Situation awareness of power system based on static voltage security region

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Abstract: Situation awareness is a key factor in preserving power system security, as it enables effective and timely decision-making and reactions by the operators to the potential incidents. In order to identify operating status of large power system integrated with wind farms, this study presented a method of situation awareness based on static voltage security region (SVSR). Firstly, index of voltage security margin is proposed based on the limit induced bifurcation to quantify the level of the power system voltage security. Then, the authors calculate the hyper-planes of SVSR boundary by combination of quasi-steady-state equation and heuristic algorithm. These hyper-planes, obtained by off-line computation, assist in online assessment of security state and load margin. Furthermore, a wind power forecast technique is used to produce a new wind speed series for a given correlation between two wind farms, which support the situation projection. Finally, the correctness and effectiveness of the proposed method is demonstrated by cases studied in the modified IEEE 9-bus and IEEE 118-bus system.

1 Introduction

Power system situation awareness aims at mastering the security situation of power grid accurately and effectively through three steps, namely, perception, comprehension, and projection. With the growing expansion of the power grid scale and the continuously increased complexity of grid operation, fast and accurate estimation of the system operation state has become the major concern for dispatchers.

The security state awareness method based on precise system component model is not suitable for the large-scale interconnected power grid. At the same time, it is difficult for dispatchers to take preventive measures or emergency control in a timely manner, due to the data transmission frequency of monitoring devices and the calculation speed of real-time fault analysis tools.

In this case, the static voltage security region (SVSR) is proposed to evaluate the power system security status quickly by analysing the relative position of the operating point in the security region space. Its advantages in real-time monitoring are expected to be applied in the situation awareness, one of the important functions in the control centre.

The security region method was first proposed in 1970s by F.F. WU and was defined subsequently as the set of state variables such as injection power, voltage, and phase angle [1]. This method has been widely used in some applications, such as line thermal stability, voltage stability, small disturbance stability, and transient stability in recent years [2–5]. A robust master-slave two-level coordinated SVSR is proposed in [2] to protect wind units from serious over-voltage and low-voltage problems. A heuristic method for estimating the shortest radius of power system security region in node injection space is proposed in [3]. In [4], aiming at the real-time dispatch problem, a new concept of effective steady-state security region is proposed. Makarov et al. [5] have put forward the security region framework model that applies for all essential constraints, including thermal, voltage stability, transient stability, and small signal stability. This model can collect data by using synchronous phasor measurement unit, and achieve real-time perception and on-line monitoring of the wide area power system.

Meanwhile, some problems still remain to be fully explored. For instance, whether the correlation between the capacities of the grid-connected wind power would affect the voltage security margin and the impact of the stochastic and uncontrollable characters of wind power with high permeability on grid security status.

To solve the above problems, the following research has been carried out in this paper. Firstly, index of voltage security margin based on the limit induced bifurcation (LIB) has been proposed for the real time evaluation of power system security level. Then, the auto regression moving average model and time-shifting technique are used to simulate and predict the correlated wind speed time series. Moreover, this paper proposes an iterative approach based on heuristic algorithm and constructs a set of secure region model through offline calculation to meet the needs of online security evaluation. Finally, the correctness and feasibility of the proposed method are proved by the test system.

2 Voltage security margin index

In the analysis of static voltage stability, two types of system instability are usually studied. One is saddle node bifurcation (SNB), that is, when the system is approaching the bifurcation point, the power flow is often not convergent. The other is the LIB, as shown in Fig. 1. \( P_r \) represents base load capacity. When the generator is in reactive power limit state, i.e. \( Q_{lim} < Q_{G} \), the voltage of the system will decrease gradually until the voltage limit is reached, along with the increase of load. The critical operating point of LIB is the reactive/voltage constrained switching point. Then, the generator cannot maintain constant voltage amplitude and the system will suddenly collapse, that is LIB.

The parameters of active power are used to calculate the index of voltage security margin in this paper. The voltage security margin of load and generator buses can be calculated as

\[ \Delta P = P_{Smax} - P_0 \] (1)

\[ \text{VSM} = \frac{\Delta P}{P_0} \times 100\% \] (2)

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The SVSR model is defined as follows:

\[ \Omega_y = \left\{ (P_G, P_L, Q_L) \mid f(x) = y, V \in R_v, \right\} \]

where \( P_G \) and \( Q_G \) denote the injection active power and reactive power vector of generator bus, respectively; \( P_L \) and \( Q_L \) denote the injection active power and reactive power vector of load bus, respectively; \( f(x) = y \) represents the power flow equations; \( V \) and \( I_l \) denote the sets of voltage and line currents, respectively; \( R_v \), \( R_G \), and \( R_L \) represent the bus voltage amplitude constraints, generator reactive power production constraints, and line currents limits, respectively.

According to SVSR model, the voltage security margin calculation should be extended to the multi-dimensional space. Equation (4) defines the minimum L1 norm distance from the operating point to the boundary of the SVSR in the injection power space. Equation (5) defines the voltage security margin

\[ \lambda = \min_{P \in \Omega} \|P - P_0\|_1, \omega_i, \in \partial \Omega_y \]

\[ VSM = \frac{\lambda}{\|P_0\|_1} \times 100\% \]

where \( P' \) is the operating point at the SVSR boundary; \( \omega_i \) and \( \Omega_y \) denote the hyper-plane of the security region boundary and sets of boundaries, respectively.

### 3.1 Prediction model of wind farm output and correlation analysis

In the security region model, the wind farm is regarded as the PQ bus. Its active power can be obtained from the mechanical power, which is related to wind speed, regardless of the slip effect. The wind speed series can be calculated by (6) with the consideration of the randomness of the actual wind speed [6]

\[ SW_1(t) = \mu_s(t) + \sigma_s(t) s_1(t) \]

where \( \mu_s(t) \) and \( \sigma_s(t) \) denote the average wind speed and the standard deviation of wind speed at the wind farm \( k \) within the period of \( t \), respectively; \( s_1(t) \) is the scale function time series of wind speed. According to the autoregressive moving average (ARMA) model, the scale function is illustrated as follows:

\[ s_1(t) = \sum_{i=1}^{n} \varphi_i s_1(t-i) + \sigma(t) - \sum_{j=1}^{m} \theta_j a(t-j) \]

where \( n, m, \varphi_i \), and \( \theta_j \) are parameters of ARMA model; \( a(t) \) is a Gaussian white noise sequence.

Since the wind speed series have a strong correlation when wind farms are of close geographic position. Equation (8) gives the calculation method for correlation coefficient of wind speed series of wind farms \( k1 \) and \( k2 \)

\[ r = \frac{\sum_{i=1}^{N} (SW_{1k1i} - \bar{SW}_{1k1})(SW_{1k2i} - \bar{SW}_{1k2})}{\sqrt{\sum_{i=1}^{N} (SW_{1k1i} - \bar{SW}_{1k1})^2} \sqrt{\sum_{i=1}^{N} (SW_{1k2i} - \bar{SW}_{1k2})^2}} \]

where \( \bar{SW}_{1k1} \) and \( \bar{SW}_{1k2} \) denote the expectation and variance functions, respectively. In addition, the time-shifting technique is used to simulate wind speed series with different correlation. According to (9), wind speed series at \( t - K \) can be derived, \( K \) and \( t_o \) represent the integer and decimal part, respectively. Using the linear interpolation technique, the wind speed \( y_t \) can be given by [6]

\[ y_{k+i} = (1 - t_o)y_t + t_o y_{t+1} \]

where \( y_t \) denotes the original wind speed series; \( y_t \) is the shifted wind speed series. The actual output of wind farm is determined by the capacity of wind turbines [6].

### 3.2 Calculation of SVSR boundary

After the incorporation of wind farms into the power system, it is necessary to introduce the partial derivatives of the wind power to the terminal voltage as well as the phase angle in the original Jacobi matrix \( J \), as shown

\[ J_i = \begin{bmatrix} \frac{\partial \Delta P_w}{\partial V_k} & \frac{\partial \Delta Q_w}{\partial V_k} \\ \frac{\partial \Delta P_w}{\partial \theta_k} & \frac{\partial \Delta Q_w}{\partial \theta_k} \end{bmatrix} \]

where \( \Delta P_w \) and \( \Delta Q_w \) denote the change of wind farm active and reactive power production, respectively; \( V \) and \( \theta \) denote the voltage and phase angle of the bus, respectively.

Based on the quasi-steady-state equation and the inverse matrix of Jacobi matrix, the approximate expressions of voltage variation are obtained as

\[ \Delta V_a = \sum_{k \in L \cup W \cup G} H_{ab} \Delta P_L + \sum_{k \in L \cup W \cup G} S_{ab} \Delta Q_L + \sum_{k \in G} R_{ab} \Delta V_{gi} \]

where \( \Delta V_a \) is the variation of voltage amplitude of \( a \)th bus; \( H_{ab}, S_{ab}, \) and \( R_{ab} \) are sensitive matrix of active power and reactive power of \( a \)th bus; \( L, W \) and \( G \) denote the sets of load, wind farm and generator buses, respectively. The variation of the \( a \)th bus voltage amplitude satisfies the following constraint under the \( a \)th case

\[ \Delta V_a \leq V_{a}^\text{max} + \sum_{k \in L \cup W \cup G} H_{ab} (P_{Li} - P_{Li}^\text{max}) + \sum_{k \in L \cup W \cup G} S_{ab} (Q_{Li} - Q_{Li}^\text{max}) + \sum_{k \in G} R_{ab} (P_{gi} - P_{gi}^\text{max}) \leq V_{a}^\text{max} \]

where \( V_{a}^\text{max} \) is the voltage amplitude of the \( a \)th bus under the \( a \)th case; \( P_{Li}^\text{max} \) and \( Q_{Li}^\text{max} \) denote the injection active power vector and reactive power vector of the \( k \)th load bus under the \( a \)th case, respectively. \( P_{gi}^\text{max} \) is the injection active power of the \( i \)th generator bus under the \( a \)th case.

Then (12) is transformed to (13) describing the lower and upper boundary of the SVSR in \( a \)th bus (see [11])
Considering the definition of LIB, the lower limitation of the voltage amplitude, namely, the first part of (13), is used to calculate the security region in this study. Then, put the critical point \( V^x = V^x_{\text{min}} \), \( P^x_{Li} = P^x_{Li} \), \( Q^x_{Li} = Q^x_{Li} \) and \( P^x_{Gi} = P^x_{Gi} \) into (13), and obtain

\[
\sum_{\ell \in \mathcal{E}_{GW}} R_{\ell d} P^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} S_{\ell d} Q^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} H_{\ell d} P^x_{\ell d} \leq \sum_{\ell \in \mathcal{E}_{GW}} H_{\ell d} P^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} S_{\ell d} Q^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} R_{\ell d} P^x_{\ell d}
\]

(14)

If the critical operating point is given, then the sensitivity matrix in the critical operating state is known. After normalisation, the approximate range of the security region calculated by the lower bound of voltage amplitude can be obtained, as

\[
\sum_{\ell \in \mathcal{E}_{GW}} a_{\ell i} P^x_{\ell i} + \sum_{\ell \in \mathcal{E}_{GW}} b_{\ell i} Q^x_{\ell i} + \sum_{\ell \in \mathcal{E}_{GW}} c_{\ell i} P^x_{\ell i} \geq 1
\]

(15)

where \( a_{\ell i}, b_{\ell i} \) and \( c_{\ell i} \) are the coefficients of the hyper-plane.

### 3.3 Iterative calculation of critical operating point based on heuristic algorithm

According to Section 2.2, the boundary of the SVSR is calculated based on critical operating point. This section proposes a method for obtaining critical operating point by heuristic algorithm. In this method, the growth of generation and load towards the direction where bus voltage decreases the fastest, until the critical point is obtained. The steps of the proposed method are as follows:

**Step 1**: Initialise a secure operation point and determine the system topology and security constraints. Set iteration steps \( Sp = 1 \).

**Step 2**: Take the inverse of the Jacobi matrix in (10) and obtain voltage-sensitivity matrix, as shown in (16). The number of generator buses and load buses including wind farms are denoted as \( m \) and \( n \)

\[
X^Sp = \{ R_{ji}, H_{ji}, S_{ji} \} = \begin{bmatrix}
\frac{\partial \Delta \mu_i}{\partial P_{j1}}, & \ldots, & \frac{\partial \Delta \mu_i}{\partial P_{ji}}, & \ldots, & \frac{\partial \Delta \mu_i}{\partial P_{j1}}, & \ldots, & \frac{\partial \Delta \mu_i}{\partial \Delta Q_{i1}}, & \ldots, & \frac{\partial \Delta \mu_i}{\partial \Delta Q_{i1}}
\end{bmatrix}
\]

(16)

**Step 3**: Determine the worst power increasing direction to lower the \( u_{th} \) i.e. the amplitude of \( th \) bus.

\[
\begin{cases}
X^0_{ph} = \min_{i} \left( \frac{\partial \Delta \mu_i}{\partial P_{ji}} \right) \\
X^0_{qh} = \min_{i} \left( \frac{\partial \Delta \mu_i}{\partial Q_{ji}} \right)
\end{cases}
\]

(17)

Observing (17) the worst load-generation increasing direction for deteriorating voltage security of the system is that the \( th \) generation and the \( th \) load increase power. Therefore, the worst load-generation increasing direction at iteration step \( Sp \) is as follows:

\[
\begin{aligned}
P^h_{Gi} &= P^h_{Gi-1} + k \cdot \Delta h \\
P^h_{Li} &= P^h_{Li-1} + k \cdot \Delta h \\
Q^h_{Li} &= Q^h_{Li-1} + k \cdot \Delta h \cdot \eta
\end{aligned}
\]

(18)

When calculate SVSR critical point of the generator buses, the maximum reactive power of this generator must be guaranteed. In the process of approaching the LIB critical point, additionally, the bus voltage must be greater than the secure voltage limits, hence conditions (i) and (ii) are given with the consideration of the SNB.

The situation awareness process is illustrated in Fig. 2, which consists of offline computation and real-time monitoring. The SVSR is obtained considering various scenarios, such as contingency sets, unit expansion and line reconstruction. The real-time monitoring is conducted with short-term forecasted data, i.e. load demand and renewable sources.

Fig. 2 Situation awareness based on SVSR

\[
\begin{aligned}
V^\text{min}_d &= V^\text{min}_d - \left( \sum_{\ell \in \mathcal{E}_{GW}} H_{\ell d} P^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} S_{\ell d} Q^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} R_{\ell d} P^x_{\ell d} \right) + \sum_{\ell \in \mathcal{E}_{GW}} H_{\ell d} P^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} S_{\ell d} Q^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} R_{\ell d} P^x_{\ell d} \\
V^\text{max}_d &= V^\text{max}_d - \left( \sum_{\ell \in \mathcal{E}_{GW}} H_{\ell d} P^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} S_{\ell d} Q^x_{\ell d} + \sum_{\ell \in \mathcal{E}_{GW}} R_{\ell d} P^x_{\ell d} \right)
\end{aligned}
\]

(13)
4 Case study

The modified IEEE 9 bus test system and IEEE 118 bus test system are adopted in this paper to illustrate the correctness and effectiveness of the proposed method.

4.1 Test case based on modified IEEE 9 bus system

The modified IEEE 9 bus test system is illustrated in Fig. 3, from which we can see that the wind farm is connected to Bus 7. Given that this wind farm is consisted of 14 sets of 1.5 MW wind turbines with a power factor of 0.9. The bus voltage amplitude limits are $P_{\text{lim}}=0.9$, and the transfer capacity limit of the power line is two times of the rated transfer capacity.

Assume that the operating point is iterated to the critical point of the SVSR at the lower limit of the voltage amplitude of the Bus 9. This critical point, based on heuristic algorithm, is $[P_2, P_5, P_6, P_8, P_9, P_{10}, Q_2, Q_5, Q_6, Q_9, Q_{10}, Q_{13}]=[1.63, 1.35, 0.00, −0.9, 0.00, −0.79, 0.00, −1.75, 0.00, −0.3, 0.00, −0.25, 0.00, −0.9]$. Then, the Bus 9 SVSR boundary coefficients are illustrated in Table 1.

The coefficient of $Q_9$ is $−0.422$, its absolute value is far greater than that of other parameters, indicating the direct correlation between the injection reactive power and the voltage amplitude of Bus 9. Moreover, the greater the injected reactive power is, the farther the operating point is from the boundary of the voltage security region. These results are consistent with the real power system.

Assume that the operation point is iterated to the SVSR critical point of the Bus 2 and Bus 3, then Bus 2 and Bus 3 have been transformed into PQ nodes during the process of approaching the LIB and satisfy $Q_2 = Q_{2 \text{lim}} = 40 \text{ MW}$, $Q_3 = Q_{3 \text{lim}} = 20 \text{ MW}$. The boundary coefficients of the SVSR are shown in Table 2.

4.2 Test case based on modified IEEE 118 bus system

The IEEE 118 bus system is used as the test system to calculate the boundary of SVSR. This boundary expression contains 118 injection power variables and 117 security region hyper-planes of the monitoring bus. Table 3 only shows the power variable with a greater magnitude of the corresponding coefficients of the security region boundary of Bus 95.

In power system, the bus which is likely to cause voltage collapse and other security accidents are defined as voltage weak bus. Therefore, on-line monitoring voltage weak bus plays an important role in ensuring the security and stability of the power system.

Fig. 3 IEEE 9 bus system integrated wind farm

![Fig. 3 IEEE 9 bus system integrated wind farm](image)

Table 1 Hyper plane coefficients of Bus 9 SVSR boundary

| parameters | $P_2$ | $P_5$ | $P_6$ | $P_9$ | $P_{10}$ |
|------------|-------|-------|-------|-------|---------|
| coefficients | 0.093 | 0.075 | −0.005 | −0.150 | 0.011 |

| parameters | $P_8$ | $P_9$ | $Q_2$ | $Q_5$ | $Q_6$ |
|------------|-------|-------|-------|-------|-------|
| coefficients | −0.122 | 0.071 | −0.048 | 0.072 | −0.082 |

| parameters | $Q_2$ | $Q_5$ | $Q_6$ |
|------------|-------|-------|-------|
| coefficients | 0.082 | −0.104 | −0.076 | −0.422 |

Fig. 4 shows the closest L1 norm distance from the current operating point to the boundary of the SVSR. It also can be seen from Fig. 4 that the shortest distance between the system operating point and the voltage security boundary is calculated by voltage limits of Bus 21 and Bus 53, indicating these two buses under the current operating state are more prone to voltage security incidents. Based on the offline calculation of SVSR, the average time to estimate the VSM is merely 0.013 s.

Since the heuristic algorithm is used in the boundary computation, the distance between the operating point and the security region boundary could reflect the VSM of each bus. In accordance with the modal analysis method, the voltage stability weak bus of IEEE 118 bus system is determined by the value of participation factors [7]. Moreover, the four most unstable modes are shown in Table 4.

The voltage stability weak buses determined by modal analysis method are basically similar to weak buses calculated by proposed method. The difference comes from the fact that the modal analysis of weak buses is mainly related with the topological structure, and moreover the security region method considers the current operating status of power system too. For system dispatchers, the VSM can be quantified according to the security region, and this margin can provide strong support for the demand response policy implementation.

In the modified IEEE 118 bus system, wind farms are connected to buses 26, 59, 73, 77, and 92. The rated capacity of wind farm is 200, 150, 75, 100 and 120 MW. The sample data of 24 hours wind

![Fig. 4 L1-norms distance from operating point to the SVSR boundaries](image)

Table 2 Hyper-plane coefficients of Bus 2 and Bus 3 SVSR boundary

| parameters | $P_2$ | $P_4$ | $P_5$ | $P_6$ |
|------------|-------|-------|-------|-------|
| coefficients | −0.171 | 0.318 | −0.134 | 0.004 |
| $P_3$ | 0.121 | −0.057 | −0.1015 | −0.065 |
| coefficients | 0.077 | −0.027 | 0.099 | −0.120 |
| $P_6$ | −0.147 | −0.074 | −0.357 | −0.064 |

| parameters | $Q_2$ | $Q_3$ | $Q_4$ |
|------------|-------|-------|-------|
| coefficients | 0.079 | — | −0.098 | 0.184 |
| $Q_5$ | — | −0.713 | 0.013 | −0.423 |

| parameters | $Q_6$ | $Q_7$ | $Q_8$ |
|------------|-------|-------|-------|
| coefficients | −0.098 | 0.254 | 0.017 | 0.168 |

| parameters | $Q_9$ | $Q_{10}$ | $Q_{13}$ |
|------------|-------|-------|-------|
| coefficients | 0.089 | −0.198 | −0.002 | −0.182 |
speed were selected from the data collected by National Renewable Energy Laboratory. As shown in Table 5, there is a certain correlation between the wind speed series at the Bus 73 and Bus 77, and the wind speed series with different correlation coefficients can be simulated by (6)–(9).

The voltage security margin index from 01:00–24:00 can be calculated by (4) and (5), as shown in Fig. 5. The distribution of VSM under four cases are [1.04%, 1.29%], [0.97%, 1.34%], [0.76%, 1.47%] and [1.55%, 2.63%]. The comparison between cases 1, 2, 3, and 4 demonstrates that the greater the correlation between wind farm outputs, the bigger the fluctuation range of VSM is. By comparing cases 3 and 4, it can conclude that the VSM increases along with the decrease of the capacity of wind farm.

The reactive power, absorbed by wind farms, fluctuates with the wind speed, and the reactive power transfer is likely to cause voltage instability in the light of mechanism analysis. The randomness and uncontrollability of the wind power give rise to the increase of the power flow uncertainty and decrease of situation awareness capability.

Taking power system integrated wind farms as an example, this study uses the VSM to reflect the operating status of the power system. Besides, the application of the proposed method can be extended by incorporating the distributed energy sources and spatial load forecasting method. By putting predicted data into the security region model, the VSM in a near future can be calculated. As an important part of system situation awareness, the proposed index could provide information for operators to master the power grid statue.

5 Conclusion

In order to master the operating status of power grid, a SVSR based situation awareness method is proposed. First of all, the index of voltage security margin, based on the LIB condition, is put forward for real-time evaluation of power system security status. Then, the ARMA model and the time shift technique are used to predict the wind speed series with correlation. Finally, the boundary of the SVSR is obtained by integrating quasi-steady-state equations with heuristic algorithm. The numerical results show that the proposed method is applicable to weak bus monitoring and security evaluation.

The results of the modified IEEE 118 bus system indicate that the higher the correlation between wind farms outputs, the larger the fluctuation range of VSM. On the other hand, the voltage security margin will increase when the wind farm capacity is reduced. Additionally, the application of the situation awareness method to the demand response will be discussed in the following research.

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7 References

[1] Wu F.F., Kumagai S.: ‘Steady state security regions of power systems’, IEEE Trans. Circuits Syst., 1982, 29, pp. 703–711.
[2] Ding T., Bo R., Sun H., et al.: ‘A robust two-level coordinated static voltage security region for centrally integrated wind farms’, IEEE Trans. Smart Grid, 2016, 7, pp. 460–470.
[3] Liu K., Ge G., Chang N.: ‘Estimating the shortest radius of power system security region in node injection space’, Eng. Technol., 2012, 15, pp. 1–7.
[4] Cheng F., Yang M., Han X., et al.: ‘Real-time dispatch based on effective steady-state security regions of power systems’, PES General Meeting-Conference & Exposition, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5.
[5] Makarov Y.V., Du P., Lu S., et al.: ‘PMU-based wide-area security assessment: concept, method, and implementation’, IEEE Trans. Smart Grid, 2012, 3, pp. 1325–1332.
[6] Xie K., Billinton R.: ‘Considering wind speed correlation of WECS in reliability evaluation using the time-shifting technique’, Electr. Power Syst. Res., 2009, 79, pp. 687–693.
[7] Gao B., Morison G. K., Kundur P.: ‘Voltage stability evaluation using modal analysis’, IEEE Trans. Power Syst., 1992, 7, pp. 1529–1542.