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Posted Date: 20 January 2026

doi: 10.20944/preprints202601.1409.v1

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Article

Simulation of Synchronous Generators Connected in Power System Using PSS/E Software-Case

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Abstract

This paper investigates the operational performance and stability of a regional power grid with a high penetration of small hydropower plants operating under rated conditions. Grid monitoring and simulation results reveal that voltage levels frequently exceed permissible limits and exhibit significant fluctuations. The primary radial configuration of the network is the cause of often the outages of transmission lines that occur at times of peak generation. These conditions adversely affect generator operation and may contribute to equipment degradation. To enhance grid reliability and ensure stable hydropower plant operation, several mitigation measures are proposed, including the reinforcement of the transmission network through the construction of new lines to enable a ring configuration, the mandatory implementation of excitation control systems for generating units, the establishment of a real-time grid operation center, and the deployment of real-time diagnostic tools for optimized generator utilization. The proposed measures give a very handy scheme to raise voltage stability, operational reliability, and the safe inclusion of distributed hydropower generation into regional power systems.

Keywords: synchronous generators; hydropower plant; renewable energy; power systems; PSS/E

1. Introduction

Small and medium hydropower plants (SHPs) play an increasingly important role in the diversification of electricity generation and the enhancement of energy security worldwide [1–6]. The hydropower generation capacity of Albania has been witnessing a remarkable increase, particularly attributed to the establishment of small hydropower plants (SHPs) through private investments and concession-based schemes [7]. This trend does not only mean the more efficient use of the already existing hydropower resources but also the better support of the national electricity grid in terms of reliability.

The geographical distribution of small hydropower (SHP) plants has been very large and this practice has been very beneficial for the performance of the entire power system by the aforementioned factors, especially in the case of rural and outlying areas [8–10]. New plants coming online and old ones getting better through rehabilitation have shown to give the grid better energy and quality [11,12]. Over the past few years, around 630 MW of SHPs have been connected to the Albanian power grid, thus raising the country's electricity output considerably and enhancing system reliability [13].

Despite these advantages, the integration of SHPs as distributed generation sources introduces technical challenges related to system operation and stability [14]. System monitoring has revealed voltage fluctuations and various transmission line faults that can adversely affect the operation of

synchronous generators connected to the grid [15,16]. Disturbances like short circuits may produce severe electromechanical transients, potentially leading to loss of synchronism and compromising system security if not properly addressed [17].

Transient stability analysis in this context is indispensable for evaluating the ability of synchronous generators in hydropower plants to keep operating without major disturbances [18]. The commonly accepted definition of power system stability is that it is the system's ability to recover to the normal operating condition after being disturbed [19]. In case the forces that bring the system back to its stable condition are weaker than those that disturb it, then instability could occur which will lead to generator desynchronization and, in the worst-case scenario, complete system failure [20]. Transient stability analysis usually takes into account disturbances like the ones mentioned, such as short circuits, sudden load changes, or loss of generation [21].

This paper investigates the transient stability of a medium-power hydropower plant connected to the Albanian transmission network. A typical area with several hydropower plants is chosen as the basis for the case study. The dynamic response of the synchronous generator is studied considering different faults on the transmission line, such as single-phase, two-phase, two-phase-to-ground, and three-phase short circuits. Time-domain simulations are performed with the assistance of the PSS®E software package and for the most critical disturbance scenario which is a three-phase short circuit, the relay protection operating time is calculated as the critical time [22].

Unlike existing studies, this work presents a protection-oriented transient stability analysis of a medium-power hydropower synchronous generator connected to the Albanian transmission network, explicitly determining critical clearing times under realistic transmission line fault scenarios using PSS®E simulations.

The results provide practical insights into generator dynamic performance and protection coordination, supporting the secure and reliable integration of hydropower plants in power systems with increasing penetration of distributed renewable energy sources [23,24].

2. The Current Landscape of Small and Medium Hydropower Plants

In the late 1990s, small hydropower plants accounted for approximately 10% of the total installed generation capacity in Albania [25,26]. The installed capacity of individual plants ranged between 100 and 400 kW.

Over the past decade, interest from private investors in small hydropower development has increased significantly. As a consequence, nearly 80 concession agreements have been granted for the development and operation of small hydropower plants, representing an installed capacity of roughly 650 MW and an estimated annual electricity generation of about 1,827 GWh. The total investment required for the construction of these plants is estimated at approximately €289 million.

Table 1 depicts selected small and medium hydropower plants constructed in recent years in Albania, based on data from the [27]

Table 1. Small and medium hydropower built.

Generation plant	installed capacity [MW]
HPP “Smokthine”	9.2
HPP “Sranik”	4.6
HPP “Arras”	4.8
HPP “Xhyre”	4.8
HPP “Pobreg”	12.3
HPP “Vlushe”	14.2
HPP “Faqe kuq”	6.4
HPP “Martanesh”	10.5
HPP “Verba”	5
HPP “Sasaj”	10.6
HPP “Tervol”	10.6

HPP “Streka”	5.35
HPP “Kabash”	5.8
HPP “Stavec”	6.52
HPP “Zall xhuxhe”	4.7
HPP “Mireshti”	4.47

It should be noted that, until the 1990s, the power system operated under a conventional unidirectional scheme, with electricity flowing from generating units through transmission lines to the distribution network. In recent years, however, the commissioning of new generating units particularly small and medium hydropower plants (SHPs) has altered this operating paradigm. As a result, power flows have increasingly reversed direction, from the distribution network toward the transmission system.

Most SHPs were linked to the power system via radial transmission lines at voltage levels of 10 kV, 35 kV, or 110 kV. In many cases, the energy produced by these plants exceeds the transmission line capacity. This situation especially occurs during the rainy season, when SHPs operate at their maximum capacity.

To analyze the electrical system parameters under these conditions, operational data were obtained from the Transmission System Operator (OST), complemented by measurements collected using a Fluke power analyzer was employed on the low-voltage side of the 110 kV Burrel–Peshkopi transmission line. The recorded data indicate that voltage levels at various nodes along the transmission line fluctuate within wide limits, leading to operational challenges for the power system.

In many situations, particularly during the rainy season, full-capacity operation of SHPs results in transmission line overloading. Consequently, OST is forced to curtail generation from these units. Frequent transmission line outages were also observed, adversely affecting the proper operation of the generating units and, in some cases, causing damage to turbine generator assemblies. Furthermore, when generating units operate at full capacity, voltage levels often exceed permissible limits, and power quality issues such as voltage flicker are observed within the system.

3. Synchronous Generator Model

3.1. Mathematical Model of a Synchronous Generator

As highlighted above, one of the problems in the power system is the improper operation of synchronous generators in generating units. Figure 1 circuit representation of an idealized a synchronous generator, salient – pole type. As shows by figure 1, synchronous generator has three phase stator windings (a, b, c) and three rotor windings, field winding f, direct damper winding D and quadrature damper winding Q. The mathematical equations of the circuit model shown in figure 1 are given as follows:

$$u_a = \frac{d\psi_a}{dt} - r_s i_a \tag{1}$$

$$u_b = \frac{d\psi_b}{dt} - r_s i_b \tag{2}$$

$$u_c = \frac{d\psi_c}{dt} - R_s i_c \tag{3}$$

$$u_e = \frac{d\psi_e}{dt} + r_e i_e \tag{4}$$

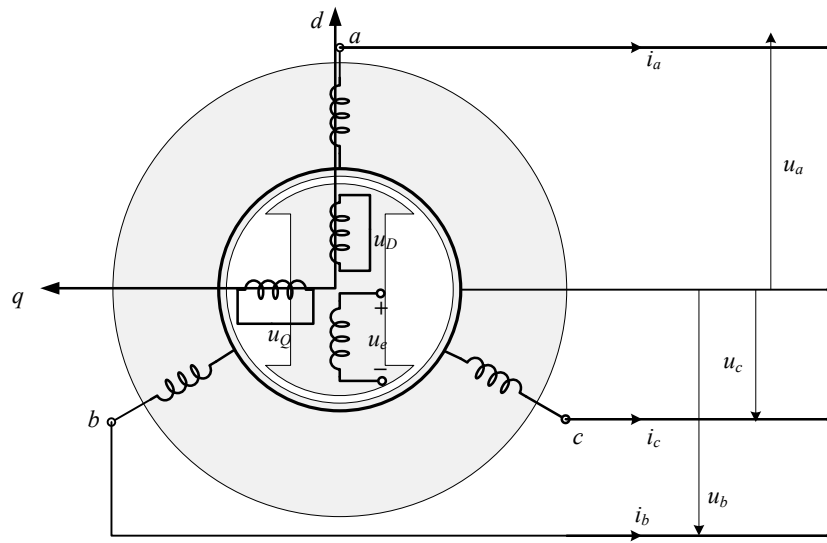


Figure 1. Circuit representation of an idealized synchronous generator, salient – pole type.

$$0 = \frac{d\psi_D}{dt} + r_D i_D \quad (5)$$

$$0 = \frac{d\psi_Q}{dt} + r_Q i_Q \quad (6)$$

$$t_m - t_e = \frac{J}{p} \frac{d\omega_r}{dt} + D\omega_r \quad (7)$$

Where:

ψ_a, ψ_b, ψ_c instantaneous values of the stator flux linkages in stator phases a, b, c respectively.

i_a, i_b, i_c instantaneous values the stator currents in phases a, b, c.

u_a, u_b, u_c instantaneous values of the stator voltages in phases a, b, c.

u_e , the value of excitation voltage.

r_s , the resistance of a stator phase winding.

r_e , the resistance of excitation winding.

ψ_e, ψ_D, ψ_Q instantaneous values of the rotor flux linkages windings, (field, direct, and quadrature damper windings).

i_e, i_D, i_Q instantaneous values of currents in the rotor windings e, D, Q respectively.

r_Q , the resistance of q-axis damper winding.

r_D , the resistance of d-axis damper winding.

t_m , mechanical torque.

t_e , instantaneous values of electromagnetic torque.

D damping coefficient.

J moment of inertia

ω rotor speed

p the pole pairs.

The total flux linkages in the stator phases in terms of winding currents, if it assumed that the magneto motive forces distribution is sinusoidal in space (the effect of space harmonics are neglected) and if there are no zero-sequence stator current, are expressed as follows [14]:

$$\begin{aligned} \psi_a = & -i_a \left[L_0 + L_{\delta 2} \cos 2\theta \right] + i_b \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos \left(2\theta + \frac{\pi}{3} \right) \right] \\ & + i_c \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos \left(2\theta - \frac{\pi}{3} \right) \right] + M_{ae} i_e \cos \theta + M_{aD} i_D \cos \theta - M_{aQ} i_Q \cos \theta \end{aligned} \quad (8)$$

$$\begin{aligned}\psi_b = & i_a \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos(2\theta + \frac{\pi}{3}) \right] - i_b \left[L_0 + L_{\delta 2} \cos 2 \left(\theta - \frac{2\pi}{3} \right) \right] \\ & + i_c \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos(2\theta - \pi) \right] + M_{ae} i_e \cos \left(\theta - \frac{2\pi}{3} \right) \\ & + M_{ad} i_D \cos \left(\theta - \frac{2\pi}{3} \right) - M_{aq} i_Q \sin \left(\theta - \frac{2\pi}{3} \right)\end{aligned}\quad (9)$$

$$\begin{aligned}\psi_c = & i_a \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos \left(2\theta - \frac{\pi}{3} \right) \right] + i_b \left[\frac{1}{2} L_{\delta 0} + L_{\delta 2} \cos(2\theta - \pi) \right] \\ & - i_c \left[L_0 + L_{\delta 2} \cos 2 \left(\theta + \frac{2\pi}{3} \right) \right] + M_{ae} i_e \cos \left(\theta + \frac{2\pi}{3} \right) \\ & + M_{ad} i_D \cos \left(\theta + \frac{2\pi}{3} \right) - M_{aq} i_Q \sin \left(\theta + \frac{2\pi}{3} \right)\end{aligned}\quad (10)$$

The total flux linkages of the rotor windings, are expressed as follows [5]:

$$\psi_e = L_{ee} i_e + M_{ed} i_D - M_{ae} \left[i_a \cos \theta + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3) \right] \quad (11)$$

$$\psi_D = M_{ed} i_e + L_{DD} i_D - M_{ad} \left[i_a \cos \theta + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3) \right] \quad (12)$$

$$\psi_Q = L_{QQ} i_Q + M_{aq} \left[i_a \sin \theta + i_b \sin(\theta - 2\pi/3) + i_c \sin(\theta + 2\pi/3) \right] \quad (13)$$

Where

L_0 constant value of self-inductance of the stator phase winding

$L_{\delta 2}$ the amplitude of the harmonic self-inductance vary by θ_r of stator phase winding.

$M_{ae}=M_{be}=M_{ce}$ the magnitude of the mutual inductance between a stator phase and the excitation windings.

$M_{ad}=M_{bd}=M_{cd}$ the magnitude of the mutual inductance between a stator phase and the d-axis damper windings.

$M_{aq}=M_{bq}=M_{cq}$ the magnitude of the mutual inductance between a stator phase and the q-axis damper windings.

L_{ee}, L_{DD}, L_{QQ} the self – inductance of excitation, d-axis, and q-axis windings.

$M_{ed}=M_{De}$ the amplitude of mutual inductance between field (excitation) and d-axis damper windings.

The set of equations (1) till (7), together with the rotor motion equation (8), represents the mathematical model of the synchronous machine expressed in phase coordinates. As can be observed, this model consists of differential equations with variable coefficients, since both self and mutual inductances depend on the rotor position θ_r . The time-varying nature of these coefficients introduces significant computational challenges when equations (1) till (7) were used to directly solve for phase quantitie.

3.2. Park's Transformation

The equations described in the previous paragraph define the mathematical model of the synchronous machine, in which the inductances vary with the rotor angle θ_r , resulting in differential equations with variable coefficients that are difficult to solve. To overcome this issue, the stator quantities are transformed into the rotating $dq0$ rotor reference frame. By applying the transformation matrix T_{dq0} , the stator voltage equations are expressed in $dq0$ coordinates [28]:

$$\begin{aligned}\mathbf{u}_{dq0} &= \mathbf{T}_{dq0}(\theta_r) \mathbf{u}_{abc} \\ \mathbf{i}_{dq0} &= \mathbf{T}_{dq0}(\theta_r) \mathbf{i}_{abc} \\ \boldsymbol{\psi}_{dq0} &= \mathbf{T}_{dq0}(\theta_r) \boldsymbol{\psi}_{abc}\end{aligned}\quad (14)$$

Where

$T_{dq0}(\theta_r)$ is a matrix transformation applied only to the stator winding quantities

$$T_{dq0} = \frac{2}{3} \begin{bmatrix} \cos \theta_r & \cos(\theta_r - 2\pi/3) & \cos(\theta_r - 4\pi/3) \\ \sin \theta_r & \sin(\theta_r - 2\pi/3) & \sin(\theta_r - 4\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (15)$$

By expanding equation (14), synchronous generator's mathematical model is derived in the dq0 reference frame, with equations along d and q axis:

$$\begin{aligned} u_d &= \frac{d\psi_d}{dt} - \psi_q \omega_r - r_s i_d \\ u_q &= \frac{d\psi_q}{dt} + \psi_d \omega_r - r_s i_q \\ u_e &= \frac{d\psi_e}{dt} + r_e i_e \\ 0 &= \frac{d\psi_D}{dt} + r_D i_D \\ 0 &= \frac{d\psi_Q}{dt} + r_Q i_Q \end{aligned} \quad (16)$$

The flux linkage in terms of winding currents are as follow:

$$\begin{aligned} \psi_d &= -L_{\sigma d} i_d + L_{ad} (-i_d + i_e + i_D) \\ \psi_q &= -L_{\sigma q} i_q + L_{aq} (-i_q + i_Q) \\ \psi_e &= L_{\sigma e} i_e + L_{ad} (i_e + i_D - i_d) \\ \psi_D &= L_{\sigma D} i_D + L_{ad} (i_e + i_D - i_d) \\ \psi_Q &= L_{\sigma Q} i_Q + L_{aq} (i_Q - i_q) \end{aligned} \quad (17)$$

Electromagnetic torque expression

$$m_e = \psi_d i_q - \psi_q i_d \quad (18)$$

Where

u_{sd}, u_{sq} are the instantaneous direct- and quadrature-axis components of the stator voltage, respectively, expressed in the rotor reference frame.

i_{sd}, i_{sq} are the instantaneous direct- and quadrature-axis components of the stator current, expressed in the rotor reference frame.

$L_{\sigma d}, L_{\sigma q}$ are the leakage inductance on the d – axis and q-axis.

L_{ad}, L_{aq} are the common mutual inductance on the d – axis and q-axis.

$L_{\sigma D}, L_{\sigma Q}$ are the leakage inductance of direct and quadrature windings.

The equations (7), (15), (16) and (17) denotes the synchronous machine mathematical model in the dq0 rotor reference frame. As observed, this model consists of differential equations with constant coefficients, since self and mutual inductances do not vary by rotor position θ_r .

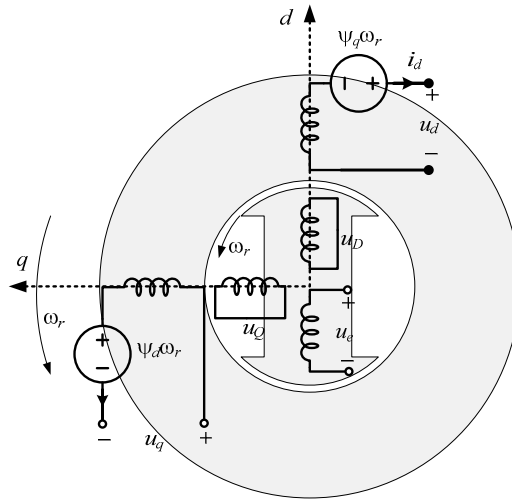


Figure 2. Schematic representation of the two-phase synchronous machine in dq0 reference frame.

Since the zero-sequence component is neglected in the generator analysis, the two-reaction representation is simplified, thereby facilitating the formulation of the generator equations.

4. Case Study: Simulation of Seta Hydropower Plant Under Different Power System Scenarios.

The northeastern part of Albania known as the Dibra region spans both sides of the Drini i Zi Valley, which hosts one of the country's major river systems. Eight small hydropower plants (SHPs) in the Dibra area link to the main power grid via 110/35 kV transmission lines. All SHPs considered in this study are of the water-diversion type, i.e., run-of-river (RoR) plants. This section analyzes a representative medium-capacity generating unit, namely the Setës Hydropower Plant, focusing on operational issues observed in the electrical power system. Figure 4 presents the single-line diagram of the Dibra regional power system used for the analysis.

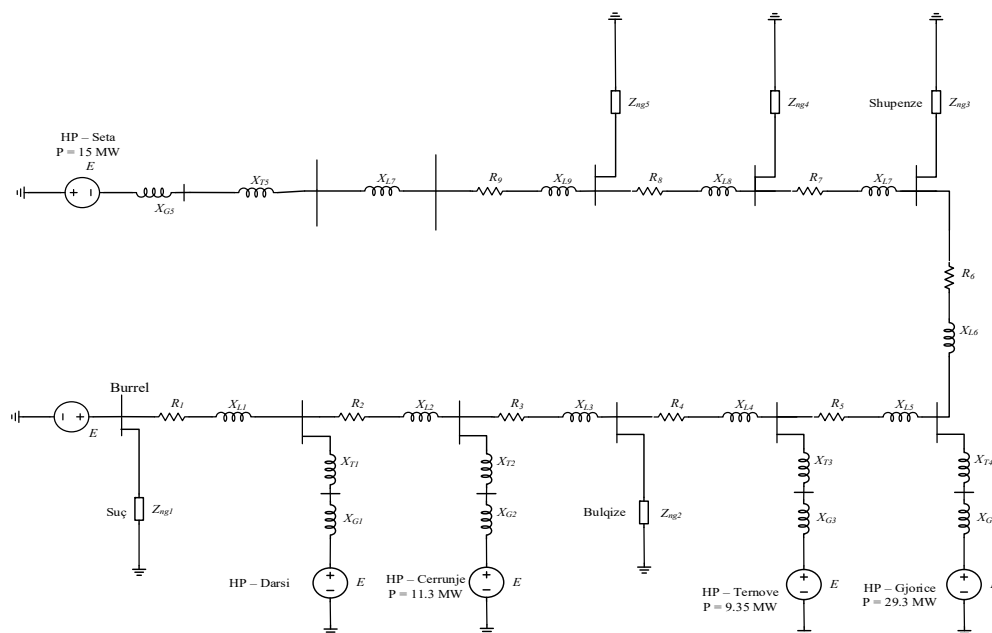


Figure 4. Single-line diagram of the region of power system analysis.

The voltage profile of Seta bus bars monitoring for 24 h are shown in Figure 5.

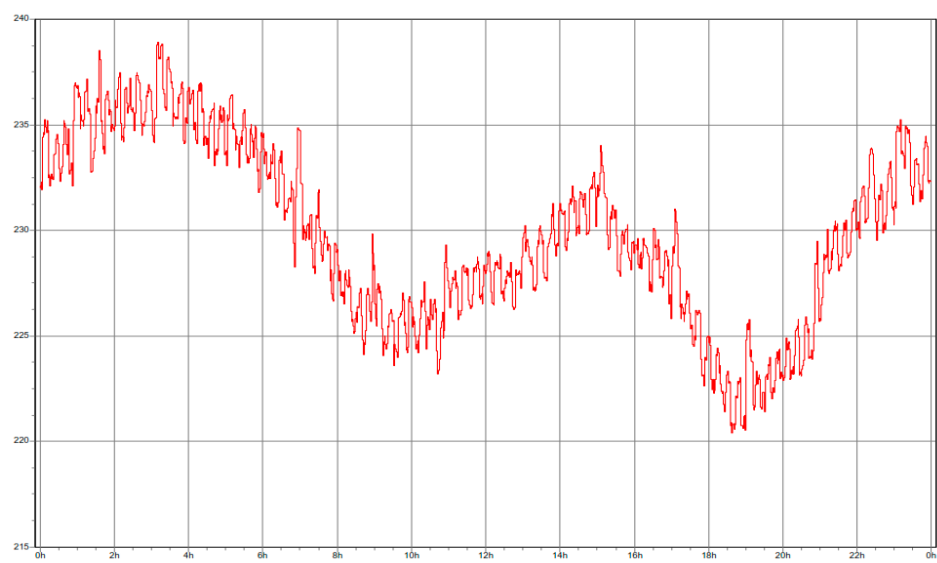


Figure 5. The voltage profile of Seta bus bars monitoring for 24 h.

To assess the dynamic stability of the generators at the Seta Hydropower Plant, transient simulations were carried out using a comprehensive system model, assuming operation at rated capacity. The Seta Hydropower Plant is represented by three generating units, each equipped with its respective control systems. The excitation systems are modeled using standard block-diagram representations of static excitation schemes commonly adopted in power system studies. For each analyzed scenario, four graphical results will be focused on:

- a. Rotor angle (degrees)
- b. Slip of synchronous generator (p.u.)
- c. Active power of synchronous generator (p.u.)
- d. Voltage bus profile (p.u.)

All simulations are conducted over 10 seconds, with the fault occurring at $t = 1$ s. In the table 2 are shown the data of synchronous generator installed at Seta hydropower plant.

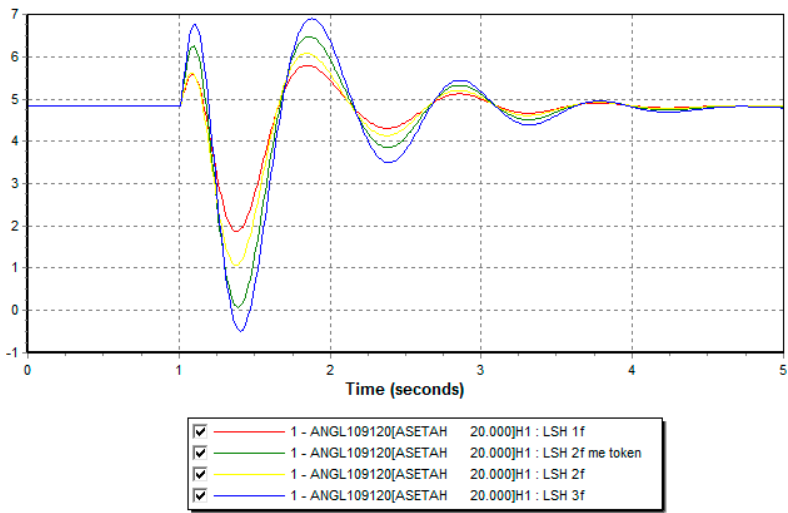
Table 2. Data of synchronous generator installed at Seta hydropower plant.

Discription	Parameter	Value
Rated power	S	6200 kVA
Rated voltage	V	6000 V
Rated current	I	597 A
Synchronous speed	n_s	500 rpm
Phase stator resistive winding	r_s	0.015 p.u.
Current ratio	SCR	0,73
d-axis transient reactance	x'_d	0,25 p.u.
q-axis synchronous reactance	x_q	0.5 p.u.
d-axis synchronous reactance	x_d	0.85 p.u.
Stator leakage reactance	x_l	0.1 p.u.
q-axis transient reactance	x'_q	0.15 p.u.
d-axis subtransient reactance	x''_d	0.15 p.u.
q-axis subtransient reactance	x''_q	0.2 p.u.
Negative reactance	$x^{(2)}$	0.06 p.u.
zero reactance	$x^{(0)}$	0.1 p.u.
q-axis open-circuit subtransient time constant	T''_{q0}	0,05 s
d-axis open-circuit subtransient time constant	T''_{d0}	0,03 s

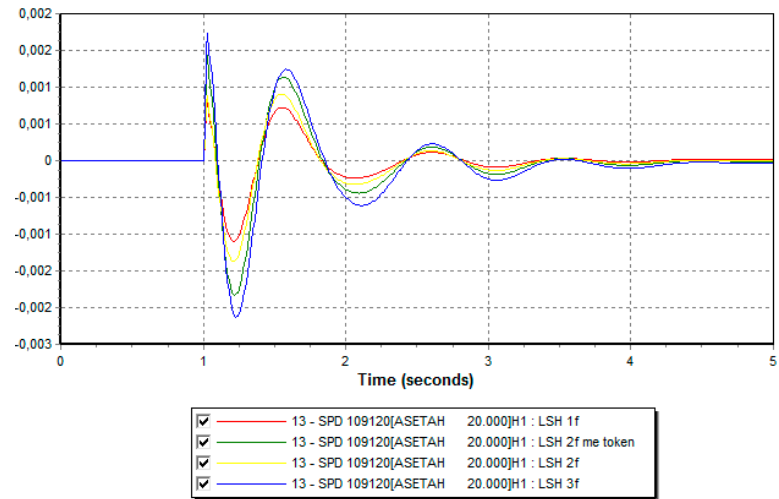
d-axis open-circuit transient time constant	T'_{d0}	5 s
Negative time constant	T_a	0,15 s
Inertia constant	H	1.3 s

4.1. Analysis of Fault Scenarios

This section presents simulation results for the synchronous generator under different fault scenarios occurring on the transmission line. Four different fault cases were simulated: three-phase, two-phase, two-phase-to-ground, and single-phase short circuits, all with clearing time $t = 0.02$ s. Figure 6 illustrates rotor angle variations, and slip of synchronous machine. It has been shown that the most severe condition occurs during a three-phase short-circuit fault, which results in significant rotor angle deviations.



(a)



(b)

Figure 6. (a)-rotor angle (b)-slip of synchronous generators under faults conditions.

Additionally, Figure 7 depicts the active power and voltage level. Figure 7a shows the data obtained from the simulation in the case of 1, 2 and 3-phase short circuit of active power as well as the voltage change on the bus bars of the synchronous generator.

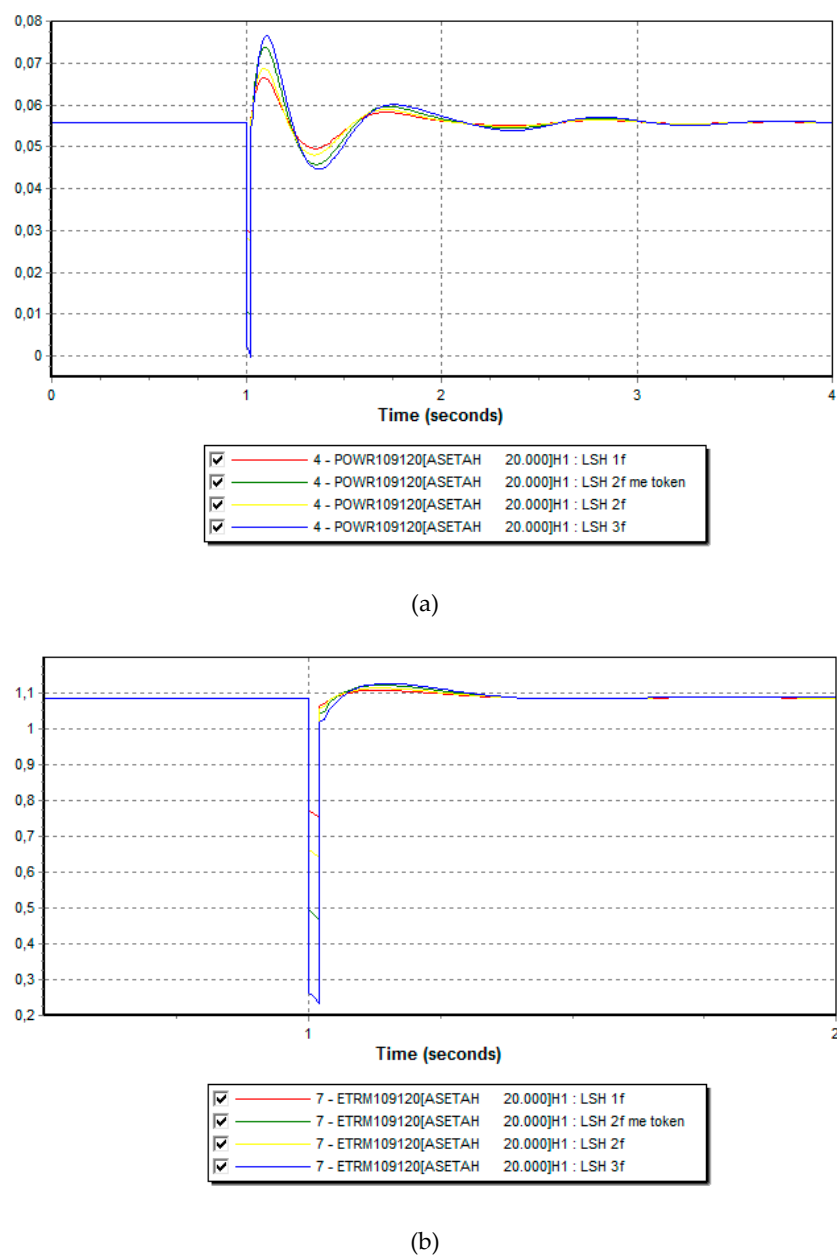
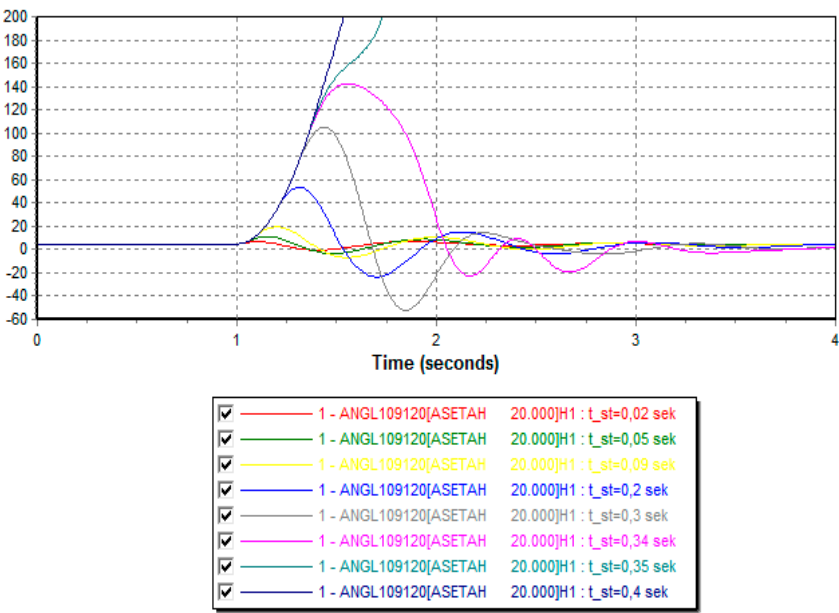


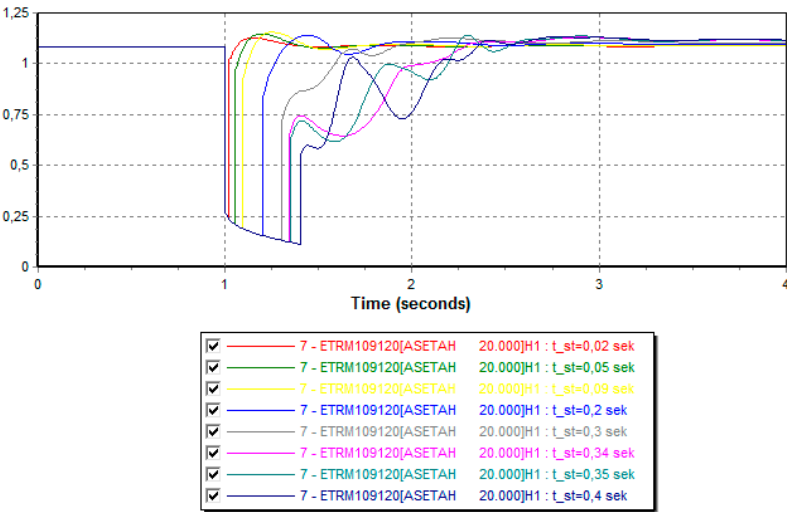
Figure 7. (a)-Active power (b)-bus bars voltage profile under different faults.

4.2. Determination of Critical Clearing Time

To determine critical clearing time, three-phase Short-circuit faults at the 110 kV bus bars were simulated by increasing fault duration time. Figure 8 shows rotor angle variation for different clearing times. The critical clearing time is identified as 0.34 s.



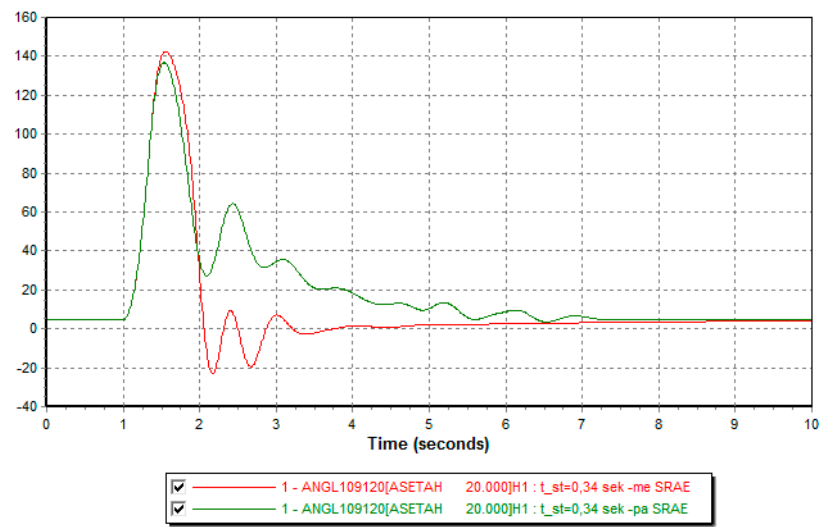
(a)



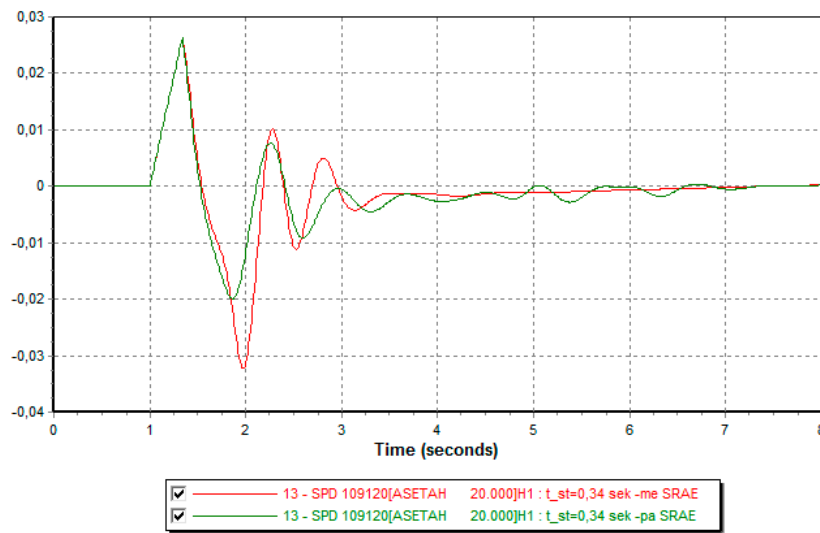
(b)

Figure 8. (a) - Rotor angle (b) - bus voltage profile under different clearing times.

Further simulations compare generator operation with and without excitation regulator. Figures 9 and 10 depicts rotor angle, speed, active power, and voltage. Results clearly indicate reduced transient duration when the excitation regulator is active.

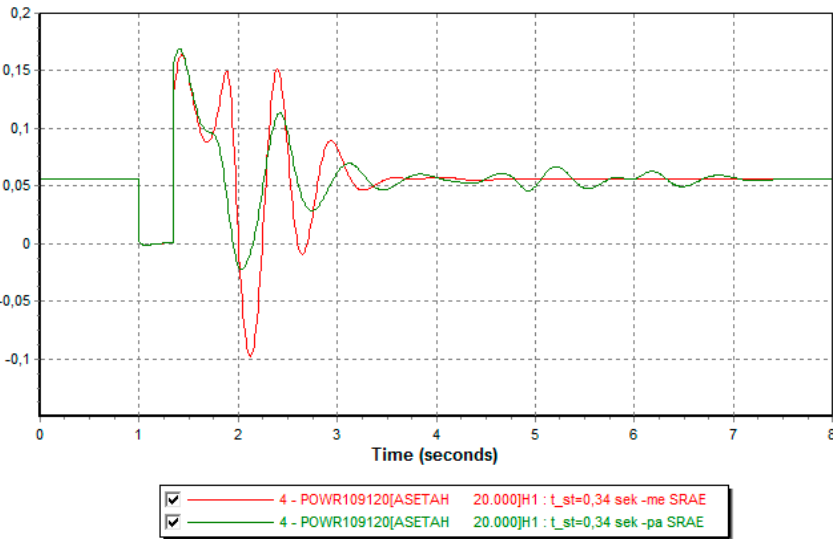


(a)

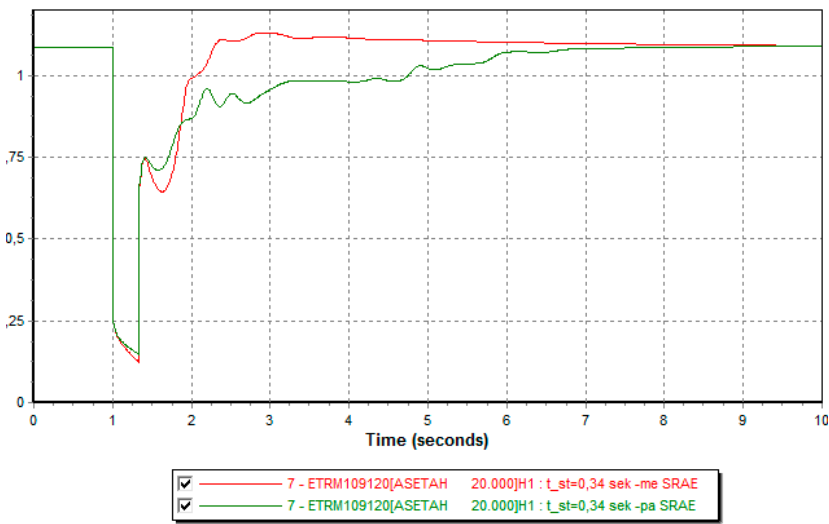


(b)

Figure 9. (a) - rotor angle (b) slip of synchronous generator during fault



(a)



(b)

Figure 10. (a) - active power (b) - bus voltage with a three-phase short-circuit fault.

5. Summary and Conclusions

Monitoring of the power grid reveals that voltage levels exceed allowable limits and experience fluctuations. Due to the radial structure of the network, frequent line outages occur, especially when generating units operate at rated capacity. Transmission lines operate over loaded, activating protection systems. Voltage fluctuations and frequent outages disrupt generator operation and may cause damage. To mitigate these effects, the following measures are recommended:

- Construction of new transmission lines to transform the radial network into a ring structure.
- Mandatory use of excitation regulators for generating units.
- Establishment of a real-time operation center.
- Implementation of real-time diagnostics for efficient generator utilization.

Author Contributions: Conceptualization, all authors; methodology, all authors; validation, B.L., and A.E.; investigation, K.D.; data curation, A.B. and A.P; writing—original draft preparation, A.B. and K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Polytechnic University of Tirana, Albania.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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