2000년도 대한전기학회 하계학술대회 논문집 2000.7.17-20

왜곡된 P-e곡선의 변환에 의한 전력계통 최대허용부하의 향상된 추정 방법

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Improved Method of Maximum Loadability Estimation in Power Systems By Transforming the Distorted P-e Curve

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Abstract: This paper presents an improved method to estimate the maximum load level for heavily loaded power systems with the load-generation variation vector by using the elliptic pattern of the P-e curve. The previous study suggested a simple technique of removing e-f coupling, where only high voltage load flow solutions to calculate transforming angle of system reference is needed.

The proposed algorithm is improved to require only one load flow solution at a specific load level in addition to the operating point at the beginning stage, which reduces the computation time and the iteration number of estimation. The proposed method can be efficiently applied to heavily loaded systems with the combination of CPFlow when the reactive power limit and ULTC are considered. In this paper, the effect of ULTC on the estimation of maximum loadability index is also investigated. The proposed algorithm is tested on New England 39 bus system and IEEE 118 bus system.

I. Introduction

Voltage stability has been one of the most important and urgent issues in modern power system operation due to the significant number of serious system failures by voltage instability. It is well known that the load limit concerned with voltage stability gives more precise information to the operators rather than the stability indices representing the proximity to the collapse point in some sense [1-5]. In this respect, the CPFlow (Continuation Power Flow) method has been introduced to calculate the maximum loadability in spite of its time-consuming iterative process [1]. The drawback of the CPFlow method can be covered by reducing the number of iteration remarkably with the aid of accurate estimation of the maximum loadability. Consequently, it has become one of recent research trends regarding voltage stability to calculate the maximum loadability with the aid of the CPFlow method [3].

The previous study suggested a method to estimate maximum load level (λ_{max}) by using the elliptic properties of P-e curve. This is based on the fact that the power flow equations can be represented by pure quadratic form in terms of state variables [e, f] with respect to the rectangular coordinate. An efficient method is proposed to estimate the maximum load level by applying the fitting method directly to the distorted ellipse. It has been shown that it can be a powerful tool to estimate λ_{max} with fast convergence characteristics. However, this method has a drawback of requiring the load flow solutions at 3 different load levels.

As an extension of the earlier studies [3], this paper presents an improved method to estimate the maximum load level by using the P-e curve. A simple technique is developed to remove the e-f coupling for some specified bus, where only high voltage load flow solutions to calculate transforming angle of system reference is needed. With the use of the undistorted ellipse the proposed algorithm can be improved to require only one load flow solution at a specific load level in addition to the operating point at the beginning stage.

The proposed method can be efficiently applied to heavily loaded systems with the combination of CPFlow when the reactive power limit and ULTC are considered. The proposed algorithm is tested on New England 39 bus system and IEEE 118 bus system with the consideration of ULTC effects, which shows that the maximum load level can be efficiently estimated with remarkable improvement in estimation speed and accuracy.

II. Removing Algorithm of e-f coupling

It is well known that P-e curve shows elliptic property with the system load increase. However, the P-e curve has the coupling between variable e and f, which makes the curve pattern somewhat unusual. In the paper, simple technique is presented to remove the of e-f coupling, which requires only high voltage load flow solutions to calculate transforming angle of system reference is needed.

The load flow equations can be expressed in terms of the rectangular components as

$$G_{pp} e_p^2 + \sum_{q \neq p} (G_{pq} e_q e_p - B_{pq} f_q e_p + G_{pq} f_q f_p + B_{pq} e_q f_p) + G_{pp} f_p^2 = P_p^{sp} \quad (1)$$

$$- B_{pp} e_p^2 + \sum_{q \neq p} (G_{pq} e_q f_p - B_{pq} f_p f_q - G_{pq} e_p f_q - B_{pq} e_p e_p) - B_{pp} f_p^2 = Q_p^{sp} \quad (2)$$

With the simple manipulation of $[(1) \times B_{pp} + (2) \times G_{pp}]$, the following algebraic equation can be obtained.

$$[B_{pp}(\sum_{q\neq p}(G_{pp}e_q - B_{pq}f_q)) - G_{pp}(\sum_{q\neq p}(G_{pq}f_q + B_{pq}e_q))]e_p$$
$$+[B_{pp}(\sum_{q\neq p}(G_{pq}f_q + B_{pq}e_q) + G_{pp}(\sum_{q\neq p}G_{pq}e_q - B_{pq}f_q))]f_p$$
$$= B_{pp}P_p^{sp} + G_{pp}Q_p^{sp} \quad (3)$$

Let us consider (e', f') satisfying (3), which is obtained by rotating by the system reference with angle θ_s. Then we can determine the θ_s by making the coefficient of e'_p be zero as follows:

$$\theta_s = \tan^{-1}\left(-\frac{[B_{pp}(\sum_{q\neq p}(G_{pp}e_q - B_{pq}f_q)) - G_{pp}(\sum_{q\neq p}(G_{pq}f_q + B_{pq}e_q))]}{[B_{pp}(\sum_{q\neq p}(G_{pq}f_q + B_{pq}e_q) + G_{pp}(\sum_{q\neq p}G_{pq}e_q - B_{pq}f_q))]}\right) \quad (4)$$

By removing the e-f coupling, the P-e curve can be expressed as an undistorted ellipse. Hence, for the first estimation of maximum load level, the proposed algorithm requires only one load flow solution at a specific load level in addition to the operating point at the beginning stage. This reduces the computation time and the iteration number of estimation. The proposed method can be efficiently applied to heavily loaded systems with the combination of CPFlow when the reactive power limit and ULTC are considered. Figure 1 shows the original P-e curve and the transformed P-e curve of Bus 5 of IEEE 14 Bus System.

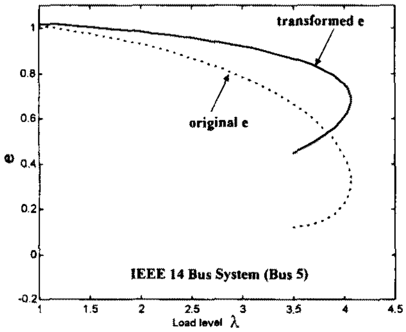

Fig. 1 Transformed P-e curve of IEEE 14 Bus System by the proposed method

As noted above, two load flow solutions are required for the first estimation process. From the second estimation process, the proposed estimation algorithm uses three load flow solutions for more accurate estimation.

III. Maximum Loadability Estimation with the consideration of ULTC

One of the key mechanisms in voltage instability is the voltage regulation performed automatically by the tap changing devices of main power delivery transformers.

The ULTCs are slowly acting, discrete (discontinuous) devices changing the tap by one step at a time, if the voltage error remains outside a deadband longer than a specified time delay. One important constraint in ULTC operation is that the variable tap ratio has a limited regulation range:

$$a^{min} < a < a^{max} \quad (5)$$

In this paper, a^{min} is fixed to 0.90 pu and. a^{max} is fixed to 1.10 pu. The tap size of a tap step is fixed to 0.00625 (5/8 %).

With Senario 2 of load increase in [3] (increasing both the load and the corresponding generation reallocation), the system voltages are observed. It is noted that when the ULTC effects is considered, generally the P-e curves of the buses sustained by ULTCs lose their elliptic properties In a case where the weak bus is sustained by an ULTC, we suggest that the weak bus should be changed into the bus to which the ULTC is connected The P-e curve of the bus which is not sustained by ULTC, shows fairy good elliptic property. Figure 2 shows that the P-e curves of a sample 6 bus system. The extended bus 6′ is connected to bus 6 via ULTC.

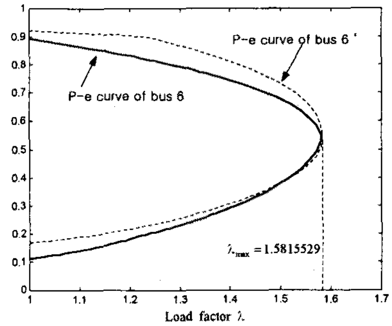

Fig. 2 P-e curves of bus 6 and 6' of sample 6-bus system

For the first estimation of maximum load level, the $\lambda - e$ curve can be described the undistorted elliptic equation for by the following general form:

$$\lambda^2 + \alpha e_i^2 + \beta\lambda + \gamma e_i + \zeta = 0 \quad (6)$$

Differentiating with respect to λ the (6) gives the following equation.

$$2\lambda + 2\alpha e_i \dot{e}_i + \beta + \gamma \dot{e}_i = 0 \quad (7)$$

The 4 coefficients in (6) can be computed if we know two upper load flow solutions and two derivatives of them at different load levels. With simple algebraic manipulation of (6), we can derive a formula to estimate the maximum load level $\hat{\lambda}_{max}$ as follows:

$$\hat{\lambda}_{max} = \frac{-\alpha\beta + \sqrt{(\alpha\beta)^2 + \alpha(\gamma^2 - 4\alpha\zeta)}}{-2\alpha} \quad (8)$$

Since only one load flow solution at λ_2 is requrired for the first estimation, the estimation time can be remarkably reduced. In order to calculate the exact maximum load level λ_{max}, it is required to repeat the estimation procedure by updating the load solution points. To avoid the divergence of load flow calculation in case of overestimated $\hat{\lambda}_{max}$, we adopt the CPflow method where λ is regarded as a variable to be found with an initial value $\hat{\lambda}_{max}$ [1].

IV. Numerical Tests

The proposed algorithm is tested on New England 39 bus system and IEEE 118 bus system, which shows that the maximum load level can be efficiently estimated with remarkable improvement in estimation speed and accuracy. First, maximum loadability indices are estimated without the consideration of ULTC effects. The effects of ULTC in the estimation of maximum load level are also investigated for New England 39 bus system.

When $\lambda = 1$, the system load and generation is identical to the base case. The exact and the estimated maximum load levels are denoted by λ_{max} and $\hat{\lambda}_{max}$ respectively.

Table 1 ~ Table 2 show the estimation results of three test systems. Although the proposed algorithm reduces the number of load flow calculation that greatly affects the estimation time, the first estimation error is larger than that of the earlier studies [3]. We experienced that the rotating angle θ_s changes as system load increases and we conjecture that is the cause of large estimation error at the first estimation process. Currently we are concentrating on calculating the constant rotating angle θ_s regardless of system load level.

Table 1. Test Results with New England 39-Bus System
(Weak Bus : Bus 7, λ_{max} = **2.211824**)

Iteration	Estimation of Maximum Load Level				
	λ_1	λ_2	λ_3	$\hat{\lambda}_{max}$	Error%
1	1.000000	1.100000		2.137517	3.35953
2	1.000000	1.100000	2.137517	2.204433	0.33415
3	1.100000	2.137517	2.204433	2.211542	0.01274
4	2.137517	2.204433	2.211542	2.211824	0.00000

Table 2. Test Results with IEEE 118-Bus System
(Weak Bus : Bus 38, λ_{max} = **3.239807**)

Iteration	Estimation of Maximum Load Level				
	λ_1	λ_2	λ_3	$\hat{\lambda}_{max}$	Error%
1	1.000000	1.500000		3.098308	4.36751
2	1.000000	1.500000	3.098308	3.363589	3.82065
3	1.500000	3.098308	3.232573	3.240332	0.01620
4	3.098308	3.232573	3.239184	3.239807	0.00000

To investigate the effect of ULTC in estimating the maximum loadability index, we modified New England 39 bus system by adding several ULTCs. All of the constant leakage reactances of ULTC are fixed to $X_t = 0.01$[pu]. Since we modified the original system, the maximum load level of each system is different from the previous simulation where ULTC effects are not considered. The estimation results by the proposed algorithm are give in Table 3, which shows that the proposed method can estimate the exact maximum load level with three or four estimation tries even though the ULTC effects are considered.

Table 3. Test Results with the modified New England 39-Bus System
(Weak Bus : Bus 7, λ_{max} = **1.884433**)

Iteration	Estimation of Maximum Load Level				
	λ_1	λ_2	λ_3	$\hat{\lambda}_{max}$	Error%
1	1.000000	1.100000		1.872694	0.62294
2	1.000000	1.100000	1.872694	1.884613	0.00955
3	1.100000	1.872694	1.883232	1.884436	0.00016
4	1.872694	1.883232	1.884301	1.884433	0.00000

V. Conclusions

This paper presents an improved method to estimate the maximum load level by using the P-e curve. A simple technique is developed to remove the e-f coupling for some specified bus, where only high voltage load flow solutions to calculate transforming angle of system reference is needed. The proposed algorithm is improved to require only one load flow solution at a specific load level in addition to the operating point at the beginning stage, which reduces the computation time and the iteration number of estimation.

The effect of ULTC on the estimation of maximum loadability index is investigated. The numerical results show that the proposed method can be efficiently applied to heavily loaded systems with the combination of CPFlow when the ULTC are considered. The proposed algorithm is tested on New England 39 bus system and IEEE 118 bus system

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