Evaluation of Power System Transient Stability and Definition of the Basic Criterion

Ž. Eleschová, M. Smitková and A. Beláň

Abstract— Power system stability is defined as an ability of the power system to reestablish the initial steady state or come into the new steady state after any variation of the system's operation value or after system´s breakdown. The stability and reliability of the electric power system is highly actual topic nowadays, especially in the light of recent accidents like splitting of UCTE system and north-American blackouts. This paper deals with the potential of the evaluation in term of transient stability of the electric power system within the defense plan and the definition of the basic criterion for the transient stability – Critical Clearing Time (CCT).

Keywords—critical clearing time (CCT), defense plan, power system (PS), synchronous generator, transient stability, three-phase fault.

I. INTRODUCTION

THE electric power system instability can be interpreted using various methods depending on system configuration and operational status. Traditionally the question of stability has been connected to maintaining synchronous operations. The production of electricity is secured primarily using synchronous generators and for this reason it is important to secure their synchronism and parallel operation and therefore the question of stability has mainly hinged on the transient stability of synchronous machinery and on the relationship between active power and the rotor angle of the generator. Electric power system instability of course can also appear even if synchronous operation of the generators is not interrupted. Here the problem is more related to voltage control and the ability to maintain appropriate voltage within individual system circuits. Voltage instability mainly appears in extremely overloaded systems with lengthy transmission lines and weak system.

The results of analysis completed for large system outages (blackouts) have led to conclusions and recommendations that should be followed for transmission system operations. In particular these include:

- It is important to preventing such an outage from causing a chain reaction of outages with regards to the fact that it is not completely possible to avoid the occurrence of a failure in the system,
- It is absolutely necessary to secure valid N-1 safety criteria,
- The transient stability of the synchronous generator must be secured,
- Voltage stability in the electric power system must be secured (sufficient reactive power in the system),
- Monitoring and control of overloads on transmission elements in the transmission system.

II. METHODS FOR TRANSIENT STABILITY OF POWER SYSTEM ANALYSIS

There are three methods for analysis of the transient stability of power grid system:

- Direct methods,
- Simulation methods,
- Hybrid methods.

A. Direct methods

Direct methods for analyzing transient stability allow the direct calculation of the reserve or the limit of transient stability.

As opposed to simulation methods, during their application it is not necessary to explicitly calculate a system solution using a differential equation to describe the transient behavior of the electric power system over time; on the other hand this can result in relatively conservative results.

The most frequently used method is the method of area equality, which is useful for the model: one synchronous machine – an infinite bus. This means that the transient stability of a single generator or an equivalent generator is evaluated (equivalent replacement for a number of generators) with respect to the other parts of the system (infinite bus). The result from the application of this method is the critical rotor angle of the generator, i.e. the transient stability limit for the given machinery. In order to practically evaluate transient stability it is necessary to know the critical time within the given contingency, e.g. a short-circuit fault– Critical Clearing Time (CCT), which, if exceeded, results in a permanent breach in the synchronous operation of the evaluated generator. In order to define CCT it is necessary to know the development of rotor angle over time and in order to do this it is necessary to know the differential swing equation for synchronous machinery.

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0 \Delta P}{T_m S_n} \tag{1}$$

B. Simulation methods

The most frequent method for evaluation transient stability is a time simulation of a previous event, i.e. the resolution of the system using non-linear differential equations using numerical integration methods. Simulation methods as opposed to direct methods serve to verify both the stability of a single generator as well as the stability of the entire or a part of the electrical system.

III. ANALYSIS OF THE TRANSIENT STABILITY AS A PART OF THE DEFENSE PLAN

Transmission system operators, as well as scientific community, pay attention to the power system stability and safety. On the present, questions of the power system stability and safety are high actual. It is necessary to find out such preventive measures to avoid severe contingencies in the power system operation, e.g. blackout.

A defense plan against extreme contingencies is one of the basic strategic documents necessary in this field in order to avoid crisis situations that can lead to blackout.

One of the basic tasks that the defense plan is to resolve is the analysis of the transient stability of the power system; in addition it is to propose measures to preserve transient stability.

Transient stability should be evaluated on the basis of the following indicators and results from simulations:

− CCT estimate for a three-phase fault for all synchronous generators connected to the transmission system,

− Dynamic simulation of N-1 contingencies with two types of transmission line outages:

- Tripped line outage,
- Tripped line outage after a short-circuit (100 ms after the fault occurs).

− Dynamic simulation of N-k contingencies - substation shutdown (switch off all feeders) after a short-circuit on bus bur in the given substation (100 ms after the fault occurs).

− Dynamic simulation of N-k contingencies – based on the given scenario: line outages, short-circuit on line, unexpected protection activities, protection malfunctions, circuit-breaker failure,

− Dynamic simulation in order to verify current split places (substation) in the transmission system.

From the results of dynamic simulations of the contingencies and scenarios shown above it follows that the highest (negative) influence on the stability of generators working in the transmission system is exerted by N-k contingencies (selected results are on Figs. 1-4).

The likelihood of such events is fairly low; however it remains necessary to include and focus on such scenarios within the resolution of defense plans.

An occurrence of three-phase faults on power line and clearing within a short period of time (up to 100 ms) does not represent a large risk to the power system in terms of transient stability. For this reason it is necessary to ensure that generators operating in the electric power system have a CCT of higher than 100 ms.

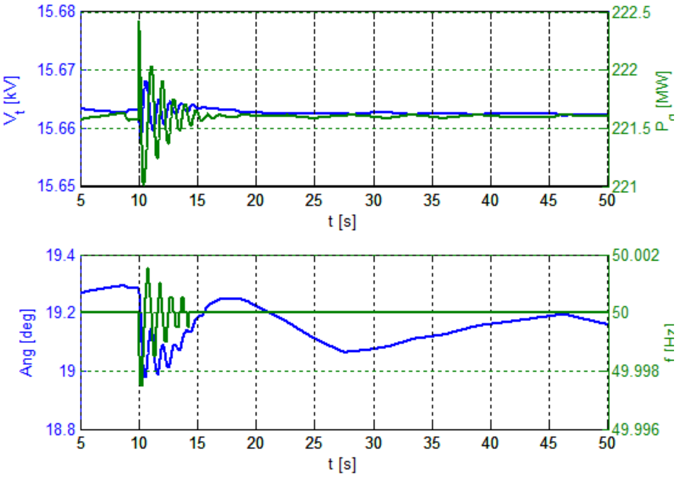

Fig. 1 Swinging of generator in NPP after tripped line outage (N-1 contingency)

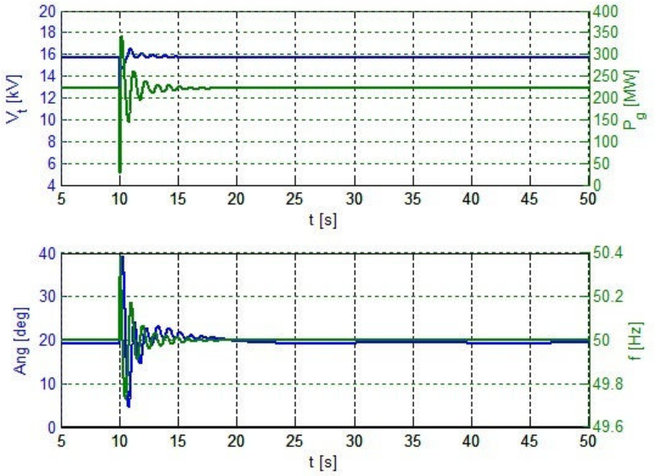

Fig. 2 Swinging of generator in NPP - tripped line outage after a short-circuit (100 ms after the fault occurs)

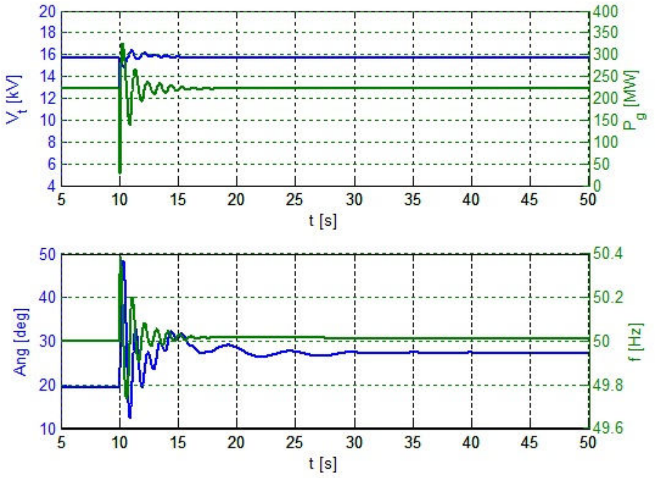

Fig. 3 Swinging of generator in NPP after a short-circuit on bus bur (100 ms substation shutdown (switch off all feeders) after the fault occurs) - N-k contingencies

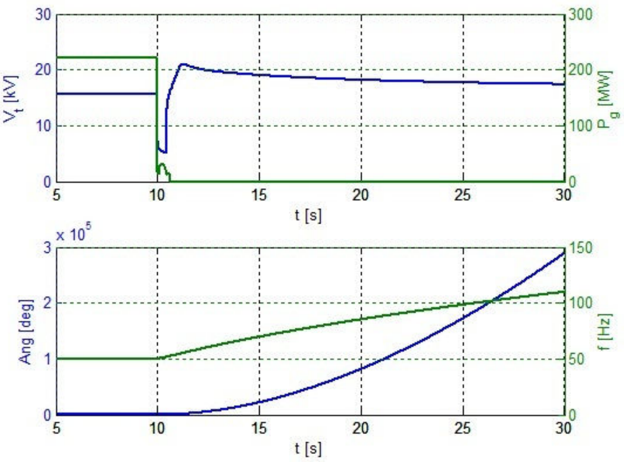

Fig. 4 Swinging of generator in NPP after N-k contingencies – based on the given scenario: (short-circuit on line + circuit-breaker failure) – loss of synchronisms

IV. CRITICAL CLEARING TIME

A. Definition

CCT is the principal criterion to transient stability assessment and every generator connected to the power system should have CCT longer than the operational time of circuit breaker in power system, even while CCT is not sufficient criterion to evaluate transient stability when considering various scenarios of severe faults occurrence in power system (multiple contingencies).

CCT value is based on the most severe failure with the influence on synchronous generator transient stability in the most unfavorable place of occurrence, i.e. the three-phase fault on the nearest bus bar of power substation, where the generator is connected.

It means that CCT calculated for three-phase fault on nearest bus bar of individual generator will be sufficient to sustain transient stability of synchronous generator for all remaining types of fault in the more distant places in power system with times shorter than CCT. Thus, if operational time of circuit breaker in the system is shorter than the smallest value of CCT (smallest CCT of individual generators in the power system), the occurrence of short-circuit in power system should not threaten transient stability of generators.

It's important to underline, that during fault on bus bar in real operation occurs disconnection of all outputs from this bus-bar. Since this is N-k contingency, it is necessary to examine the reaction of generators on this contingency by the means of transient simulation. It could be considered the scenario of protection failure (activation of backup protections), or breaker failure (activation of breaker failure relay), this can be considered as N-k contingency too and it is necessary to examine reaction of generators on this event by the means of transient simulation.

B. Algorithm of Calculation and Verification

Algorithm for calculation or simulation of CCT duration is defined as follows:

1. three-phase fault on the nearest bus bar of power substation, where the generator is connected,
2. fault sustained while generator preserves its transient stability,
3. disappearing of fault.

Verification of the CCT was based on transient stability analysis of single generator in NPP (Nuclear Power Plant). The most important parameters of generator: Sn = 259 MVA, Vn = 15,75 kV, $x'_d = 0{,}269$, H= 4.9450 s.

Examined generator and equivalent model of the power system (as seen on Fig. 5) has been modeled in Matlab Simulink using One Machine Infinitive Bus (OMIB) model.

This model demonstrate typical example of transient stability examination – three-phase fault on one of two parallel lines and its subsequent disconnection. This variant was executed in Matlab Simulink and also by numerical computation.

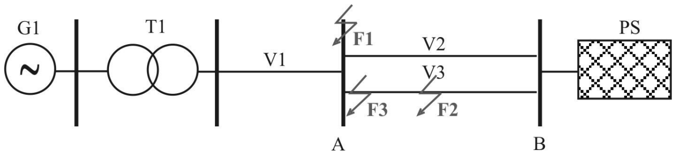

Fig. 5 Equivalent model for transient stability examination of generator in NPP

Three-phase fault in three locations were simulated in Matlab Simulink:

1. fault on bus bar in substation „A“,
2. fault on V3 line, in the middle,
3. fault on V3 line, near substation „A“.

Length of line V3 is at about 15 km.

The simulation algorithm – three-phase fault on bus bar in substation „A“:

1. fault occurring on bus bar,
2. fault sustained while generator preserves its transient stability,
3. disappearing of fault.

The simulation algorithm – three-phase fault on V3 line:

1. fault occurrence on power line,
2. fault sustained while generator preserves its transient stability,
3. disconnection of power line, where fault occurred.

Steady-state before short-circuit strike:
Substation „B“ V = 414.6 kV,
Generator power: P = 221.6 MW, over-excited state.

Infinite bus – substation „B“ which represents entire power system in this model and was modeled with three values of short-circuit power:

- ideal with very high short-circuit power,
- $S''_k = 6\,GVA$,
- $S''_k = 2{,}5\,GVA$.

Simulation outcome is summarized in the following table.

Table 1 CCT determined by transient simulation in Matlab Simulink

Place of failure	Ideal - very high short-circuit power	$S''_k = 6\,GVA$	$S''_k = 2{,}5\,GVA$
substation “A”	CCT = 310 ms	CCT = 290 ms	CCT = 265 ms
power line V3, in the middle	CCT = 500 ms	CCT = 300 ms	CCT = 270 ms
power line V3, near substation “A” – 10% of line length	CCT = 340 ms	CCT = 290 ms	CCT = 270 ms
power line V3, near substation “A” – 1% of line length	CCT = 300 ms	CCT = 285 ms	CCT = 265 ms

CCT value for ideal bus bar (infinite bus) has been significantly higher than for lower short-circuit power, particularly for simulation of fault in the middle of the power line.

Simulation verified, that CCT value is dependent on short-circuit power, hence “hardness” of power system against which is generator examined.

CCT can be calculated using method of area equality. This criterion can be used for qualitative evaluation of transient stability – we can easily and illustratively obtain critical value of rotor angle in synchronous generator and so determine the border of transient stability in examined machine. Based on the equation solution of the rotor swinging can be defined critical time of fault duration, i. e. ascension time of rotor in synchronous generator while it reaches critical angle $\delta_{critical}$.

Transient stability can be analyzed using areas – accelerating S+ and decelerating S–:

S+ = S– – transient stability border – critical angle value
S+ > S– – transient stability loss
S+ < S– – transient stability preservation

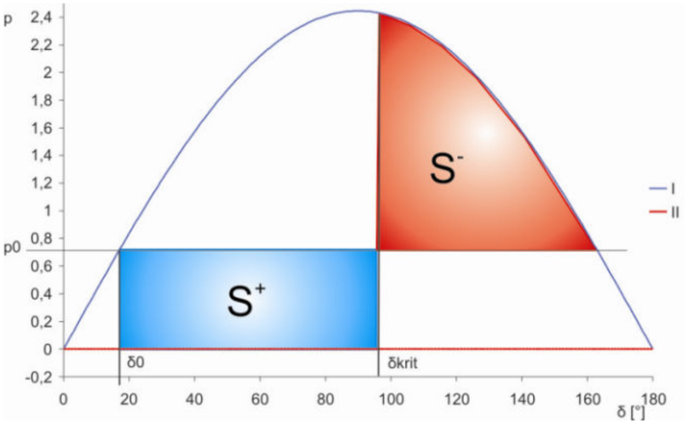

Fig. 6 Transient stability assessment for three-phase fault on bus bar (curve maximum before and after fault are the same, curve max. – fault state is null)

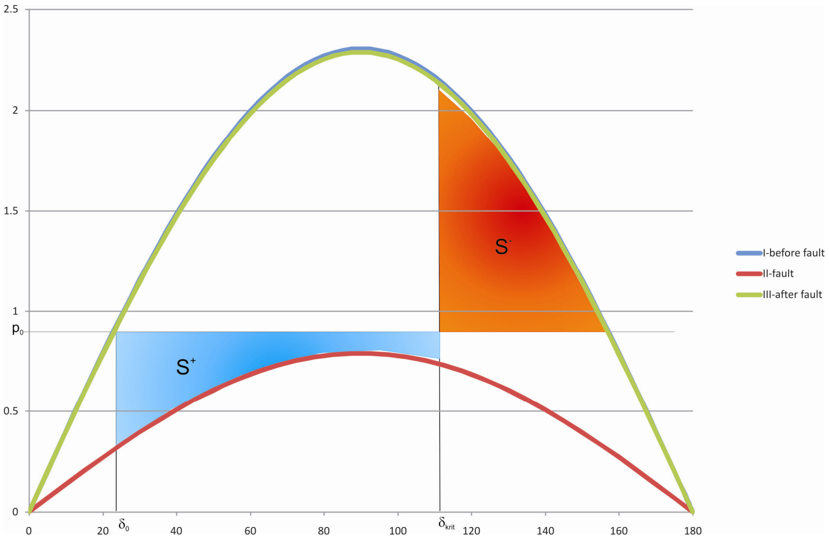

Fig. 7 Transient stability assessment for three-phase fault on power line and its subsequent disconnection

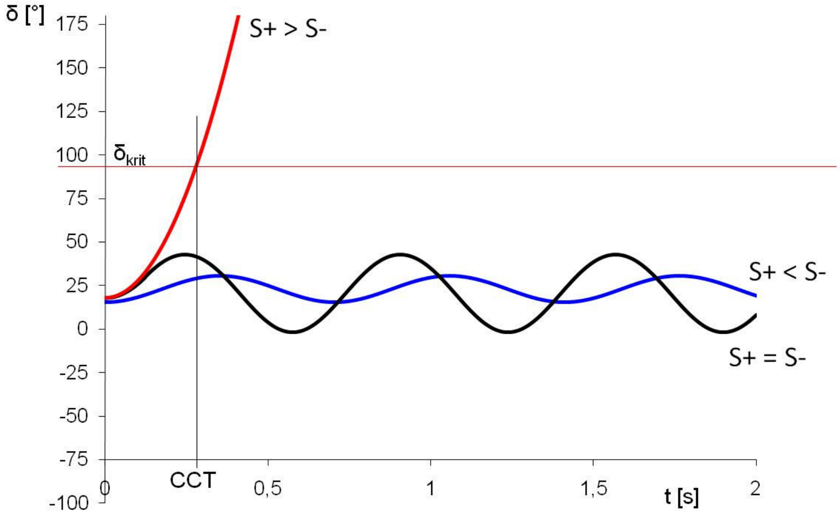

Fig. 8 Development of rotor angle over time (damping is neglected)

The numerical solution was modeled in the configuration according to the Fig. 5.

Transient stability was examined using the CCT value for three-phase fault on bus bar in substation „A“ and for three-phase fault on one of parallel lines (in the middle and near substation „A“), so we evaluated the same conditions that were simulated in Matlab Simulink.

Steady-state before short-circuit strike:
Substation „B“ V = 414.6 kV,
Generator power: P = 221.6 MW, over-excited state.

Preconditions for transient stability numerical calculation on synchronous machine in the case of transient event – three-phase fault:

- electromotive force (e.m.f) of generator is constant before the failure, during the fault and after it, because we do not consider AVR on generator,
- voltage in substation „B“ is constant before the failure, during, and after it – by definition of infinite bus,
- only coupling reactance changes, because of changes in configuration.

Results of calculations – values of curve maximum P = f(δ) for the state before fault p_m^I, during the fault, p_m^{II} and state after the fault clearing p_m^{III}, coupling reactance values, critical angle values, and CCT values are in the following table.

Table 2 Results of numerical simulations - application of areas equality criterion and solution of differential equation

Place of failure	x^{I} [p.u.]	p_m^{I} [p.u.]	x^{II} [p.u.]	p_m^{II} [p.u.]	x^{III} [p.u.]	p_m^{III} [p.u.]	δ_{critical} [°]	CCT [ms]
substation “A”	0,464	2,61	∞	0	0,464	2,61	98,2	320
power line V3, in the middle	0,464	2,61	1,354	0,89	0,467	2,59	134,2	667
power line V3, near substation “A” – 10% of line length	0,464	2,61	4,901	0,247	0,467	2,59	103,1	357
power line V3, near substation “A” – 1% of line length	0,464	2,61	44,8	0,027	0,467	2,59	98,5	323

C. Verification based on dynamic simulation on model Slovak Power System

This verification has been based on model of Power System in Slovak Republic. Model was adjusted so that in NPP Mochovce is switched only single generator, since CCT calculation is based on the presumption, that transient stability of generator is examined against the power system.

Two models were used for this simulation: one with all lines from V. Ďur substation switched on and second with only parallel lines from V. Ďur to Levice substations switched on (lines V495 and V492 switched off). Second variant of model with switched off lines V425 and V492 was chosen intentionally, to demonstrate typical example of transient stability examination – three-phase fault on one of two parallel lines and its subsequent disconnection.

Those models were carried out with the following simulations:

1. fault on bus bar in V. Ďur substation,
2. fault on V490 line, in the middle,
3. fault on V490 line, near V. Ďur substation.

The simulation algorithm – fault on bus bar in V. Ďur substation:

1. fault occurring on bus bar,
2. fault sustained while generator preserves its transient stability,
3. disappearing of fault.

The simulation algorithm – fault on V490 line:

1. fault occurrence on power line,
2. fault sustained while generator preserves its transient stability,
3. disconnection of power line, where fault occurred.

Steady-state before short-circuit strike:
V. Ďur substation U = 415 kV,
Levice substation U = 414.6 kV,
Mochovce generator power: P = 221.6 MW, over-excited state.

Simulation outcome is summarized in the following table. Simulations were calculated with the step 10 ms for increasing fault duration time.

Upper mentioned CCT values in the model with switched-on lines V425 and V492 are obtained because in this power system configuration the on V. Ďur substation is higher value of short-circuit power. Dependence of CCT value from short-circuit power is proved by the simulation in Matlab Simulink.

Table 3 CCT determined by transient simulation on model of Slovak Power System

Place of failure	Switched-off lines V425 & V492	Switched-on lines V425 & V492
fault on bus bar in V. Ďur substation	260 ms	280 ms
fault on V490 line, in the middle	270 ms	310 ms
fault on V490 line, near V. Ďur substation – 10% of line length	270 ms	290 ms
fault on V490 line, near V. Ďur substation – 1% of line length	255 ms	280 ms

V. FACTORS AFFECTING THE LENGTH OF CCT

Results of the simulation in MATLAB Simulink bring the evidence that CCT duration is affected also by the following factors:

- short-circuit power as well as voltage in transmission substation, where the generator is connected, i.e. the place with the most unfavorable conditions for occurrence of three-phase fault, based on transient stability assessment,
- operational condition of analyzed generator (underexcited generator, or overexcited generator).

Influence of voltage and short-circuit power on CCT duration in transmission system substation, where the generator is connected have its graphical representation in Figs. 9 and 10.

Results of the simulation positively confirm that for the transient stability of synchronous generator is underexcited state worse operational condition than overexcited.

CCT duration dependence on short-circuit power in power substation points to interesting fact – this dependence is nonlinear and from certain value of short-circuit power the CCT doesn't rise.

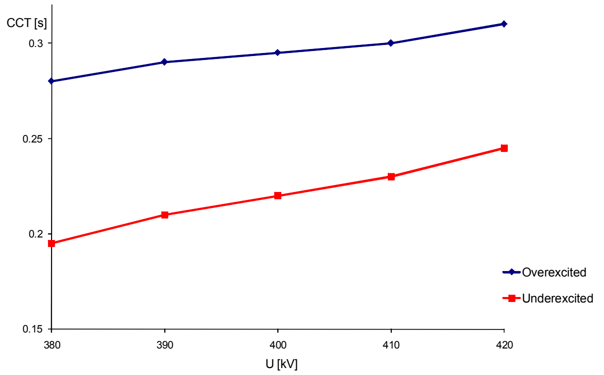

Fig. 9 Influence of voltage on CCT duration in transmission power substation

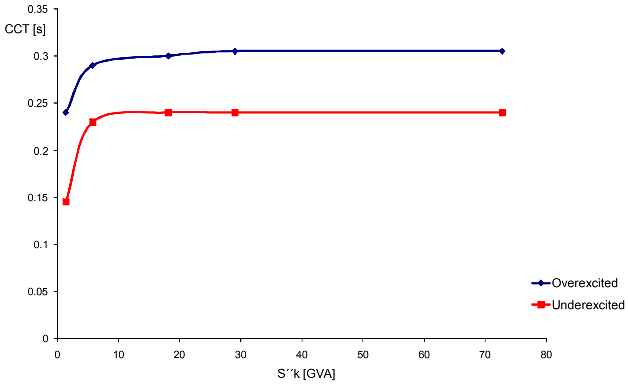

Fig. 10 Influence of short-circuit power on CCT duration in transmission power substation

VI. CONCLUSION

Nowadays, the reliable and the secure operation of the power system is a very actual issue.

One of the most important criterions for the reliable and secure system operation is validity of the basic criterion of the transient stability – CCT.

CCT was defined as maximal duration of three-phase fault (as the most severe failure for transient stability of generator) on the nearest bus from examined generator (as the most unfavorable place of occurrence).

The algorithm of calculation consisted of:

1. fault occurring on the nearest bus bar,
2. fault sustained while generator preserves its transient stability,
3. disappearing of fault.

Simulations in Matlab Simulink as well as numerical calculation demonstrated, that CCT value obtained with this method is the shortest, even shorter then with fault occurring on power line with subsequent disconnection of this line.

Then the CCT value obtained for three-phase fault on the nearest bus form examined generator is the most severe failure for transient stability of generator.

If this calculated CCT value is longer than operational time of circuit breaker in power system, then the generator will sustain its transient stability in the case of more distant faults (with the shorter duration than CCT).

It’s important to underline, that in considered scenarios of multiple contingencies in power system (fault occurring on bus bar followed by disconnection of all outputs on this bar, or scenario of distant protections failure, or breaker failure), verification by the transient simulation is necessary.

CCT is then principal criterion to transient stability assessment and every generator connected to the power system should have CCT longer than the operational time of circuit breaker in power system, even while CCT is not sufficient criterion to evaluate transient stability when considering various scenarios of severe faults occurrence in power system (multiple contingencies).

Analysis of transient simulation verified, that CCT value is dependent on short-circuit power in power system (i.e. its "hardness"). CCT value based on area equality criterion and the solution of differential equation of generator’s rotor swinging is conservative and thus the CCT value has to be obtained using the transient simulations in high-quality transient model of power system.

Analysis of transient simulation results proved, that CCT duration is partially dependent on short-circuit power. But even very low values of short-circuit power does not influence CCT duration.

CCT duration is unequivocally influenced by the operational state of generator, where the most unfavorable state is underexcited. This factor has to be accounted for when investigating CCT.

Analysis proved also the influence of voltage on CCT duration and the linearity of this dependency. To maintain voltage stability we recommend the operation of transmission system with elevated voltage on power substations. Higher voltage on substations influences also transient stability of transmission system, because of its positive impact on CCT duration.

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