Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 18, No.3, pp. 149~155 May 2004 논문 18-3-23

단일 선로고장시 정적 안전도 향상을 위한 유연송전기기 운전 방안

(A Security-oriented Operation Scheme of FACTS Devices to Cope with A Single Line-faulted Contingency)

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요 약

본 논문에서는 상정사고 해석을 통해 결정된 가장 심각한 단일 선로고장에 대하여 부하차단이나 재급전을 하지 않고, 유연송전기기의 운전만으로 안전도를 향상시켜 이를 극복할 수 있는 방법을 제시하였다. 즉, 직렬, 병렬, 직병렬보상기기 등 유연송전기기의 각 종류별로 정적 안전도 여유를 최대화하고 안전도 지수를 최소화하는 방법을 개발하였고, 이를 통하여 각 유연송전기기의 최적 운전점을 결정하는 방법을 개발하였다. 여기서, 정적 안전도 지수는 선로 조류 및 모선 전압에 관한 안전도를 정량화하여 식으로 나타낸 것이다. 안전도 지수가 작아지면 안전도 여유는 커지는데, 본 논문에서는 안전도 지수를 반복계산법으로 최소화하였다. 본 논문에서 제안한 방법은 IEEE 57모선 계통에 적용하여 제안된 방법의 정당성을 수치적으로 입증하였다.

Abstract

This paper presents how to find proper operating points of FACTS devices to enhance the steady-state security level considering line contingency analysis. Three generic types of FACTS devices such as series controllers, shunt controllers, and series-shunt controllers are introduced and applied to maximize a security margin and to minimize security indices. Security indices related to line flows and bus voltages are utilized and minimized iteratively in this paper. Contingency analysis is performed to detect the most severe single line fault. In various load conditions, FACTS devices are tested to establish appropriate preventive or corrective action without generation re-dispatching or load shedding. The FACTS operation scheme is verified on the IEEE 57-bus system in a line-faulted contingency.

Key Words : FACTS (Flexible AC Transmission Systems), Operation Scheme, Security Margin, Security Indices, Line Contingency Analysis

1. Introduction

Recently, power industry is experiencing a new challenge of deregulation and liberalization. The operation mechanism of power system becomes more and more complicated, and uncertainties of

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1차심사 : 2004년 4월 7일
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new energy market get higher than that of vertically integrated power system. And power system can be operated in less secure state following unexpected line congestions and low voltages. Therefore, the power system security is vital to the competitive environment for reliable power supply in the deregulated power industry.

Construction of new transmission lines can be the most efficient method to operate the stable power systems. But, it becomes a time-consuming process due to political and environmental reasons including NIMBY. So, more attractive method is to make full use of the existing transmission lines. That is, the application of FACTS devices on the system is an alternative to improve the power system steady-state security.

FACTS devices are known to improve the stability of network, such as the transient stability and the small signal transient stability, and to reduce the flows in heavily loaded lines and support voltages by controlling their parameters including series impedance, shunt impedance, current, voltage and phase angle [1]. In addition, FACTS devices can carry line flows close to rating capacity and maintain bus voltages at the desired level and consequently can improve the power system security in contingency.

There are some researches that take an interest in increasing the maximum megawatt power transfer the most with series controllers [2], and evaluating the impact of FACTS controller on available transfer capability (ATC) enhancement [3]. As described in the Interim report : Causes of the August 14th Blackout in the United States and Canada [4], however, one of the main reasons of this blackout is known as closely connected with the voltage collapse following line congestion.

This paper presents a security-oriented operation scheme of FACTS devices to enhance the steady-state security level in terms of both the low voltage and the line overloads considering a line contingency analysis. The type and installation principle of FACTS devices are mentioned to demonstrate case studies. Quantities of security margin are defined in a P-V curve and security indices related to line flows and bus voltages are utilized and minimized iteratively. As a result of minimization, an operating point of each FACTS device is determined to increase the security margin and to reduce the security index [5]. The proposed FACTS operation scheme is verified on the IEEE 57-bus system with FACTS devices in a line-faulted contingency.

2. FACTS Devices

2.1 Types of FACTS Devices

FACTS devices can be categorized into three types, such as series controllers, shunt controllers and combined series-shunt controllers [6].

Series controllers such as TCSC (Thyristor Controlled Series Compensator), SSSC (Static Synchronous Series Compensator) and TCPAR (Thyristor Controlled Phase-Angle Regulator) can be used to alleviate line overloads and increase transfer capability. Shunt controllers such as SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) can compensate for the voltage by injecting directly or indirectly reactive power at the low voltage bus. The Combined series-shunt controllers such as an UPFC (Unified Power Flow Controller) can be employed in the system to release power flow congestion as well as support voltages, since it combines the features of both series controllers and shut controllers.

2.2 Installation of FACTS Devices

In case of series controllers, such as TCSC and TCPAR, the sensitivity analysis with respect to reduction of performance index related to active power flows [7] and the sensitivities of power transfer capacity with respect to line admittance to increase power transfer capability have been considered [8]. And in order to determine the optimal site of voltage-control devices like SVC, the participation factor is used as an index for controllability of the voltages at the nose point [9]. Based on these researches, the principles for choosing locations of installation of series controllers, shunt controllers and combined series-shunt controllers are as follows:

- Series Controllers : To distribute uniformly line flows and adjust the load margin, the candidate lines of series controllers are determined by computing the sensitivity of the loadability margin with respect to the line admittance [8]. Calculation of this sensitivity is performed at specific lines that directly suffer from the congestion problem as well as lines which are located near the overloaded lines. Therefore, the candidate sites will be these lines.
- Shunt Controllers : There are some correlations between the candidate buses of shunt controllers and the V(voltage)-Q(reactive power) sensitivity at each bus [9]. However, its sensitivity is calculated at given buses where a chronic low voltage occurs. To improve the voltage profile, a bus which experiences the severest low voltage problem is selected preferentially through the calculation of the V-Q sensitivity.
- Combined Series-Shunt Controllers such as an UPFC : Because an UPFC can release the line overloads and support voltages by control all kinds of variables, its location can be decided in the system parts where both line flow congestion and low voltage problems occur.

As mentioned above, sensitivity analysis to determine the proper locations of series controllers and shunt controllers is achieved at a few lines or buses where line congestions or low voltages happened, since it would be a quite time-consuming task to deal with every line and bus.

3. Security Margin

The power system security is the ability to withstand a set of credible contingencies from internal or external cause of power system and to continue operating without interruption of power supply to the customers [7].

As power systems have become more complex and more heavily loaded, they can be operated in unstable or insecure situations like cascading thermal overloads, frequency collapse and voltage instability and so on. For the secure operation of power systems, it is important to ensure the required level of the security margin. it is defined by the difference between an operating point and the nose point in the P-V characteristic curve, as shown the Fig. 1. If this margin has a relative large value, the power system is more secure state and can endure the particular contingency.

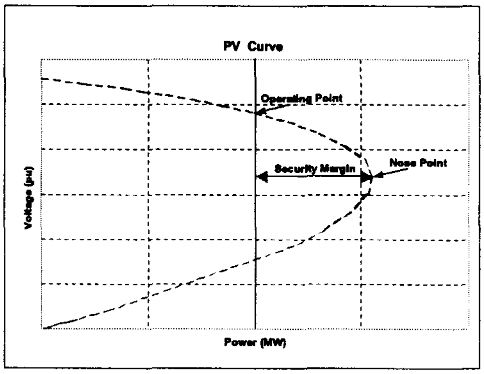


Fig. 1. Security Margin

4. Security Indices

The security index that indicates security level in contingency analysis is expressed as follows. It is used to indicate the security of each contingency [10], [11].

$$J_P = \sum_k a_k \left(\frac{P_k}{P_k^{Max}}\right)^2 \tag{1}$$

$$J_V = \sum_m b_m (V_m - V_m^{ref})^2 \tag{2}$$

where,

k : number of transmission lines
m : number of load buses
a_k, b_m : weight factors
P_k : active power transfer on the k-th line
P_k^{Max} : maximum of active power transfer over the k-th line
V_m : voltage magnitude at bus m
V_m^{ref} : reference voltage magnitude at bus m

Jp is the security index which means the even distribution of total active flow and Jv is the security index which means how much the bus voltage is close to the reference voltage. If the number of overloaded lines decreases, the value of Jp would be reduced. Similarly, when the bus voltage is close to the desired level, Jv would be a small value.

5. Security Management

Fig. 2 shows procedure of security management by FACTS operation to enhance steady-state system security, including contingency analysis and security assessment part by FACTS operation.

Contingency analysis is composed of line contingency analysis, contingency selection, and detection of overloaded lines and low-voltage buses. Although the purpose of contingency analysis is to predict the change of line flow and bus voltage following transmission line outages, generator outages and transformer outages [10], resultant changes after only line outages are considered in this paper. The lists of overloaded lines and low-voltage buses are recorded from every line contingency analysis, and then the most critical contingency is determined. The severity of a contingency situation is based on the number and level of the line congestion and bus voltage problems from the line contingency analysis.

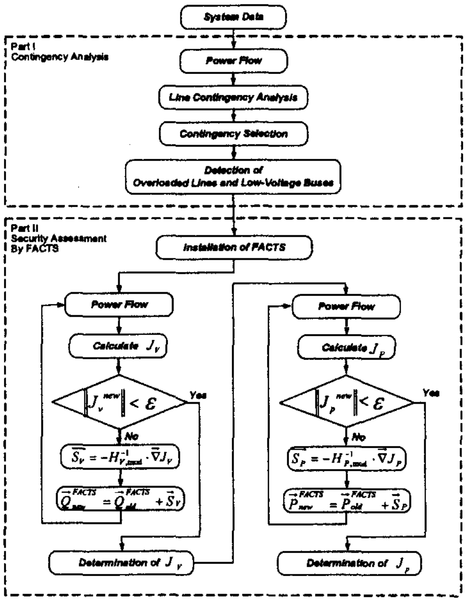


Fig. 2. Security Management by FACTS

Security assessment includes the installation procedure of FACTS and the algorithm of minimizing both Jp and Jv simultaneously. The proper location of each FACTS device has been pre-determined according to the installation principles of it. And it is reasonable to determine the controlled reactive powers from minimization of Jv at first and then to determine the controlled active powers from Jp minimization, because the number of variables in shunt compensation is less than that of variables in series compensation. In this algorithm, active and reactive power are assumed to be decoupled. As shown in Fig. 2, values of active and reactive power of an UPFC are updated by minimizing direction vectors, Sp and Sv, respectively, until convergence is achieved. $H_{p,\mathrm{mod}}$ and $H_{p,\mathrm{mod}}$ in Fig. 2 represent the modified hessian matrices respectively. Detailed procedures of derivation appears in reference [5].

6. Case Study

The proposed security enhancement by FACTS operation has been employed to the IEEE 57-bus system to examine minimization of security indices. In order to demonstrate the performance, some criteria and assumptions are applied as follows.

- Per-unit base is equal to 100MVA.
- It could be interpreted as secure state if range of node voltage is to be from 0.95 to 1.05 and the value of each line is to be within its value that is fixed as thermal limit in the system data.
- It is assumed that as soon as a line contingency occurs, system state directly changes to the steady-state corrective state due to a quick removal of disturbance by FACTS operation.
- The capacity of FACTS devices is assumed enough to minimize the security index Jp and Jv.

The proposed algorithm to minimize the security index has been tested on the IEEE 57-bus system in Fig. 3. It has 7 generators, 80 lines and 57 buses. In this sample system, an average load (100%) and a heavy load (110%) according to load level are considered. First, N-1 line contingency analysis was carried out. As a analysis result, the most severe line contingency is identified as line 7-29. The contingency severity based on the number and level of the line congestion and bus voltage problems was determined.

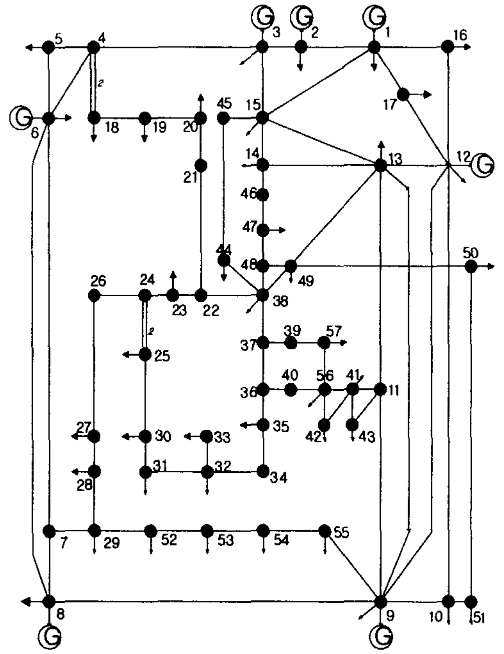


Fig. 3. Security Management by FACTS

Table 1 shows overloaded lines and low voltage buses in each case with a line 7-29 fault.

Table 1. Overloaded Lines and Low Voltage Buses in Each Cases

Case	Overloaded Lines	Low Voltage Buses
Average Load with a Fault	8-9, 53-54, 54-55, 38-48,9-55	19, 20, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 42, 52, 53, 54, 56, 57
Heavy Load with a Fault	1-2, 2-3, 8-9, 1-15, 14-15, 14-46, 46-47, 47-48, 53-54, 54-55, 11-43, 38-48, 9-55	19, 20, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 42, 52, 53, 54, 56, 57

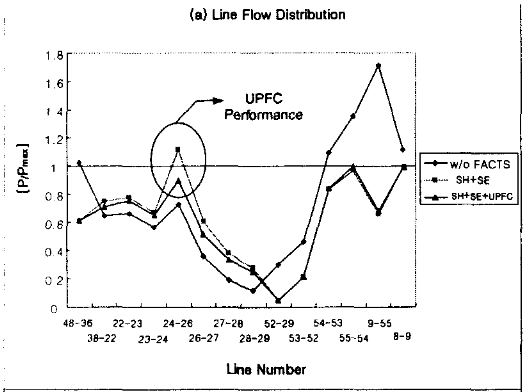
6.1 FACTS Operation in Average Load with a Line Fault

It is observed that 5 transmission lines were overloaded and voltage magnitudes of 24 buses are less than 0.95 [p.u.] in average load with 7-29 line fault.

In order to support voltage, 4 shunt controllers were installed in bus 29, 52, 31 and 20, and 3 series controllers were installed in line 8-6, 9-55 and 38-48 to alleviate congestion. One UPFC was located between bus 26 and bus 24 to cope with overloads from series compensation in line 9-55 and to improve the voltage profiles. Especially, the danger of overloads was observed to disappear in a line 24-26 due to operation of an UPFC.

Table 2. Security Indices in Average Load

	W/O FACTS	FACTS Operation
Jp	27.051	24.950
Jv(*10)	18.232	9.164



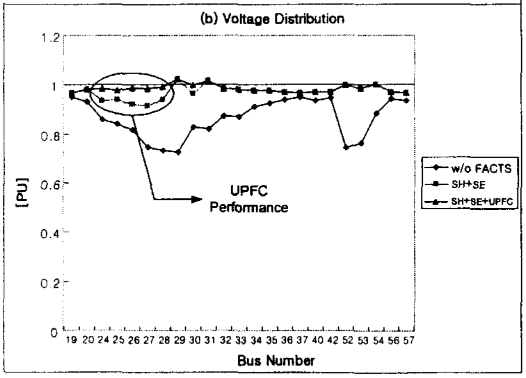


Fig. 4. Distribution of line flows and bus voltages in average load with a line fault
(SH - Operation of Shunt FACTS Devices
SE - Operation of Series FACTS Devices)

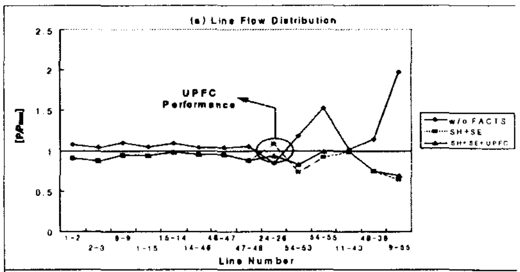
Table 2 shows that the minimized security indices were 24.950 and 9.164 respectively due to FACTS operation. Fig. 4 shows distribution of line flows and bus voltages in average load with 7-29 line fault. It is observed that all overloaded lines became values not exceeding P_{max} and all low voltage buses became values near 1 [p.u.] due to FACTS operation.

6.2 FACTS Operation in Heavy Load with a Line Fault

In heavy load with 7-29 line fault, 13 transmission lines were overloaded and 27 buses had voltage values less than 0.95 [p.u.] as shown Table 1.

Table 3. Security Indices in Heavy Load

	W/O FACTS	FACTS Operation
Jp	36.733	31.485
Jv(*10)	25.971	11.272



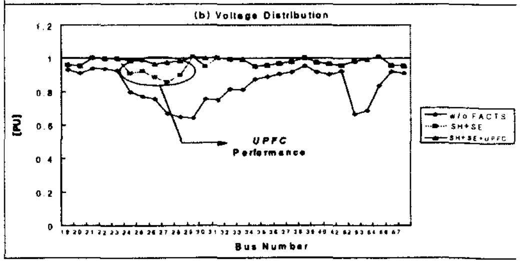


Fig. 5. Distribution of line flows and bus voltages in heavy load with a line fault

Two additional shunt compensators were installed in bus 27 and 57 in comparison with the case of the average load with 7-29 line fault. Also, two additional series compensators were installed in lines 1-16 and 11-43. One UPFC was located in line 26-24. Table 3 shows change in the security indices in a heavy load with a line fault without FACTS and with FACTS operation. Fig. 5 shows distribution of line flows and bus voltages. As shown in Table 3 and Fig. 5, Jp is reduced to 31.485 and Jv is also reduced to 11.272, respectively. This suggests that the system has enhanced the system security by FACTS operation.

7. Conclusions

This paper suggests the security-oriented operation scheme of FACTS devices considering a line contingency analysis. The summary is as follows:

- After the severest single-line outage, line congestion and low-voltage problems can be solved by the proposed FACTS operation scheme without generation rescheduling.
- Level of security margin is maximized and both kinds of security indices are simultaneously minimized by the proposed method. Consequently, the steady-state security has been enhanced.
- Distribution of line flows and bus voltages after minimization of both indices shows the enhancement of the system security by FACTS operation.

Acknowledgement

This work was supported by 2003 Research Fund of Myongji University.

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