2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece

Effective and Robust Case Screening for Transient Stability Assessment

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***Abstract* -** Reducing the computational burden of transient stability assessment (TSA) by filtering out most risk-free faults effectively and rapidly without any false-filtering will be significant especially for on-line and uncertainty TSA. This paper presents such a rapid and robust case screening algorithm based on Extended Equal Area Criterion (EEAC). The time-varying degree of an equivalent image system can be reflected by comparing the analysis results of Static EEAC (SEEAC), which neglects all time-varying factors, and that of Dynamic EEAC (DEEAC), which partially considers the time-varying factors. The stable faults can be hierarchically screened out with 3 rules. Different sequences for performing the 3 rules can only affect the computational efficiency, but not the robustness of this algorithm. Excellent performance of this framework is verified by 28 sets of data from 7 actual Chinese provincial power systems with various operating conditions: all the actual unstable contingencies are captured and the screening rate of actual stable cases is above 86%. The average computational time is 86%-96% reduced comparing to TSA with the full IEEAC method.

***Keywords* -** Transient stability, quantitative analysis, Extended Equal Area Criterion (EEAC), time-varying character, the quantization of time-varying degree, case screening

1. Introduction

The requirement for TSA on speed and accuracy is increased with the rapid evolution of modern power system as well as the increasing risk. Numerical integration is the only way to deal with systems containing complex models and discrete scenarios, however the obtained time response curves can only give qualitative results for TSA. Moreover, its huge computational burden also limits the application in on-line TSA tasks as well as uncertainty analyses tasks.

Case screening is one of the measures to reduce the computational burden. Highly stable cases can be filtered out with some assigned rules to avoid further detailed calculation.

For robustness of the screening, indexes should be defended based on the physical essence of power system transient stability, so that unstable or near-unstable faults won't be ignored in any circumstances. Moreover, for effectiveness of the screening, the computational burden for screening must be negligible compared to what can be saved.

Screening methods filter out cases with high degree of stability to avoid detailed analysis by using simplified TSA algorithm in order [1], early termination of the integration [2], modification of the analyzing process for batched cases [3], direct screening with experiential criterion [4], pattern recognition in feature space [5-16], sensitivity analysis of stability margin [17], or the coordination among some methods with different degree of simplification to balance the accuracy and computational burden [3,18].

The screening framework proposed in [1] identifies the harmless faults according to the mean square error of the generators' angle offset compared to the center of inertia, and ranks the remaining cases by comparing the equivalent kinetic energy at the fault clearing time τ and the minimum kinetic energy after the fault. However, important factors on unstable modes, potential energy and critical energy are all neglected.

Based on EEAC, Ref. [2] takes the maximum difference between every pair of adjacent swings' kinetic energy, the mean difference among all pairs of adjacent swings' kinetic energy, as well as the area enclosed by actual and ideal $P-\delta$ curves as indexes to predict the stability of follow-up swings and possibly early terminate the numerical integration.

In [3], all contingencies are evaluated one after the other for the same value of τ, then the procedure is performed again with an increased τ until all cases become unstable to avoid searching the critical clearing time (CCT or t_c) for each contingence in an isolate way.

A composed security index considering the weighted sum of the angle deviations, kinetic energy and potential energy etc. during a short period after fault is used for case screening in [4]. Ref. [5] uses artificial neural network (ANN) technique to handle the feature parameters, e.g. each unit's power angle and its velocity and acceleration at the fault moment and the designated time τ to screen cases.

Ref. [18] designed a multi-layer screening scheme based on the BCU method to filter out stable cases with the accuracy of the unstable equilibrium point increasing layer-by-layer.

The above methods are confined to the case space. While in on-line environment, TSA must be applied periodically to follow the changes of operation conditions. In [17], stability margins and dynamic modes resulting from the previous cycles are used to confirm the validity of last rounds' results to filter out faults that need no further detailed analysis for the present cycle. The method has been validated by large scale of industry applications.

To ensure that any unstable cases will never be screened out, screening rules and algorithms should be developed on a relatively strict theoretical basis, and the thresholds should never be designed for any individual cases. It is usually very difficult for those screening methods relying on pattern recognition or ANN technique to meet the robustness requirement of TSA.

Enhancing the quantization ability of TSA and reducing the computational burden are considered incompatible and studied in isolation ways. The former represented by direct methods usually overlook computational complexity, while the latter represented by equivalent modelization and parallel computation are confined to generalized simulation techniques.

Various direct methods based on Lyapunov theory can neither guarantee the robustness of qualitative analysis nor achieve the aim of rapid assessment. However, based on the stability mechanisms, quantization and rapidity are coordinated very well in EEAC [19]. Nevertheless, more improvement should be done due to the expending scale and more complex models of power systems.

EEAC method composes three versions of EEAC, namely Static EEAC (SEEAC), Dynamic EEAC (DEEAC) and Integrating EEAC (IEEAC). Among them, SEEAC and DEEAC both play crucial roles in recognizing the controlling mode rapidly and executing sensitivity analysis analytically. For each case study, EEAC algorithm firstly performs analytical SEEAC to obtain the initial solution η^{SE} (or t_c^{SE}). Then DEEAC with partial consideration of time-varying factors is executed to obtain more accurate stability margin η^{DE} (or t_c^{DE}). Finally, the exact result η^{IE} (or t_c^{IE}) can be acquired by IEEAC based on strictly mappings of the time response curves. In other words, fully analytical SEEAC and quasi-analytical DEEAC should be called before the execution of IEEAC based on detailed model and exact integration.

η^{SE} reflects the transient stability degree of power systems strictly for and only for classical models with ideal two-cluster dynamics; η^{DE} is more accurate than η^{SE} since DEEAC relaxes the assumption of SEEAC that freezing the deviation angles of generator units within the same group to some extent; η^{IE} strictly reflect the transient stability of various models and dynamics without any assumptions.

In this paper, the robustness of case screening is ensured by SEEAC and DEEAC based on stability mechanisms. Since the information needed for screening is the existing intermediate results of EEAC algorithm and their computational burdens are small, the robustness and effectiveness of screening which are usually contradictory can be coordinated skillfully. The proposed method is evaluated by 7 engineering systems with various operating conditions.

2. Review of EEAC

EEAC is the quantitative theory of multi-machine trajectory stability

Numerical integration methods assume that the time-varying parameters of a multi-machine system can be "frozen" as constant ones, and the non-linear factors may be linearized in and only in the same integration step. So the time-varying nonlinear differential equations may be transformed into the time-unvarying linear differential equations within one step of integration, therefore all state variables at the end of each integration step can be forecasted.

EEAC theory inherits comprehensively the achievements of numerical integration and maps the integration trajectories onto a series of uncorrelated plants of state variables utilizing the full rank linear transformation, no matter in which way disturbed trajectories of multi-machine system are obtained, e.g. large step Taylor series expansion, symplectic geometry algorithm, symplectic algebraic dynamics algorithm and predictor-corrector algorithm. Therefore, qualitative and quantitative stability assessment of higher dimensional system can be transferred into the data mining of image trajectories strictly without any new hypothesis. EEAC algorithm aims at the disturbed trajectories other than the original mathematic model, so it can be implemented on any integrable, high-dimensional, time-varying and non-linear motion systems.

The image in extended phase plane is the motion trajectory of one machine infinity bus (OMIB) system with time-varying parameters. Both transient energy at each time moment and the critical energy at the dynamic saddle point (DSP) can be obtained. The stability degree of this image trajectory can be reflected by the difference between these two energy values. Stability limits of the image system can be estimated with sensitivity analysis. So stability margin, stability limit and dominant mode of original system can be acquired according to the minimum principle. In summary, EEAC is a strict quantitative TSA method in the meaning of integration accuracy and its total computational burden can be greatly reduced due to the quantitative ability.

Three complementary versions of EEAC with different assumptions of multi-machine trajectories

SEEAC, DEEAC and IEEAC are three stages of EEAC algorithm's development process, as well as the three steps of EEAC algorithm's procedure [19].

Based on the disturbed trajectories obtained with numerical integration of sufficient accuracy, IEEAC maps the resultant trajectories onto a set of OMIB planes with the same time-step used for integration. The stability analysis can be quantitatively performed for each image OMIB system with time-varying parameters. IEEAC deals with time-varying factors of an OMIB model accurately and robustly without more assumptions than numerical integration does. IEEAC guarantees the accuracy and robustness of EEAC algorithm.

With the hypothesis of ideal two-group dynamics, SEEAC which is the TSA method especially for power systems with classical model neglects all time-varying factors in image space and its essence is model aggregation technique so that large error may be introduced. With SEEAC, stability margin in analytical form can be obtained at the cost of a negligible computational burden. These intermediate solutions are invaluable for the whole EEAC.

In DEEAC, trajectories during and after fault are gained tactfully through 4 times of the self-adaptive large-step Taylor expansion. And utilizing the trajectory aggregation technique which greatly relaxing the assumption of SEEAC that freezing the deviation angles of generator units within the same group, the 4 sine curves are dealt with respectively. DEEAC, which is the interface between SEEAC and IEEAC, plays an important role in enhancing the whole performance of EEAC.

The computational accuracy is enhanced from SEEAC to DEEAC, then to IEEAC at the cost of gradually increasing computational burden. Regarding DEEAC as the bridge, EEAC algorithm framework coordinates the analytical ability of SEEAC and the accuracy of IEEAC to give full play to their advantages so that both stringency and rapidity of TSA can be acquired.

The engineering applications of EEAC theory

SEEAC and DEEAC algorithm have been used for electric power system planning [20], operation planning [21] and on-line stability assessment [22] quickly after being successfully developed. With the establishment of IEEAC, international software package FASTEST which includes these three versions of EEAC has been developed and widely applied to American utilities and Canadian research institute [24].

Based on EEAC，the so-called Wide ARea Monitoring Analysis Protection-control (WARMAP) system has been served in East China Power Grid since December 2006, which is the first blackout defense system in the world [25]. So far, WARMAP has been implemented and put into daily services in the dispatching and communication centers of State Grid, China Southern Power Grid, East China Power Grid and many provincial power grids of China, covering 4/5 Chinese territory, as shown in Figure 1. Among which, the first closed-loop control system in the world has been made in Jiangsu Power Grid.

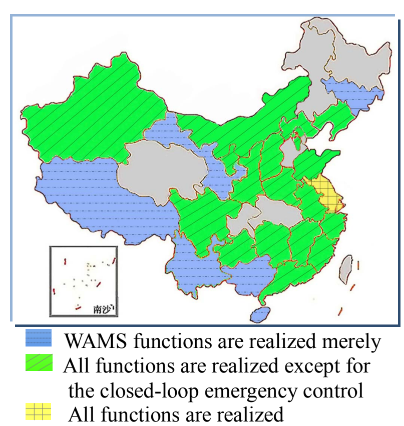

Fig. 1 The coverage area of the WARMAP systems in China

3. EEAC's enlightenment to case screening

The assumption of algorithms and their ability of reflecting time-varying character

Due to the precondition that freezing the deviation angles of generators in the same group and keeping the parameters of image OMIB system unchanged before next event occurring, η^{SE} given by SEEAC can't reflect both non-coherent inside a group and complicated models. DEEAC relaxes this assumption, so η^{DE} is more accurate than η^{SE} . IEEAC updates the image system at the beginning of every integration step, therefore, η^{IE} strictly reflects the influence of all the complex factors under the meaning of integration precision.

Assessment results of the above three versions of EEAC are identical in and only in circumstances of ideal two-group dynamics with classical models, and the difference among these results becomes larger with the stronger time-varying degree or non-linearity. Regarding η^{IE} as the standard, the time-varying degree of image system can be reflected by the error of η^{SE} (or η^{DE}). And all the simulation results unanimously confirm that with the increasing τ , time-varying degree of image system as well as the aforementioned error become stronger and stronger.

Strict case screening is a deadlock

According to the requirements of case screening, if η^{DE} is positive and adequately greater than $\left|\eta^{DE}-\eta^{IE}\right|$, IEEAC executions for this case can be saved. Thus, screening rule (1) can be obtained.

$$\eta^{DE} > 0.5\eta^{IE} > 0 \tag{1}$$

However, because of the essential characters of the time-varying image systems, η^{IE} can't be estimated accurately based only on η^{SE} and η^{DE} . In other words, the objective (reducing the computational burden of IEEAC) and the precondition (knowing η^{IE}) of this rule form a deadlock problem. Therefore, rule (1) is not feasible.

The solution of the deadlock and its feasibility

On one hand, based on multi-step Taylor series expansion and mapping in large step length, DEEAC relaxes the assumption of SEEAC about the ideal homology within one group and partly considering the influence of image system's time-varying character; on the other hand, above-mentioned influence can be fully reflected by IEEAC which maps the multi-machine trajectories onto a set of OMIB planes with the same step of the integration. Hence, the errors of η^{SE} , η^{DE} and η^{IE} are successively as the maximum, the median and the minimum.

For one case, $\eta^{DE}=\eta^{SE}$ means that there is no time-varying factors in the image system, so $\eta^{IE}=\eta^{DE}$. Under other circumstances, though η^{IE} can't be estimated directly according to η^{SE} and η^{DE} , the difference between η^{SE} and η^{DE} can reflect the time-varying degree of image system qualitatively, and then the error of η^{DE} can be assessed approximately. That is to say, the smaller the value $\left|\eta^{DE}-\eta^{SE}\right|$, the weaker the time-varying degree of the image OMIB system. This gives a reasonable deduction that the corresponding value of $\left|\eta^{IE}-\eta^{DE}\right|$ is also small, then its TSA can be approximately done based on η^{DE} for the sake of calculation saving.

The screening effectiveness can be guaranteed by SEEAC and DEEAC on account that η^{SE} and η^{DE} are not only the solutions of analytical and quasi-analytical methods whose computational burden are small, but also the intermediate results of EEAC algorithm framework.

In order to filter stable cases as much as possible at the expense of the minimal computational burden without any false-filtering, the heart of the matter is the screening rules and the screening framework.

Ideas on the screening rules

Up to this point, case screening can be converted into the following transcendental judgment, namely whether η^{IE} is sufficiently greater than zero according to the known η^{SE} and η^{DE} . Though there is no priori functional relationship among η^{SE} , η^{DE} and η^{IE} , their monotonous changing relationship may help resolving this qualitative problem. Thus the screening rule can be set as below: for one case, if $\eta^{DE}-\eta^{SE} \geq \varepsilon > 0$, then it is considered that $\eta^{IE} > \varepsilon$ and judgment of stability can be achieved. The increase of the value ε means the debasement of screening efficiency and the augment of screening credibility.

Ideas on the screening framework

If any unstable or near-unstable cases can't be false-filtered with any rule, layered screening framework can be designed with the "or" logic among multi-rules, that means cases which satisfy only one rule can be filtered out for the enhancement of screening efficiency. Otherwise, "and" logic should be used; in other words, cases satisfying multi-rules can then be filtered for the robustness of screening.

4. The time-varying degree of image system

The time-varying degree of disturbed trajectories with the assigned τ

For the dominant image OMIB system, the time-varying degree with the assigned τ may be reflected in per-unit form for the robustness, seeing formula (2):

$$\sigma_1(\tau) = \frac{\left|\eta^{DE}(\tau) - \eta^{SE}(\tau)\right|}{\max\left\{\left|\eta^{SE}(\tau)\right|, \left|\eta^{DE}(\tau)\right|\right\}} \tag{2}$$

The impact of the time-varying factors to stability margin can be decomposed into P axis effect and δ axis effect respectively according to the definition of energy. According to the dynamic procedure, the impact can also be decomposed into the kinetic energy increasing stage and the kinetic energy decreasing stage. These impacts can counteract or encourage mutually.

The time-varying degree of disturbed trajectories under quasi-critical condition

If different ways of influence are mutually counteracted, directly comparison between $\eta^{SE}(\tau)$ and $\eta^{DE}(\tau)$ may conceal the actual time-varying degree. In addition, if τ is much less than CCT, the impact of time-varying factors to kinetic energy increasing area A_{inc} is underrated and that to kinetic energy decreasing area A_{dec} is overrated under critical condition. If τ is much more than CCT, the situation will be opposite.

If the fault is cleared at time t_c^{SE}, corresponding $A_{inc}^{SE}(t_c^{SE})$ equals $A_{dec}^{SE}(t_c^{SE})$, influences of time-varying factors to both are considered evenly. Therefore, other than the viewpoint of formula (2), the area difference expressed in formula (3)~(5) reflect the time-varying degree of image system from a new perspective. It is easy to prove that the values of the following three algebraic expressions are all zero for ideal two-group dynamics with classical model and they are increased monotonously with the enhancement of time-varying factors.

$$\Delta A_{inc}(t_c^{SE}) = A_{inc}^{SE}(t_c^{SE}) - A_{inc}^{DE}(t_c^{SE}) \tag{3}$$

$$\Delta A_{dec}(t_c^{SE}) = A_{dec}^{SE}(t_c^{SE}) - A_{dec}^{DE}(t_c^{SE}) \tag{4}$$

$$A^{DE}(t_c^{SE}) = A_{dec}^{DE}(t_c^{SE}) - A_{inc}^{DE}(t_c^{SE}) \tag{5}$$

Considering the different numerical relationship between each formula and time-varying factors, the maximum one among formula (3)~(5) is selected for the robustness of screening rule as is shown in formula (6) where it is also in per-unit form for the comparability under different power systems and screening circumstances.

$$\sigma_2 = \frac{\max\left\{\left|\Delta A_{inc}(t_c^{SE})\right|, \left|\Delta A_{dec}(t_c^{SE})\right|, \left|A^{DE}(t_c^{SE})\right|\right\}}{\max\left\{A_{inc}^{SE}(t_c^{SE}), A_{inc}^{DE}(t_c^{SE})\right\}} \tag{6}$$

5. Case screening rules

The composition of inequity rules

The under-mentioned screening rules are composed according to the approximate stability margin, the time-varying degree of disturbed trajectories with the assigned τ as well as the time-varying degree under the quasi-critical condition. The basic concept is that cases with an approximate stability margin high enough and sufficiently weak time-varying degree can be filtered out since there will be no difference between qualitative assessment results of the strict and rough TSA method.

Screening rule 1: $\tau \le \varepsilon_1$, and $\eta^{SE}(\tau) > \varepsilon_2$

Screening rule 2: $\sigma_2 \le \varepsilon_3$, and $\eta^{SE}(\tau) > \varepsilon_4$

Screening rule 3: $\sigma_1(\tau) \le \varepsilon_5$, and $\eta^{DE}(\tau) > \varepsilon_6$

The setup of threshold values

The above-mentioned screening rules are based on solid theoretical basis and the corresponding threshold values show definite physical significance. So according to the principle of none false-filtering, sufficiently strong threshold values can be concluded based on abundant simulations of various power systems and checked with a large number of cases.

For the robustness of screening algorithm in various circumstances, threshold values of τ and the time-varying degree should be kept unchanged. Meanwhile, for the enhancement of screening rate, threshold value of stability margin can be set piecewise increased with τ since the time-varying degree is weaker for a smaller τ. It should be specially emphasized that all threshold values including the segmented one are unchanged for various systems, models as well as different faults.

6. The screening framework

Knockout of the redundant rules

A rule that can filter out what other rules cannot do is suited to be brought into screening framework; the one that can be replaced by others should be rejected from the framework. The above-mentioned three screening rules are selected with these principles.

The coordination of screening rules

Based on solid theoretical basis, the three rules filter out risk-free faults from different point of views and guarantee that all unstable cases will not be false screened out. Therefore, the proposed layered framework efficiently screens out the cases satisfying at least one rule. Obviously, different sequences of the three rules can only affect the computational efficiency, but not the total screening rate of this framework. Therefore, their applied order can be optimized for minimizing the computational burden.

Through the simulations of Hainan (data of 2009), Shandong (data of 2004 and 2012, noted as Shandong1 and Shandong2 respectively), Jiangxi (data of 2011), Xinjiang (data of 2012), Henan (data of 2011), Zhejiang (data of 2012) province power systems under original operation condition, it draws conclusion that framework built in sequence of rule 1, 2, 3 can obtain the best screening performance, as is shown in Fig.2.

7. The validation of case screening

Simulation systems are still the above-mentioned 7 power systems (totally 1106 cases, among which 859 cases are actual stable and 247 cases are actual unstable), bus bar and line three-phase permanent faults under original and modified conditions are tested respectively. Each case's fault clearing time is random selected from 0.08s to 0.40s for the robustness.

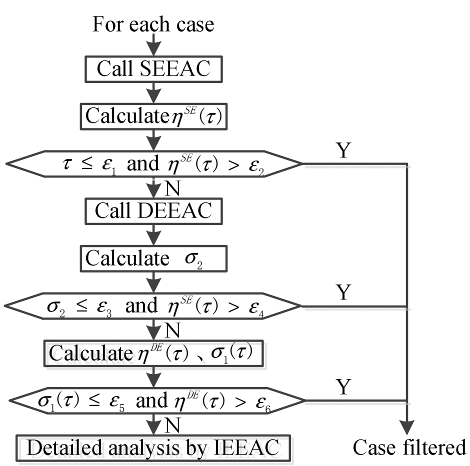

Fig. 2 Screening Framework

3 indexes reflecting the screening performance are screening rate, false-filtering rate and acceleration effect, seeing formula (7)~(9):

$$Screening\ Rate = \frac{N_f}{N_{as}} \times 100\% \tag{7}$$

$$False-filtering\ Rate = \frac{N_{afu}}{N_f} \times 100\% \tag{8}$$

$$Acceleration\ Effect = \frac{T_I}{T_f} \tag{9}$$

Where N_f means the number of filtered cases by the screening framework; N_{as} means the number of actual stable cases; N_{afu} means the number of actual filtered unstable cases; T_I means the average computation time of one case calculated by IEEAC except for initialization calculation; T_f means the average computation time of one case filtered by screening framework except for initialization calculation.

The acceleration effect is *f* means that if one stable case can be filtered among each *f* cases, the additional computational burden due to the screening framework is equal to that is saved. It is the equilibrium point of computational burden when *f*=1, and the larger *f*, the better the acceleration effect. Test results are shown in Table 1 and 2.

Table 1 Performance of the screening framework under original operating condition

Power system	Fault location	Nr of cases	Screening rate	False-filtering rate	Acceleration effect
Hainan	Bus	29	84.00%	0.00%	27.86
	Line	51	79.59%	0.00%	18.80
Jiangxi	Bus	39	89.74%	0.00%	11.00
	Line	68	93.65%	0.00%	7.87
Shandong1	Bus	33	71.43%	0.00%	11.82
	Line	60	96.30%	0.00%	11.20
Shandong2	Bus	20	93.75%	0.00%	9.85
	Line	64	78.57%	0.00%	15.80
Zhejiang	Bus	36	85.71%	0.00%	10.45
	Line	44	73.68%	0.00%	15.90
Henan	Bus	20	100.00%	0.00%	11.70
	Line	29	84.00%	0.00%	11.56
Xinjiang	Bus	20	100.00%	0.00%	9.59
	Line	40	83.33%	0.00%	9.15
Total tests		553	86.70%	0.00%	14.09

For different actual power systems, the screening rate maintains 70%-100% without any false-filtering and the average analysis time of each case is 1-2 orders reduced comparing to TSA with the full IEEAC method based on the same rules and threshold values.

Table 2 Performance of the screening framework under modified operating condition

Power system	Fault location	Nr of cases	Screening rate	False-filtering rate	Acceleration effect
Hainan	Bus	29	71.43%	0.00%	14.71
	Line	51	100.00%	0.00%	6.90
Jiangxi	Bus	39	89.74%	0.00%	10.40
	Line	68	93.85%	0.00%	8.59
Shandong1	Bus	33	71.43%	0.00%	7.15
	Line	60	96.43%	0.00%	10.11
Shandong2	Bus	20	93.75%	0.00%	10.43
	Line	64	83.93%	0.00%	10.66
Zhejiang	Bus	36	85.71%	0.00%	7.56
	Line	44	76.92%	0.00%	9.43
Henan	Bus	20	80.00%	0.00%	9.74
	Line	29	85.19%	0.00%	10.62
Xinjiang	Bus	20	100.00%	0.00%	12.61
	Line	40	71.43%	0.00%	10.50
Total tests		553	85.70%	0.00%	11.39

8. Conclusion

The accuracy grades of SEEAC, DEEAC and IEEAC depend on their ways of handling the time-varying factors of an image OMIB system. Neglecting these factors, SEEAC is of analytical solutions at a big cost of accuracy. Due to partially reflecting these factors by using large-step mapping, DEEAC is about 4 times slower than SEEAC with improved accuracy. Strictly reflecting these factors by keeping the mapping step same as the integration step, IEEAC is very accurate, however about 100 times slower than SEEAC. EEAC takes advantages from SEEAC's analytical solutions and IEEAC's accuracy, and take DEEAC to link the other two versions of EEAC. The time-varying degree of an image system can be deduced by the difference between η^{SE} and η^{DE}. In other words, a small value of the above difference means that η^{DE} can be a good approximation of η^{IE}. In such cases, IEEAC execution can be saved, provided that η^{DE} is reasonable positive. Three rules are derived to identify stable cases based on the mechanisms of transient stability and the complementary 3 versions of EEAC. A multi-layer framework is also built to screen cases. Its robustness and efficiency are evaluated under various operation conditions and fault scenarios for different actual power systems.

Acknowledgements

This work is jointly supported by State 973 Project (No. 2013CB228204), State 863 Project (No. 2011AA05A105), NSFC (No. 91024028), SGCC (SGCC-MPLG003-2012, YS11002), and NSF of Jiangsu Province, China (No. BK2011136)

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