한국박용기관학회지 제28권, 제5호, pp. 837~846, 2004. 7 (ISSN 1226-9549)
Journal of the Korean Society of Marine Engineers

UPFC 이상변압기 모델을 사용한 유연송전장치 일차민감도 해석

안승원† · Thomas W. Gedra*

(원고접수일 : 2004년 4월 21일 , 심사완료일 : 2004년 6월 2일)

First-Order Sensitivities for FACTS Devices using UPFC Ideal Transformer Model

Seung-Won An† · Thomas W. Gedra*

Abstract : This paper presents a screening technique for greatly reducing the computation involved in determining the optimal location and types of Flexible AC Transmission System (FACTS) devices in a large power system. The first-order sensitivities of the generation cost for various FACTS devices are derived. This technique requires solving only one optimal power flow (OPF) to obtain sensitivities with respect to FACTS device control variables for every transmission line. To implement a sensitivity-based screening technique, we used a new UPFC model, which consists of an ideal transformer with a complex turns ratio and a variable shunt admittance. A 5-bus system based on the IEEE 14-bus system was used to illustrate the technique.

Key words : FACTS (유연송전장치), screening technique (선별기술), OPF (최적조류해석), sensitivity analysis (민감도해석), UPFC (통합전력제어기), UPFC ideal transformer model (UPFC 이상변압기 모델)

1. Introduction

FACTS devices have been effectively used to increase controllability of electric power flow in large interconnected transmission networks in order to fully utilize existing transmission systems. Power electronics based FACTS devices include Static VAR Compensators (SVCs), Unified Power Flow Controllers (UPFCs), Advanced Series Compensators (ASCs), Static Phase Shifters (SPSs), etc. FACTS technology has been successfully implemented in several places including an excellent application of the UPFC at the AEP Inez substation in Ohio, USA. Since the FACTS devices, especially UPFCs, require a high capital cost to install, they cannot

† 책임저자(오클라호마 주립대학교 전기공학과), E-mail : aseung@okstate.edu, T : 405-744-2470(U.S.A)
* School of Electrical and Computer Engineering, Oklahoma State University, USA

be installed in every possible transmission line. Thus, a need exists for developing a cost-benefit analysis technique to deter-mine if the FACTS devices would be beneficial and, if so, the best location to install and the type of the FACTS devices.

In principle, determining the optimal location for a FACTS device is simple. For each possible location, we place a FACTS device in the power system model and calculate the cost savings with respect to a base case (with no new FACTS devices installed). The operating cost at each time and for each potential location is determined using an optimal power flow (OPF) program. However, the computa-tional burden of evaluating this annual value for every line is immense because an OPF problem must be solved for each line and for various representative times of year. Therefore, an efficient screening technique is desired to identify only the most promising locations and types of the FACTS devices so that at each point in time throughout the year, the exhaustive calculations described above do not have to be carried out for every location that is a candidate for installing the FACTS device. Instead, we solve only one "base-case" OPF problem for each point in time, from which UPFC sensitivities can be easily computed.

The UPFC has the capability to control voltage magnitude and phase angle, and can also independently provide (positive or negative) reactive power injections. Therefore the UPFC can provide voltage support as the SVC, control of real power flow as the SPS or the ASC, and other functions. So, we were able to use the UPFC model to obtain the first-order sensitivities of the total generation cost for other related FACTS devices.

The UPFC injection model[1] and the uncoupled model[2] have been proposed for steady-state power flow analysis.

These models can be easily incorporated into steady-state loadflow or OPF problems.

However, in these models four UPFC control variables depend on the UPFC input and output currents and voltages, and both models require adding two additional buses to the loadflow or OPF problem formulation. The voltage and current relationships between UPFC input and output need to be included explicitly.

In addition, a constraint on real power conservation must be added, thereby reducing the degrees of freedom to three.

The dual variables associated with real and reactive power balance at these fictitious buses are meaningless, but their addition only serves to increase the problem size. Therefore, these models are undesirable for our UPFC sensitivity analysis. To overcome these problems, we used a new steady-state mathematical model for an ideal UPFC, which consists of an ideal transformer with a complex turns ratio and a variable shunt admit-tance[3]. In this model, UPFC control variables do not depend on UPFC input and output voltages and currents, and therefore addition of fictitious input and output buses are not necessary. This model is easily combined with transmission line models using ABCD two-port represen-tations, which can then be converted to Y-parameter representations. Thus, the UPFC model is embedded in the Y_{bus}

matrix, and so the size of the Y_{bus} matrix is not changed. Furthermore the system Y_{bus} matrix is modified in only 4 locations.

The proposed technique is implemented on our 5-bus system (based on the IEEE 14-bus case). To verify the effectiveness of the screening technique, the actual cost savings for each transmission line is obtained using the UPFC uncoupled model[2].

2. OPERATING PRINCIPLES OF UPFC

A UPFC consists of a shunt transformer, a series transformer, power electronic switching devices and a DC link, as shown in Fig. 1[4]. Inverter 1 is function-ally a static VAR compensator assuming that inverter 2 is not connected. It injects reactive power in the form of current at the shunt transformer, and the current phasor $\vec{I_T}$ is in quadrature to the input voltage $\vec{V_I}$. Inverter 2 by itself represents the so-called advanced series compensator (ASC) assuming that inverter 1 is not connected. It injects reactive power by adding voltage through the series transformer. The injected voltage $\vec{V_I}$ is in quadrature to the receiving end current $\vec{I_0}$. Now if we connect inverter 1 to inverter 2 through a DC link, inverter 1 can provide real power to inverter 2.

Therefore the UPFC can independently control real and reactive power injections through the series transformer, but the real power injected at the series transformer is provided by the shunt transformer through the DC link. Inverter 1 must provide the real power used by inverter 2 via the DC link, but can also independently inject reactive power (positive or negative) through the shunt transformer.

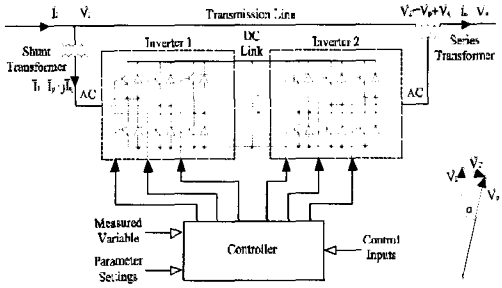


Fig. 1 General UPFC scheme [4]

3. OPF WITH UPFC

Suppose that a UPFC is installed in transmission line *ik*. The mathematical formulation of the OPF with the UPFC can be expressed as

$$\min_{y,x_{ik}} C(y, x_{ik}) \qquad (1)$$

subject to :

$$h_i(y) = 0, \qquad i = 1, \cdots, n$$
$$g_j(y) \le 0, \qquad j = 1, \cdots, m$$

where

- $C(y, x_{ik})$ is the total generation cost.
- y is a vector of decision variables.
- $x_{ik} = [T_{ik} \quad \phi_{ik} \quad \rho_{ik}]^T$ is a vector of the UPFC control variables in line *ik*.
- $\{h_i : i = 1, \cdots n\}$ is the set of equality constraint functions.

$-\{g_j : j=1,\cdots m\}$ is the set of inequality constraint functions.

We use the UPFC ideal transformer model to construct the equations for OPF with a UPFC. It is important to note that the number of quality constraints is the same as that of the base case OPF with no UPFC. This is because the UPFC control variables do not depend on UPFC input and output voltages and currents, and the UPFC model is embedded in the $\mathbf{Y}_{bus}$ matrix, and because we ignore UPFC operational limits. Now, let us construct the Lagrangian for the OPF problem as

$$\mathcal{L}_O(y,\lambda,x_{ik}) = C(y,x_{ik}) + i = \sum_{i=1}^{n} \lambda_i h_i(y,x_{ik}) + \sum_{j=1}^{m} \mu_j g_j(y,x_{ik}), \quad (2)$$

where λ_i and μ_J are the Lagrange multipliers for the equality and inequality constraints, respectively. To solve the proposed OPF problem with inequality constraints, we use the primal-dual interior-point method. At the optimum, the last term of (2) must satisfy the complementary slackness condition such that $\mu_j g_{j=0}$ for each $j=1,\ldots,m$. Therefore, if an inequality constraint is binding, we could treat it as an equality constraint, and we could ignore it if it were not binding. Since we are using interior-point methods (not active-set methods) we do not have to distinguish between active and inactive constraints until the OPF problem is solved [5]. This avoids ″cycling″ behavior in the active set which sometimes occurs with active set method such as Newton′s. Then, to derive the first-order sensitivities, we rewrite (2) as

$$\mathcal{L}_O(y,\lambda,x_{ik}) = C(y,x_{ik}) + \sum_{j\in\mathcal{A}} \lambda_j h_j(y,x_{ik}), \quad (3)$$

where $\mathcal{A}$ is the set of active constraints, once they are known.

4. FIRST-ORDER SENSITIVITY ANALYSIS

Let us consider the case where the UPFC is inserted in line ik, and the UPFC ideal transformer model is used for the analysis. The marginal values (MVs) of the UPFC, to be installed in line ik, are simply the amounts by which the total cost of system operation could be changed by allowing a small change of the UPFC control variables in line ik. We can obtain the MVs by assuming that there is a UPFC in line ik, but that the UPFC is not operating. So we add three extra constraints

$$T_{ik} = T, \quad \phi_{ik} = \phi, \quad \rho_{ik} = \rho$$

to the original OPF problem, and for simplicity, we denote the constraints as $x_{ik} = x$ in vector form. Then, the new Lagrangian can be written

$$\mathcal{L}_{ik}(y,\lambda,x_{ik},\lambda_x) = C(y,x_{ik}) + \sum_{j\in\mathcal{A}} \lambda_j \cdot h_j(y,x_{ik}) + \lambda_x^T(x - x_{ik}), \quad (4)$$

where

$$\lambda_x = [\lambda_T \quad \lambda_\phi \quad \lambda_\rho]^T.$$

We define the function $\lambda_x^*(x)$ to be the optimal value of the Lagrange multiplier on the constraint $x_{ik} = x$. Here, we are most interested in $\lambda_x^*(x = x_0)$, which is associated with the constraints

$$T_{ik}=1,\quad \phi_{ik}=0,\quad \rho_{ik}=0.$$

This is because the OPF problem when solved with the UPFC control parameters $x=x_0$ yields the same result for y and λ as the base case where there is no UPFC in line ik. Using the first-order conditions for the solution of the OPF problem for $x_{ik}=x_0$,

$$\frac{\partial L_{ik}}{\partial x_{ik}}=0 \tag{5}$$

we can solve for $\lambda_x^*(x_0)$ to obtain

$$\lambda_x^*(x_0)=\left[\frac{\partial C(y^*,x_{ik})}{\partial x_{ik}}+\sum_{j\in A}\lambda_j^*\frac{\partial h_j(y^*,x_{ik})}{\partial x_{ik}}\right] \tag{6}$$

Note that

$$\frac{\partial C(y^*,x_{ik})}{\partial x_{ik}} \text{ and } \lambda_j^*\frac{\partial h_j(y^*,x_{ik})}{\partial x_{ik}}$$

are easy to compute. Equation (6) indicates that the marginal value $\lambda_x^*(x_0)$ can be determined once we know y^* and y^*, which are obtained from the base case OPF with no UPFC. Thus, if we know y^* and y^*, we can obtain the first-order sensitivities of cost with respect to UPFC control variables x_{ik} for each possible transmission line by solving only the base-case OPF. Since the UPFC model is embedded in the $\mathbf{Y}_{bus}$ matrix, as explain-ed in [3], the first-order UPFC sensitivity analysis is only associated with complex power injections at buses i and k, and the thermal limit of transmission line ik if it is binding. If transmission flow is limited by steady-state stability, such constraints ($|P_{ik}|\le P_{\max}$ or $|\theta_i-\theta_k|\le\theta_{\max}$) can be included as well. For any value of the UPFC parameter x, the interpretation of the multiplier $\lambda_x^*(x)$ is the marginal change in the total generation cost as the constraint $x_{ik}=x$ is changed slightly. If such a change is allowed, it would be made to improve the objective function. The sign of λ_x^* determines the desired direction of the change in components of x_{ik}. Therefore, only the absolute value of the multiplier matters. As we vary x from x_0 to the set of optimal values x_{ik}^*, the multiplier will vary from the marginal value $\lambda_x^*(x_0)$ to the value $\lambda_x^*(x_{ik})=0$. This is because if we constrain x_{ik} to be equal to its unconstrained optimal value, the multiplier for this constraint must be zero.

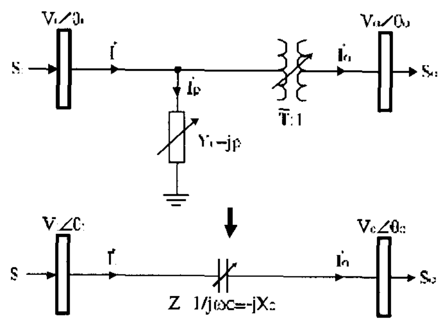


Fig. 2 Advanced series compensator in a transmission line

5. FIRST-ORDER SENSITIVITIES FOR OTHER FACTS DEVICES

The dual variables λ_T, λ_ϕ, and λ_ρ in the UPFC sensitivity analysis do not directly represent the marginal values of the ASC and the SVC since these devices have different control variables. So we must represent the first-order sensitivities of cost function for the ASC and the SVC using the results obtained from the base-case OPF. Let us first consider the ASC. We assume that the UPFC operates only as the ASC, as shown in Fig. 2 The input voltage can be expressed as

$$\vec{V}_1 = \vec{V}_0 - j\vec{I}_0 X_c = \vec{V}_0 \left\{ 1 - j\frac{\vec{I}_o}{\vec{V}_o} X_c \right\} \tag{7}$$

$$\begin{aligned} \bar{T} &= \frac{\vec{V}_I}{\vec{V}_o} = 1 - j\frac{\vec{I}_o}{\vec{V}_o}X_c = 1 - \frac{I_o}{V_o}X_c\angle\left(\pi/2 + \delta_o - \theta_o\right), \\ &= 1 + \frac{I_o}{V_o}X_c\sin(\delta_o - \theta_o) - j\frac{I_o}{V_o}X_c\cos(\delta_o - \theta_o). \end{aligned} \tag{8}$$

Equation (8) can be used to express the change of the ideal transformer turn ratio with respect to X_c, that is

$$\begin{aligned} \frac{d\bar{T}}{dX_c} &= e^{j\phi}\left[\frac{dT}{dX_c} + jT\frac{d\phi}{dX_c}\right] \\ &= -\frac{I_o}{V_o}\angle\left(\pi/2 + \delta_o - \theta_o\right), \\ &= \frac{I_o}{V_o}\sin(\delta_o - \theta_o) - j\frac{I_o}{V_o}\cos(\delta_o - \theta_o). \end{aligned} \tag{9}$$

Thus,

$$\begin{aligned} \frac{dT}{dX_c} &= \frac{I_o}{V_o}\sin(\delta_o - \theta_o - \phi), \\ \frac{d\phi}{dX_c} &= -\frac{1}{T}\frac{I_o}{V_o}\cos(\delta_o - \theta_o - \phi). \end{aligned} \tag{10}$$

The complex power injected at the shunt admittance in the UPFC ideal transformer model is written by

$$\bar{S}_T = \bar{S}_I - \bar{S}_o = -j\rho\left|\bar{T}\right|^2\left|\vec{V}_o\right|^2, \tag{11}$$

and the complex power injected at the ASC in terms of voltage is written by

$$\bar{S}_I - \bar{S}_o = \left(\vec{V}_I - \vec{V}_o\right)\vec{I}_o^* = -jX_c\left|\vec{I}_o\right|^2. \tag{12}$$

Using (11) and (12), the shunt admittance can be expressed as

$$\rho = X_c\frac{\left|\vec{I}_o\right|^2}{\left|\bar{T}\right|^2\left|\vec{V}_o\right|^2}, \tag{13}$$

and the first order derivative of the shunt admittance with respect to X_c, is obtained by

$$\frac{d\rho}{dX_c} = \frac{\left|\vec{I}_o\right|^2}{\left|\bar{T}\right|^2\left|\vec{V}_o\right|^2}. \tag{14}$$

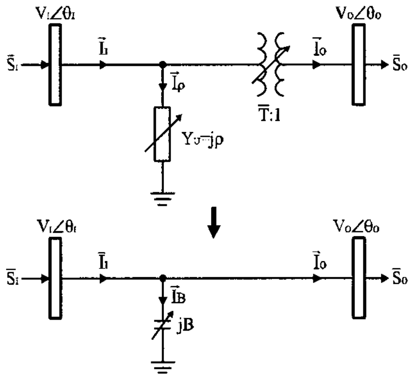


Fig. 3 Static VAR compensator in a transmission line

With (10) and (14), the first-order sensitivity of the ASC with respect to X_c can be obtained by

$$\begin{aligned} \lambda_{X_c} &= \lambda_\rho\frac{d\rho}{dX_c} + \lambda_T\frac{dT}{dX_c} + \lambda_\phi\frac{d\phi}{dX_c}, \\ &= \lambda_\rho\frac{\left|\vec{I}_o\right|^2}{\left|\bar{T}\right|^2\left|\vec{V}_o\right|^2} + \lambda_T\frac{I_o}{V_o}\sin(\delta_o - \theta_o - \phi) \\ &\quad - \lambda_\phi\frac{1}{T}\frac{I_o}{V_o}\cos(\delta_o - \theta_o - \phi). \end{aligned} \tag{15}$$

At $\overline{T}=1\angle 0$ and $\rho=0$, the above expression for

λ_{X_c} reduces to

$$\lambda_{X_c}=\lambda_T\frac{I_o}{V_o}\sin(\delta_o-\theta_o)-\lambda_\phi\frac{I_o}{V_o}\cos(\delta_o-\theta_o)+\lambda_\rho\frac{|\vec{I}_o|^2}{|\vec{V}_o|^2}. \quad (16)$$

Now, we consider the UPFC operating only as the SVC, as shown in Fig. 3 The complex power injected by theSVC in terms of current is written by

$$\overline{S}_I-\overline{S}_o=\vec{V}_I\left(\vec{I}_o-\vec{I}_o\right)^*=-j\left|\vec{V}_I\right|^2B. \quad (17)$$

where B is the shunt admittance of the VAR compensator. The shunt admittance of the UPFC ideal transformer model can be expressed by rearranging (11) and (17), that is

$$\rho=B\frac{|\vec{V}_I|^2}{|\overline{T}|^2|\vec{V}_o|^2}. \quad (18)$$

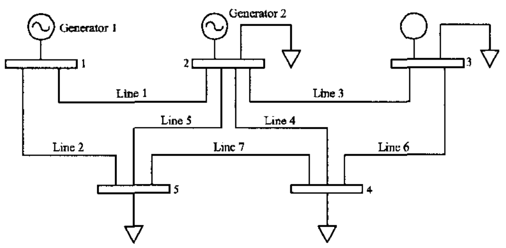


Fig. 4 Diagram of 5-bus subset of IEEE 14-bus system [6]

and the first-order derivative of the shunt admittance with respect to B is obtained by

$$\frac{d\rho}{dB}=\frac{|\vec{V}_I|^2}{|\overline{T}|^2|\vec{V}_o|^2} \quad (19)$$

Since the ideal transformer does not generate or consume the reactive power, we have

$$\frac{d\overline{T}}{dB}=0. \quad (20)$$

Thus, the first-order sensitivity of the SVC with respect to B can be obtained by

$$\lambda_B=\lambda_\rho\frac{d\rho}{dB}=\lambda_\rho\frac{|\vec{V}_I|^2}{|\overline{T}|^2|\vec{V}_o|^2}. \quad (21)$$

At $\overline{T}=1\angle 0$, the above expression for λ_B reduces to

$$\lambda_B=\lambda_\rho\frac{|\vec{V}_I|^2}{|\vec{V}_o|^2}. \quad (22)$$

6. RESULTS AND DISCUSSION

The proposed sensitivity method was tested on a 5-bus system derived from the IEEE 14-bus system (available on www.ee.washington.edu/research/pstca/). Fig. 4 shows the 5-bus system[6]. The line input data for the 5-bus system is given in Table 1. The system consists of two generators at buses 1 and 2, and one synchronous condenser at bus 3. The generation cost function, measured in \$/hr, is assumed to be

$$C(P_G)=\alpha+\beta\cdot P_g+\gamma\cdot P_G^2. \quad (23)$$

Table 1 Line input data for 5-bus system (S_{base}=100MW)

Line#	Bus-Bus	R pu	X pu	Y pu	S_{max} MVA
1	1-2	0.01938	0.05917	0.0528	120
2	1-5	0.05403	0.22304	0.0492	90
3	2-3	0.04699	0.19797	0.0438	75
4	2-4	0.05811	0.17632	0.0374	75
5	2-5	0.05695	0.17388	0.0340	75
6	3-4	0.06701	0.17103	0.0346	75
7	4-5	0.01335	0.04211	0.0128	75

Table 2 Generator input data for 5-bus system

#	α	β	$\gamma \times 10^3$	P_{max}	P_{min}	Q_{max}	Q_{min}
				MW		MVAR	
1	692.32	11	0.820	250	45	150	-100
2	692.32	12	0	150	15	50	-40
3	0	0	0	0	0	40	-40

Table 3 Load input data and bus voltage limits for 5-bus system

Bus#	P_{total}	Q_{total}	V_{max}	V_{min}
	MW	MVAR	pu	pu
1	0	0	1.08	0.95
2	21.72	4.41	1.08	0.95
3	94.06	19.10	1.08	0.95
4	91.61	18.60	1.05	0.95
5	51.48	10.45	1.05	0.95

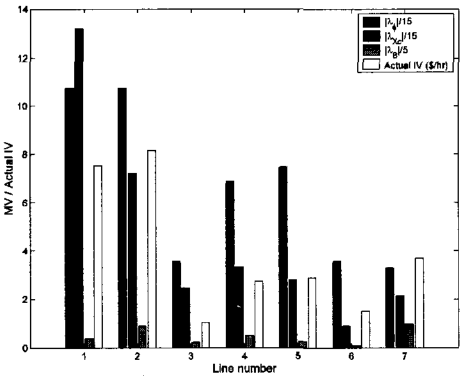


Fig. 5 Marginal and incremental values for 5-bus system

where P_G is the unit's real power generation level measured in MW. The generator input data is summarized in Table 2. Generator 1 has a smaller marginal cost than generator 2 for any P_{G1} and P_{G2} within the respective allowable generation ranges. Loads are assigned such that the current flow constraint in line 1 is binding (we assume that thermal constraints limit line flow for this example). The load input data and bus voltage limits are given in Table 3. We assume that a UPFC is installed in the middle of the transmission line. The marginal values ($|\lambda_\phi|$, $|\lambda_{X_C}|$ and $|\lambda_B|$) for the 5-bus system are shown in Fig. 5 Transmission lines 1 and 2 produce high MVs or ($|\lambda_\phi|$, and $|\lambda_{X_C}|$). Thus, the two lines appear to be the most promising places to install the UPFC. In addition, an SPS or an ASC could be a candidate for either line. To compare our sensitivity based screening technique with actual saving resulting from UPFC installation in each candidate line, a full OPF with a UPFC in each candidate line is implemented to obtain the total cost savings, also called the actual incremental value (IV). As shown in Fig. 5, we can see hat the lines with higher MVs usually produce higher IVs. This provides confidence that MVs and IVs are related enough to use for screening for optimal locations. For the 5-bus case, Table IV shows real power generation, transmission line losses and the total generation cost. Since the generation marginal cost, adjusted for marginal losses at bus 1 is lower than that at bus 2, it is profitable to obtain more real power from generator 1 as long as its adjusted marginal cost stays lower and no operational limits are reached. For the optimal location of the UPFC, transmission losses may not be minimized since our objective is cost minimization. An important thing to note is that it is more economical to locate the UPFC at the heavily-loaded high voltage line 1 since it allows more power to be transmitted on the under -utilized line 2 while preventing line 1 from overloading. Eventually, no further savings due to UPFC operation can be achieved because of the voltage constraint at bus-2.

Table 4 Real power generation, line loss and total generation cost for 5-bus system

UPFC Location	P_{G1} MW	P_{G2} MW	P_{loss} MW	P_{total} \$/hr
Base case	198.18	71.60	10.51	4460.1
Line 1	219.31	51.18	11.64	4452.6
Line 2	224.56	46.19	11.90	4451.9
Line 3	196.85	72.77	10.77	4459.0
Line 4	202.45	67.40	10.99	4457.3
Line 5	204.52	65.40	11.11	4457.2
Line 6	196.85	72.73	10.73	4458.6
Line 7	202.59	67.22	10.95	4456.4

7. CONCLUSIONS

We have proposed the first-order sensitivity technique to screen for the optimal locations and to determine the best types of the FACTS devices in a large power system by ignoring the transmission lines with low MVs, and running a full OPF only for the lines with higher MVs to obtain actual IV. We have also derived the first-order sensitivities for the ASC and the SVC using the results obtained from the base-case OPF. The UPFC ideal transformer model has been developed for the sensitivity analysis. This model does not require adding two extra buses, and the UPFC is embedded in the $\mathbf{Y}_{bus}$ matrix. Currently, we are developing methods based on second-order sensitivities to provide improved estimated incremental values as compared to the first-order methods.

REFERENCES

[1] M. Noroozian, L. Angquist, M. Ghand -hari, and G. Anderson. "Use of UPFC for optimal power flow control," *IEEE Trans. on Power Delivery*, Vol. 12, No. 4, pp.1629-1634, Oct. 1997.

[2] Seungwon An and Thomas W. Gedra. "Estimation of UPFC value using sensitivity analysis," in *Proc. of the 2002 Midwest Symposium on Circuits and Systems*, Tulsa, OK, Aug. 2002.

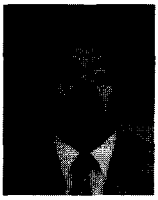
[3] Seungwon An and Thomas W. Gedra. "UPFC ideal transformer model," in *North American Power Symposium*, pp. 46-50, Oct. 2003.

[4] L. Gyugyi. "Unified power-flow control concept for flexible AC transmission systems," in *IEE Proc. on Generation, Transmission and Distribution*, Vol. 139, No. 4, pp. 323-331, Jul. 1992.

[5] Stephen G. Nash and Ariela Sofer. "Linear and nonlinear programming," The McGraw-Hill Companies, Inc., 1996.

[6] Parnjit Damrongkulkamjorn, Prakash K. Arcot, Peter Dcouto, and Thomas W. Gedra. "A screening technique for optimally locating phase shifters in power systems," in *Proc. Of the IEEE/PES Transmission and Distribu -tion Conference*, pp. 233-238, Apr. 1994.

저 자 소 개



안승원 (Seung-Won An)

He received his BSE degree from Korea Maritime University, Busan, Korea, and his MS and PhD in electrical engineering from OSU in 1999 and 2004. His research interests include power economics, power electronics, and power systems and control. Prior to joining OSU, he has worked as a system engineer and has secured several patents from Korea, England and China.

Thomas W. Gedra

received his BES and MSE degrees from The John Hopkins University, and his PhD from UC Berkeley. He is currently an associate professor in the School of Electrical and Computer Engineering at Oklahoma State University in Stillwater, Oklahoma. His research interests include power systems, power system economics, and stochastic systems and control.