Examining the Transmission Capacity Limits under Steady State Stability Criteria in the Operation of Electricity Market

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Abstract

The development of Electricity Market (EM) has shaped different market models, including the variety of management and transaction methods. The target of EM is to ensure the transparency, competition of market participants, while maintaining high operational reliability for the power system. The more abundant the transaction models, the more complicated the calculating to maintain the safety operation of power system, especially in the EM with flourishing bilateral trading contracts. This is due to the fact that the more bilateral transmission, the more difficult it is to monitor transmission capacity limits, particularly to track the power transmission limits under steady state stability criteria. For this kind of criteria, the current calculation methods are very limited, and need to be developed. Based on the method proposed in [4], this paper studies algorithms and application programs to quickly calculated and examine the bus transmission capacity limit and bilateral transmission capacity limit under the stability criteria. Example calculation is carried out for the Ward-Hale 6 bus and IEEE 39 bus system.

Keywords: Power system stability, Power transmission limit, Asymptote extrapolating method, Aperiodic instability, Electricity market, Bus transmission capacity, Bilateral transmission capacity.

1. Introduction

In advanced Electricity Market (EM), apart from biding activity for selling or buying electricity in the auctions, the EM participants can sign a bilateral contract (BC) for direct trading. The BCs help maintain the stable operation of EM in long term. Due to the prohibition of BC and all earlier electricity trading was only bid through the auctions, a serious electricity crisis of California happened in 2000. This unexpected event raised the electricity market price in California up to 2000 US$/MWh [1], subsequently caused the economic loss of 40 Bil. US$ [2], leading to one big electricity company to bankruptcy. Many of retailers and generating companies also were facing bankruptcy at that time. In order to avoid the consequences of California EM, the United Kingdom immediately allowed BC trading in its EM [1]. On studying EM's aspects of many countries in the world, Stephen Littlechild and F. P. Sioshansi [3] proved that the allowance of BC beside the biding activity is one of ten crucial factors affecting the success of EM.

However, the success of BC may be hampered by the power capacity transmission limits of the grid. The power injected at a given bus might not be extracted at another bus as the BC contract because of technical limits of the transmission system, causing the power system instability or violating other technical standards such as the voltage variation limits or thermal limit of conductors.

Therefore, for any power system, the maximum active power at a given source bus supplied to a given load bus considering above technical factors must be known exactly. This technical issue needs to be solved continuously together with the economic problem in the SMO - System Market Operator. Because of the complexity of stability problems, the current maximum power transmission in the grid is now the thermal limits. The level of stability reserving for transmission system is still being studied.

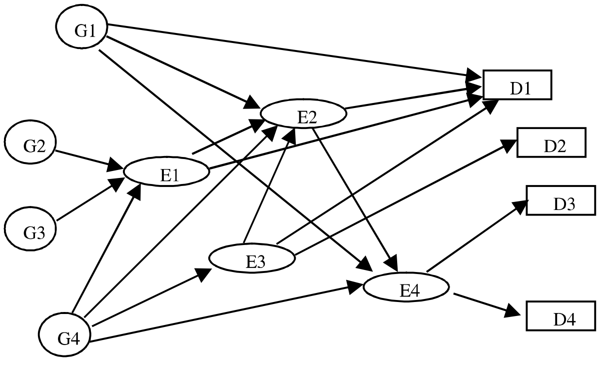

Fig. 1. Trading in Electricity Market

This paper proposes an approach to determine the Bus Transmission Capacity and the maximum power of Bilateral Transmission through the use of

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asymptote extrapolating method (AEM). The theoretical basis of the AEM method is explained fully in our another paper ([4]).

2. A summary of theoretical basis for AEM and its applicability in Electricity market

2.1 The bus transmission power capacity limit and the additional transmission power limit of bilateral transmissions

The operating state of an electricity market is illustrated in Figure 1 [5], with several power plants (G1, G2, G3, and G4) that supply power to loads D1, D2, D3 and D4. The market entities are power plants (G_i), intermediaries (E_i) and electrical loads (D_i - the electricity retailer).

It is possible to visualize the complex functioning of the market through bilateral contracts in Figure 1. Power plants can sell electricity to intermediaries, then intermediaries will sell electricity to loads (e.g., G2, G3, G4 sell electricity to E1, then E1 sells electricity to D1). Moreover, power plants can sell electricity directly to the load (G1 sells to D1). There is also the possibility that intermediaries buy and sell electricity for profit (e.g., E1, E3 sell electricity to E2, E2 sells to E4). For some electricity markets, entity E_i may be the only electricity trading company controlled by the state.

The development of the EM model, with a variety of trading methods, has improved market operations considerably. However, the management to ensure power system security is also much more complex. That is due to the fact that the more transmission options there are, the more limited the ability to track transmission limits, especially the transmission limit under stability conditions. Every transaction must ensure not to violate the maximum power limit injected into or extracted from a bus [5]. In addition, with bilateral contract, it is necessary to ensure that the power exchange is lower than the capacity limit which can be received on a load bus from a given source bus. There are the concepts of transmission capacity limitation as follows.

Bus transmission capacity (P_{btc}): is the maximum power that could be injected into the bus (for a source bus) or extracted from a bus (for a load bus).

Additional Bilateral Transmission Capacity (P_{atc}): The maximum active power increases compared to operating state value when transferring power from a given source bus to a given load bus.

In order to figure out the exact P_{btc} and P_{atc} values, it is necessary to solve three fundamental extremes: finding the thermal power transmission limit (P_{btcT}, P_{atcT}), finding the transmission limit according to the voltage drop criterion (P_{btcV} , P_{atcV}), and defining the power transmission limit according to the stability criterion of the system (P_{btcS}, P_{atcS}). Even the stability limit calculation has many types, such as limit by dynamic stability, limit by steady state stability (or small-signal stability). The steady state stability limit is of great interest because it is the parameter to evaluate the stability of the current operating power system. After calculating the types of power transmission limits for each criterion, the final power transmission limit is determined as follows:

$$P_{btc} = \mathrm{MIN}\ (P_{btcT}, P_{btcV}, P_{btcS}).$$

$$P_{atc} = \mathrm{MIN}\ (P_{atcT}, P_{atcV}, P_{atcS}).$$

This study is concerned with the P_{btc} and P_{atc} values according to static stability criteria. This criteria is more vulnerable to violations in modern power system with complicated diagrams and long distance for power transmission.

2.2 Stability limit state of the power system and the calculation bus transmission capacity limit under the AEM method

Stability limit of the power system has been extensivly studied. For each stability criterion, a stablility limit can be found corresponding to that criterion. Lyapunov's [6] theory of stabilility criterion is considered to be the general criterion for general kinesthetic systems. In power system field, Lyapunov's criteria are specified into many practical criteria such as Hurwitz algebra, Mikhailov frequency, Markovits or aperiodic instability criteria. After all, the aforementioned practical criteria could be used to examine the characteristic equation of the differential equation system describing the condition of power system. If all the roots of the characteristic equation (eigen value λ_i of the characteristic matrix) have a negative real part, then the system is stable. The stable limit is where there exists a root with the real part crossing the imaginary axis.

For aperiodical instability criteria, the stable state limit is characterized by the Jacobi determinant Det (J) of the state matrix of the power system, Det (J) = 0. If Det (J) <0, the system is aperiodical instability. Conversely, if Det (J) > 0, theoretically the system has a solution, but whether this solution is the actual long-term stability of the steady state mode or not depends on many conditions, such as voltage requirements, frequency and damping capability of small oscillation. However, these conditions are guaranteed if the frequency and voltage regulators are not violated [7]. Therefore, the state at Det (J) = 0 is considered a marginal operating state of the power system [7] -[8].

The AEM method of determining the power system stability limit is essentially based on the above criteria but in a different approach. Under this method, the active power P_i and the reactive power Q_i injected into the bus i (as equations describing the steady state of power system) are assumed to be the surface in the states space of the variables δ_i, U_i. The power angle α is the angle created by the normal vector of the surface $P_i(\delta_i, U_i)$ (or $Q_i(\delta_i, U_i)$) with the tangent vector of the curve created by the remaining power surfaces (see also [4], [9]). If α = 90° then the system is in a state of stability limit (see Figure 2). In [4], it was also proved that the state α = 90° coincides with Det (J) = 0. As a result, in essence, the stability criterion of the power angle α coincides with the aperiodical instability criterion.

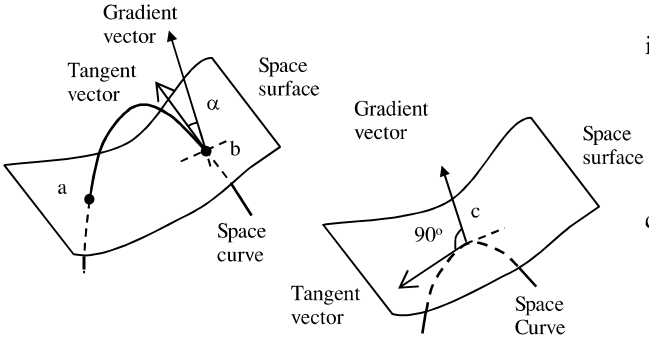

Fig. 2. Nomal operation and stability limit state of power system

Considering a system with n bus with an equilibrium bus of n + 1, the steady state equations of the power system are:

$$P_i = \sum_{j=1}^{n+1} y_{ij} U_i U_j \sin(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i = -\sum_{j=1}^{n+1} y_{ij} U_i U_j \cos(\delta_i - \delta_j - \theta_{ij})$$

In which: i = 1, 2, ..., n;

n+1: number of bus in the system. The equilibrium node is numbered n + 1, and $\delta_{n+1} = 0$;

P_i, Q_i: active and reactive power injected into bus i (negative number for load bus).

$\theta_{ij} = \Psi_{ij} - 90^o$ with Ψ_{ij}, y_{ij} : phase angle and module of reactance Y_{ij}.

δ_i , U_i : phase angle and module of voltage at bus i.

The fact is that power systems characteristic is very complex. Specifically, when the change of power states is at only one bus, the major variables are U_i and δ_i of the bus. A fully analysis of the components in the expressions of P_i and Q_i [4] proposed the approximation of P_i with sinusoidal function and Q_i with the parabolic function. Using the above conditions, we can approximate the complex curve by a simpler curve which can be determined its parameters. Specifically, the parameters of the curve (amplitude and phase angle of the sinusodial function, coefficients a, b, and c of the parabol fuction) are completely determined by Tangent and Gradient at the intersection point of the surface and the curve (at current state). The active power limit at bus i is determined as below formulation:

$$P_m = \sqrt{P^{*2} + [\frac{\nabla f_i * Tag_i}{\|Tag_i\|}]^2} \qquad (1)$$

For Pi* is the current active power of bus i; Δfi is the normal vector of the space surface, coordinates:

$$\nabla f_i = (\frac{\partial f_i}{\partial x_1}, \frac{\partial f_i}{\partial x_2}, ..., \frac{\partial f_i}{\partial x_{2n-s}})^t .;$$

Tag_i is the tangent vector of the curve, with coordinates:

$$Tag_i = (M_{i1}, M_{i2}, ..., M_{i(2N-m)})^t ,$$

$$\|Tag_i\| = \sqrt{(M_{i1})^2 + (M_{i2})^2 + ... + (M_{i(2N-s)})^2}$$

Mark || || indicates the Euclid standard distance of the vector.

M_{ij}: algebraic adjoint of elements on row i of the Jacobian matrix.

For reactive power, the maximum reactive power extracted from bus i is determined by the formula:

$$Q_m = - b^2/4a \qquad (2)$$

In which:

$$a = \frac{\frac{\nabla f_i * Tag_i}{\|Tag_i\|} . U_i - Q^*}{U_i^2} ; b = \frac{\nabla f_i * Tag_i}{\|Tag_i\|} - 2aU_i$$

Q*, U_i: is the reactive power and voltage at the bus i of the operating state.

Obviously, the above calculation formulas are determined based on the current parameters of powe system, so the AEM is a fast predictive methods of stability limits. The accuracy of the method is sufficiently high and suitable for practical application [4].

2.3 Application of AEM method in Pbtc and Patc calculation for electricity market operation

In the SM operation, the calculation of Pbtc and Patc norms is usually very large due to the requirements for continuously assessment of power system condition. Considering the maths: Suppose the Li bus needs to buy more power capcity ΔP, which power plant should supply this power to ensure system stability? The maths will be solved if we know the "distance" of the stability limit of a series of ΔP transmission limits scenarios from each power plant to the Li bus. In other words, it is requireed to know the stability reserve factor under each scenario. Cases with larger stability reserves will have an advantage in trading. Conversely, if the reserve factor is low, the SMO needs to limit or not permit trading. Other problems related to the increase or decrease of power generation of power plants have the same meaning - leading to the calculation of a series of power capacity limits at each bus under different scenarios. With the above scenarios, the application of AEM will be very effective.

The block diagram computed program using the AEM method can be illustrated as shown in Figure 3. The program is actually an additional module in the steady state calculation program of a power system, which links the use of operating parameter data (including the Jacobian matrix and the necessary state parameters), including the injecting power at buses corresponding to the column number in the Jacobian matrix.

Assuming that the power system consists of n + 1 nodes. The source bus provides the additional power of the additive load, which is interpreted as an equilibrium bus with the default number of n + 1. Changing the supply bus location (corresponding to node n + 1) allows us to consider the bilateral transaction options between the load bus i and the different source bus. In particular, it is possible to determine the transmission stability reserve ratio when transfering power from source G_k to load L_i:

$$K_{ki} = \frac{P_{im} - P_i^*}{P_{im}} 100\%$$

3. Calculating P_{btc} and P_{atc} Matrix of Power system by AEM method

3.1 Analysis of calculation results for Ward-Hale 6-Bus System

The Ward-Hale 6 Bus consists of two source buses and three load buses, as shown in Figure 4, as detailed in the documentation [10].

Using the AEM method and the calculation model as shown in Figure 3, the P_{btc} and P_{atc} matrices, as well as the system transmission reserved stability matrix are determined, as presented in Table 1.

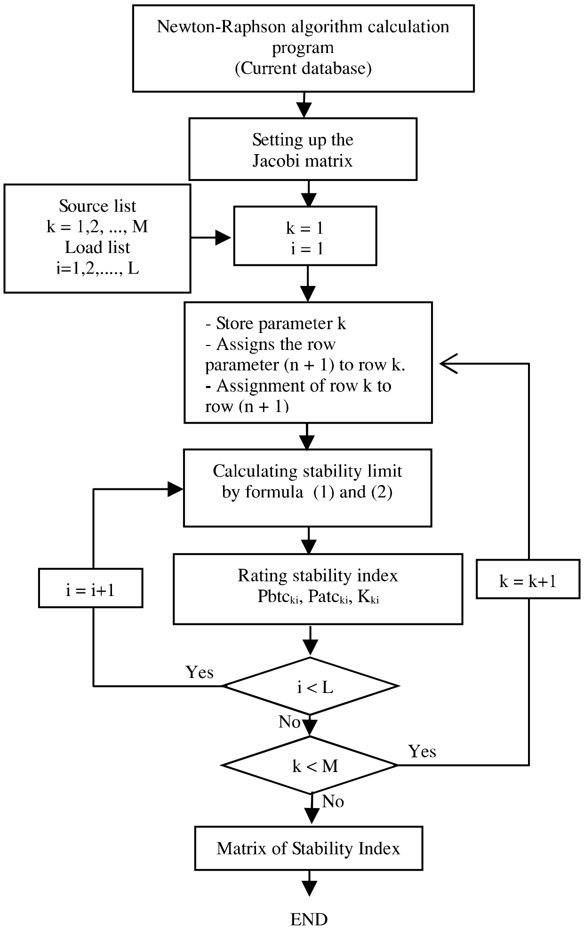

Fig. 3. Diagram calculating Matrix of Stability Index

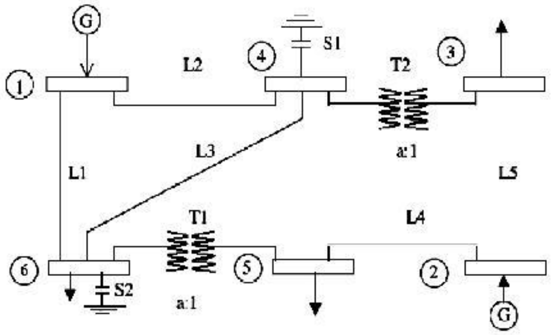

Fig. 4. Ward & Hale 6 bus diagram

Table 1. P_{btc}, P_{atc}, and K_{dt} matrices (%) of the Ward-Hale 6 bus scheme

P_{btcij}	G1	G2	P_{atcij}	G1	G2	K_{dt}(%)	G1	G2
L3	120.1	86.6	**L3**	65.1	31.6	**L3**	54.2	36.5
L5	89.8	91.0	**L5**	59.8	61.0	**L5**	66.6	67.0
L6	126.0	83.6	**L6**	76.0	33.6	**L6**	60.3	40.2

Unit: P_{btc}, P_{atc}: MW

The results show that, for bilateral trading in the EM, the load at bus 3 receiving power from the bus 1 power plant has more transmission advantage than receiving power from the power plant 2 due to the larger transmission capacity limit Pbtc (120.1 MW vs. 86.6 MW), the larger bilateral additional transmission capacity limit Patc (65.1 MW vs. 31.6 MW), the stability reserve as compared to initial state was also higher (54.2% vs.36.5%). Looking at Figure 4, we can also see the rationality of the results. Although the load bus 3 connects directly to source 2, the transmission line is too long, the total reactance L5 line (0.723 + j1.05) is much larger than the total reactance of line L2 (0.08 + j0.37) and transformer T2 (0 + j0,133) between bus 3 and bus 1.

Load bus 6 also shows that bilateral trading with source bus 1 will be significantly more advantageous in terms of transmission capacity limit, as the transmission maximum capacity is greater than if receiving power from source 2.

Load 5, although connected directly to source bus 2, is not superior regarding bilateral trading, due to relatively long line connection L4 (0.282 + j0,64), not advantageous as short lines L1, L4, L3 connections from source bus 1.

3.2 IEEE 39 Bus Power System

In the IEEE 39 bus diagram, there are 10 power plants and 19 additional electrical loads. As a result, there are about 190 potential bilateral power trading contracts. IEEE 39 diagram and power sources-loads buses are shown in Fig. 5. Detailed bus-branch parameters of the IEEE 39-Bus can be found in [11].

Using the matrix calculation program of the bus transmission power capacity limit and the additional transmission power capacity limits of bilateral trading under AEM, results are produced as in Table 2 below.

Noticeably, different pairs of power plants - loads have different bilateral transmission limits. The relative position of the pair source - load determines the maximum transmission capacity that can be increased between two bus and limits the power extracted from the load bus. For example, load at bus 20, if receiving more power from the G4 or G5 power plants, then by far more (535 MW and 423 MW) can be purchased, but if buying electricity from other plants, only a few more tens of MW can be purchased (from G9, only up to 34.8 MW is purchased).

The Pbtc and Patc matrix table provides an overview picture of the transmission limits of the power system if bilateral source-load transmissions occur. Based on the data in the table, it is possible to determine which contracts should not be made, for example, load 1 should not buy more power from G2 to G9 power plants, but only from G1 or G10. The fact is that the L1 load is large enough, close to the stability limit. Similarly, load 8 should not buy more power from G5, G7, G9 sources because of very low transmission reserve capacity (less than 10%), Patc also has only 38-51 MW. Instead, the L8 should buy power from the G2, G3 for more power capacity and better for the stability of power system.

Concerning remote load buses, if not specify Pbtc and Patc, it will be very difficult to find the best way to buy electricity. For example, load L15, L16 are located in the middle of the power system. Based on Patc, we notice that it is best that these two loads buy electricity from G2, G3, G4, and should not buy from G9.

Table 2. P_{atc} Matrix of IEEE 39 bus

P_{atc}	G1	G2	G3	G4	G5	G6	G7	G8	G9
L1	436	61	65	38	22	41	24	67	20
L3	198	170	191	140	80	150	88	190	70
L4	150	173	198	93	53	100	58	106	42
L6	433	573	548	299	221	311	232	319	195
L7	287	357	342	149	92	158	100	168	75
L8	188	221	213	81	47	87	51	94	38
L12	397	482	622	302	223	313	235	313	195
L15	162	165	197	186	100	199	110	143	65
L16	152	146	171	215	110	231	122	142	66
L18	252	229	255	234	142	248	154	248	119
L20	78	76	89	536	423	127	67	74	35
L21	162	157	182	230	123	404	181	153	75
L23	166	162	186	237	131	627	345	158	81
L24	155	150	174	219	114	262	140	146	69
L25	265	199	219	176	107	186	117	463	118
L26	259	222	243	224	143	236	154	322	210
L27	181	157	177	169	97	180	106	206	109
L28	197	168	185	171	108	181	117	251	453
L29	164	138	153	141	87	150	94	213	705

Unit: MW

Table 3. IEEE 39 bus transmission stability reserve Matrix

K_{dt}(%)	G1	G2	G3	G4	G5	G6	G7	G8	G9
L1	28	5	6	3	2	4	2	6	2
L3	38	35	37	30	20	32	22	37	18
L4	23	26	28	16	10	17	10	18	8
L6	98	98	98	97	96	97	96	97	96
L7	55	60	59	39	28	40	30	42	24
L8	27	30	29	14	8	14	9	15	7
L12	98	99	99	98	97	98	97	98	96
L15	34	34	38	37	24	38	26	31	17
L16	32	31	34	40	25	41	27	30	17
L18	61	59	62	60	47	61	49	61	43
L20	11	11	12	46	40	17	10	11	5
L21	37	37	40	46	31	60	40	36	22
L23	40	40	43	49	35	72	58	39	25
L24	33	33	36	42	27	46	31	32	18
L25	54	47	49	44	32	45	34	67	34
L26	65	62	64	62	51	63	53	70	60
L27	39	36	39	38	26	39	27	42	28
L28	49	45	47	45	34	47	36	55	69
L29	37	33	35	33	23	35	25	43	71

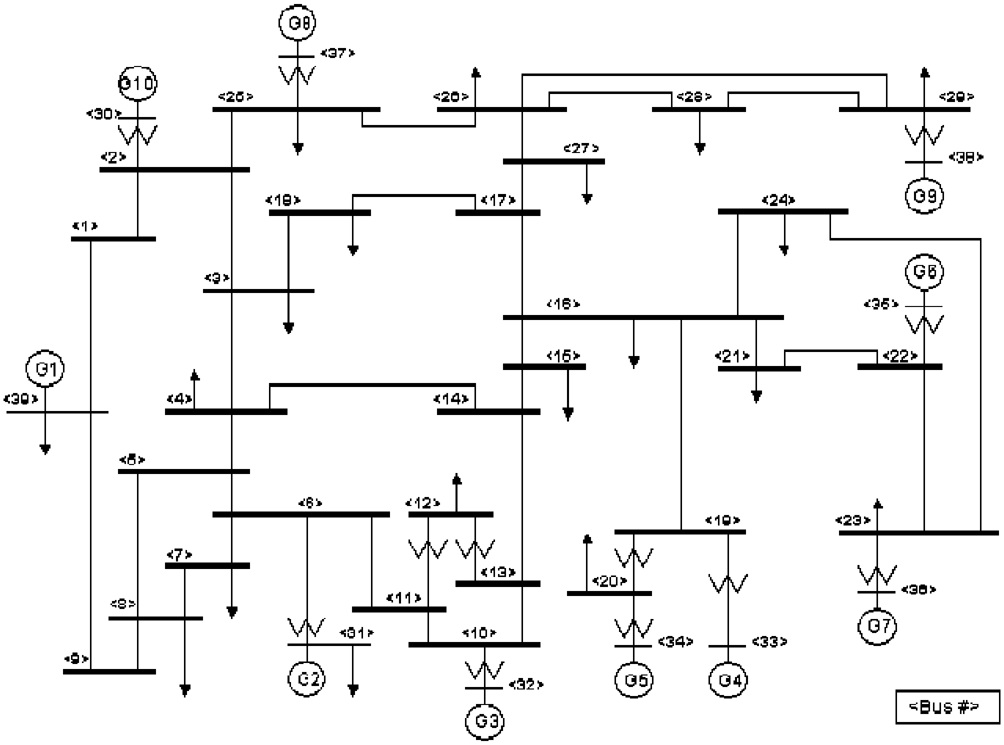

Fig. 5. IEEE 39 bus diagram

4. Conclusion

The development of the EM model and the bilateral transmission contract have led to the urgent requirements to manage the transmission limitation under stability criteria.

Based on the asymptote extrapolating method AEM, it is possible to build an algorithm and fast power transmission limit detection of between buses under stability criteria. The proposed method allows defining a transmission stability reserve matrix corresponding to the different bilateral transaction modes between the source and load buses. The result data is very useful for management and regulation of EM activities, to ensure and improve the stability of the power system.

Simulation results confirmed the rationality and effectiveness of the proposed method.

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