INDICES FOR FAST CONTINGENCY RANKING IN LARGE ELECTRIC POWER SYSTEMS

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Abstract—The liberalization of the electricity market induces a large variety of scenarios that may lead power systems close to their operation limits. This supports the need for on–line dynamic security assessment (DSA) of the grids, in order to provide operators with a clear insight of the current network state. The on–line application of DSA to a realistic network needs adequate methods to screen the large amount of contingencies to be examined by DSA tools. This paper proposes some practical heuristic indices for Transient Stability contingency pre–filtering and ranking in an on–line DSA session.

I. INTRODUCTION

DSA [1] usually concerns TSA (Transient Stability Assessment) and VSA (Voltage Stability Assessment). VSA can be studied by QSS (Quasi Steady-State) methods [2], whereas TSA, [3]-[5], is usually carried out through three methods: a) Time–Domain (T-D) simulation based methods, accurate, but time–consuming; b) direct methods [6], which are quick, but inaccurate; c) hybrid methods which collect the advantages of the two aforementioned methods.

Hybrid methods, [3], allow to carry out quick evaluation of TSA and to preserve a good accuracy of the models for the grid components. For example, hybrid method in [3] transforms the trajectories of a multi-machine power system provided by a time-domain program into the trajectory of a One-Machine-Infinite-Bus (OMIB) equivalent. At each time step of the time-domain simulator the OMIB parameters are refreshed in order to accurately assess the transient stability of the equivalent.

To identify the modes of separation of the system machines, the hybrid method [3] considers their post-fault swing curves computed via a time-domain program; at each step of this program, it sorts the machines in decreasing order of their rotor angles, identifies the very first largest angular deviations (largest gaps) between any two adjacent machines thus sorted, considers as candidate critical clusters those which are “above these largest gaps” and computes the corresponding candidate OMIB’s parameters. The procedure is stopped as soon as a candidate OMIB reaches its unstable conditions.

The adopted method is derived from the Equal-Area Criterion (EAC) which allows to determine the Critical Machines and to compute stability margins.

Even though hybrid methods are fast and accurate, it is still useful to maintain a phase of contingency pre–filtering to avoid wasting a large amount of time for the security assessment of very stable contingencies. This time may be better used to try preventive or corrective control actions.

This is even more important for those TSA tools based on heuristic approaches and pure T–D simulations, because each of the stable contingencies, which represent the majority of the contingency set, needs a simulation time usually longer than for an unstable case, as termination algorithms speed up the simulation of unstable contingencies.

This paper aims at giving a contribution to the contingency pre-filtering and ranking process during a TSA session in an on-line DSA application.

The application of the indices proposed in the paper to an IEEE test system and to a large realistic power system is promising in predicting the machines which go out of step in unstable contingencies and in ranking the severity of the contingencies themselves.

II. PROPOSED INDICES FOR TSA

Some practical indices for fast transient instability detection are proposed in this section: a) individual indices; b) global indices.

A. Individual Transient Instability (ITI) indices

The individual indices are calculated for each machine in the grid. When they are compared with one another, they indicate the (potentially) critical set of machines and the critical machine (the most advanced of the machines belonging to the critical set, that is the machine which first goes out of step). They are useful to determine a preventive redispatching of the injected active powers from the critical machines to the non–critical ones.

The procedure for the identification of the critical set/machine is the following: 1) at first, the values of the indices for all the machines are calculated; 2) these values are put in a descending order; 3) the differences among subsequent terms are calculated. The largest gap between two indices separates the “critical” set of machines from the non–critical one. The former is composed by the machines with the
values of their individual indices above the largest gap. Fig. 1 schematizes the selection algorithm of the “critical set”.

![Diagram of the selection algorithm for the critical set](image)

**Fig. 1. Scheme of the selection algorithm for the critical set.**

Three practical indices have been proposed:

\[ ITI_1 = \frac{P_{\text{max}}}{\sum_{i}^{} P_{\text{max},i}} \times \left( \frac{V_{\text{nom},i}}{V_i} \right) \times |\Delta V_i| \times |\Delta \omega_i| \]  

(1)

\[ ITI_2 = \frac{P_{\text{max}}}{\sum_{i}^{} P_{\text{max},i}} \times |\Delta V_i| \times |\Delta \omega_i| \]  

(2)

\[ ITI_3 = \left| \Delta \sigma_i \right| \]  

(3)

The meaning of the symbols is explained in Appendix A.

The first index has been obtained aggregating different quantities assumed to be interesting for TSA problem identification, such as the initial active power, the apparent power injected by each machine, the voltage and speed deviation immediately after the fault application. The tuning of the relevant exponents for each component of ITI_1 has been carried out by a “trial and error” approach.

The second individual index ITI_2 indicates that the most critical machines have high initial power injections, low initial voltage and high fault-on increase of speed.

Assuming the same simulation time step \( \Delta t \), according to the third individual index ITI_3 the most critical machines have the highest initial acceleration with respect to the Center of Inertia (COI) which is defined in Appendix A and consists in a weighted average of the generator speeds with generator inertias acting as weights.

The identification of the critical set can be used to preventively redispatch the injected active powers from the machines of the critical set to the non-critical machines. Some intuitive guidelines to actuate the preventive shift of generation from the machines of the critical set to the non-critical set are the following [3]:

- Equally from all the machines of the critical set;
- Proportionally to the nominal power of the respective machine of the critical set;
- Proportionally to their respective inertia.

Similar methods can be adopted to reallocate generation to non-critical machines, but experience [3] shows that this reallocation marginally affects transient stability.

**B. Global Transient Instability (GTI) index**

The Global Transient Instability (GTI) index is aimed at identifying the most critical contingencies to be further examined in an in-depth analysis, starting from an initial set of plausible contingencies (e.g. N-1 line contingencies).

The idea of global indices for contingency ranking is not new in literature [7]. However, they often require the T-D simulation for a significant interval after the fault clearing and they also need the calculation of both the kinetic and the potential energy of the power system. The calculation of the potential energy in turn is usually strongly based on simplified modelling assumptions.

On the contrary, the global heuristic index proposed in this paper is based on the following observation inferred from an extended simulation experience [8]: in a stable contingency the value of the system kinetic energy \( E_k \) at the fault clearing time \( t_\text{cl} \) is lower than in an unstable contingency and the absolute value of the relative time derivative of \( E_k \) (i.e. \( |\dot{E}_k|/E_k \)) is higher than in an unstable contingency.

Thus, the proposed GTI index, named Kinetic Energy based Transient Instability index, is:

\[ KETI = \frac{|\dot{E}_k|}{E_k} = \frac{E_k^2}{E_k \dot{E}_k} \]  

(4)

The meaning of the symbols is explained in Appendix A.

This index needs the T–D simulation of the system behaviour until the time instant \( t_\text{cl} + \Delta t \), immediately after the fault clearing. Moreover it concentrates on the kinetic energy which can be easily evaluated without simplified modelling assumptions.

**III. INDICES VALIDATION METHODOLOGY**

**A. Test systems and simulation tools**

The validation of the indices has required the simulation by a T-D simulator of large set of contingencies both on simple test networks and on large power systems. As a preliminary investigation, an IEEE test system has been analyzed within a tool for power system simulation in the MATLAB environment, named PST [9]. The simulations on this test system are aimed at setting up the individual indices and the global index and at identifying the most promising individual index which is then used for the analysis of the model of a large realistic network.

In particular, the simulation of a realistic model of the HV Italian transmission grid has been carried out by means of SICRE, a T–D simulator [10] for large power systems.

The proposed indices have been calculated in MATLAB. In particular, the indices validation in large power systems in SICRE is the result of a series of activities for the realization of an integrated MATLAB-SICRE tool for dynamic security assessment of large power systems [11].

The MATLAB-based procedure allows to generate a set of contingencies that can be sequentially processed by SICRE DSA manager, henceforth defined “the DSA Manager”. This
function checks the fulfillment of the security requirements (angle stability, voltage collapse, post-contingency violations) and it is also used to compute the Critical Clearing Time (CCT) of each contingency. The output files generated by the DSA Manager are then analyzed by MATLAB.

B. Proposed Instability criterion

In order to evaluate the performance of the proposed indices, it is necessary to define an instability criterion used as a reference and to calculate the CCT of the examined contingencies by time domain simulations.

The transient stability criterion used in time domain simulations is the default criterion adopted in SICRE and it is based on the maximum angular deviation between the rotor angle of each machine and the COI angle. This is a well-known heuristic method used in time domain simulations.

The application function to identify a possible loss of synchronism calculates the COI angle of the grid:

\[ \delta_{COI} = \sum_{i} \left[ \delta_i \times M_i \right] / \sum_{i} M_i \]  

(5)

where \( M_i \) indicates the inertia constant of machine \( i \).

Then, the initial deviation \( \Delta \delta_{COI} \) between the rotor angle of each machine and the COI angle is evaluated:

\[ \Delta \delta_{COI} = [\delta_i - \delta_{COI}]_0 \]  

(6)

The criterion to detect instability is heuristically based on the evaluation of the maximum angular deviation, given by equation (7). When \( \Delta \delta_{COI} \) reaches a maximum threshold (typically 180°), the function declares the loss of synchronism of the machine.

\[ \Delta \delta_{COI} = \delta_i - \delta_{COI} - [\delta_i - \delta_{COI}]_0 \]  

(7)

This check is carried out also for a reasonable time after the loss of synchronism of the most advanced machine, in order to identify also the whole (possible) set of machines which go out of step.

The instability criterion allows to find the CCT’s of the contingencies of a predefined set.

During simulations, SICRE is able to evaluate how many islands are present in the grid model and to which island each machine belongs. For each grid island, the simulator implements the heuristic instability criterion described above.

C. Global Transient Instability index validation procedure

The procedure for the GTI index validation acts according to the following steps:

1. At first one clearing time \( CT \) is fixed;
2. The GTI index values are calculated for all the contingencies of the set, assuming the clearing time defined in step 1;
3. By a trial and error method the CCT (i.e. the clearing time of the marginally stable case) of each contingency is calculated; the heuristic method above is adopted to assess the loss of synchronism. This is the most time consuming phase of the procedure;
4. The contingencies are then ranked by sorting the GTI indices in descending order (thus building the “GTI-based” contingency ranking list);
5. The same contingencies are ranked by sorting the CCT’s in ascending order (thus building the “CCT-based” contingency ranking list).

The factor which is calculated to evaluate the effectiveness of the GTI index is the so called “capture ratio”, already used in literature [7]. If one considers the first \( N \) ranked contingencies in the CCT–based contingency ranking list and \( M \) out of \( N \) are also included in the first \( N \) elements of the GTI–based contingency ranking list, then the capture ratio of the index is given by \( M/N \) for a contingency set size equal to \( N \).

D. Individual Transient Instability index validation procedure

ITI indices are calculated at the time instant immediately after the fault application and they are independent from the fault duration.

For each contingency of the set, the procedure for ITI indices validation acts according to the following steps:

1. The contingency is simulated and the relevant ITI index values are calculated;
2. The critical set is identified through the selection algorithm illustrated in section II.A;
3. the contingency is simulated with a clearing time set to the marginally unstable case. The machines which go out of step are identified;
4. the sets of critical machines at steps 2 and 3 are compared.

The two validation procedures (for GTI and ITI indices) which have been separated in the paper for the sake of clarity are carried out in parallel. In fact the time-domain simulations used to identify the CCT’s also provide the quantities for the calculation of the values of ITI indices and the information of the critical machines in marginally unstable cases.

IV. VALIDATION RESULTS

At first, the validation of the indices has been carried out on an IEEE test system in PST in order to set up the indices and identify the most promising ITI index. After that the GTI index and the promising ITI index have been applied to the study of a model of a large realistic power system in SICRE.

A. Validation for the considered IEEE Test system

The considered test system is the IEEE 10-machine, 39-bus New England network [12], shown in Fig. 2.
The analyzed contingencies consist in a zero-impedance three-phase short circuit applied near each terminal of the lines inside the grid. The fault is removed by opening the ends of the affected line. The clearing time (CT) chosen for the calculation of the GTI index values is 300 ms. The contingency set consists of 66 contingencies: in fact there are 34 lines inside the grid, but the contingencies which divide the grid into two separate parts (i.e. the contingencies applied to line 16-19) are not considered, because the calculations hold valid for only one electric island.

1) ITI indices

This paragraph is aimed at comparing one another the proposed ITI indices. Only the contingencies with CCT lower than 400 ms (that is a reasonable limit for the CCT investigation) are considered.

Fig. 3 shows the estimated critical machine (blue O) by three individual indices ITI_1, ITI_2 and ITI_3 and the actual critical machine found by T-D simulation (black X). The blue circles represent the critical machine according to the proposed indices (see section II.A), while the black crosses indicate the machine which first goes out of step in T-D simulations.

The first proposed individual index ITI_1 has a good performance. It correctly identifies the critical machine in 36 out of 39 unstable contingencies. As a final comment, the best performing individual indices are ITI_1 and ITI_3.

Now some comments to the estimated critical sets are proposed. In contingencies number 26 and 29, respectively associated to faults at lines 22-21 and 23-24, ITI_1 and ITI_3 seem to fail. However, the critical machine identified by ITI_1 and ITI_3 belongs to the actual critical set, obtained through time-domain simulations. Moreover the actual critical machine in contingency 29 (i.e. machine 6) belongs to the critical set identified by index ITI_1.

2) GTI index

In order to assess the effectiveness of the GTI Index by comparison with the time-domain simulator SICRE, it is necessary to calculate the CCT’s for all the contingencies.

Fig. 4 is a scatter plot where the y-axis shows the GTI Index values and the x-axis shows the CCT values. A decreasing trend between the values of the GTI Index and the CCT’s of the analyzed contingencies is evident, at least for CCT’s lower than 400 ms (a reasonable limit for the CCT investigation).

The higher the GTI index the lower the CCT of the contingency. The GTI Index values are thus useful to compare the severity of the contingencies belonging to the analysis set. In fact, given the same CT for the calculation of the GTI index, the contingencies with the highest GTI index values have the lowest CCT’s.

TABLE I shows the CCT-based severity ranking list and the GTI-based severity ranking list containing the first 20 contingencies.
It can be noticed that even if the order is not strictly the same in the two lists, the contingencies with the lowest CCT’s (for example, failure at lines 29-28, 29-26 and 28-29) are classified in the top part of the GTI-based contingency ranking list.

<table>
<thead>
<tr>
<th>Ranking number</th>
<th>GTI Index</th>
<th>Contingency</th>
<th>CCT [ms]</th>
<th>Contingency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3304.90</td>
<td>failure29_26</td>
<td>113</td>
<td>failure29_28</td>
</tr>
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<td>2</td>
<td>2983.90</td>
<td>failure28_29</td>
<td>131</td>
<td>failure29_26</td>
</tr>
<tr>
<td>3</td>
<td>2596.90</td>
<td>failure29_28</td>
<td>141</td>
<td>failure28_29</td>
</tr>
<tr>
<td>4</td>
<td>1499.30</td>
<td>failure28_26</td>
<td>154</td>
<td>failure6_11</td>
</tr>
<tr>
<td>5</td>
<td>1461.80</td>
<td>failure6_11</td>
<td>164</td>
<td>failure6_5</td>
</tr>
<tr>
<td>6</td>
<td>1172.50</td>
<td>failure6_5</td>
<td>168</td>
<td>failure28_26</td>
</tr>
<tr>
<td>7</td>
<td>1021.00</td>
<td>failure6_7</td>
<td>173</td>
<td>failure5_4</td>
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<tr>
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<td>failure6_6</td>
<td>173</td>
<td>failure6_7</td>
</tr>
<tr>
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<td>failure5_4</td>
<td>178</td>
<td>failure5_6</td>
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<td>failure26_28</td>
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<td>failure26_25</td>
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</tr>
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<td>541.00</td>
<td>failure25_2</td>
<td>206</td>
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<td>15</td>
<td>487.20</td>
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<td>391.80</td>
<td>failure25_26</td>
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<td>17</td>
<td>345.10</td>
<td>failure10_13</td>
<td>222</td>
<td>failure25_2</td>
</tr>
<tr>
<td>18</td>
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<td>226</td>
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</tr>
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<td>19</td>
<td>326.60</td>
<td>failure11_6</td>
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<td>20</td>
<td>318.30</td>
<td>failure11_10</td>
<td>226</td>
<td>failure8_9</td>
</tr>
</tbody>
</table>

Fig. 5 shows the capture ratio of the GTI Index as a function of the contingency set size.

The performance of the GTI index is good. It reaches a 100% effectiveness for several low values of the contingency set N (defined in section III.C) and it always maintains a value higher than 80% also for small size contingency set.

![Capture ratio as a function of the size of the contingency set](image)

Fig. 5. Capture ratio as a function of the size of the contingency set – IEEE test system

This is even more valuable if one considers that the calculation of the proposed GTI Index requires only the simulation of the contingency in the during-the-fault period in a time domain simulator, while other indices in literature, like in [7], require also the simulation of a remarkable post-fault time interval.

B. Validation for the considered large power system

The realistic power system considered for this work is a model of the Italian HV transmission grid implemented in SICRE. The model describes the national 220 and 400 kV transmission lines and the equivalents referred to foreign countries.

The overall model includes 1471 buses, 2525 (physical) nodes, 518 generators, 1076 transformers, 1159 HV lines and 215 power plants.

I) GTI Index

As the GTI index seemed promising in a small scale power system, its application to a large power system has been tested. This paragraph describes the first results obtained from the use of the GTI index for contingency ranking purposes on the aforementioned model of the Italian HV transmission grid.

The considered contingencies refer only to 400 kV transmission lines and they consist in a zero-impedance three-phase short circuit applied in the middle of the line and cleared by opening both the terminals of the line.

On one side, the DSA Manager has been used to sequentially calculate the CCT’s of a set of 176 line contingencies. The upper limit for the CCT search has been set to 400 ms. After the analysis, the MATLAB-based procedure found out 65 contingencies with a CCT lower than 400 ms.

As mentioned in section III.C, a fixed clearing time has to be adopted to calculate the GTI index. Techniques for the choice of the adequate clearing time are under investigation. The simulations carried out so far demonstrate that the GTI index maintains a good performance for a range of CT (100-250 ms) close to the typical intervention times of HV protection relays.

Fig. 6 shows the influence of the CT value for the calculation of the GTI index values, by showing the capture ratio curves for three different CT’s. As one can notice, the performance of the index remains good for all the three considered CT values: for CT=200 ms the capture ratio is always higher than (or equal to) 80% for N larger than 9; it reaches 78.8% only once, for N=33.

For CT=150 ms the GTI index first becomes higher than 80% (84.6%) for N=13; for larger values of N the values of the capture ratio are always higher than 80% (with only one exception for N=29, when the capture ratio is 79.3%).

![Capture ratio vs contingency set size](image)

Fig. 6. Influence of the CT values adopted for the calculation of the GTI index – Italian transmission grid model

For further remarks the value of 240 ms has been considered.
The proposed GTI and ITI indices have been calculated for all 176 contingencies. Then 65 contingencies with a CCT lower than 400 ms have been identified together with their relevant GTI index values. Thus, a reduced GTI index–based contingency ranking list (based on the above mentioned 65 contingencies) has been created by sorting the selected GTI index values in descending order. TABLE II shows the first 20 contingencies of the CCT–based and the reduced GTI index–based contingency ranking lists. As a further remark, the first 20 most critical contingencies in the reduced GTI index-based contingency ranking list coincide with the first 20 most critical contingencies in the complete GTI index-based list, which is a confirmation of the ranking capability of the GTI index.

From TABLE II one can notice that the GTI Index is able to classify the most critical contingencies in the top part of its contingency ranking list. The proposed GTI Index correctly captures the most dangerous contingencies, located in different areas of the system.

TABLE II
REDUCED GTI INDEX-BASED AND CCT-BASED CONTINGENCY RANKING LISTS (ITALIAN TRANSMISSION GRID MODEL)

<table>
<thead>
<tr>
<th>Number</th>
<th>GTI Index</th>
<th>Contingency</th>
<th>CCT [ms]</th>
<th>Contingency</th>
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<tbody>
<tr>
<td>1</td>
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<td>87</td>
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</table>

The capture ratio already performs well for contingency set sizes between 10 and 20. At N=11 the capture ratio is 91% and already at N=8 it is equal to 63%. Globally the performance can be considered good because the capture ratio is always higher than 80% for N larger than 9.

2) **Individual index ITI 1**

Another objective of the analysis consists in evaluating the performance of the individual index ITI_1 in identifying the critical machines. For all the 65 contingencies with a CCT lower than 400 ms the DSA Manager provides information about the machines which go out of step during the time domain simulation. On the other side, thanks to the MATLAB-SICRE integration developed to improve the SICRE DSA environment, the ITI_1 index has been calculated for all the considered 176 contingencies.

From the simulations carried out, it can be noticed that all the machines which are signalled for loss of synchronism in the time domain simulation are included in the critical set, estimated by ITI_1, in 53 cases out of 65. In 8 out of 65 cases they are partially included inside the critical set estimated by ITI_1. In 46 cases the most advanced machine of the critical set identified by ITI_1 index is also the first machine which goes out of step. In 3 out of 65 cases, where the individual index ITI_1 seems to fail, the critical set identified by ITI_1 is (however) made up of generating units belonging to the same power plant of the critical machine signalled by the DSA Manager.

V. FURTHER DEVELOPMENTS

Present efforts are being carried out for the elaboration of new contingency ranking indices based on corrected kinetic energy definition. These indices exploit the individual indices which allow to identify the cluster of critical machines from non-critical machines. From literature [13] it is known that after the fault clearing the corrected kinetic energy between the critical and non-critical machine clusters reaches zero if the contingency is stable otherwise it remains positive. Thus the calculation of the corrected kinetic energy derivative at $t_{ct}$ + $\Delta t$ (indicated as $\dot{E}_{corr, pf}$) may represent a good indicator of transient stability. A first proposal of Corrected Kinetic Energy based index $Index_{corr}$, is given by:

$$Index_{corr} = \dot{E}_{corr, pf}$$  \hspace{1cm} (8)

The definition of the corrected kinetic energy and of some auxiliary quantities is given in Appendix B.

$Index_{corr}$ has been tested on the analyzed model of the Italian HV transmission grid and some preliminary results are shown below. Individual index ITI 3 has been used to define the cluster separation in the grid due to contingencies application. Fig. 7 shows the capture ratio for CT equal to 300 ms, and ITI3.

![Fig. 7. Capture ratio plot for CT equal to 300 ms, using ITI3 to identify the critical machine cluster](image-url)

It can be noticed that the capture ratio shows a satisfactory performance: it is 100% for N <= 3 and for most N values it is higher than 70%. Further investigations are being carried out to assess the dependence of this index on the choice of CT’s and individual indices.
VI. CONCLUSION

The paper has proposed some Individual Indices and one Global Index for Transient Stability Assessment in power systems. The simulations carried out on an IEEE test power system show that the Individual Indices, above all ITI_1 and ITI_3, are able to identify the critical machine in almost all the unstable contingencies. The proposed Global Index, based on the kinetic energy derivative, has a good correlation with the CCT of the contingency and it allows to compare the severity of the contingencies themselves. It can be calculated by simulating only the “during fault” period in a time domain simulator. This last aspect is very important for an on-line application of this screening and ranking tool.

The application of the indices to a large realistic power system has confirmed the good performance of the first Individual Index (ITI 1), which detects the most advanced machine of the critical set in most contingencies, and of the proposed Global Index (KETI) which is able to select and rank the most critical contingencies.

Further activities are focused on corrected kinetic energy-based indicators which exploit the proposed individual indices to identify the critical machine cluster and which provide the first promising results on large realistic networks.

REFERENCES


APPENDIX A. LIST OF SYMBOLS

\[ P_i^f \] initial active power injected by the i-th machine on system base

\[ P_{\text{corr}} \] initial active power injected by the i-th machine on system base

\[ t_f \] time instant of fault application

\[ \Delta t \] simulation time step

\[ S^c_{\text{fault-i}} \] apparent power injected by the i-th machine (on system base) at \( t = t_f + \Delta t \)

\[ \Delta V_i \] initial p.u. voltage drop at the i-th machine terminals at \( t = t_f + \Delta t \)

\[ V_{\text{clCorr}} \] speed variation of the i-th machine’s terminals

\[ V_{\text{fault-i}} \] initial voltage at the i-th machine’s terminals

\[ M_i \] inertia constant of the i-th machine

\[ \omega_{\text{col}} = \sum_{j=1}^{N_{\text{CR}}} M_j \omega_j / \sum_{j=1}^{N_{\text{NC}}} M_j \] Center of Inertia (COI) speed

\[ \Delta \omega_j \] initial variation of \[ \omega_j = \omega_0 - \omega_{\text{col}} \]

\[ E_{\text{Corr}} = E_s(t_f) + \sum_{i=1}^{N_{\text{CR}}} \frac{1}{2} M_j (\omega_j(t_f))/\Delta t \] Total kinetic energy at the fault clearing time \( t_f \)

\[ E_{\text{Corr}}(t_f + \Delta t) - E_{\text{Corr}}(t_f)/\Delta t \] time derivative of the \( E_{\text{Corr}} \) immediately after the fault clearing

APPENDIX B. CORRECTED KINETIC ENERGY: SOME DEFINITIONS

\[ M_j^C \] inertia constant of the j-th critical machine

\[ M_h^NC \] inertia constant of the h-th non-critical machine

\[ \omega_{\text{CR}} = \sum_{j=1}^{N_{\text{CR}}} \frac{M_j^C \omega_j}{\sum_{j=1}^{N_{\text{CR}}} M_j^C} \] COI of critical cluster speed (CR= number of critical machines)

\[ \omega_{\text{NC}} = \sum_{h=1}^{N_{\text{NC}}} \frac{M_h^NC \omega_h}{\sum_{h=1}^{N_{\text{NC}}} M_h^NC} \] COI of non-critical cluster speed (NCR= number of non-critical machines)

\[ M^C = \sum_{j=1}^{N_{\text{CR}}} M_j^C \] equivalent critical cluster inertia

\[ M^NC = \sum_{h=1}^{N_{\text{NC}}} M_h^NC \] equivalent non-critical cluster inertia

\[ M^{ext} = M^C \times M^NC / (M^C + M^NC) \] Overall equivalent inertia

\[ \omega_{eq} = \omega_{\text{CR}} - \omega_{\text{NC}} \] Equivalent system speed

\[ E_{\text{Corr}} = \frac{1}{2} M_{eq}^{ext} \omega_{eq}^2 \] Corrected kinetic energy of the system

\[ E_{\text{Corr}}(t_f + \Delta t) - E_{\text{Corr}}(t_f)/\Delta t \] time derivative of the \( E_{\text{Corr}} \) immediately after the fault clearing