

Revised transient stability index for smart grids

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Abstract

In this paper the physical concept, calculation method and application possibilities of a novel stability index are briefly summarized. The details of the calculation method resulting in a better characterization of the dynamic security of the power system are published. The aim of our work is to develop a stability index for filtering stability calculation cases made for network development planning and to provide a possibility of real-time stability monitoring for power system dispatchers. Simulation results of model network are described, conclusions are drawn and evaluated.

Keywords

dynamic stability · mathematical approach · equal area method · transient stability index.

1 Introduction

There are different methods known from the literature to analyze the effects of changes on the state of the power system, which possibly endanger the synchronism of the power system (especially the generators). These methods can be grouped as detailed in Table 1.

Analysis of the changes in type B primarily becomes necessary when tuning the dynamic parameters of the controller equipments. For the operator (dispatcher), analysis of the possible effects of A and C-type disturbances can deliver the most relevant information. The system model and the investigational methods are well-known for the analyses of type A, these are regularly utilized for real-time and analytic calculations. The analysis of the distance from the limit of static transmission capacity nowadays primarily means the assessment of fulfilment of the so-called N-1 criterion by means of real-time or off-line contingency analysis, supplemented by checking for violations of load- or voltage-limits. It is questionable whether it is worth to perform further examinations on a given system state, which would determine some quantity relevant for the extent of safety of the system status. And it also would be able to show the decreased degree of static safety in cases when the system status is considered safe when examined by traditional methods. The analysis of type C disturbances is usually referred to as DSA (Dynamic Security Assessment) which covers primarily transient stability assessment methods. The task of transient stability assessment of a given system state is to determine whether a new equilibrium state can evolve in the system (i.e. all machine units can keep their synchronous operation) after clearing of a fault (or other kind of disturbance) and after the electromechanical oscillations caused by it, or one or more machine units will become unstable and fall out of synchronism.

In row C there is a method called: *b) Direct stability estimation methods (without time-domain simulation)*, one of these methods was chosen for our research. It is possible to examine the transient stability by means of time-domain simulation of the electromechanical processes or by so-called direct methods of transient stability assessment. For time-domain calculations, a detailed dynamical model is required, on which the simula-

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Tab. 1.

Characteristics of the changes	Quantities relevant for assessing robustness against the changes	Tools of investigation	Methods of investigation
A. Small-scale, slow rate (tendencies)	Distance from the static transmission capacity	Load-flow calculation on a static system-model	Analysis of different initial system states, contingency analysis
B. Small-scale, inducing electromechanical oscillations	Rate of damping of the electromechanical oscillations	Linearization around given operating point, stability assessment methods of linear systems	Analysis of the oscillations caused by given excitation
C. Large-scale changes, several subsequent events, instantaneous	Distance from the limit of the dynamic transmission capacity, dynamic stability reserves, rate of damping of the electromechanical oscillations, possibility of a new equilibrium system state	a) Time-domain simulation on a non-linear, dynamic system model. b) Direct stability estimation methods (without time-domain simulation)	Analysis of the effects of severe and fast disturbances (e.g. line faults, switching, etc.)

tion of different faults at various locations and several durations can be performed. The number of such cases may be very high, therefore it is required such as suitable accuracy of results, transparent amount of calculation and a format of results easy to evaluate and understand – can often not be met simultaneously. For the detailed, time-domain analysis of transient processes, the available software are based on sophisticated numerical methods for the solution of the network’s multiple coupled, nonlinear differential equation systems, which have a relatively simple physical background. Results from such software tools are accurate, but the needed computational capacity can be considerable, and for complex systems, often only a high number of simulations can lead to the correct decision on which fault cases have to be considered at all for stability assessments. Determining the places and types of failures affecting the system mostly requires practice and very good knowledge of the system’s behavior and characteristics therefore the automatic calculation is rather difficult. From the above considerations it is clear that measuring or describing „transient stability” of a certain case with one single quantity is by far not a trivial task. For this reason, several „stability indices” have been worked out in the 1980s, common properties of which are following: calculation of the index value for a certain case does not require time-domain simulation, therefore process of calculation is much simpler and faster, but some kind of approximation based on a physical approach is used for dealing with the multi-machine power system model, therefore results are less accurate. Detailed description of these principles can be found in the reference [1], [2]. In this paper a novel calculation method of the transient stability index named as Revised Transient Stability Index (RTSI) is introduced. Furthermore RTSI was compared with the known Transient Stability Index.

2 Calculation method of RTSI

Main steps are as follows:

- 1 The aim is to get the short-circuit currents any location of interest.

- 2 If a short-circuit happens on the generator of interest, the current is flowing from the generator and from the rest of the system. It is easy to obtain the so called remaining system’s impedance and the load changes caused by the short-circuit.
- 3 The next step is using the equal area method to get the load changes. A short-circuit was simulated at any location, and the caused load change (dP) was calculated for every machine.
- 4 From the dP_{max} values the accelerations, the Δ' and the Δt values were calculated for all cases.

To simplify the calculation procedure it was necessary to get an overall, simplified system model, which is based on the following considerations. In case of simulating an arbitrary machine’s short-circuit, in this situation at one “side” of the bus the short-circuited machine is located and at the other "side" a virtual machine can be rendered. This model is general in the sense that any topological changes, or examined machines sufficiently accurate results.

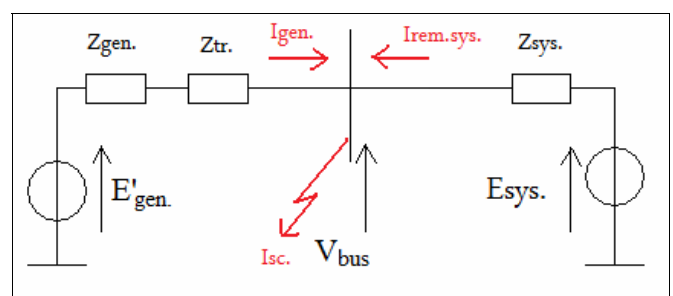


Fig. 1. „Single machine – remaining system” model

The parameters, however, only some of the electrical equipment is given. From these parameters were calculated the “remaining system’s” parameters.

This process was as follows:

The first step is to calculate a 3-phase (also a majoring criterion) short-circuit.

The idea: the short-circuit current consists of two parts: current fed by the generator and the current fed by the remaining

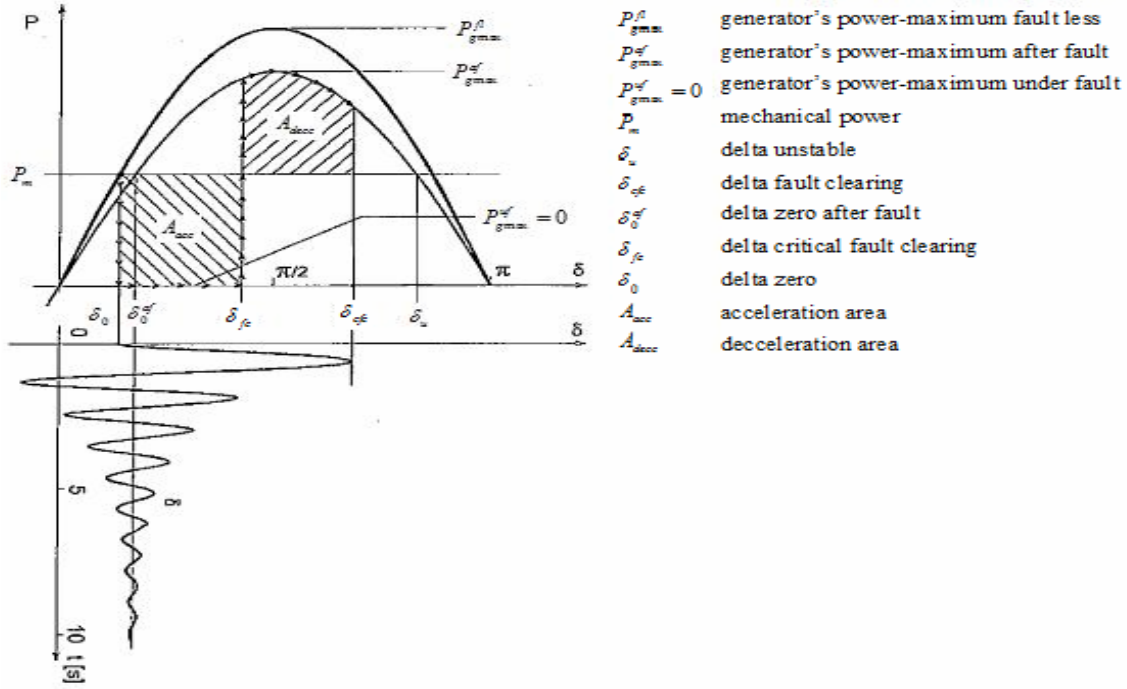


Fig. 2. The equal area method

system. The generator's current is calculable; detracting this value from the short-circuit current of the bus, the "remaining system's" short-circuit current has to be got.

1 Generator's short-circuit current:

$$i_{3\phi gen.} = \frac{E'_{gen.}}{\sqrt{3}(Z_{gen.} + Z_{tr.})} \quad (1)$$

The buses' short-circuit currents can be get from the simulator. If the "remaining system's" short-circuit current is known, its short-circuit power and impedance can be calculated.

$$S_{sc.} = \sqrt{3} |V_{bus}| |I_{rem.sys.}^{3\phi}| \quad (2)$$

2

$$Z_{rem.sys.} = \frac{V_n^2}{S_{sc.}} \quad (3)$$

Thus, almost every parameter of the model is known: generator's voltage, impedance, transformer's impedance and the impedance of the "remaining system". (The reason that generator and transformer were used as well is, there was a need by the simulator software.) The missing parameter is the voltage of the "remaining system", which can be calculated by the following considerations: the "remaining system's" impedance is a constant value. Before the fault will flow the generator's current through the model, which results in the X_H impedance voltage drop. (Because this is a lossless model, the impedances are: $Z = jX$.) This voltage plus the voltage of the bus give the voltage of the "remaining system":

$$E_{rem.sys.} = V_{bus} - \sqrt{3}jX_{rem.sys.}i_{gen.} \quad (4)$$

The model is ready for use. An efficient algorithm written in MatLab environment implements the calculations.

3 The "remaining system's" parameters have been determined using the method of equal-areas to get the RTSI.

The first step is to determine the P_{max} . This requires an X_{trns} transfer impedance, which is the amount of the generator's, the transformer's and the "remaining system's" impedance. And the absolute voltage values of the generator and the "remaining system":

$$P_{gmax} = \frac{|E'_{gen.}| |E_{rem.sys.}|}{X_{trns.}} \quad (5)$$

$X_{trns.}$ transfer impedance will changed accordingly to fault and/or clearing of fault by switching off faulted branch.

$|E'_{gen.}| |E_{rem.sys.}|$ absolute values are permanent.

δ_0 can be calculated from this formula: $P_0 = P_{max} \cdot \sin \delta_0$

And $\Delta\delta$ can be determined with the help of the equal-area method (for details: [5]).

$$A_{acc} = A_{decc}$$

$$P_m * \Delta\delta_{cf} = \int_{\delta_{fc}}^{\delta_u} (P_{max}^a * \sin \delta - P_m) d\delta \quad (6)$$

evaluating the integral

$$P_m \cdot \Delta\delta_{cf} = P_{max} \cdot (\cos \delta_{fc} - \cos \delta_u) - P_m \cdot (\delta_u - \delta_{fc}) \quad (7)$$

introducing

$$\Delta\delta \equiv \delta_{fc} - \delta_0, \quad (8)$$

and denoting:

$$P_m \Delta\delta = P_{max}(\cos(\delta_0 + \Delta\delta) - \cos \delta_u) - P_m(\delta_u - \delta_0 - \Delta\delta) \quad (9)$$

$$0 = P_{max}(\cos(\delta_0 + \Delta\delta) - \cos \delta_u) - P_m(\delta_u - \delta_0) \quad (10)$$

$$\cos(\delta_0 + \Delta\delta) = \cos \delta_u + \frac{P_m}{P_{\max}}(\delta_u - \delta_0) \quad (11)$$

$$\delta_0 + \Delta\delta = \arccos\left(\cos \delta_u + \frac{P_m}{P_{\max}}(\delta_u - \delta_0)\right) \quad (12)$$

$$\Delta\delta = \arccos\left(\cos \delta_u + \frac{P_m}{P_{\max}}(\delta_u - \delta_0)\right) - \delta_0 \quad (13)$$

4 Once the angular acceleration caused by the short-circuit is known, than ε has to be defined, i.e. the angular acceleration. In order to find out the value of the angular acceleration caused by the fault, the machines' electric masses and angular momentum has to be known. The masses are defined, and the angular momentum can be calculated by the following:

$$M_i = \frac{H_i \cdot S_{ni}}{\pi \cdot f_n} \varepsilon = \frac{P_s}{M_i} \rightarrow \Delta t = \sqrt{\frac{2 \cdot \Delta\delta}{\varepsilon}} \quad (14)$$

$$\left\{ P_s = P_m - P_{\max}^{af} \cdot \sin \delta_0 \right\}$$

After completing the model, and the required calculations, the next phase is the simulation. Various system states were tested, and with the help of the Power World and our program written in MatLab the angular accelerations and the critical clearing times could be calculated.

3 The algorithm converted to MatLab

The determination of the RTSI - what means a lot of calculation on a variety of system state - requires a lot of time and high computational demand. Excel implementation is transparent and traceable, gives adequate monitoring and debugging, however, is not suitable for a large number of calculations. Management of the many manual parameter defining is burdensome and difficult. So there is a need to develop an algorithm that can easily and quickly identify and define the generators angular accelerations. The Electric Networks Exercises [4] was used. In particular, a short-circuit has to be achieved, and then from that the other values can be calculated. Some basic considerations have to be mentioned before the algorithm could be presented.

The calculation is intended that for any topology and for short-circuit at arbitrary bus is possible to get the short-circuit currents of certain branches or transmission lines. In many cases it is sufficient to know only the short-circuit currents at the short-circuited node connecting branches. It is assumed, that the short-circuit is impedance-less, metallic short-circuit. The short-circuit currents were determined by the method of symmetrical components.

In this model 3-phase short-circuits were calculated in loaded system state. The load's bus voltage – before the short-circuit – is known from the Power World's load-flow. Accordingly, the load's node impedance is calculated for a replacement. The loads were substituted with this constant admittance.

$$y_{fi} = y_{i0} = \frac{\hat{S}_{ci}}{\hat{U}_{ci} \cdot U_{ci}} = \frac{\hat{S}_{ci}}{|U_{ci}|^2} \quad (15)$$

The admittance of the generator-transformer unit connected to the given node:

$$y_{10} = \frac{1}{j(x_d' + x_{tr})} \quad (16)$$

The admittance matrix which defines the high voltage system can be extracted from the Power World. This has to be amended for the new replacement version accordingly. I.e. to the main diagonal has to be added the loads' and the transformer-generator unit's impedance.

The modified nodal admittance matrix inverse:

$$[y_c]^{-1} = Z_c = [Z_{ij}] \quad (17)$$

The short-circuit currents were calculated by the Thevenin-method. The network – for any node – can be replaced by a voltage source (no load voltage) and a measuring point impedance. On this basis, the voltages behind the subtransient reactance not considered, the impedance parameters are transient values. The necessary equations to determine the short-circuit current flows are the next:

$$I_{zh} = \frac{U_h^0}{Z_{hh}} \quad (18)$$

$$U_j = U_j^0 - Z_{hj} I_{zh} \quad (19)$$

$$I_{ji} = (U_j - U_i) y_{ji} + U_j \frac{y'_{ji}}{2} \quad (20)$$

Calculating the short-circuit currents flowing on the transmission lines (I_{ji}), the effect of the shunt branches can be neglected, and in this case:

$$I_{ji} = -I_{ij} \quad (21)$$

So there is an algorithm, which allows you to calculate the bus voltages and the branch currents during the fault. Our task is now only one step to get the load changes caused by the short-circuit. This procedure was realized in a custom tailored MatLab routine.

4 Testing, comparison and results

For detailed examination purposes and verifying results a network analyzer software package (called HTSW) – developed by the Department of Electric Power Engineering, TU Budapest – was used for the TSI calculations. With the help of the program steady states of networks (load-flow calculations), effects of several faults and breaker operations during transients can be analyzed. In addition to the steady-state analysis, dynamic simulations were also calculated. The program is able to handle two synchronous systems operating with different frequency. The RTSI method was calculated by Power World Power Systems Analysis Software for the steady-state simulations. Power World Simulator is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days.

The software contains a highly effective power flow analysis package, capable for solving systems of up to 100 000 buses effectively.

Power World offers several optional add-ons to extend analyzing capabilities of the simulator. The model topology is shown in Fig. 3, which was created by using Power World SAS.

5 Model description

The modeled network is part of the Hungarian transmission system. It consists of the 400/120 kV Győr (G4) and the 120/20/10 kV Mosonmagyaróvár (MO1) substations, the overhead lines connecting them, and the medium voltage network of the latter substation. This part of the grid includes the following generators: a large machine at the 400 kV side of Győr (G4) (this serves as the system slack), three 5 MW gas turbines at the 120 kV side of Mosonmagyaróvár (MO1G), and two wind farms at the 120 kV (MO1S) and the 20 kV (MSZ20) side of Mosonmagyaróvár. The capacity of the wind farms is 50 MW.

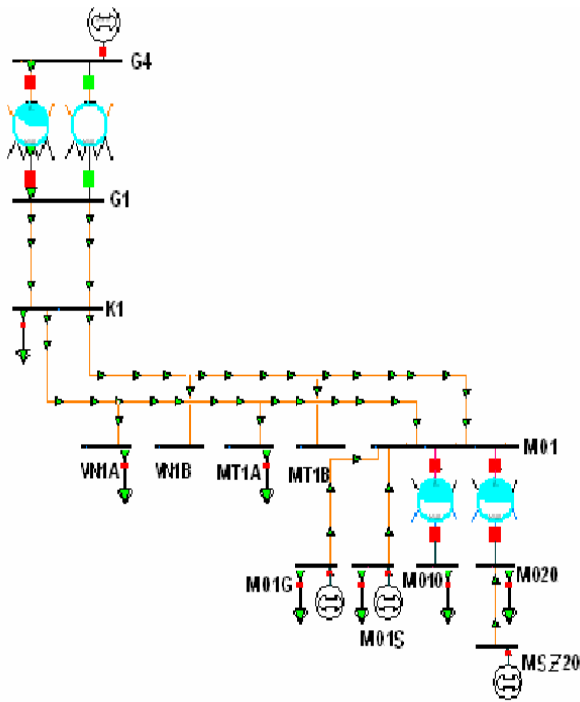


Fig. 3. The topology of the model network

The network model consists of:

- high- and middle voltage lines
- and buses (400-120-20 and 10-kV)
- transformers
- lines, parallel-lines
- generators and loads.

The sources may be power and/or voltage controlled. In the model there are:

- two wind power plants connected to MO1S and MSZ20 buses,

- three 5 MW gas turbines (connected to the MO1G bus)
- and a large machine (connected to the G4 bus) as a system slack bus in case of parallel operation with large network.

During island operation, the gas turbines are the system slack. In the two wind power plants 25 × 2 MW wind turbines are in operation. The loads are frequency and voltage dependent.

6 Simulated cases

Different system states were calculated. Fault analysis were simulated in case of synchronous operation and in island operation as well.

Tab. 2. Variation of the simulation

	P_{gen}	P_{load}
Synchronous operation	↑↓	—
	—	↑↓
Island operation	↑↓	—
	—	↑↓

The island operation was established with a switch-off at MT1A-VN1A and MT1B-VN1B lines, and this way the two system frequencies were developed. The following examination consisted of several steps: the network operated as an island i.e. the MO1 bus and geographically close loads and sources form an island. The feasibility of island operation was examined. Different operation situations and faults were simulated; size of voltage change was examined.

There is an example in Table 3 and Table 4 for the simulation process. In Table 3 the 3 phase short-circuit is on the MSZ20 bus, and the wind turbines power is 7.98MW. The load changes caused by the fault can be seen in row dP-HTSW and dP-Matlab. Under these parameters are the calculated angular accelerations with the two different methods. From these parameters were calculated the Δ and the Δ' values.

Table 4 is similar to Table 3, the difference is the system state: in 4 it is in island operation.

Tab. 3. Calculation results in synchronous operation, the fault is at MSZ20 machine terminal

	Synchronous operation		
	MO1G	MO1S	MSZ20 #3phsc
M	0.557	1.751	0.700
Ps[MW]	8.000	38.440	7.980
dP-HTSW [p.u.]	0.660	1.810	8.040
dP-Matlab [p.u.]	1.120	1.890	8.040
ϵ -HTSW [rad/sec ²]	1.185	1.034	11.481
ϵ' -Matlab [rad/sec ²]	2.011	1.080	11.481
CCT [sec]	0.570		
Δt [sec]	0.492		

7 Simulation results, characteristics

A lot of system states were simulated and the parameters were calculated. From the many calculation results the characteristics

Tab. 4. Calculation results in island operation, the fault is at MSZ20 machine terminal

	Island operation		
	MO1G	MO1S	MSZ20 #3phsc
M	0.557	1.751	0.700
Ps[MW]	8.600	38.000	7.980
dP-HTSW [p.u.]	3.360	4.670	7.980
dP-Matlab [p.u.]	2.630	1.290	7.980
ε-HTSW [rad/sec²]	6.032	2.668	11.395
ε-Matlab [rad/sec²]	4.721	0.737	11.395
CCT [sec]	0.470		
Δt[sec]	0.542		

can be drawn. On the vertical axis are the values of the angular acceleration, and on the horizontal axis are the clearing times. At the TSI method the CCT (critical clearing time) was calculated by a time-domain simulator, with an iteration method manually. (Details in Appendix.)

Contrarily the equal area method was used to get the Δt parameters to the RTSI method. And with the help of the MatLab routine it is automatic.

From the results, it can be concluded that in some cases TSI provided relevant and valuable information on the dynamic security of the system; while in other cases, the RTSI method has the same or even better results.

Comparing the two characteristics, it is easy to recognize, that the RTSI method provides more accurate results. The R^2 -approach for TSI is only 0.4, compared with RTSI where it is 0.75. ($R^2=1$ means the best fitting.)

The RTSI calculation points suit better at the expected chart, than the TSI method results.

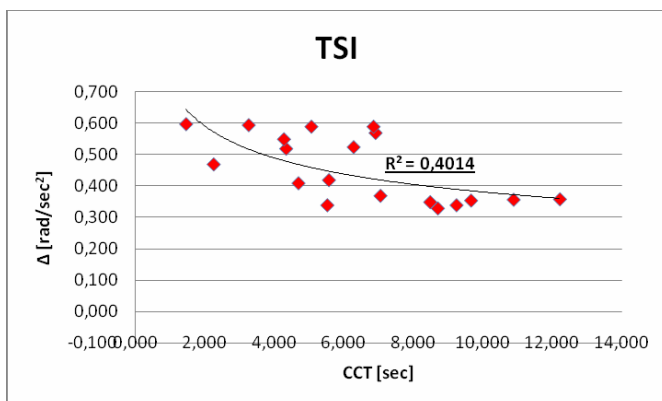


Fig. 4. the characteristic by the TSI method

8 Conclusion and summary

Advantages of the RTSI method:

- The RTSI characteristic shows a clearly monotonous correlation between Δ' values and Δt , the least squares method gives a better result: $R^2=0.75$.

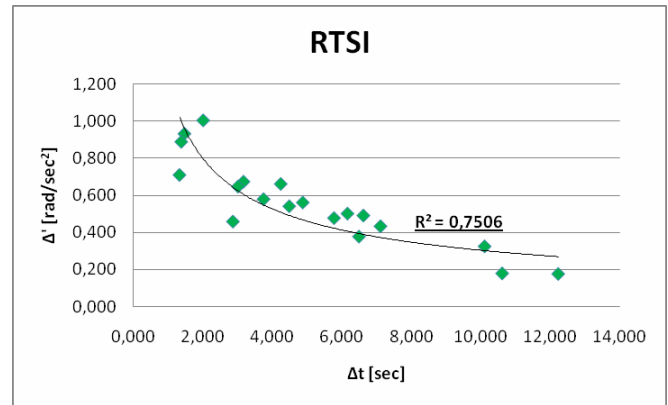


Fig. 5. the characteristic by the Δt method

- It is possible to get information on dynamic security of particular system states, based on the value of examined index, rather than by using other methods.
- A complete MATLAB Toolbox was created. With the help of this software, it is easy to get the RTSI characteristics. The Power World simulator can send the admittance matrix; afterwards the calculation is automatic.
- The stability indices were originally created to reduce number of calculations by substituting complicated, time-domain analyses. Nowadays this aim has lost its importance as a consequence of available computational capacity growth. However, stability indices can be very useful to monitor stability state of the system on-line by automatic calculations.
- In case of large system the number of calculations can be very high. The calculation of time-domain analysis is faster nowadays, but it takes plenty of time. In this cases could be useful the new method as well.

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Appendix

The basic idea is that calculation of angular accelerations of the machine units at the instant fault can be used to get useful information about the system. An index can be formulated from these accelerations that will give information about the disturbance on the whole system. The calculation method is described in the following points:

Assuming that a 3Φ -fault occurs at the node of i -th machine unit at $t=0$. Calculate the angular accelerations of the examined machine units (relative to a reference machine – noted by index n), and find the maximum of these values:

$$\varepsilon_i^r = \max_{k=1..n-1} |\varepsilon_k - \varepsilon_n|$$

Calculate the average angular acceleration of the whole system:

$$\bar{\varepsilon} = \frac{1}{n} \cdot \sum_{j=1}^n \varepsilon_j^r$$

Calculate the difference of each acceleration from this average:

$$\Delta_i = |\varepsilon_i^r - \bar{\varepsilon}|$$

After calculating Δ_i for the case of the fault occurring at all examined machines, TSI can be defined as:

$$TSI = \max_{i=1..n} \Delta_i$$

In order to become familiar with the characteristic values, behavior and meaning of the obtained TSI values, the results with time-domain simulation of the same cases need to be compared. One of the most characteristic results of these simulations is the critical clearing time, i.e. the maximal duration of the fault before clearing, after which all machine units can return to synchronous operation in a new equilibrium. It is possible to get reliable information based on the value of Transient Stability Index. The correspondence between TSI and CCT values is strictly monotonous, so critical clearing times can be unambiguously estimated.