Determining the Impact of Coefficients of Forced Excitation of Two Different Excitation Control Systems of Large Synchronous Generators on the Transient Stability of Electric Power Systems

Abstract. This paper presents a comparative analysis of the impact of the forced excitation coefficients of two different excitation control systems of large synchronous generators on the transient stability of electric power systems. The analysis is based on the mathematical model of the synchronous generator of the seventh order based on Park’s transformations and a simplified and sufficiently accurate model of excitation control systems. The model simulates the operation of the generator unit as a one-machine system connected to the infinite bus through a double transmission line during a normal operating regime followed by a short circuit fault disturbance causing challenging the transient stability of the system.

Streszczenie. W artykule przedstawiono analizę porównawczą wpływu współczynników wzbudzenia wymuszonego dwóch różnych układów regulacji wzbudzenia dużych generatorów synchronicznych na stabilność przejściową systemów elektroenergetycznych. Do analizy wykorzystano model matematyczny generatora synchronicznego siedemnastego rzędu oparty na transformacjach Parka oraz uproszczony i wystarczająco dokładny model układów sterowania wzbudzeniem. Model symuluje pracę agregatu prądootwarcia jako systemu składającego się z jednej maszyny podłączoną do nieskończoności przez podwójną linię przesyłowej podwójnej napięcia na przeciwieństwie normalnego trybu pracy, po którym następuje zakłócenie zwarcie, powodujące wywieranie dla przejściowej stabilności systemu. (Wyznaczanie wpływu współczynników wymuszonego wzbudzenia dwóch różnych układów sterowania wzbudzeniem dużych generatorów synchronicznych na stabilność nieustaloną systemów elektroenergetycznych)

Keywords: Synchronous generator, excitation systems, transient stability, forced excitation.

Słowa kluczowe: Generator synchroniczny, układy wzbudzenia, stabilność przejściowa, wzbudzenie wymuszone.

Introduction

Excitation control systems of large synchronous generators play a significant role in the stability of electric power systems, especially on their transient or dynamic stability. The importance of excitation control systems in ensuring system stability is enhanced in modern power [1].

This is affected due to several aggravated relevant factors related to stability in such large, interconnected PS such as increased transmission reactance and machine parameters of large new turbogenerator units. More specifically by the prevailing trends in the design and development of new large synchronous generators, which are characterized by further deterioration of electromagnetic or mechanical parameters that results due to the trends and objectives of generator manufacturers of getting the lowest possible cost of generating units, smaller investment volumes per unit of power [2]. The increased generator reactance due to increased magnetic fluxes and their linkages in magnetic circuits is one of the parameters which are decreasing metrics of synchronous generators that is clearly reflected on the system stability [3].

If the negative impacts of the aggravated parameters on the transient and dynamic system stability could not be compensated or if the system’s technical criteria in terms of maintaining transient stability of power systems could not be satisfied than manufacture of such large new generator units would not amount to much good [4]. Hence the modern excitation control systems whose impact on the preservation and enhancement of the transient and indeed dynamic power system stability is by far operationally strongest and most efficient has the highest priority in the specter of solutions sought to address and optimize this issue [5]. Furthermore, aiming to additionally enhance and optimize the issue of maintenance of transient stability in large, interconnected power systems.

In view of this excitation control systems of large synchronous machines are the most important for positively affecting and improving the transient stability of power systems. More specifically, such factors as the excitation voltage ceiling, rate of response of excitation current, average rate of change of excitation current, increase of the excitation voltage towards its ceiling [6]. The magnitude of forced excitation coefficients as well as other parameters such as time constants of excitation control systems, as key factors impacting excitation current improving and enhancing especially the transient power system stability, as well as other system parameters many of which are mutually inter-related [7].

The principal and the final system stability indicator is clearly the load angle representing the angle between the vector of the generated electromotor force (EMF) and the infinite bus voltage vector as the reference bus voltage [8]. If the load angle does not exceed the critical load angle value, maximum load angle defining the transient stability limit during the disturbance then the transient stability will be preserved [9]. In view of this the excitation control system must have as fast response as possible, preferably an instantaneous or a nearly step increase of the excitation field voltage with no-delay response practically inertia less field voltage with no-delay response practically inertia less in its rise towards the excitation voltage ceiling to argument and preserve transient stability of the system [10]. Such a response is the factor that is related and determines the critical time of the fault clearing time having caused the power system disturbance switch and thus limit and/dampen as much and as fast as possible the disturbance fall out caused by the fault that might have challenged the maintenance of the transient stability of operation of the synchronous generator connected to the infinite bus of the system [11].

The effects of two typical excitation control systems of large synchronous generators in power systems will hence be comparatively analyzed from this perspective in this paper as well as from the aspect of their impact and efficiency of maintaining and enhancing transient stability in
power systems due to serious faults and disturbances. The two such typical excitation systems are:

- Conventional electromechanical DC excitation systems
- Thyristor-rectifier AC excitation systems

The impact of various cases of fault-caused disturbances on the transient stability of the system will be compared based on the related and relevant resulting change of load angle caused by the disturbances affecting and indeed challenging and endangering the maintenance of the transient stability of the power system being analyzed. The three-phase short circuit on large synchronous machine busbars is the gravest of the possible occurring faults that accordingly has the most serious impacts on the generator itself and its transient stability as indeed on the transient stability of the entire power system [12]. However, the three-phase fault short circuit on the generator busbars is extremely relatively uncommon due to their complete protection and mechanical closure [13]. Hence, for the purpose of this analysis the 3-phase fault will be applied simulated relatively and interchangeably close to the beginning of the connecting double transmission line, thus electrically relatively near to the generator busbars.

The two excitation systems analyzed were installed on the generator units of the TPP Kosovo A, the first one initially having been a conventional DC excitation system that was at a later stage reconstructed and replaced with an AC thyristor-controlled excitation system.

Case study - description of the power system

The case study system is a one-machine system of a synchronous generator connected to the infinite bus of the system through a block-transformer and double transmission lines as shown in Fig.1.

Fig.1. Block-transformer and double transmission lines connected to the infinite bus.

Table 1. TPP KOSOVO A TGV-200 synchronous generator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_n )</td>
<td>MW</td>
<td>Nominal active power</td>
<td>200</td>
</tr>
<tr>
<td>( U_n )</td>
<td>kV</td>
<td>Nominal voltage</td>
<td>15.75</td>
</tr>
<tr>
<td>( L_n )</td>
<td>kA</td>
<td>Nominal current</td>
<td>8.25</td>
</tr>
<tr>
<td>( \cos \phi_n )</td>
<td></td>
<td>Power factor</td>
<td>0.85</td>
</tr>
<tr>
<td>( G_D )</td>
<td>( \text{tm}^2 )</td>
<td>Generator flywheel moment of inertia</td>
<td>25</td>
</tr>
<tr>
<td>( x_{df} )</td>
<td>( \Omega/km )</td>
<td>Direct – axis subsynchronous reactance</td>
<td>0.19</td>
</tr>
<tr>
<td>( x_{df} )</td>
<td>( \Omega/km )</td>
<td>Direct – axis transient reactance</td>
<td>0.295</td>
</tr>
<tr>
<td>( x_r )</td>
<td>( \Omega/km )</td>
<td>Direct – axis reactance</td>
<td>1.84</td>
</tr>
<tr>
<td>( T_{dz} )</td>
<td>s</td>
<td>Leakage reactance</td>
<td>0.145</td>
</tr>
<tr>
<td>( T_{dz} )</td>
<td>s</td>
<td>Subtransient short circuit time constant</td>
<td>0.1375</td>
</tr>
<tr>
<td>( T_{dc} )</td>
<td>s</td>
<td>Short circuit time constant</td>
<td>1.1</td>
</tr>
<tr>
<td>( T_{20} )</td>
<td>s</td>
<td>Open circuit time constant</td>
<td>6.4</td>
</tr>
<tr>
<td>( T_{a} )</td>
<td>s</td>
<td>Amplification time constant</td>
<td>0.447</td>
</tr>
<tr>
<td>( T_{i} )</td>
<td>s</td>
<td>Inertia time constant of inertia</td>
<td>6.040</td>
</tr>
</tbody>
</table>

In the case study the large synchronous generator simulated is of the TGV-200 generator type installed in the Thermal Power Plan Kosovo A /TPP KOSOVO–A/ - three identical generator units. The relevant machine parameters are given in Table 1. The fault is introduced relatively and interchangeably close to the beginning of the connecting double transmission line as shown below in Fig. 1 describing the case study.

Relevant data for its electromechanical excitation system with DC excitation are shown in Table 2.

Table 2. TPP KOSOVO A - Conventional electromechanical DC excitation control system parameters of the case study TGV-200 generator unit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{fd} )</td>
<td>V</td>
<td>Field voltage</td>
<td>500</td>
</tr>
<tr>
<td>( I_{fd} )</td>
<td>A</td>
<td>Field current</td>
<td>1940</td>
</tr>
<tr>
<td>( T_{fd} )</td>
<td>s</td>
<td>Field time constant</td>
<td>1</td>
</tr>
<tr>
<td>( U_{fd,max} )</td>
<td>V</td>
<td>Maximum field voltage</td>
<td>980</td>
</tr>
<tr>
<td>( I_{fd,max} )</td>
<td>A</td>
<td>Maximum filed current</td>
<td>4100</td>
</tr>
<tr>
<td>( dU_{fd,max}/dt )</td>
<td>V/s</td>
<td>Maximum field changing</td>
<td>730</td>
</tr>
</tbody>
</table>

This generator excitation systems of the mentioned three identical units of the TPP KOSOVO – A of type TGV-200 were of a conventional electromechanical DC exciter system with an external mechanical drive provided by a three-phase asynchronous motor mechanically driving the main DC exciter. The main exciter mechanical drive was thus provided as supplied directly from the power plant supply system busbars, practically from an independent power supply source being clearly independent of the generator voltage and/or load.

Hence as such, for the purpose of this analysis it can certainly be considered as a direct excitation system with independent mechanical drive practically mechanically coupled to the generator-turbine axis. Namely the busbars of the power plant supply system can be considered connected to the power system infinite busbar with constant system voltage source providing the asynchronous motor drive of the main exciter with constant torque. In Table 3 are given the relevant data for the block transformer and the double transmission lines.

Table 3. TPP KOSOVO A - Synchronous generator block-transformer and double transmission line data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_n )</td>
<td>MVA</td>
<td>Nominal Power</td>
<td>240</td>
</tr>
<tr>
<td>( P_{cu} )</td>
<td>kW</td>
<td>Active losses</td>
<td>950</td>
</tr>
<tr>
<td>( U_k )</td>
<td>%</td>
<td>Short circuit current voltage</td>
<td>11.3</td>
</tr>
<tr>
<td>( m_{12} )</td>
<td></td>
<td>Transformer ratio</td>
<td>15.75/242</td>
</tr>
<tr>
<td>( r )</td>
<td>( \Omega/km )</td>
<td>Line resistance</td>
<td>0.08</td>
</tr>
<tr>
<td>( x_m )</td>
<td>( \Omega/km )</td>
<td>Line reactance</td>
<td>0.4</td>
</tr>
<tr>
<td>( l_1 )</td>
<td>km</td>
<td>Line 1 - length</td>
<td>40</td>
</tr>
<tr>
<td>( l_2 )</td>
<td>km</td>
<td>Line 2 - length</td>
<td>160</td>
</tr>
</tbody>
</table>

The mathematical model of the synchronous machine is simulated as represented in the complete model of the seventh order based on Park’s equations with the set of seven differential equations. The double transmission lines and block-transformer are represented with their line equivalent reactance per unit length. The magnetic saturation component, hysteresis and changes in mechanical moment related to rotational speed changes as well as the turbine governor speed control inertia are considered negligible [14].

Mathematical model of the synchronous generator

- Synchronous generator in this case study contains:
  - Three stator windings.
  - Three rotor windings.
a. Excitation winding, and
b. Two damper windings

Since there are permanent flux linkages among the synchronous generator due to the windings that are magnetically interlinked or coupled, their mutual flux linkages, or mutually coupled, their mutual flux linkages, the respectively derived mutual machine inductances are a function of rotor positions [15]. Thus, due to their permanent rotational changes, these reciprocal mutual flux linkages, or mutual inductances are time-and-position dependent and different for each rotor position on a given time [16]. Based on the Park transformation theory, the three stator phase windings are substituted with two equivalent windings on the two rotational axis d and q [17]. The results in these two equivalent stator windings d and q rotating together with the rotor and its windings and thus providing constant values for all the above-mentioned mutual flux interlinkages and thus in constant values of resulting mutual inductances among the six stator and rotor windings of the synchronous machine making them time-invariant [18]. Thus, the two fictitious equivalent stator windings d and q have the respective values such as voltages, currents, fluxes, and parameters as presented in Fig.2 obtained as projections of the actual phase values a, b, c on the d and q axis of these two fictitious equivalent stator windings [19].

![Fig.2. Synchronous generator stator parameters in d-q coordinates](image)

Thus, the mathematical model describing the synchronous generator will be expressed and formulated in the form of the state-space model and respective equation form respectively in the Park’s equations summing up the complete set of differential equation the general form of which is [20]:

\[
\frac{dx}{dt} = f(X, Y, t)
\]

where \( x \) represents the state vector respectively the state variables that define the state of the system, \( y \) is a driving function.

In this set the linear form of the equation is:

\[
G(Y, t) = X
\]

According to the general theory of electric machines, Park’s equations describe electromagnetic processes in stator windings:

\[
\psi_{fd} = u_{fd} \cdot i_{fd} + \frac{d\psi_{fd}}{dt}
\]

\[
0 = r_{kd} \cdot i_{kd} + \frac{d\psi_{kd}}{dt}
\]

\[
0 = r_{qk} \cdot i_{qk} + \frac{d\psi_{qk}}{dt}
\]

where \( \psi_{fd}, \psi_{kd}, \psi_{qk} \) are rotor windings fluxes, \( u_{fd}, i_{fd} \), are field voltage and field current, \( i_{kd}, i_{qk} \) are dumping windings currents in d and q axes, \( r_{fd} \) is field windings resistance, \( r_{kd}, r_{qk} \) are dumping windings resistances in d and q axes.

The differential equation of the second order describing the rotor motion is separated in two differential equations of the first order, which according to Park transformations assume the following form:

\[
\frac{dT}{dt} = T_r(\psi_{d}i_{q} + \psi_{q}i_{d})
\]

\[
\frac{dy}{dt} = \omega
\]

where \( T_r \) is rotor mechanical time constant, \( T_t \) is turbine mechanical torque, \( \omega \) – is rotor speed, \( \gamma \) – angle between phase a and d axe, \( \psi_{d}, \psi_{q} \) are fluxes in d and q axes, \( i_{d}, i_{q} \) – d and q component of stator current, \( \gamma \) – angle between phase a and d axe. The synchronous machine fluxes are now defined as follows:

\[
\psi_{d} = x_{kd}i_{q} + x_{qk}i_{kd}
\]

\[
\psi_{q} = x_{qk}i_{d} + x_{kd}i_{q}
\]

\[
\psi_{d} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}
\]

\[
\psi_{q} = x_{ad}i_{q} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{fd} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{kd} = x_{ad}i_{q} + x_{ad}i_{d} + x_{ad}i_{q}
\]

\[
\psi_{q} = x_{ad}i_{q} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{d} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{q} = x_{ad}i_{q} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{ad} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{kd} = x_{ad}i_{q} + x_{ad}i_{d} + x_{ad}i_{q}
\]

\[
\psi_{q} = x_{ad}i_{q} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{d} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

Because the Park equations must have the general form of equation (1), the currents of each generator winding must be determined from equations (6) and replaced into the set of equations (3-5). Finally, the nonlinear differential equations system assumes the following form [21]:

\[
\frac{d\psi_{d}}{dt} = \psi_{q} + \psi_{d} + x_{ad} + x_{ad}x_{ad} + \frac{d\psi_{k}}{dt} = \psi_{k}(x_{ad} + x_{ad}x_{ad})
\]

\[
\frac{d\psi_{q}}{dt} = \psi_{q} + \psi_{d} + x_{ad} + x_{ad}x_{ad}
\]

where determinant \( \Delta \) is:

\[
\psi_{d} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{q} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

\[
\psi_{d} = x_{ad}i_{d} + x_{ad}i_{q} + x_{ad}i_{q}
\]

where \( x_{ad}, x_{aq} \) are damper windings mutual reactance, \( x_{kd}, x_{kq} \) are damper windings reactances in d and q axes, \( x_{d}, x_{q} \) – synchronous reactances of synchronous generator in d and q axes.
Thus, the entire synchronous machine as a mathematical model is fully described by the set of seven nonlinear differential equations. This represents the mathematical model of the seventh order for the simulated generator that fully and accurately describes the relevant electromagnetic and mechanical processes defined by the state variables of the synchronous machine [22]. It can also be referred to as the full set of seven equations that define the state of a synchronous machine, even though this definition applies to the uncontrolled synchronous generator as it does not include equations excitation control systems or speed governor control [23]. Thus, the generator state variable vector is:

$$[X] = [\psi_d, \psi_q, \psi_{fe}, \psi_{ke}, K_0, \delta]^T$$

where, \(\delta\) represents the generator load angle.

### Mathematical model of excitation control systems

Nowadays, various types of excitation control systems are applied for excitation control of synchronous generators [24]. They can be described analytically using various mathematical models, depending on the type, degree of detail, parameters available or degree of detail required in the analysis [25]. According to the recommendations of the IEEE Excitation Systems Subcommittee Report most synchronous generator excitation control systems may be categorized as Type I of the relevant excitation system division, as illustrated in the schematic block-diagram in Fig.3 [26].

$$u_{d} = [u_{d} + (u_{d} - u_{d}) (1 - \exp(-t_{jd}T_{jd}))]$$

where, \(u_{d}\) is nominal excitation (field) voltage, \(u_{d}\) is maximum excitation (field) voltage, \(t_{jd}\) is simulation time.

The additional expressions describing the functional dependency and the relevant constraints of the main exciter output voltage response during operation for this type of excitation control system are given below (27-30) [28]. They represent a credibly approximated simplified analytical set of equations expressed in algebraic form, clearly avoiding unnecessary additional set of three differential equations as given in the following equations [30]:

$$\begin{align*}
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d} \\
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d} \\
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d}
\end{align*}$$

where, \(K_{max}\) and \(K_{min}\) are maximal and minimal value of forced excitation coefficients.

Fig.4 shows the schematic diagram of a direct ac thyristor-rectified excitation control system.

$$\begin{align*}
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d} \\
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d} \\
K_{min}u_{d} &\leq u_{d} \leq K_{max}u_{d}
\end{align*}$$

where, \(K_{max}\) and \(K_{min}\) are maximal and minimal value of forced excitation coefficients.

Fig.5 shows the schematic diagram of the simulated direct ac thyristor-rectified excitation control system.
The above given set of equations in state variable form for the synchronous generator with the fully accurate mathematical model of the seventh order along with its related excitation control system with a simplified mathematical model described with the algebraic equations approximating with sufficient accuracy the entire system. It should be noted that all expressions for the simulation and analysis are given in pu system, including time, which is then easily converted back to the respective original units based on the appropriate proportions of the pu conversions. The reciprocal system of pu system defines 1 pu as the voltage producing the generator nominal voltage in the iron-gap characteristic.

**Results obtained and respective interpretations.**

The Numerical methods are used to solve the systems of equations. In this case the Runge-Kutta method of the fourth degree is found to be the most suitable. The solution is preceded by the calculation of all parameters in equations using corresponding expressions obtained from known for the generator and its excitation control system data, as well as for the determination of the fault initial conditions. Determining the initial conditions includes specifying the state vector which contains the synchronous machine’s seven state variables [31]. They require determining the generator’s stationary operating condition in the system using state variables preceding the fault, which in this case is the nominal operating mode of the generator in the normal operating mode with grid voltage $U = \text{const}$.

The fluxes will also be constant in stationary state due to constant inductances; hence their derivatives will be zero. In the nominal operation, the angular velocity is nominal, or 1 pu. The initial values of state variables are calculated for each time increment with the numerical integration of the system of differential equations based on these conditions as applied to the respective set of equations.

A three-phase fault is introduced at the close distance from the beginning of the L2 parallel line as shown in Fig.1, at $t = 0^+$ for a duration of $t_k3 = 0.19$ [sec], after which the protection disconnects the faulted line. Following the simulation, the change in generator load angle is used as a transient stability indication for generators with:

- Direct DC excitation system
- Direct AC thyristor excitation system and simulations are carried out for two different forced excitation coefficients:

  $K_{fs} = 2 \text{ pu}$

  $K_{fs} = 3 \text{ pu}$

The transient stability of the system is determined in the first electromechanical oscillation of the power system. For all the four cases simulated and analyzed, the load angle changes are calculated, and respective curves drawn based on the results of the numerical solutions of the differential equations system as graphically displayed in Fig.6. Even with a high forced excitation coefficient of $K_{fs} = 3 \text{ pu}$ (Figure 6, curve 2), the curves 1 and 2, which describe the change in the generator’s load angle of the DC excitation control system reveal that the generator fails to maintain transient stability. This is pronounced even more with a lower forced excitation coefficient of $K_{fs} = 2 \text{ pu}$ (Fig.6, curve 1).

In the case of the AC thyristor-rectified excitation control system with forced excitation coefficient of 3 pu, as well as for 2 pu, the extremely fast rate of response of the excitation voltage increase allows for maintaining the transient stability (curves 3 and 4) even in the case of short circuits faults close to the generator busbars that are otherwise typically difficult to sustain. This is achieved by the inertia-less practically zero time constant of the AC thyristor-rectified excitation control systems boosting full excitation practically with no time-delay and almost instantaneous action.

It can be summarized that the efficiency of thyristor systems in providing efficiently not only maintaining the transient stability, but also for efficiently maintaining of the dynamic, long-term electro-mechanical stability of power systems, as well as providing for other significant advantages over conventional electromechanical systems such as damping electromechanical oscillations in power systems.

The slow rate of response, the increase of the excitation voltage of the DC excitation systems, for both forced excitation coefficients 2 and 3 appear to be linear. Curves 1 and 2 of the excitation voltage change of the conventional DC electromechanical in Fig.7, also due to the scale in the graphic representation, they in fact have exponential forms. However, with a very low gradient, the rate of increase also during forced excitation is insufficient for proving and maintaining transient stability during such fault regimes.

![Fig.6. Load angle change of excitation systems.](image)

**Fig.6. Load angle change of excitation systems.**

![Fig.7. Excitation voltage change of the conventional DC electromechanical excitation system.](image)

**Fig.7. Excitation voltage change of the conventional DC electromechanical excitation system.**

Fig.8 shows the AC thyristor excitation control system excitation current changes relating to the aperiodic component of the stator current during the short circuit, which extinguishes with time constant $T_s$. The shape of this characteristic curve is fully compatible with what has also been described in the literature [1]. As shown in Fig.8, the change in direct excitation current for the practically inertia-less AC thyristor-control excitation systems, which has the alternative component 50 [Hz] due to the aperiodic component of the stator current during the short circuit being dampened and extinguished with the time constant $T_s$.

This characteristic curve’s shape is clearly compatible with what is elaborated in the respective literature [2]. Fig. 9 shows the stator current change during fault with the
Simultaneous aperiodic component visible due to the asymmetric displacement of the respective oscillogram. Fig.10 shows the curves of the generator electromagnetic torque during faults, respectively, for the conventional DC excitation systems as well as the AC thyristor-rectified excitation control systems. All values are presented in relative or per unit system.

**Fig.8.** DC field current of thyristor excitation control system related to the aperiodic component of stator current.

**Fig.9.** Fault stator current during fault.

**Fig.10.** Synchronous generator electromagnetic torques during fault.

### Conclusion

The impact of forced excitation coefficients of two different types of synchronous generator excitation systems on the transient stability has been analyzed. The two excitation systems analyzed were installed on the generator units of the TPP Kosovo A, the original one being a conventional DC excitation system that was later reconstructed and replaced with an AC thyristor-controlled excitation system. The analysis has yielded the following conclusions.

In terms of synchronous generator transient stability, the thyristor-controlled excitation system is much more efficient in maintaining transient stability than the DC conventional one even for comparatively lower coefficients of forced excitation.

Increasing the forced excitation coefficients of thyristor-controlled excitation systems raises the limit of transient stability and significantly reduces the related electromechanical oscillations.

Increasing the forced excitation coefficient of conventional DC excitation systems has no significant impact on improving or maintaining transient stability.

The excitation control systems of large synchronous generators, especially those operating under challenging transient stability conditions necessarily must be AC thyristor-controlled excitation systems, preferably with higher coefficients of forced excitation.

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