Maximization of Transmission System Loading Margin with Optimal Generation Direction

Y. C. Chang

Department of Electrical Engineering, Cheng Shiu University

Abstract-- **It becomes vulnerable to face voltage instability incurred from over-utilized existing facilities or any contingency due to gradually increasing system load or regional electricity demands. A good generation direction (GD) can alleviate voltage instability and thus increase the loading margin (LM) for power systems to accommodate more power transfers. This paper proposes an optimal GD seeking method based on a particle swarm optimization (PSO) algorithm involving in the continuation power flow (CPF) process to compute the maximum LM. Three objective functions are investigated for possibly different purposes. They are maximum LM, minimum generation cost, and minimum generation cost and maximum LM at the same time. The results obtained with the three objectives and the cost participating factor (*Cost PF*) approach are compared each other to validate the proposed method.**

Index Terms--**Continuation power flow, generation direction, loading margin, particle swarm optimization, static voltage stability**

I. Introduction

ONE of the widest focused problems in power industry is that a lot of power utilities around the world ever suffered from voltage collapse due to difficulties in building transmission facilities to accommodate the constantly increasing system demands [1]. Several power system changes that mainly contribute to voltage collapse are in general resulted from increased loading, short of reactive power, load recovery dynamics, and line tripping or generator outages [2].

Among the main factors to maintain voltage stability, power system configuration, generation and load patterns are the most focused [3-4]. The control of relevant facilities, such as shunt capacitor (SC), automatic voltage regulator (AVR), on-load tap changer (OLTC) and installed flexible ac transmission systems (FACTS) devices at the weakest buses and/or transmission lines [5-7], can release voltage instability and thus increase loading margin; however, a poorly scheduled generation or load pattern might lead to system instability and reduce LM. In an open transmission access environment, this phenomenon would be more obvious due to increasingly competitive biddings and growing amount of various power transactions. From system dispatching point of view, generation patterns or GD are much easier to control to mitigate the voltage instability for system operators than load patterns due to its controllable nature [10].

A good GD can maximize the power transfer capability of transmission networks before reaching a system limit. The limit can be a voltage collapse point, a low voltage or a line thermal rating, etc. In general measures, the generation of each participating generator is raised at a predefined rate, or according to their spinning reserves. In competitive markets, it is more worthwhile to find a permissible GD for deriving the maximum LM based on economical concern.

Several literatures to seek for the maximum LM of transmission systems were proposed. In [8], for maximizing LM from a base-case state, the singularity of the system Jacobian is considered as a constraint and used to solve the subsequent Lagrangian formulated problem. While in the proposed method of [9], various objective functions, such as generation cost, LM, and/or fixed generator power factors, are composed into one single objective with weighting factors to exploit different utilizations under considering static voltage stability. In [10], through the coordination of two weighting factors, the composed single objective is used to minimize the cost difference between the supplies and demands and to maximize the LM as well.

Based on the normal vector, the method proposed in [11] indicates the intersection of the hypersurface for the generation boundary (or low voltage limit) with a hyperplane tangent to the hypersurface to determine the maximum LM resulted from the GD of the participating generators. While in [12], the proposed method relates the effect of LM to one generation parameter and, thus, it is suitable for seeking the best GD for one single generator to find the maximum LM. In [13], using the generation participation factors derived from a modal analysis, the impacts of the generators around a bus voltage critical bifurcation point were proposed. Because the analysis is manipulated near the critical point, it can be used to anticipate or estimate the maximum LM prior to voltage instability.

The maximum LM related to each participating generator is first approximated by using a polynomial function in [3], and then, with a linear combination of these LMs, the maximum LM contributed by all the participating generators is evaluated. To determine the GD for deriving the maximum LM while minimizing the generation cost, in [4], an economics based GD searching method is proposed, in which a two step optimization procedure is employed. Similar with the traditional economic dispatch (ED) power flow method, the first step increases the power supply by the participating generators to the most under stability condition, and then, the second step is used to deal with the convergence problem in

Corresponding author: ycchang@mail.csu.edu.tw (Ya-Chin Chang).

the CPF procedure when achieving a critical bifurcation point in first step.

In this paper, a GD optimization problem to determine the maximum LM while maintaining static voltage stability with or without involving generation cost in the objective is proposed. The solution method is based on the particle swarm optimization (PSO) algorithm involving in the CPF process to seek for the maximum LM for each particle, which represents a set of candidate generation increments (or GD) for the participating generators to supply the constantly increasing system demands. Three objective functions are used for different purposes. With the loading parameter used as the first objective, the maximum LM for the specific loading increments can be calculated. Taking minimum generation cost as the second objective, the LM is maximized based on the minimum generation cost; thus, the LM derived will be the one correspondent to the minimum generation cost. Combined with the two objectives, the third objective is to maximize the maximum LM and minimize the generation cost at one time, and thus, the result derived is a compromise between the maximum LM and minimum generation cost. The optimal GD for the participating generators related to various objectives can be determined directly by using the proposed PSO-based solution method. To validate the proposed method, the test results in the modified IEEE 30-bus system obtained from the three objectives are compared with each other and those derived from *Cost PF* approach.

II. Problem Description

The power system model can be formulated as a functional vector including the system nonlinear real and reactive power flow balance equations in the following form:

$$\mathbf{F}(\boldsymbol{\theta}, \mathbf{V}) = \mathbf{0} \tag{1}$$

where the vectors of the state variables $\boldsymbol{\theta}$ and $\mathbf{V}$ denote system bus phase angles and load bus voltage magnitudes. A base-case power flow can be obtained with the system equations.

When an uncontrollable loading factor λ associated with LM, that would drive the system from one stable equilibrium point to another, is inserted into the power flow equations, the system equations become:

$$\mathbf{F}(\boldsymbol{\theta}, \mathbf{V}, \lambda) = \mathbf{0} \tag{2}$$

If generation and/or load increases are on bus i, the real and reactive power balance equations can be described by:

$$\sum_{j=1}^{n} P_{ij}(\boldsymbol{\theta}, \mathbf{V}) - P_{io} - \lambda(\Delta P_{Gi}) + \lambda(\Delta P_{Li}) = 0 \tag{3}$$

$$\sum_{j=1}^{n} Q_{ij}(\boldsymbol{\theta}, \mathbf{V}) - Q_{io} + \lambda(\Delta Q_{Li}) = 0 \tag{4}$$

where P_{ij} and Q_{ij} are the real and reactive power flows from bus i through line i-j; $P_{io} = P_{Gio} + P_{Lio}$ and $Q_{io} = Q_{Lio}$ are the base case injections to bus i; as related to the future load increase, the loading increments ΔP_{Gi}, ΔP_{Li} and ΔQ_{Li} are respectively generation real, load real and reactive powers on bus i, $i \in \mu$, μ being the set of the PQ buses with loading increments. If increases are not allowed, loading increments ΔP_{Gi}, ΔP_{Li} and/or ΔQ_{Li} would be zero.

For a specific value of loading factor λ, the $\mathrm{LM} = \lambda \sum_{i \in \mu} \Delta P_{Li}$ and thus maximum $\mathrm{LM} = \lambda_{critical} \sum_{i \in \mu} \Delta P_{Li}$ where $\lambda_{critical}$ being the maximum value of λ, which will be obtained once a saddle-node bifurcation point is reached due to the increased system demand. The maximum LM can also be referred to as the maximum static voltage stability margin (VSM) for a specific loading level.

In the proposed strategy, the generation increments ΔP_{Gi} $\forall i \in \nu$, ν being the set of the generators at the PV buses participating in supply for increased system demand, are regulated to seek for the maximum LM, is shown in a vector form as follows:

$$\mathbf{\Delta P_G} = [\Delta P_{G2} \ldots \Delta P_{Gi} \ldots]^{\mathrm{T}} \tag{5}$$

where all generation increments must be confined within the permissible incremental ranges, i.e.

$$0 \le \lambda \Delta P_{Gi} \le P_{Gi}^{\max} - P_{Gio}, \quad \forall i \tag{6}$$

In computation, in order to include transmission loss into each generation increment, the respective searching ranges are given below:

$$0 \le \Delta P_{Gi} \le (1+\eta) \sum_{j \in \mu} \Delta P_{Lj}, \quad \forall i \tag{7}$$

where let $0 \le \eta \le \eta_{\max}$, $\eta_{\max}$ is determined according to different system conditions.

With the GD considered as variables, the system equations in (2) can be reformulated as a vector form:

$$\mathbf{F}(\boldsymbol{\theta}, \mathbf{V}, \mathbf{\Delta P_G}, \lambda) = \mathbf{0}, \ \lambda \ge 0 \tag{8}$$

If a set of generation increments is determined, the associated GD for the participating generators can be calculated by:

$$gd_i = \frac{\Delta P_{Gi}}{\sum_{i=1 \& i \in \nu} \Delta P_{Gi}} \tag{9}$$

where gd_i represents the percentage of the total generation increments for generator i.

As GD is simply determined by the *Cost PF* approach [11], the GD for each participating generator i should be maintained as:

$$gd_i = \frac{\Delta P_{Gi}}{\sum_{i=1 \& i \in \nu} \Delta P_{Gi}} = \frac{1/C_i^{"}}{\sum_{i=1 \& i \in \nu} 1/C_i^{"}} \tag{10}$$

III. CPF Procedure

With a generation increments (GD) $\mathbf{\Delta P_G}$ given and starting at $\lambda = 0$, a base state can be obtained first with a conventional power flow program, and the subsequent values of λ can be solved using the CPF procedure. During the procedure, when λ cannot be increased due to bus voltage instability, eventually the maximum $\mathrm{LM} = \lambda_{critical} \sum_{i \in \mu} \Delta P_{Li}$ can be derived with the $\mathbf{\Delta P_G}$.

The CPF uses a predictor-corrector scheme along the loading increment path to find the subsequent λ values. While the corrector is only a slightly modified Newton-Raphson power flow, predictor is quite unique from anything found in a conventional power flow and deserves detailed attention. The procedure is introduced as follows [14].

Predictor

After the base state obtained, a prediction of the next solution can be made by taking an appropriately sized step in a direction tangent to the solution path (loading path). Thus, the first task in the predictor process is to calculate the tangent vector. This tangent calculation is derived by first making derivative to both sides of (2) as follows:

$$\begin{bmatrix} \mathbf{F_\theta} & \mathbf{F_V} & \mathbf{F}_\lambda \end{bmatrix} \begin{bmatrix} \mathbf{d\theta} \\ \mathbf{dV} \\ d\lambda \end{bmatrix} = \begin{bmatrix} \mathbf{0}_\theta \\ \mathbf{0}_V \end{bmatrix} \tag{11}$$

The left side of (11) is a partial derivative matrix multiplied by a differential vector. The matrix is the conventional load flow Jacobian augmented by the column vector $\mathbf{F}_\lambda$ that is directly associated with the loading increments. In order to find a unique solution, an important barrier must be overcome. This problem arises when variable λ was inserted into the power flow equations but the number of equations remains unchanged. Thus, one more equation is required. This problem can be solved by choosing a non-zero magnitude, say 1, from one of the components in the tangent vector. Since the equations in (11) are all linear, let $d\lambda$ equal 1 to simply denote the tangent vector and suppose λ will increase in each step until a $\lambda_{critical}$ reached. (11) is then augmented and becomes:

$$\begin{bmatrix} \mathbf{F_\theta} & \mathbf{F_V} & \mathbf{F}_\lambda \\ & \mathbf{e}_\lambda & \end{bmatrix} \begin{bmatrix} \mathbf{d\theta} \\ \mathbf{dV} \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{0}_\theta \\ \mathbf{0}_V \\ 1 \end{bmatrix} \tag{12}$$

where $\mathbf{e}_\lambda$ is an appropriately dimensioned row vector with all elements equal to zero except the $(n_G + 2n_L + 1)^{th}$, which is equal to 1 associated with the unit change of λ.

Once the tangent vector is obtained by solving (12), the predication can be made by:

$$\begin{bmatrix} \mathbf{\theta}^* \\ \mathbf{V}^* \\ \lambda^* \end{bmatrix} = \begin{bmatrix} \mathbf{\theta} \\ \mathbf{V} \\ \lambda \end{bmatrix} + \delta \begin{bmatrix} \mathbf{d\theta} \\ \mathbf{dV} \\ 1 \end{bmatrix} \tag{13}$$

where " * " denotes the predicted solution for a subsequent value of λ and the scaling factor δ should be appropriately chosen during each predication so that the solution can be within the convergence radius of the corrector.

Corrector

The corrector process is used to modify the predicted solution onto the solution path (loading path) with one of the state variables being ascertained into an additive equation, say x_k^*. Then, the new set of equations would be:

$$\begin{bmatrix} \mathbf{F}(\mathbf{x}, \lambda) \\ x_k - x_k^* \end{bmatrix} = [\mathbf{0}] \tag{14}$$

One of the voltage magnitudes on the PQ buses will be denoted as x_k^*, assuming on bus *k*, which has the most negative value in the prediction. The augmented equations, with an additive equation and a variable λ inserted, can be solved by a slightly modified Newton-Raphson power flow method. In this paper, a CPFLOW program developed in [15] is used for dealing with the saddle-node bifurcation point on the loading path. Taking into account the specific $\mathbf{\Delta P_G}$ (or GD), the corresponding maximum LM along the specific loading path will be solved using the following proposed method.

IV. Optimal Generation Direction Approach

The increased generation cost due to a specific LM is formulated as a quadratic function below:

$$\begin{aligned} C_G &= \sum_{i=1\&i\in v} [(a_{Gi}P_{Gi}^2 + b_{Gi}P_{Gi} + c_{Gi}) - (a_{Gi}P_{Gio}^2 + b_{Gi}P_{Gio} + c_{Gio})] \\ &= \sum_{i=1\&i\in v} a_{Gi}(P_{Gi}^2 - P_{Gio}^2) + b_{Gi}(P_{Gi} - P_{Gio}) \quad \text{(US\$/Hr)} \end{aligned} \tag{15}$$

where $P_{Gi} = P_{Gio} + \lambda \Delta P_{Gi}$ is the real power generation of generator *i*. a_{Gi}, b_{Gi} and c_{Gi} are the coefficients of the generation cost.

A. Maximum LM Problem Formulation

For a base-case given, the problem to seek for the optimal GD and derive the maximum LM for specific loading increments is formulated as follows:

$$Max \quad f \tag{16}$$

$$s.t. \quad (6)\text{-}(8)$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad \forall i \in \{1, 2, \ldots, n_G\} \tag{17}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad \forall i \in \{1, 2, \ldots, n_G\} \tag{18}$$

Equations (17) and (18) are real power and reactive power generation limits, respectively. The three objective functions for testing are given below:

a) To operate at maximum LM, $f = \lambda$.

b) To operate at minimum generation cost, $f = -C_G$.

c) To operate at maximum LM and minimum generation cost as well, $f = -C_G / \lambda$.

B. Proposed solution method

The proposed solution method is based on the PSO algorithm involving in the CPF procedure to solve for system LM. The bus voltages and λ are sought through the CPF procedure along the loading path each iteration. The solution algorithm is shown in Fig.1.

A set of generation increments is denoted as the individual particles and reproduced in each iteration using the PSO solution algorithm. Particle $\mathbf{x}_i$ is defined as a vector as follows:

$$\mathbf{x}_i = [\mathbf{\Delta P}_\mathbf{G}^i]^\mathrm{T}, \quad i = 1, 2, \ldots, n_p \qquad (19)$$

where n_p is the particles number and the members in particle $\mathbf{x}_i$ are denoted as the ith candidate of generation increments defined in (5).

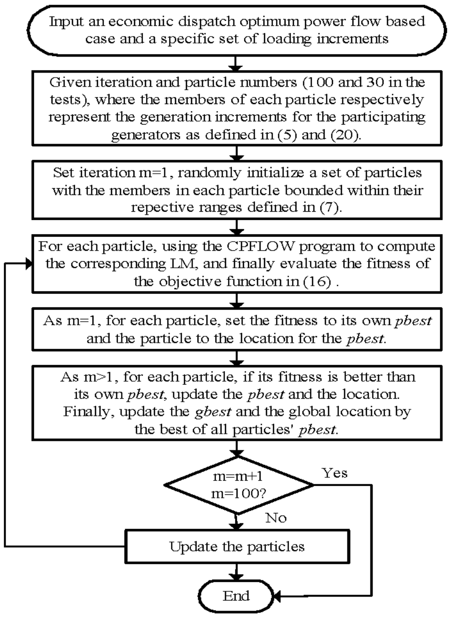

Fig. 1. Flowchart for the proposed solution algorithm

V. NUMERICAL RESULTS AND DISCUSSIONS

The modified IEEE 30-bus system shown in Fig. 2 is used for testing. The base data for the specific loading increments of the loads on buses 18 and 19, and the participating generators on buses 1, 8 and 13 are shown in Table 1, where the GD for generators G1, G8 and G13 are to be determined. For simplicity, the voltage magnitudes of the PV buses shown in the second column of Table 1 are all set to be stationary.

The data for the generation cost functions is given in Table II. Only considering bus voltage stability as the constraint, the generation increments, $\lambda_{critical}$, maximum LM and increased generation costs, derived from using the three objective functions in the proposed method and the *Cost PF* approach respectively, are shown in Table III. As can be seen that the maximum LM is obtained from $f = \lambda$ and the minimum increased generation cost obtained from $f = -C_G$. And, using $f = -C_G / \lambda$, the generation cost and the LM obtained may be the compromise between those obtained from the two other objective functions. As performance index "cost/λ" applied, the minimum index value is 307.6 for $f = -C_G / \lambda$, For example, the indices' values obtained from using $f = \lambda$ and $f = -C_G$ equating 326.0 and 309.2 are larger than that derived from using $f = -C_G / \lambda$, even though the increased generation cost and the LM obtained from using $f = -C_G / \lambda$ equating 998 (US$/Hr) and 0.824 p.u. are almost the same as 997 (US$/Hr) obtained from using $f = -C_G$ and 0.825 p.u. from using $f = \lambda$, respectively. In addition, with the generation increments shown in Table III, using (9), the GD found when using $f = -C_G$ and the *Cost PF* approach, they are 0.28, 0.15 and 0.57 and 0.48, 0.12 and 0.40, for G1, G8 and G13 respectively.

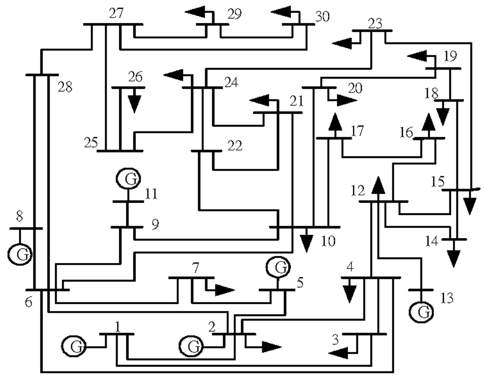

Fig. 2. Modified IEEE 30-bus test system

TABLE I
SPECIFIC LOADING INCREMENTS (p.u.)

Bus	Vol.	Base data		Loads' Increments	
		P_O	Q_O	ΔP	ΔQ
1*	1.050	0.5815	0.1116	-	-
8**	1.010	0.3597	0.2572	-	-
13**	1.050	0.6510	0.5405	-	-
18	0.9054	-0.1012	-0.0435	-0.1012	-0.0435
19	0.8979	-0.1117	-0.0375	-0.1117	-0.0375

* :slack bus; **:PV bus; 1 p.u. = 100 MVA

TABLE II
COST COEFFICIENTS

Gen.	a	b	c
1	0.0016	7.92	561
2	0.0026	7.87	72
5	0.0048	7.89	89
8	0.0064	7.85	310
11	0.0056	7.48	70
13	0.0019	7.97	78

The P-V curves for the GD obtained with the proposed method using $f = -C_G$ and the GD determined proportional to the base-case load, are depicted in Fig. 3. As found that the maximum LM obtained with the proposed method is much larger than that derived from the conventional one.

By using $f = -C_G$, the course to seek the corresponding maximum LM is shown in Fig. 4. As can be seen that the minimum cost 997 (US$/Hr) is found at the 43$^{\mathrm{th}}$ iteration and the corresponding maximum LM is 0.818 p.u. ($\lambda_{critical} = 3.225$). When the GD is determined by the *Cost PF* approach in advance by using (10), for accommodating the linearity of generation changes, a similar optimization process shown in Fig. 1 is used. It can be seen from Fig. 3 that, when the GD is achieved, the increased generation cost and the corresponding maximum LM accord with those shown in Table III.

TABLE III

GENERATION INCREMENTS, $\lambda_{critical}$, MAXIMUM LMS AND INCREASED COSTS FOR THREE OBJECTIVE FUNCTIONS AND *Cost PF* APPROACH

Gen. \ f	λ	$-C_G$	$-C_G/\lambda$	*Cost PF*
1	-0.0374	0.1036	0.1660	0.1797
8	0.3046	0.0571	0.0881	0.0449
13	0.1008	0.2116	0.1170	0.1498
$\lambda_{critical}$	3.252	3.225	3.245	3.238
LM (p.u.)	0.825	0.818	0.824	0.822
US$/Hr ($10^3$)	1.060	0.997	0.998	1.002

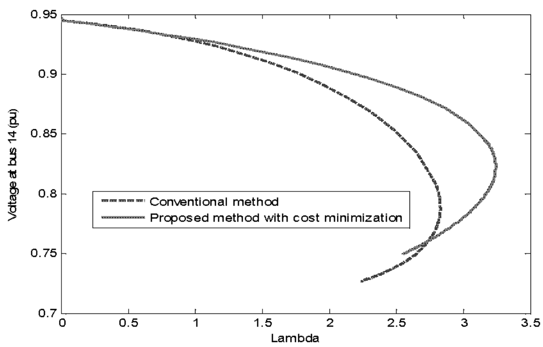

Fig. 3. P-V curves for the GD found with $f = -C_G$ by the proposed method and conventional method respectively

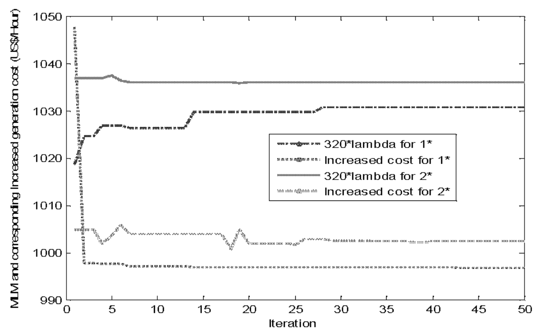

Fig. 4. Searching courses using 1*: $f = -C_G$ and 2*: *Cost PF*

The maximum LM for various generation increments of G8 versus G13 is shown in Fig. 5. It can be seen that the larger maximum LM is mainly correspondent to less generation increment for G13 (≈ 0.1 p.u.) and almost irrespective of that for G8. On the other hand, the increased generation costs corresponding to various loading increments of G8 versus G13 are shown in Fig. 6. As can be seen that the minimum generation cost can be derived with generation increments about 0.06 p.u. and 0.2 p.u. for G8 and G13, respectively. The above observations are in accordance with the results shown in Table III.

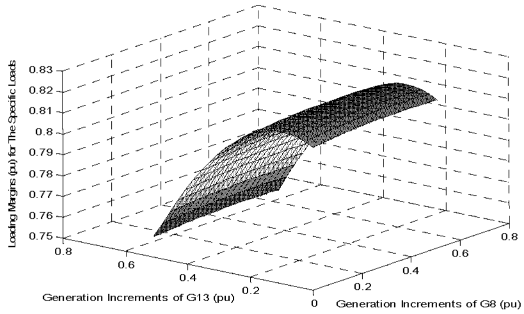

Fig. 5. Maximum LM for various generation increments (GD) of G8 versus G13

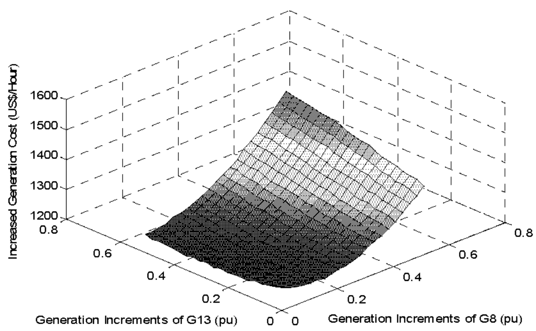

Fig. 6. Increased operating cost for various generation increments (GD) of G8 versus G13

VI. CONCLUSIONS

Facing the expectable economic development in the future, in order for the transmission systems to as much accommodate the load increases and/or minimize the increased generation cost as possible, in the paper, the problem to determine a good GD for the participating generators to enable the power system to provide a sufficient system LM is proposed. The PSO-based solution algorithm involving the CPF procedure with each particle representing a candidate GD, is proposed to solve for the LM considering static voltage stability. From the test results, the derivation of the proposed method is validated to be better than that obtained with the *Cost PF* approach. Also, all three objectives proposed are confirmed with the ability to seek a good GD for various possible purposes.

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BIOGRAPHY

Ya-Chin Chang received his Ph.D. degree from National Sun Yat-Sen University in 2002. He is an associate professor with the Department of Electrical Engineering, Cheng Shiu University, Taiwan. His current research interests are on power system operation, economics, and planning.