



Comparative Analysis of Integral-Based Indices for On-line Assessment of Power System Transient Stability

DOI:
[10.1109/ISGTEurope52324.2021.9639940](https://doi.org/10.1109/ISGTEurope52324.2021.9639940)

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Morales Alvarado, J., Ye, X., & Milanovic, J. V. (2021). Comparative Analysis of Integral-Based Indices for On-line Assessment of Power System Transient Stability. In *Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021* (Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021). <https://doi.org/10.1109/ISGTEurope52324.2021.9639940>

Published in:

Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021

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Comparative Analysis of Integral-Based Indices for On-line Assessment of Power System Transient Stability

Juan D. Morales, *St. Member IEEE*
 Department of Electrical and
 Electronic Engineering
 The University of Manchester
 Manchester, UK
 juan.morales@manchester.ac.uk

Xinlin Ye, *St. Member IEEE*
 Department of Electrical and
 Electronic Engineering
 The University of Manchester
 Manchester, UK
 xinlin.ye@manchester.ac.uk

Jovica V. Milanović, *Fellow IEEE*
 Department of Electrical and
 Electronic Engineering
 The University of Manchester
 Manchester, UK
 milanovic@manchester.ac.uk

Abstract—This paper assesses the ability of four integral-based indices calculated using the post fault rotor angles, speed deviations, and accelerations to evaluate power system's transient stability. First, the impact of the integration time for the calculation of each of the indices to provide an adequate assessment of the system stability status is assessed. Then, a more detailed evaluation and calculation of the accuracies achieved by the indices is done by looking into the direct relationship between the index values and the stability status of test simulations. Results show that the proposed indices are able to represent correctly the instability degree of the system to different extents, while at the same time identifying the limitations in their use.

Keywords—contingency screening, electrical power system, stability index, transient stability assessment, uncertainties

I. INTRODUCTION

Modern power systems are more commonly subjected to a larger number of uncertainties constraining their operating conditions, in addition to the already tight economic restrictions imposed by deregulated electricity markets. This situation is expected to be further aggravated in the foreseeable future due to the continuing increase in the use of Renewable Energy Sources (RES) for electricity production, and therefore it might drive the system operation closer to its stability limits. With the availability of Wide Area Measurement Systems (WAMS) and Phasor Measurement Units (PMUs), online Transient Stability Assessment (TSA) is becoming an attractive option to map the system dynamic behaviour in a relatively short time and provide support decisions and information for corrective control actions.

Under this scenario, contingency screening methods become necessary as they can limit the computation time to an acceptable level when utilising online TSA. To satisfy the three key requirements of online TSA, i.e., accuracy, speed and scalability, the process can be segmented into two steps [1]: ranking and selection. One of the possible solutions to the ranking process is the use of power system stability indices calculated during the transient condition. The system dynamic behaviour can be assessed by an appropriately defined stability index from either the pre or post-fault contingency event [1].

Some of the earliest defined indices can be found in [2], which are calculated after fault clearance using properties including coherency, energy conversion and Transient

Energy Functions (TEF). Enhanced by integral calculation, the aforementioned coherency-based indices were further developed into the Integral Square Generator Angle (ISGA) index, which aggregates generator angle difference and equilibrium conditions [3]. Generally, a control action that can reduce the ISGA value is more probable to be capable of dealing with the most severe disturbance. The feasibility of all these mentioned indices in the ranking stage has been validated in [1] comprehensively.

Calculated using the integral of post-fault bus angles, the Integral Square Bus Angle (ISBA) index can reflect the stress of the power system in a more general way compared to ISGA. With the installation of PMUs, ISBA can be more easily calculated, making it more suitable for online TSA [4].

In the past two decades, more stability indices have been proposed, each of which has its own features. One of the most frequently utilised indices, the Transient Stability Index (TSI), has been developed based on the ratio between the difference and sum of the transient stability threshold and maximum angle difference. In spite of its wide use, its value can be highly affected by the selection of the transient stability angle threshold [5]. The Critical Clearing Time (CCT), another of the indices frequently mentioned in this context, is generally more suitable for the validation of the feasibility of a control action or a change in operation rather than assessment of system stability [6]. More recently, a CCT-based Stability Margin Index (SMI) was defined in [7] to assess the stability status of a specific contingency. A group of reasonably popular and frequently used indices, the energy conversion-based indices [8] have been proven to be appropriate for adequately representing the transition between the transient kinetic energy and the potential energy that occurs after a fault event, which makes them worth considering for online TSA [9]. There is though, an existing consensus that direct methods for TSA, which involve an extensive use of energy-based quantities, are less accurate than Time-Domain Simulation (TDS) approaches, due to the considerable simplifications of the power system models that are necessarily required for their application [10].

In this paper, four indices, easily calculated, and directly related to the physical behaviour of generators' rotors following a disturbance, are presented and compared. They are calculated through integration of the post-fault evolution of generator rotor angles, speed deviations and accelerations over a period of time. The indices values are calculated for a very large set of operating conditions considering a realistic large test system with RES, namely a modified IEEE 68 bus test system. The accuracy of the indices and the impact of

This research is partly supported by the EU H2020 project CROSSBOW (grant agreement number: 773430), the EPSRC-India collaborative project JUICE (Grant no: EP/P003605/1), and partly by the Department of Electrical and Electronic Engineering of The University of Manchester.

the integration periods used for their calculation are comprehensively assessed. The results obtained proved the high degree of accuracy of the four studied indices and highlighted their associated or inherent limitations. All simulations were performed in a combined Matlab and DigSilent PowerFactory software environments.

II. CONSIDERED TRANSIENT STABILITY INDICES

The biggest advantage of the considered indices is that they can be easily calculated by having only the information on the evolution of the post-fault generator rotor angles. This feature makes them suitable for use in on-line applications with PMUs. Since the indices are calculated by means of integration up to a certain point in time after the fault inception, they are dependent on time. Calculation of their values at different times after the fault allows to assess how fast and consequently how accurately they can be when used to identify the transient stability status of the system.

Two types of indices based on the acceleration of generators' rotors are used. The Acceleration Index (ACI) and the Average Acceleration Index (AAI), the latter as originally proposed in [11], are defined by (1) and (2), respectively.

$$ACI_i = \int_0^T a_i(t) dt \quad (rad./s) \quad (1)$$

$$AAI_i = \frac{1}{T} \cdot \int_0^T a_i(t) dt \quad (rad./s^2) \quad (2)$$

where $a_i(t)$ (rad./s²) is the acceleration of generator i at time instant t , and T represents the integration period calculated from the fault inception at $t=0$.

The other two indices, the Speed Deviation Index (SDI) and the Rotor Angle Index (RAI) are defined by (3) and (4), respectively.

$$SDI_i = \int_0^T \Delta\omega_i(t) dt \quad (rad.) \quad (3)$$

$$RAI_i = \int_0^T \delta_i(t) dt \quad (rad.s) \quad (4)$$

where $\Delta\omega_i(t)$ (rad./s) and $\delta_i(t)$ (rad.) are the speed deviation and rotor angle of the i -th generator at time instant t , respectively.

As already mentioned, the integration period T is a key parameter, and several values will be analysed in this study. Higher T values will cover more of the system trajectory following the disturbance and hence will yield better information regarding the system stability status. On the other hand, the lower T values will provide faster evaluation of the system stability status though the assessment will be less accurate. Therefore, a compromise between speed and accuracy should be reached in the evaluation. Since mainly the assessment of first-swing stability is of interest in the present paper, T is evaluated at around the typical times of first swing oscillations, i.e., up to a value of 1 s approx.

III. IDENTIFICATION OF SYSTEM INSTABILITY

In order to evaluate the effectiveness of the proposed indices, the actual stability status of an event/simulation needs to be known. In this paper, a simulation is identified as unstable if the condition defined in (5) is satisfied.

$$\delta_T < \delta_{max} = \max(\delta_i - \delta_j) \quad (5)$$

where δ_i and δ_j represents the rotor angles of the i -th and j -th

generator, respectively, at a given time during the post-fault period, and δ_T is the threshold for instability identification. That is to say, if there is an angle difference between any two generators exceeding that threshold during the post-fault oscillations, then it is considered unstable. The δ_T threshold is set to 360° in this study, as according to [12] this can be regarded as a definitive condition of instability in multi-machine power systems.

IV. TEST SYSTEM AND ASSOCIATED UNCERTAINTIES

The test system for the present study is described in [13] and has been used in several studies for the dynamic analysis of large power networks including RES [12], see Fig. 1. It is a modified version of the IEEE 68-bus test system, 16-machine equivalent model of the New England Test System (NETS) and New York Power System (NYPS). Full details of all system components and models can be found in [13]. The nominal penetration level of the RES generation (in %) is defined by the ratio between the installed capacity of RES and conventional generation. The test case scenario used for this study has a nominal RES penetration level of 20%.

Uncertainties representing the intermittent RES production include the use of the Weibull and Beta distributions for modelling the wind speed and sun radiation for wind generators and PVs, respectively. The uncertainty for the loads is included by a scaling factor (sampled from the standard normal distribution) on top of the bus loads, which are determined according to the 24-hour load curve of the test system. A uniform distribution is used for sampling randomly the hour of the day. Detailed information about the parameter settings of the distributions can be found in [13].

After the sampling for loading and RES production, an OPF determines the conventional generation output, keeping a fixed spinning reserve of 15%. If not possible due to the limits of the generator's installed capacity, the reserve is reduced accordingly. Detailed information regarding the OPF cost functions and reserve criteria can be found in [13].

Regarding system disturbances, only three-phase self-clearing faults are considered, using a uniform distribution for sampling the faulted line and the fault location. In this way, there is an equal probability of a fault occurring at any line in the system and at any point along that line. The fault duration is modelled using a normal distribution with a mean value and standard deviation of 14 cycles and 6.67%, respectively, so that a reasonable mixture of stable and unstable events can be obtained as in previous studies for the same test system [12-14].

All uncertainties are sampled independently with appropriate probability distributions in order to reflect their behaviour in a realistic way.

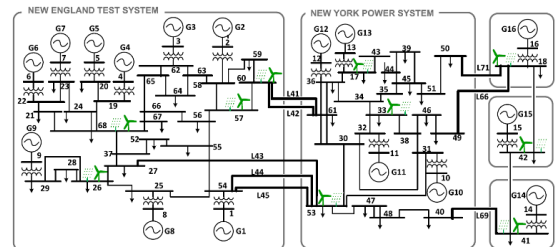


Fig. 1 Modified IEEE 68 bus test system, including RES

V. RESULTS AND DISCUSSION

A. Generation of the database with rotor angle responses

A total of N_s Monte Carlo (MC) simulations are performed, with $N_s = 10,000$ to achieve a satisfactory

assessment accuracy as in [12], where the same test system was used. The time responses, lasting 5 s each, of rotor angles of all sixteen synchronous generators in the system, obtained in each TDS, are stored in a dedicated database. The fault is applied at 1 s. The detailed description of the adopted MC approach for generating the database with rotor angle responses can be found in [13]. All simulations are performed using the DigSilent Powerfactory software.

B. The impact of the integration period

Initially, the ranges for the appropriate integration period values, T , are estimated. The idea behind this process is to find the T values that yield index results that can distinguish accurately enough, in the shortest time possible, the unstable cases from the stable ones, so that a threshold for that index can be identified, i.e., cases producing index values above that threshold are unstable (with a high probability) and vice versa. Several T values up to 1 s are tested to find a relatively broad range in which a high accuracy for the identification is observed. Once these broad ranges are identified, a finer evaluation is performed for better accuracy.

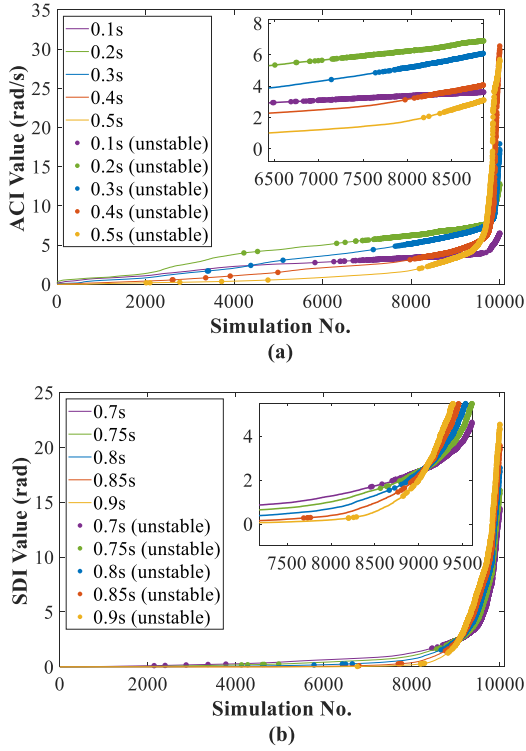


Fig. 2 Examples for (a) ACI (0.1 – 0.5 s) (b) SDI (0.7 – 0.9 s)

Initial tests indicate that T ranges between 0.1-0.5 s for the acceleration-based indices, and between 0.7-0.9 s for the RAI and SDI indices, provide higher accuracy for $T < 1$ s. Fig. 2(a) and (b) show the finer evaluation for the ACI and SDI indices as an example. In Fig. 2, the 10,000 cases in the horizontal axis are sorted in an ascending order based on the calculated corresponding index values. The figure also highlights the cases that are unstable (based on the criterion described in Section III) within each curve. It can be observed from Fig. 2(b), illustrating the SDI, that for the higher values of T , there is a higher concentration of unstable cases that occurs for higher index values, i.e., better results are obtained. This happens, as expected, for both, the SDI and RAI indices, since for the unstable cases, the rotor angles and speed deviations will increase considerably and indefinitely, especially after the loss of synchronism, which occurs broadly between 0.5-1 s for the studied test system.

On the other hand, just after the fault occurrence, a high rotor acceleration will always develop up until the point of fault clearance, after which the available deceleration capacity of the system will slow rotors down. This initial high acceleration allows both, the ACI and AAI indices to have a good performance at much shorter times compared to the angle and speed based indices. This is especially true for T values between 0.2-0.5 s, as shown in Fig. 2(a) for the ACI case, where there is a higher concentration of unstable cases for high index values. However, it can be also observed from Fig. 2(a) that the acceleration index values of the unstable cases are more dispersed compared to the SDI results. Therefore, the better performance in terms of time for the acceleration-based indices comes at a cost of a decreased accuracy. Based on these results, in all the analysis carried out in the following sections, the AAI and ACI indices will be calculated with $T = 0.2$ s, while SDI and RAI with $T = 0.9$ s, to better assess the trade-off between accuracy and speed.

C. Two-step comparison

One way of assessing the effectiveness of the proposed indices is by comparing how many times the first generators that are first-swing unstable after a disturbance (Step 1) yield the maximum index values (Step 2). The results of this two-step comparison are presented in Fig. 3 for G2 – G11. G1 and G12 – G16 are not shown as they either never yield maximum index values or are first-swing unstable.

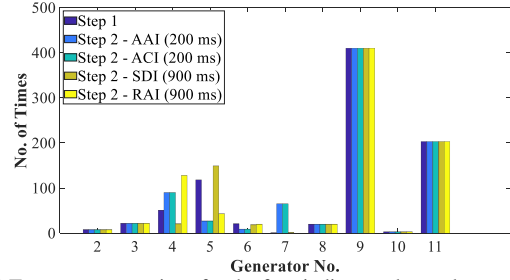


Fig. 3 Two-step comparison for the four indices under study

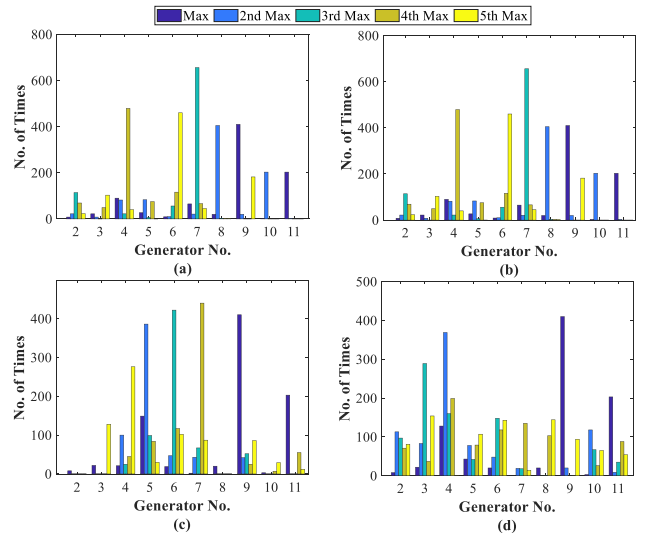


Fig. 4 Number of times G2 – G11 result in 1st – 5th maximum index value (a) AAI (b) ACI (c) SDI (d) RAI values

As shown in Fig. 3, for all generators except G4 – G7, Step 1 and Step 2, i.e., the number of times they are first-swing unstable and the number of times they are first-swing unstable and the number of times the corresponding four indices yield maximum values, are identical. As for G4 – G7, values obtained for Step 2 vary from those for Step 1 significantly. However, it can be observed that if taking all

four generators G4 – G7 as a whole, they result in a total of 191 unstable cases for both Step 1 and 2, as it is the case with each of the other generators independently. The reason for this is that G4 – G7 oscillate typically together in a multi-machine unstable pattern, as documented in [11] where the same test system and uncertainties were used. This also leads to similar index values for these four generators. E.g., in some cases, G4 goes unstable first, but G5 will produce the maximum index value, followed by G4, G6 and G7, resulting in these index values being very close to each other.

To illustrate this better, the number of times each generator yields the 1st to 5th maximum index value is presented in Fig. 4, for all indices. For example, for the AAI in Fig. 4(a), it is observed that index values for G6 that are the maximum are produced only a small number of times, however, cases presenting the 3rd and 4th maximum index values increase considerably. Similar conclusions can be drawn for the other indices. Furthermore, it should be noted that Fig. 4(a) and 4(b), illustrating the AAI and ACI, respectively, are identical. This is because, the magnitudes of the ACI and AAI are scaled versions of one another with the factor T , see (1) and (2), Hence, in the following sections, the analysis focuses only on the AAI, but the same conclusions can be extended to the ACI as well.

D. Distribution of the index values for first-swing unstable simulations

Fig. 5 shows the distribution (histograms) of the index values corresponding to the first generator that loses synchronism for all the first-swing unstable cases found.

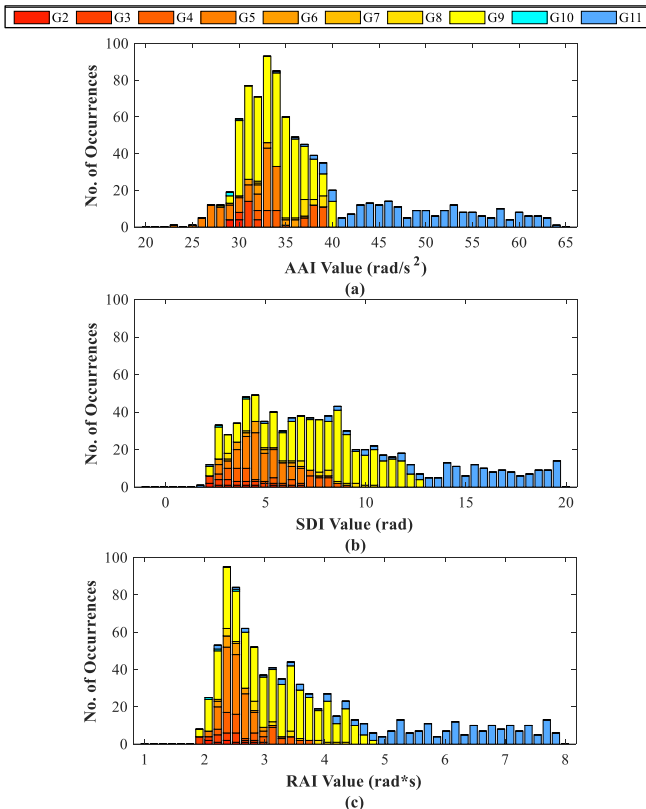


Fig. 5 Distributions (histograms) of (a) AAI (b) SDI (c) RAI values

The number and distribution of the generators producing the shown index values can be also identified by means of the colour legend provided. In the test system, G1 – G9 belong to NETS, G10 – G13 to NYPS and G14 – G16 represent external equivalent systems. G1 and G12 – G16 never yield maximum index values or are first-swing

unstable and hence are not shown in Fig. 5. G2 – G9 in NETS are displayed in red – yellow, while G10, G11 in NYPS with cyan and blue colours, respectively.

It can be seen that in most of the first-swing unstable simulations, G9 and G11 lose synchronism first (70% in total), in agreement with results in Fig. 3, in which for both steps, G9 and G11 lose synchronism 410 and 203 times, respectively. For all the generators in NETS and G10 in NYPS, when they lose stability first, they yield AAI values concentrated in the range of 25 – 40 rad./s². This range is about 2 – 13 rad for SDI and 2 – 5 rad.s for RAI. On the other hand, G11 in NYPS behaves rather differently compared to others, producing index values much greater than other generators. This makes G11 the most susceptible to larger oscillations when faults occur close to it in the system. All indices are able to indicate this behaviour, as observed in Fig. 5, in which the highest index values correspond to G11 for all cases. The acceleration-based indices are advantageous in this respect, since they can identify this behaviour in considerably less time compared to the rest.

E. Accuracy and confidence interval analysis

Another aim behind the integral-based proposed indices in this study, is to find a global threshold index value TS to be used for instability identification, i.e., simulations producing index values larger than a global threshold TS can be considered to be first-swing unstable. Therefore, an accuracy and Confidence Interval (CI) analysis is performed in this section according to the method proposed in [15]. The accuracy A_{index} of instability identification for each index is defined by (6).

$$A_{index} = \frac{N_{c,stable} + N_{c,unstable}}{N_s} \times 100\% \quad (6)$$

where $N_{c,unstable}$ is the number of unstable cases correctly classified by the index (first-swing unstable cases producing larger index values than TS , i.e., number of unstable cases correctly identified as unstable), $N_{c,stable}$ is the number of stable cases yielding smaller index values than TS (i.e., number of stable cases correctly identified as stable), and $N_s=10,000$ is the total number of cases. It should be noted that all accuracy calculations are made per generator. For example, G11 reaches instability in 204 out of the 10,000 simulations. Hence for G11, the ideal situation is that only 204 unstable simulations produce index values above the threshold TS of any index, while all other stable simulations produce values below the threshold. However, there will be some unstable cases not correctly identified and some stable cases developing high index values that will be identified incorrectly as unstable ones. The accuracy as defined in (6) takes this phenomenon into account.

According to results in Fig. 5(a), AAI values concentrate in the range of 25 – 40 rad./s² approximately. In order to search for a global value of TS , values between 25 – 30 rad./s² are tested, with a step increment of 2.5. Excluding the generators that never lose first-swing stability (G12 – G16), the accuracies per generator and corresponding 95% CIs using the AAI index are shown in Fig. 6. Results indicate that the accuracies of the AAI index for some generators vary significantly. High accuracies can be obtained for G1, G8 and G10. However, for G4, G6 – G7, involved in the multi-machine oscillation pattern described previously, the lowest accuracies are observed. Despite the general high accuracies obtained for all cases, for some generators, higher number of stable simulations produce AAI results that are larger than

the threshold TS . For example, when $TS = 25$ rad./s², G11 reaches an accuracy of 94.12%, 203 of the 204 unstable simulations are identified over this value, while as many as 587 stable simulations yield AAI values over 25 rad./s² and are misclassified. Higher TS values decrease the number of misclassified stable cases but also decrease the correctly identified unstable ones.

TS threshold values are defined according to results in Fig. 5(b) and (c) for the SDI and RAI cases, to 3.5 rad. and 2.25 rad.s, respectively. SDI and RAI produce better results compared to the acceleration-based indices, with a high overall accuracy (>99% for all generators) as seen in Fig. 7.

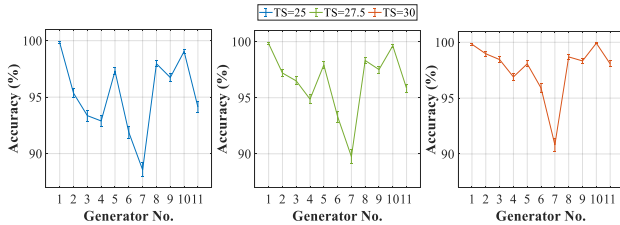


Fig. 6 Accuracies and 95% CIs of AAI for G1 – G11 for $TS = 25 - 30$ rad/s²

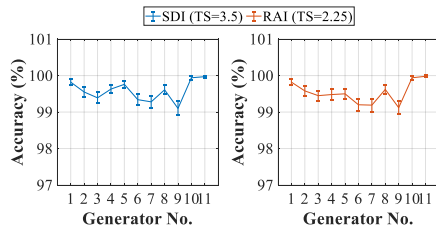


Fig. 7 Accuracies and 95% CIs of SDI and SDI for G1 – G11 for their corresponding global thresholds

Overall, it can be said that the ACI/AAI can reflect the post-fault dynamic behaviour of the most unstable generators in a relatively short time (integration period). However, the acceleration-based indices might present some drawbacks for identifying transient stability separately for each generator in the system despite showing very acceptable accuracy levels. This is related to the higher risk of identifying stable cases developing strong oscillations, and thus also high index values, as unstable. It is evident that a global threshold value TS for all the generators would be hard to find. Besides, for generators oscillating together (e.g., G4 – G7 for the studied test system in this paper), they may produce very similar rotor angle responses, posing additional challenges on the accuracy capabilities.

On the other hand, SDI/RAI operate equally well as the acceleration-based indices regarding the identification of the most unstable generators, but longer times (integration periods) would be necessary. Nevertheless, a global threshold identifying the system stability status can be found for all generators when applying these two indices, achieving extremely high accuracies over 99% for all generators.

VI. CONCLUSIONS AND FUTURE WORK

This paper introduced and evaluated the effectiveness of four integral-based indices for the on-line assessment of transient stability. All of the indices can, to a high extent, correctly identify the generators going unstable following a disturbance based on the recorded post-fault trajectories of generator rotor angles, speeds or accelerations. There is a trade-off though, between the speed and accuracy of the assessment. The accuracy of the identification of the first swing instability in excess of 90%, can be achieved with the

acceleration-based AAI/ACI indices within a very short time (typically 0.2-0.5 s) after a fault. Substantially higher, almost absolute, accuracy though (over 99%) can be obtained with the angle and speed-based RAI/SDI indices, but the assessment time increases to 0.7-0.9 s after the disturbance.

The AAI/ACI indices make use of the intrinsic high rotor accelerations that occur just after a disturbance, hence their good assessment accuracy in shorter times. They can be used to identify very quickly the most critical unstable generators in applications where the time of assessment is crucial. For some cases where stable generators show relatively high initial accelerations though, the AAI/ACI indices are prone to incorrectly identify them as unstable. On the other hand, rotor speeds and angles vary much less just immediately after a disturbance and start to increase more consistently after the fault clearance, hence increased accuracy is achieved with the RAI/SDI indices but in longer assessment times.

Considering that each system behaves rather differently following a disturbance, and the global increase in the complexity of power systems dynamic behaviour, a machine learning-based approach can be developed to set the most appropriate values for the stability indices, so that they can be used for a fast on-line transient stability assessment.

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