1780	-53532.9023	65.4814
2-5	-128066.3767	-11963.1978	43.9294		-190665.3409	-2779.8130
3-5	-64738.0113	-2205.9127	-2726.5057	-104600.5944		169.2038
4-5	0.0000	-443.5875	399.1188	-65532.3829	-89808.2516	
Base case	-41793.6798	-1724.8542	853.9414	-70029.8374	-93208.2837	145.6071

<Table 3> Line flows and PI indices for the contingent cases (after compensation)

Outage of line	*Line i-j*						
	1-2	1-4	2-3	2-5	3-5	4-5	PI flow
1-2		65 + j9.05	14.64 + j25.5	115.36 + 23.45	104.54 + 20.57	15.54 + j12.94	0.3791
1-4	69.69 + j16.98		38.36 + j31.50	160.05 + j 33.55	128.07 + j28.87	80 + j20	1.1960
2-3	3.52 + j2.20	68.16 + j7.53		126.48 + j19.43	90 + j26.33	12.42 + j14.64	0.4137
2-5	49.51 + j9.70	121.02 + j56.03	79.86 + j41.31		168.89 + j72.33	38.82 + j27.83	1.2987
3-5	7.81 + j1.88	75.05 + j24	89.05 + j4.05	211.23 + j39.37		5.72 + j1.14	2.5141
4-5	16.41 + .77	80.88 + j23.27	3 + j20.86	116.53 + j14.98	86.94 + j15.82		0.3429