Truncated Transient Stability Index for On-line Power System Transient Stability Assessment

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***Abstract*—This paper assesses the ability of a Transient Stability Index (TSI) to evaluate power systems' transient stability. The assessment is first accomplished by looking into the TSI's classification accuracy for identifying stable or unstable cases when different transient stability thresholds are used. Although suitable values for these thresholds have been found, there are still some pitfalls in the use of TSI for stability classification. A new approach for the TSI calculation, called Truncated TSI, is proposed, reducing the index's time window calculation limits. High accuracy of stability classification has been demonstrated using the proposed approach with appropriate settings of the time window parameters.**

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

I. Introduction

Modern power systems tend to operate closer to their stability boundaries considering the need for high efficiency and economic value, producing a tremendous number of probable operating conditions. Also, as the modern power system develops, significant increase in the utilisation of Wide Area Measurement System (WAMS) and Phasor Measurement Units (PMUs) can be observed. Under these conditions, 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.

By constraining the computation to a manageable level, an efficient contingency screening method is important for online TSA. Three requirements should be ideally fulfilled, accuracy, speed and scalability. Ranking and selecting are the two necessary steps for meeting the conditions mentioned above [1]. Computation of power system stability (severity) index in the transient condition can be a solution to the ranking process. Correctly defined indices can reflect the system dynamic behaviour as it is transferred from pre to post-fault contingency condition [1]. On the other hand, selecting stages defines the critical point between stable and unstable contingencies, which is usually achieved by using techniques such as data classification, data clustering, etc. [2]. This paper mainly focuses on this first stage, identification of appropriate stability indices.

Inspired by the concepts of coherency, energy conversion and Transient Energy Function (TEF), a series of stability indices are proposed in [2] based on the difference of these variables shortly following the fault clearance. Differently, the Integral Square Generator Angle (ISGA) developed in [3], an advanced modification of the coherency-based index mentioned previously, is calculated based on integrals. It provides aggregated measures of generator angle difference during transient as well as equilibrium conditions. It has also been found that when a control action reduces ISGA index value, it has great chance to be able to stabilise some of the most unstable events. Furthermore, all the indices mentioned above have been tested and compared in [1], in various aspects including accuracy, execution speed. With high capture ratio and short execution time observed, they were proved to be efficient tools in the ranking stage.

In [4], Integral Square Bus Angle (ISBA) has been developed in a similar way to ISGA, using bus voltage angles instead of generator rotor angles to reflect the post-fault system status. Compared to ISGA, ISBA can represent the overall of the power system and be calculated using PMUs over a wide area, which is a property more suitable for online TSA. Another frequently utilised stability index, Transient Stability Index (TSI) has been proposed in [5]. Calculated as the ratio between the difference and sum of the transient stability threshold and maximum angle difference, the performance of TSI is highly dependent on the selection of transient stability angle threshold value. Critical Clearing Time (CCT) and energy conversion-based stability integral indices have also been studied. CCT has been generally used to assess whether a control action or an operation change is desirable [6]. On the other hand, the energy conversion-based indices can reflect the transient kinetic and potential energy immediately following the fault clearance time instant [7], and hence are valuable for online TSA [8].

Even though TSI has been frequently used in the study of transient stability for many years [8, 9], only recently, a thorough discussion on the influence of angle thresholds for transient stability identification was performed in [10]. The impact of the transient stability thresholds on the performance of TSI, however, has not been discussed comprehensively. Moreover, the limitations of TSI and its possible improvements are also yet to be investigated.

This paper first presents detailed analysis of the influence of the chosen transient stability threshold on the TSI performance and identifies some of its limitations. Then, it proposes and tests a possible modification of TSI, namely Truncated TSI (TTSI), on a large number of scenarios using a modified IEEE 68 bus test system with renewable generation. Results show that the TTSI provides more accurate information about the system proximity to the stability boundary compared to the conventional TSI, allowing a faster identification of instability. Therefore, TTSI would be also suitable for application in on-line TSA.

II. Calcualtion of Transiet Stability Index

A. *Transient stability index definition*

The commonly used Transient Stability Index (TSI) [5], is defined by (1).

$$TSI = \frac{\delta_T - \delta_{max}}{\delta_T + \delta_{max}} \tag{1}$$

where, δ_T is a predefined transient stability threshold and the value of the angle δ_{max} depends on the angle reference frame used, described in Section II-B. Instability is reached if the condition defined by (2) is fulfilled during the post-fault rotor oscillation period.

$$\delta_T < \delta_{max} \tag{2}$$

where the system is declared unstable if TSI<0, and vice versa. The value of transient stability threshold δ_T can be chosen based on a required efficiency or accuracy.

B. Transient stability threhsold values and reference frames

The two common "reference frames" used for calculating TSI are the Maximum Angle Difference Between Any Two Generators (MADBATG) in the system reference frame and the Center Of Inertia (COI) reference frame.

In the majority of the past work, e.g., [8, 9], TSI is calculated based on the MADBATG reference frame, and δ_{max} is defined as in (3).

$$\delta_{max} = max(\delta_i - \delta_j) \tag{3}$$

where $\delta_i$and $\delta_j$represents the rotor angles of the i-th and j-th generator, respectively, at a given time during the post-fault period. Therefore, in the MADBATG frame, δ_T represents the maximum possible angular separation between any two generators that does not lead to the loss of synchronism.

As discussed in [10], for multi-machine systems, a stability threshold of 360º in the MADBATG frame means that two generators are one cycle away from one another following a severe disturbance, and it can be considered to be a definitive condition where instability has already occurred. Therefore, a threshold of 360º will be used as a benchmark for the stability identification in this paper. Past work, however, has shown that instability can actually be observed at thresholds lower than 360º [4, 10, 11]. In general, the lower the threshold is, the less accurate but faster the instability identification is [4, 10, 11]. As shown in [10], with a lower threshold of 240º, an accuracy of 99% in stability identification can be achieved. In Section V, results obtained with various thresholds used for the TSI calculation are compared with the results obtained in previous studies.

The use of the COI reference frame is also very common for measuring angles in multi-machine power systems. The COI is defined as the inertia weighted average of all rotor angles in the system. The angular position of COI is defined by (4), and its speed by (5), the latter representing the "mean motion" of the system [6].

$$\delta_{COI} = \frac{\sum_{i=1}^{n} H_i \times \delta_i}{\sum_{i=1}^{n} H_i} \tag{4}$$

$$\omega_{COI} = \frac{\sum_{i=1}^{n} H_i \times \omega_i}{\sum_{i=1}^{n} H_i} \tag{5}$$

where H_i is the inertia constant, δ_i is the rotor angle and ω_i is the speed of the i-th generator, while *n* is the total number of generators in the system. Using the COI reference frame, δ_{max} for the TSI calculation is defined by (6).

$$\delta_{max} = |\delta_i - \delta_{COI}| \tag{6}$$

According to [10], with a threshold of 180º, in the COI reference frame, the system transient stability can be assessed with an accuracy as high as 99% for a realistic and uncertain large test system. The results of the TSI calculations using different thresholds in the COI frame are also presented in the following sections.

III. TRUNCATEDL TRANSIENT STABILITY INDEX

The original definition of TSI is based on the angle difference considering the entire post-fault dynamic behavior of the system. However, in online TSA, it is desirable that the assessment is obtained shortly after a severe disturbance. Truncated TSI, as proposed in this paper, only calculates the TSI value over a specific time window *w*. This is depicted in Fig. 1(a), where it can be seen that at around 0.2 s after the fault inception, first-swing unstable and first-swing stable cases show very different rotor angles. At this time instant, the rotor angle for first-swing unstable cases is around 100°, a value that can be used to differentiate them from the first-swing stable cases.

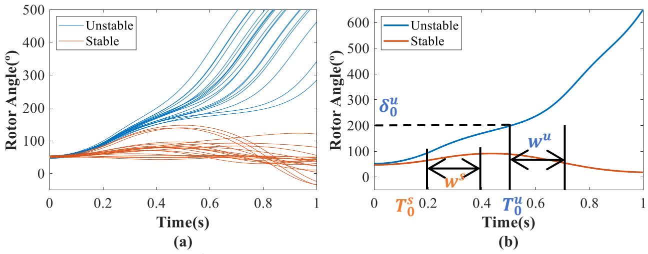

Fig. 1 An example of (a) stable/unstable simulations (b) time window parameters for Truncated TSI calculation

However, the initial time T_0 and the width of the window *w*, should be determined uniquely for different types of situations (first-swing unstable/stable) to guarantee that this approach can distinguish between the first-swing unstable cases and first-swing stable cases in a matter of a few hundred milliseconds. In this paper, the impacts of settings for the first-swing unstable initial time T_0^u, first-swing unstable window width w^u and first-swing stable window width w^s are assessed. It should be mentioned that T_0^u is defined as the time the generator that first goes unstable reaches an angle threshold of δ_0^u in the COI frame. For MADBATG, T_0^u is set to be the time the maximum angle difference first reaches δ_0^u. An illustration of the described parameters is shown in Fig. 1(b). Also, for each setting of window width and initial time, a maximum TTSI value of first-swing unstable cases $TTSI_{max}^u$ and a minimum TTSI value of first-swing stable cases $TTSI_{min}^s$ are calculated. This is because unstable cases result in larger rotor angles (and rotor angle differences), and hence will produce lower values of TSI. Ideally $TTSI_{max}^u < TTSI_{min}^s$, and all cases under the value of $TTSI_{max}^u$ are first-swing unstable (accuracy of 100%), with no first-swing stable cases misjudged and vice versa. The number of misclassified cases would be the number of first-swing stable cases producing TTSI values lower than $TTSI_{max}^u$. The value of $TTSI_{max}^u$, therefore, provides a mean for approximating the "stability boundary" as it defines the difference between first-swing stable and unstable simulations.

It should also be noted that the w^u is set in a segmented way, while w^s is set to be a fixed value. Since the T_0^u value depends on the angle threshold δ_0^u, as mentioned above, the w^u is not a fixed value. For different T_0^u values, a different w^u is applied to make sure that the time windows for unstable simulations do not exceed the time when the actual loss of synchronism in the system occurs, so that the assessment can be completed in the shortest possible time.

IV. TEST SYSTEM AND UNCERTAINTIES

The test system for the present study is described in [9] and has been used in several studies for the dynamic analysis of large power networks including Renewable Energy Sources (RES) [10], see Fig. 2. 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 used can be found in [9]. The nominal penetration level of the RES generation (in percentage) is defined by the ratio between the installed capacity of both the 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 a Weibull and Beta distribution for modelling the wind speed and sun irradiation for wind generators and PVs, respectively. The uncertainty of the system loading is modelled by a scaling factor (sampled from the standard normal distribution) multiplying the mean value of the loading in a given hour 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 [9].

After the uncertainty sampling for loading and RES generation, Optimal Power Flow (OPF) is used to determine the conventional generators' output. The cost functions used are adopted from [9].

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 [9, 10, 12].

All uncertainties are sampled independently with appropriate probability distributions [9] in order to reflect their behavior in a realistic way.

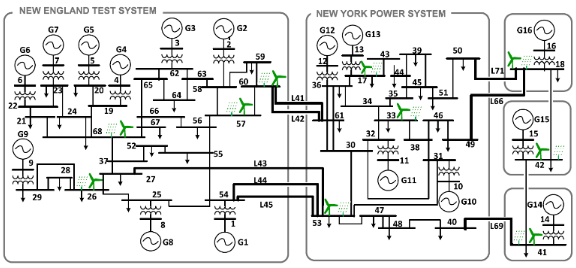

Fig. 2 Modified IEEE 68 bus test system, including RES

V. Results and Discussion

A. Generation of the testing database

A total of N_s Monte Carlo (MC) simulations are performed, with N_s=10,000 to achieve a satisfactory accuracy for the TSI as in [10], in which the same test system is used. This MC approach is further described in [9]. The post-fault simulation time is set to 5 s with the fault applied at 1 s. All simulations were performed using the DigSilent/ PowerFactory software.

B. Impact of transient stability thresholds

Accuracy results for different thresholds and frames are shown in Table I and Fig. 3. All accuracy and Confidence Interval (CI) estimations were calculated using the approach proposed in [13]. The sorting of the number of simulations in the horizontal axis in Fig. 3(a) and Fig. 3(b) is based on the results of the 360º benchmark threshold (MADBATG) in an ascending order. Though the general ascending trend with all other thresholds is maintained, it can be seen that other thresholds do not yield TSI values in the exact same order of magnitude as with the benchmark for the same events (simulations). This is even more notably observed for the COI results. Therefore, different thresholds for TSI calculations will classify events differently.

As expected and shown in Table I (where N_c represents the number of simulations that are correctly classified, and A_{TSI} represents the accuracy estimated), larger thresholds guarantee that more stable cases that produce large rotor angles are not misclassified into unstable cases. Numerically, when using the MADBATG reference frame, for thresholds between 240º and 360º, the change in accuracy is not significant (99.73% – 100%). Only 27 simulations are misclassified when using 240º as threshold. However, this value increases to 258 when decreasing the threshold to 180º, diminishing its accuracy to 97.42%. On the other hand, in the COI reference frame, the accuracy is much more sensitive towards lower thresholds. More specifically, an accuracy of 99.75% can be obtained at 180º, while the accuracy at 120º is only 89.32%. Fig. 3(c) shows the mean and most probable values of the TSI for 240º (MADBATG, orange) and 180º (COI, purple), thresholds, both of which have an accuracy of over 99% as shown in Table I, as well as of the benchmark threshold of 360º (MADBATG, green).

Table I. Accuracy Analysis for TSI Values for Different Thresholds

Threshold	Reference Frame	N_c	A_{TSI} (%)
360º	MADBATG	10,000	100.00
300º	MADBATG	9,994	99.94
240º	MADBATG	9,973	99.73
180º	MADBATG	9,742	97.42
180º	COI	9,975	99.75
150º	COI	9,794	97.94
120º	COI	8,932	89.32

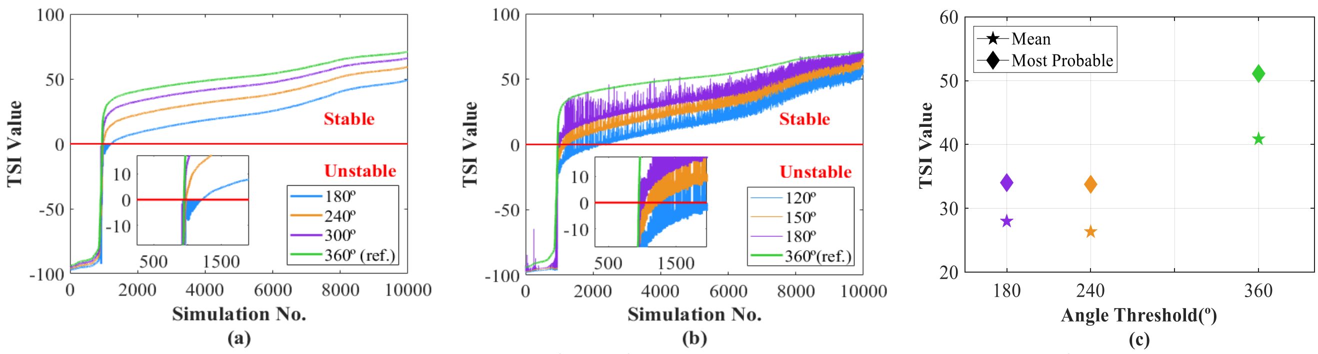

Fig. 3 Calculated TSI values in MADBATG (a) and in COI (b) reference frames and (c) mean and most probable TSI values for key thresholds

It is observed that the 240° (MADBATG) and 180° (COI) show very similar mean and most probable values, in addition to their high and close to one another accuracy. The estimation of the most probable values is performed using the Kernel smoothing function [14]. When using TSI for assessing transient stability, distribution of its values can be very dispersed, high over 0 for stable and very low below 0 for unstable events, making it difficult to define the stability boundary for the whole system, or in other words, how stable the system is. The TTSI improves the information about the system proximity to stability boundary compared to the conventional TSI and allows faster identification of instability, making it suitable for on-line stability assessment.

C. Impact of the time window on performance of Truncated TSI

A wide range of values of the time window for TTSI calculation are tested to find the appropriate combination of settings of the first-swing unstable initial time T_0^u, first-swing unstable window width w^u, first-swing stable window width w^s and angle threshold δ_0^u, as mentioned already in Section III. T_0^u influences the performance the same way as w^s does, hence it is not taken into consideration. Tested settings are presented in groups. Groups C1 – C10 are calculated in the COI reference frame, while Groups M1 – M10 in the MADBATG reference frame. Groups C1 and M1 shown in Table II are the reference ones in their corresponding frames. Since T_0^u is determined by δ_0^u according to the description in Fig. 1(b), different values of T_0^u can be obtained for each of the simulations. According to the range T_0^u is within (4th column in Table II), a corresponding w^u is allocated to the simulation. This applies to Table IV as well.

TABLE II. SETTINGS OF REFERENCE GROUPS C1 AND M1

Group No.	*δ_0^u(°)*	*T_0^u (ms)*	*w^u (ms)*	*T_0^s (ms)*	*w^s (ms)*
C1/M1	100 (COI)/ 150 (MADBATG)	T_0^u<400	250	200	200
		400<T_0^u<500	200		
		500<T_0^u<600	100		
		T_0^u>600	50		

Three cases are presented in this subsection, in which a single parameter is modified in each case while the rest stay unchanged, so that the impacts of w^s, w^u and T_0^u (associated with the change in δ_0^u) are studied.

Case I: impact of the first-swing stable window width (w^s)

The w^s settings for each group are presented in Table III, other parameters remain the same for all groups.

TABLE III. SETTINGS OF GROUPS C/M 1 – 4

Group No.	*C1/M1 (ref.)*	*C2/M2*	*C3/M3*	*C4/M4*
w^s(ms)	200	100	300	400

The results of calculations are shown in Fig. 4. It can be seen that the variations in settings have a great impact on results. For narrower time windows w^s, fewer cases would be misclassified, and a higher accuracy of results will be achieved. The lowest accuracies can be observed for Groups C4 (95.69%) and M4 (95.38%), both with w^s = 400 ms. This is mainly because for smaller w^s, the rotor angle responses of first swing stable cases have not reached their maximum value, and hence will produce larger TSI values. On the other hand, a smaller width of time window is preferred because it will speed up the instability identifications in on-line applications.

Overall, in both frames, w^s = 100 ms and 200 ms show good results. When w^s = 100 ms, best performances are observed (accuracy = 100%), and no first-swing stable cases are misjudged as unstable. Meanwhile, when w^s = 200 ms, as a more general and average setting, in conjunction with the settings of other parameters, the error is almost negligible (99.61% for MADBATG and 99.79% for COI.).

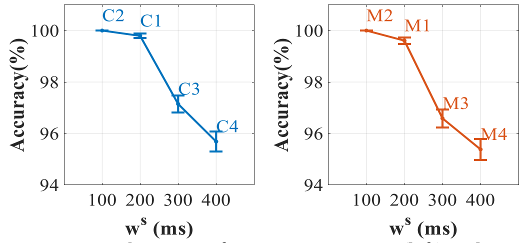

Fig. 4 Accuracy with 95% CI for Groups C1 – C4 (left) and Groups M1 – M4 (right)

Case II: Impact of the first-swing unstable window width (w^u)

Similarly, in this case, different first-swing unstable window widths, w^u, are tested. Their values are set as indicated in Table IV. The results are plotted in Fig. 5, in which the direction of the red arrow represents the increase in w^u, while w^s and T_0^u remain the same for all simulations.

TABLE IV. SETTINGS OF C/M5 AND C/M6

Group No.	*δ_0^u(°)*	*T_0^u (ms)*	*w^u (ms)*	*T_0^s (ms)*	*w^s (ms)*
C5/M5	100 (COI)/ 150 (MADBATG)	T_0^u<400	350	200	200
		400<T_0^u<500	300		
		500<T_0^u<600	200		
		T_0^u>600	100		
C6/M6		T_0^u<400	225		
		400<T_0^u<500	175		
		500<T_0^u<600	75		
		T_0^u>600	25		

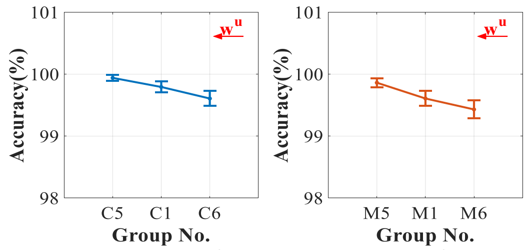

Fig. 5 Accuracy with 95% CI for Groups C1, C5, C6 (left) and Groups M1, M5, M6 (right)

As can be seen in Fig. 5, for narrower time windows w^u, more first-swing stable cases would be misclassified because some of them produce smaller TSI values than those unstable ones. The reason behind this is that narrower time windows capture rotor angles that are not different enough from those stable cases, and hence some errors would occur in the results. However, the change in accuracy is minor for all three groups, as they all yield accuracies higher than 99%. Compared to Case I, the influence of w^u is much less significant than that of w^s.

In general, when setting the value for w^u many factors need to be considered. At one hand, w^u should be large enough to facilitate more accurate differentiation between first-swing stable and unstable, while on the other, w^u cannot be too large to make sure that instability can be detected in the shortest time possible. Therefore, there is a trade-off between performance and efficiency considering the selection of appropriate w^u. The setting of Group C1 is an average/compromise and more universal setting.

Case III: impact of first-swing unstable initial time (T_0^u)

T_0^u is set to be the time when the first unstable generator reaches a rotor angle (δ_0^u) in the COI frame, while it is defined as the time when the maximum angle difference between any two generators first reaches δ_0^u for MADBATG. The smaller the angle is, the quicker it can be reached. Settings of δ_0^u and results are shown in Table V and Fig. 6, respectively.

TABLE V. SETTINGS OF δ_0^u OF GROUPS C/M 1, 7 – 10

COI	***C1 (ref.)***	***C7***	***C8***	***C9***	***C10***
δ_0^u(°)	100	110	90	80	70
MADBATG	***M1 (ref.)***	***M7***	***M8***	***M9***	***M10***
δ_0^u(°)	150	140	130	120	110

According to the results in Fig. 6, in the COI frame, increase of δ_0^u would relatively increase the accuracy to some extent, since larger angles observed during the oscillation represent a more unstable dynamic behavior of the system. For example, in Group C7 (δ_0^u=110°), the accuracy is 99.91%, while in Group C10 (δ_0^u=70°) this value decreases to 98.72%. The same phenomenon can be observed for the MADBATG frame.

Generally, higher δ_0^u values result in higher accuracy and narrower CI, meaning more reliable results. There is again a trade-off between the efficiency and the performance considering the setting of T_0^u. Smaller values of δ_0^u take less time for the generator to reach but diminishes the reliability of TTSI's transient stability assessment. A more universal selection of this value would be 100° and 140° in the COI and MADBATG frame, respectively. However, the influence of the threshold δ_0^u is not as strong as expected, as even the lowest accuracy observed in Case III (M10) is over 98%. This is because the angle threshold only determines the initial point of the extracted time window instead of the range of it.

Considering all the results presented in Case I – III, when w^s is set to be lower than 200 ms, regardless of the other two parameters, high accuracies (>98%) can always be achieved. Meanwhile, the speed of instability identification is high with low values of the w^s setting. In summary, the parameter w^s should always be considered first to guarantee high accuracy of the assessment, while the other parameters should be adjusted subsequently to improve the performance of the TTSI.

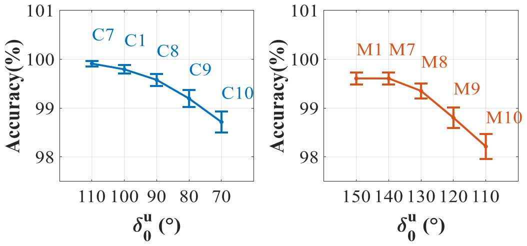

Fig. 6 Accuracy with 95% CI for Groups C1, C7 – C10 (left) and Groups M1, M7 – M10 (right)

VI. CONCLUSIONS AND FUTURE WORK

The paper introduced and discussed the use of a Truncated Transient Stability Index (TTSI). Differently from standard TSI applications found in literature, in which the TSI is calculated over the complete post-fault oscillation period, the proposed TTSI is calculated over reduced time windows in order to speed up the assessment and increase the accuracy for instability identification. The application of the TTSI is illustrated within two common angle reference frames, the Maximum Angle Difference Between any Two Generators (MADBATG) and Center of Inertia (COI).

The most influential factor for the accurate assessment of system stability using TTSI is the predefined window width for first-swing stable simulations. The accurate setting of this parameter yields high accuracy of stability assessment and ensures that the instability can be identified shortly after the fault inception. Other parameter settings, though important, are much less influential. Regardless of their levels of influence though, if the parameters are set appropriately, the TTSI is able to approximate the system stability status accurately.

It is also demonstrated that the TTSI outperforms TSI in both speed of instability identification and the accuracy of identification of system stability status. The parameter settings for TTSI calculation can vary significantly for different systems and have to be set for each system separately. It is expected though, that it would be possible to identify these settings, e.g., using data mining and Artificial Intelligence (AI) applications, based on the analysis of the system historic behavior and provide recommendations for the parameter settings and global thresholds for TTSI.

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