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# Transient Stability Analysis on Modified IEEE 14-Bus System

Ermin Šunj[1], Ammar Arpadžić[1], Mirza Šarić[1]
[1]International Burch University, Sarajevo, Bosnia and Herzegovina
ermin.sunj@stu.ibu.edu.ba
ammar.arpadzic@stu.ibu.edu.ba
mirza.saric@ibu.edu.ba

*Abstract* – **Power system stability represents an important condition of the safe and efficient operation of the electric power system. This paper presents the transient stability analysis for the case of the new generator grid connection. The analysis is performed on a modified IEEE 14-Bus test system. In total, two cases were analysed. In the first case, the analysis with the maximum installed power of the generator (250 MW) is carried out, while in the second case, the analysis is performed using the optimal generator ratings (75 MW) using the DIgSILENT PowerFactory software. The transient stability analysis was carried out under the three-phase symmetrical faults and the N-1 criterion requirements. The results indicate that power system large disturbances significantly influence system operation and characteristics. This paper demonstrates the importance of transient stability analysis, which is an important part of power system studies and must be included in generator grid connection approval.**

***Keywords - active power, IEE 14-Bus system, N-1 criterion, reactive power, rotor angle, transient stability.***

## 1. Introduction

The analysis of transient stability of electrical energy system adds up to the problem of examining the behaviour of electrical energy system under large disturbances. In the case of the three-phase short circuit fault the active power at generator terminals becomes virtually zero, which results in large unbalance at the shaft of the generator since the mechanical power remains constant. This gives the rise to rotor angle oscillations which might cause power system instability.

Usually, the system stability is investigated for three phase short circuit fault because in this case, the largest fault current is developed, which represents the most critical case. Considering the fact that the subtransient time period is very short (0,05 s) and not long enough to analyse transient stability (one rotor oscillation usually lasts around 1 s), transient stability analysis is performed in transient period [1].

The system stability is very important for the electric power systems. If the instability of the system results in the power outage then the system operators have to pay the compensation. This paper is important due to

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mentioned reason since it shows under which conditions the system will become unstable and under which conditions it will return to the stable state.

## 2. Literature review

This topic has received significant attention in the past but continues to be a relevant research topic. For example, a new technology for transient stability in distribution systems with distributed generation which showed the significance of considering the branches representation in distribution system and the benefits of applying single-pole switching for reclosers in distribution system is proposed in [2]. This proposed technology is appropriate for unbalanced networks. Authors demonstrated how successful single-pole switching is in terms of transient stability in the event of single-phase short circuits, which dominate in distribution systems.

Reference [3] investigates the transient stability of induction generators in wind farm applications under symmetrical three phase fault conditions. This paper highlighted the importance of transient stability analysis since the test system was determined to be unstable for connection of the wind farm implemented with induction generator.

Study in [4] demonstrated transient stability of an unbalanced distribution system with distributed generation with thermal turbine as a primary machine. The three-phase, two phase-to-ground, phase-phase and phase-to-ground faults in different locations of the feeder were applied in order to determine critical clearing fault time. The analysis showed that the highest critical clearing fault times have been found to short-circuit applied in distributed generation bus, which differs from what is normally found in studies of transmission case.

The research represented in [5] shows a transient stability analysis on Sarawak's Grid data system in order to prove the theory that the critical clearing time (CCT) of fault occurrence between a transmission line near and far from the generator. It was proved with the application of the same three-phase fault near and far from the generator. The CCT near the generator was 0.105 s, while the CCT far from the generator was 0.175 s. This theory is proved as well in the [6] where the authors performed the transient stability analysis on the IEEE 14-Bus System using dynamic computation for power systems (DCPS). The dependence of the type and the installed power of the distributed generator for the determination of the CCT was demonstrated in [7].

Steady state and transient analysis of real Italian distribution network with an embedded synchronous generator was presented in [8]. Authors analysed steady state voltage variation succeeding disconnection of distribution synchronous generator (DSG) and steady state voltage regulation with taking into consideration minimum and maximum demands.

Authors in [9] made a research on the influence of synchronous generator, asynchronous generator and inverter (all interfaced distributed generation) on power system transient and voltage stability. In the paper they demonstrated that the synchronous generator interfaced DGs enlarge the rotor speed deviation frequency and when a fault happens in the system, they improve the voltage drops in the buses.

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The investigation of the generators' dynamic response in the Nigeria 330-kV transmission network when a balanced three-phase fault is applied was done in [10]. Their research demonstrated that in the Nigeria 330-kV transmission network exist several critical buses and lines and when the balanced three-phase is applied to those buses and lines the system loses its synchronism.

The behaviour of the rotor angle is performed by the data acquisition via the phasor measurement unit (PMU) of voltages and currents. Also, the study in [11] presented the prediction of the system instability.

The impact of the distributed generation on power system transient stability is showed in [12]. The results revealed the impact of the distributed generation on the dynamic of the electric power system highly depends on the technology of the distributed generation.

Authors of [13] presented the three phase fault at one bus of the test 6-bus system. The fault happened after 0.3 seconds and it was cleared at 0.5 second. They presented the oscillations produced by the rotor of the generator and return to the normal state after the fast reaction of the protection.

A study in [14] shows the operation of the power system stabilizer that is built-in into one of the three generators, how it improves the clearance of the three phase fault at one of the lines in the transmission network and how it returns the system into stable state. The test system consists of three generators and seven buses.

Based on the evidence from the past research in this area, it can be concluded that power system transient stability continues to be very important are of research. In particular, this topic is important and relevant for practical engineering problems and situations, encountered by utility engineers on the daily basis.

## 3. Theoretical background

Stability of electrical energy system can be defined as an ability of a system to stay in the limits of normal behaviour after the occurrence of the fault. The system instability can be expressed differently regarding the system configuration and operation state. The system stability is traditionally attached to the maintenance of the machine synchronism i.e. rotor angle stability, although with the increase of electrical energy systems and the growth of consumption the voltage stability is becoming significant.

Two crucial concepts are needed for the comprehension of the transient stability: (i) the swing equation and (ii) the power-angle relationship. These concepts can be employed together to describe the equal are criterion.

### 3.1 Swing equation

Disturbances normally happen at frequencies greatly below the system size and some parts could be presented as passive components. Generator dynamics need to be represented. Important quantities are inertia, the mechanical torque $\tau_m$ from prime mover and the electromagnetic torque $\tau_e$ from the alternator. If $\tau_m$ is greater

DOI number: 10.14706/JONSAE2020212

than $\tau_e$ the resultant will be a positive accelerating torque $\tau_a$. The equation of motion of a rotating mass from Newton's Second Law of motion is

$$J\frac{d^2\theta_m}{dt^2} = \tau_a = \tau_m - \tau_e \tag{1}$$

In order to account for various pole numbers and thus different generators' speeds in the system and taking into account the fact that $\theta_m = \omega_m t + \delta_m$ and $\omega_m = d\theta_m/dt$, all speeds can be represented on a constant basis in relation to 50 Hz frame:

$$J\omega_m \frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \tag{2}$$

The inertia constant J varies considerably among generators of different sizes. Inertia quantity H should be defined as well since the inertia constant depends on the real size of the generator. Inertia quantity is defined as:

$$H = \frac{1}{2}\frac{J\omega_m{}^2}{VA_{base}} \tag{3}$$

$$\frac{2H}{\omega_m}\frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \tag{4}$$

Taking into account that

$$\frac{\delta_m}{\omega_m} = \frac{\delta}{\omega_s} \tag{5}$$

where $\delta$ is in electrical radians and $\omega_s$ is the frequency of the system in electrical radians per second, swing equation can be expressed as:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{6}$$

It is necessary that rotor angle oscillates around equilibrium point if the system is transiently stable while the disturbance is occurring. The machine is transiently unstable if the rotor angle grows indefinitely since it will not be able to reach the new equilibrium state [3].

### 3.2 Power-angle relationship

Power-angle relationship of a generator which is connected to an infinite bus via transmission system can be expressed as:

$$P_e = \frac{E'E_b}{X_t} \sin\delta = P_{max} \sin\delta \tag{7}$$

From (7) it can be concluded that the maximum amount of transmitted power depends on the line reactance and terminal voltages [3].

## 4. Problem definition

In the Section 5 of this paper, both the stable and unstable system scenarios are shown and discussed. The two cases were analysed. In the first case the system fails to return to the stable state even though the system protection clears the fault. The quick reaction of the protection helps the system to return to the stable state in the second case, while the untimely reaction of the protection cannot help the system to return to the stable state.

The N-1 criterion is included in order to provide additional security of the grid. It represents the ratio of the power that flow through two adjacent lines at one bus in a simple grid. The aim of the N-1 criterion is that system can work without grid elements being overloaded if one line falls out [15]. In this paper the N-1 criterion is used in determining the maximum power that can be installed in the grid such that no line is overloaded if one of them falls out. The N-1 is executed for the transient stability analysis i.e. short circuit fault simulation, so that the system will not be in the breakdown if one line falls out.

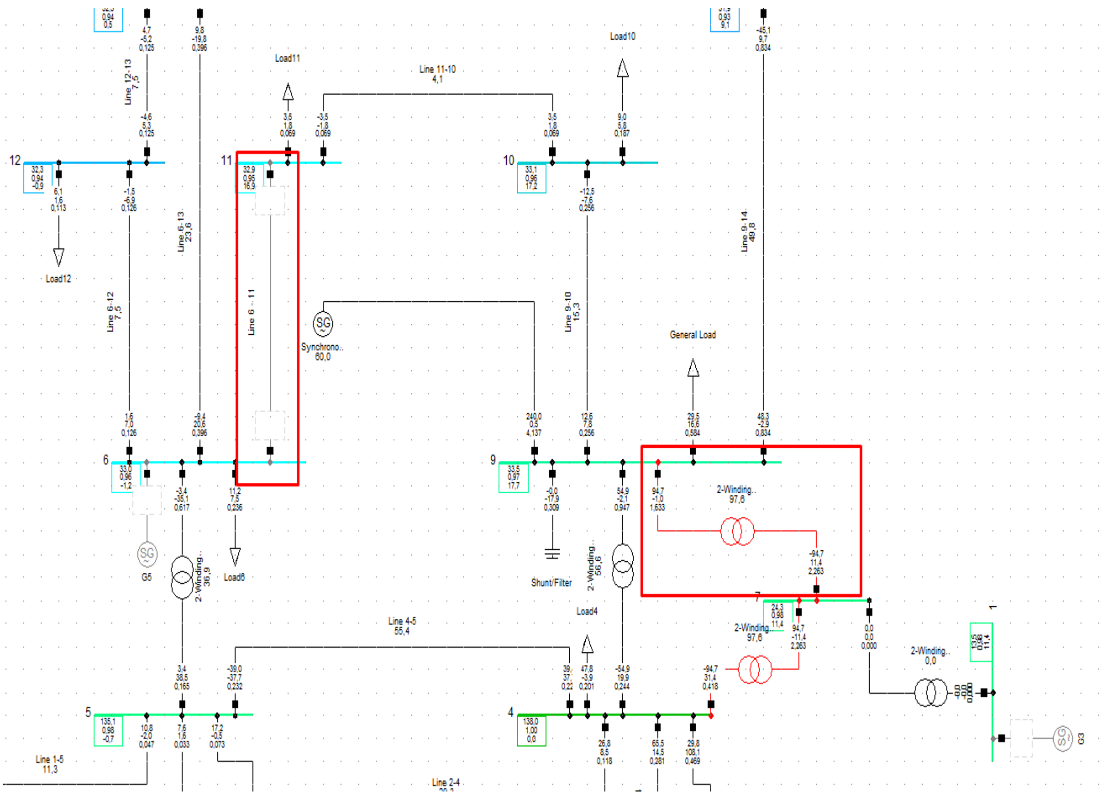


**Figure 1.** The N-1 criterion

## 5. Results and discussion

### 5.1 The test system

The connection of the generator is performed on the modified IEEE 14-Bus system. The IEEE 14-Bus system has five generators, but for the case of analysis those five generators were disconnected (grey-coloured on Figure 2) and only one generator is connected. The system is consisted from 14 buses that are connected in a way that each bus has one or more lines that either conduct in or conduct out of it. Therefore, if one line falls out of service at specific bus, that bus will not be without power supply. In this paper the bus 9 is taken as the one to which generator will be connected. The generator has power of 250 MW, which is the maximum power that the analysed grid can handle in order to satisfy the N-1 criterion. Two cases are analysed. The first case refers to the inability of the grid to become stable after the technical criterion of 0.05 seconds after the fault and 5 seconds as well. The second one refers to the ability of the grid to become stable after the technical criterion of 0.2 seconds after the fault and the inability to do that after 5 seconds.

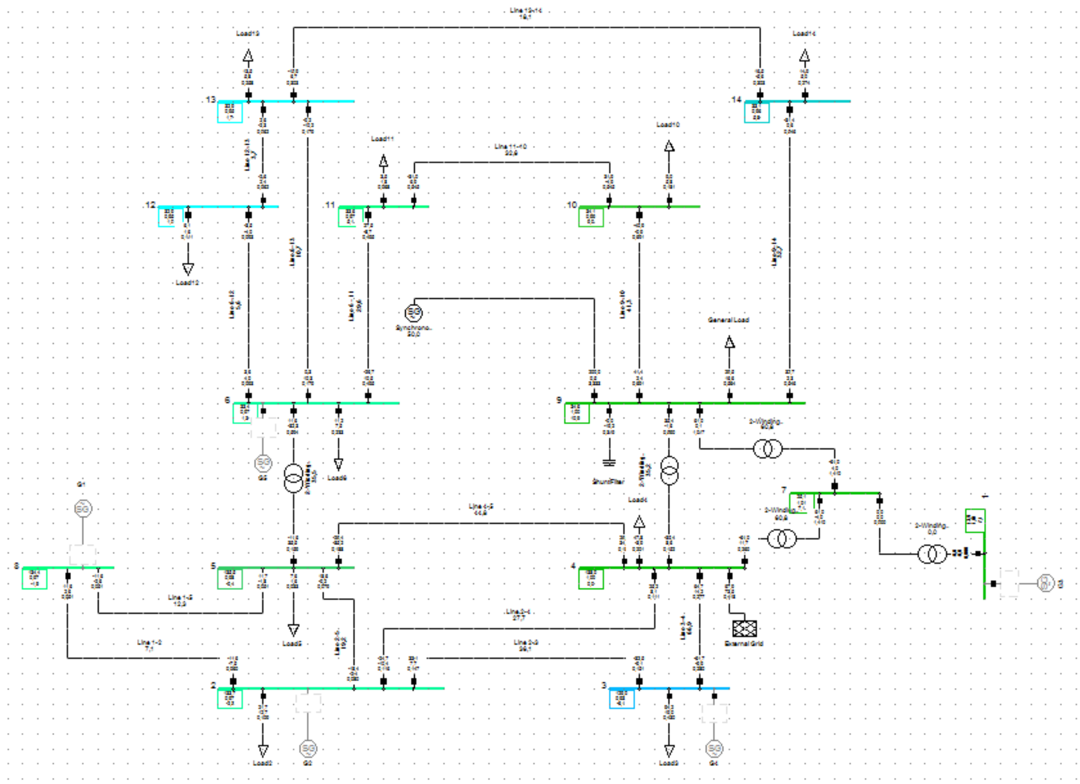

**Figure 2**. Modified IEEE 14-Bus system

### 5.2 The case I – Action of protection on the maximum installed power of 250 MW in 0.05 s and 5 s

As it was mentioned earlier, the generator is connected to the Bus 9 and the three-phase short circuit fault is simulated at line 6-11. The three-phase short circuit fault is the strongest short circuit in the system and its strength represents the strength of the system. The longer the fault is the more chances that the generator will not be stable anymore. Acting on the fault in short period of time could make the system to get back to the stable

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state. If power system components are pushed to the limit in regard to the withstanding of huge amount of power then the chances of getting back to the normal state are smaller even if the switch acts quickly. Figures 2-6 shows the generator characteristics after the switch reaction of five seconds.

Figure 3 shows the active power that is being delivered to the system by the generator. It can be seen that the fault happened at the first second and that the active power is not constant as it was before the first second. Also, it can be seen that the fault lasted for five seconds, until the sixth second, and that the system was not stable during the duration of the fault. After those five seconds the system could not manage it to return to the stable state.

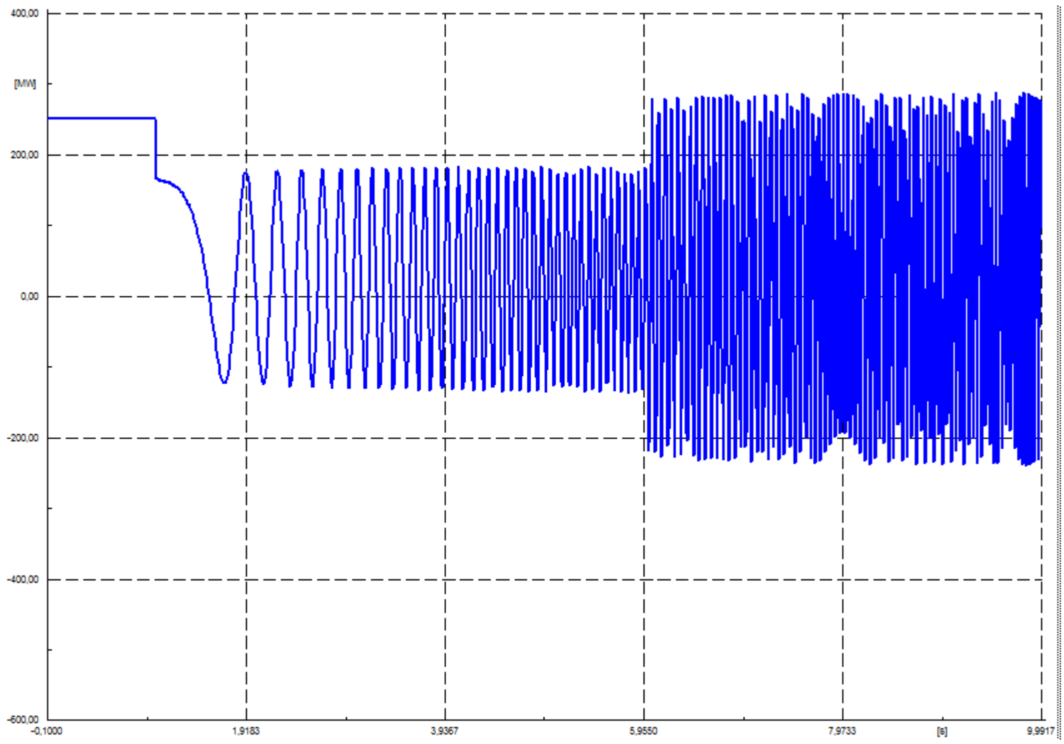


**Figure 3**. Active power of the 250 MW generator

From the Figure 4 it can be seen that the voltage was 1.02 p.u. during the normal functioning of the system. It fell below 0.35 p.u. after the fault and variated up to 0.85 p.u. during the fault. The system did not return to the stable state after the fault and the voltage variated between 0.35 and 1.30 p.u.

Journal of Natural Sciences and Engineering, Vol. 2, (2020)
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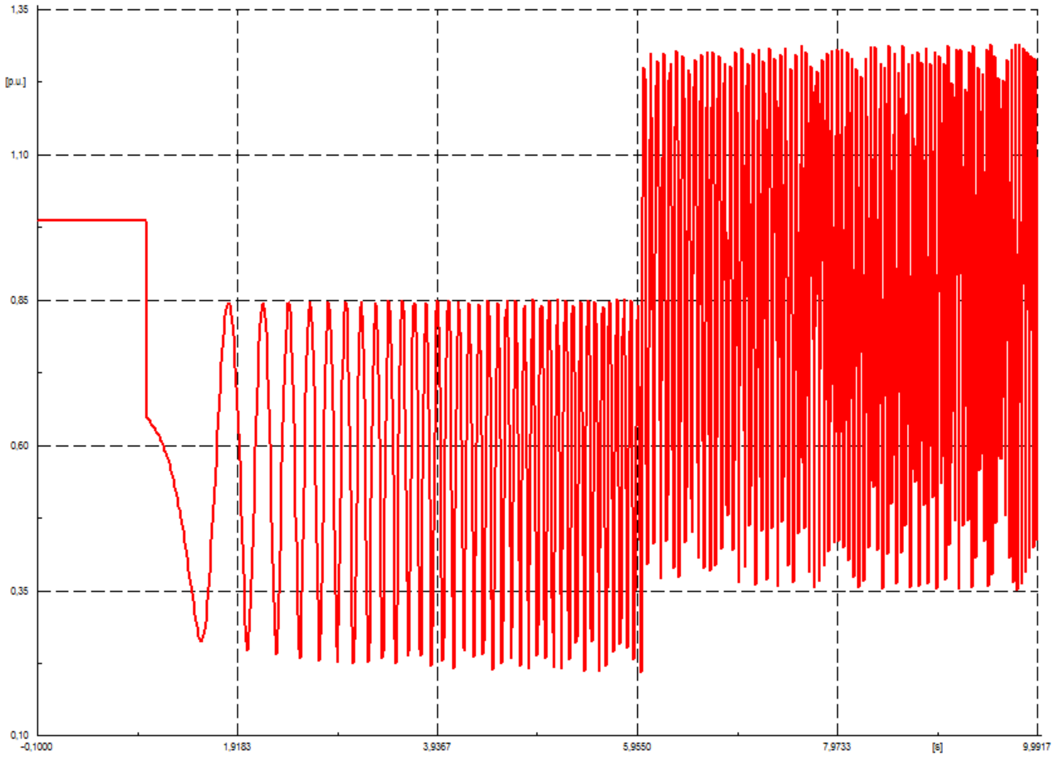


**Figure 4**. Voltage at the terminals of the 250 MW generator

Figure 5 demonstrates the reactive power (0.5 MVAr) that generator delivers to the system. The fault happens after the first second and it lasts for five seconds. After the sixth second the system was not stable anymore. During that time the generator is supplied by the reactive power which is in range from -130 to 0 MVAr.

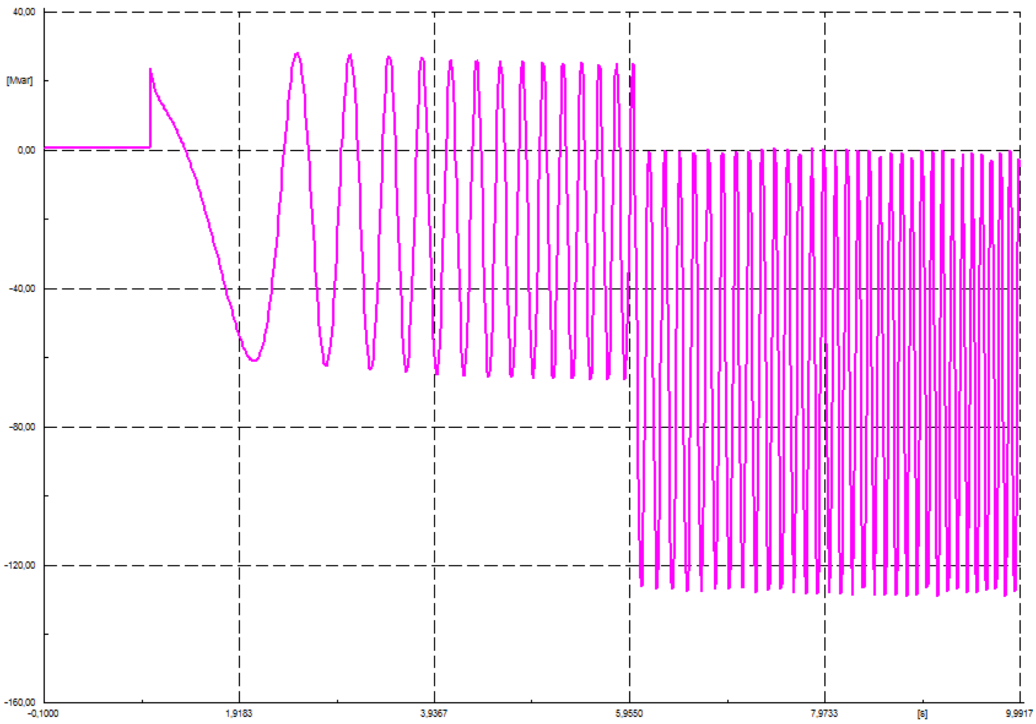


**Figure 5**. Reactive power of the 250 MW generator

The rotor angle, presented in Figure 6, starts changing after the first second and it variates between -180 and 180 degrees. After five seconds the switch did not have any effect on the rotor angle. The system was not able to return to the normal state which implies that the longer the fault lasts the chances for the rotor angle to return to the normal state are smaller.

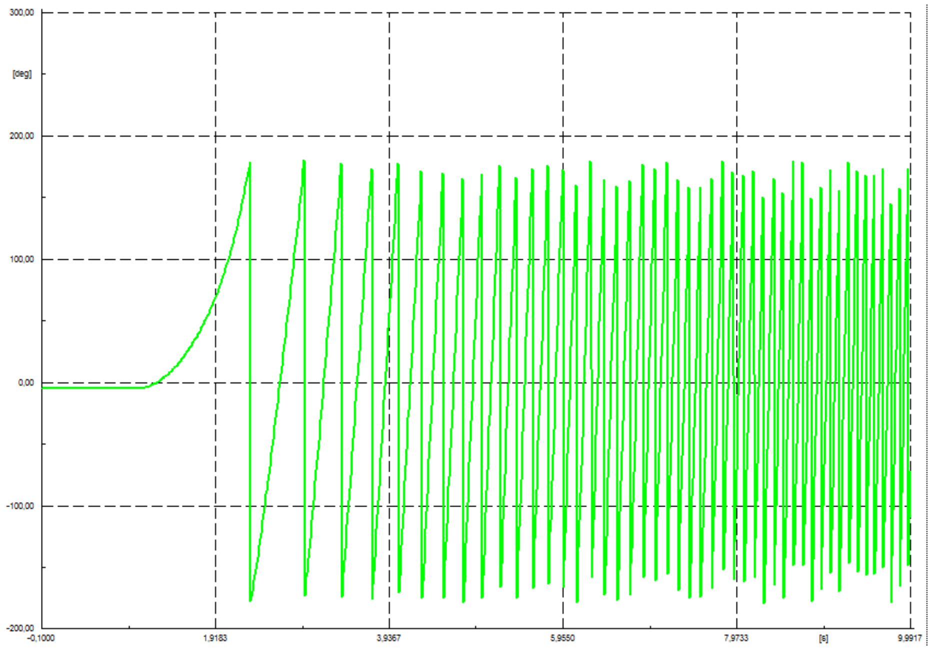


**Figure 6**. Rotor angle of the 250 MW generator

Figure 7 combines the graphs of active and reactive power, the rotor angle and the voltage. It can be seen that the short circuit happened at first second and it lasts to the sixth second when the protection starts working. Due to the huge power of the generator and the long duration of the fault the system was not able to return to the normal, stable state.

Journal of Natural Sciences and Engineering, Vol. 2, (2020)
DOI number: 10.14706/JONSAE2020212

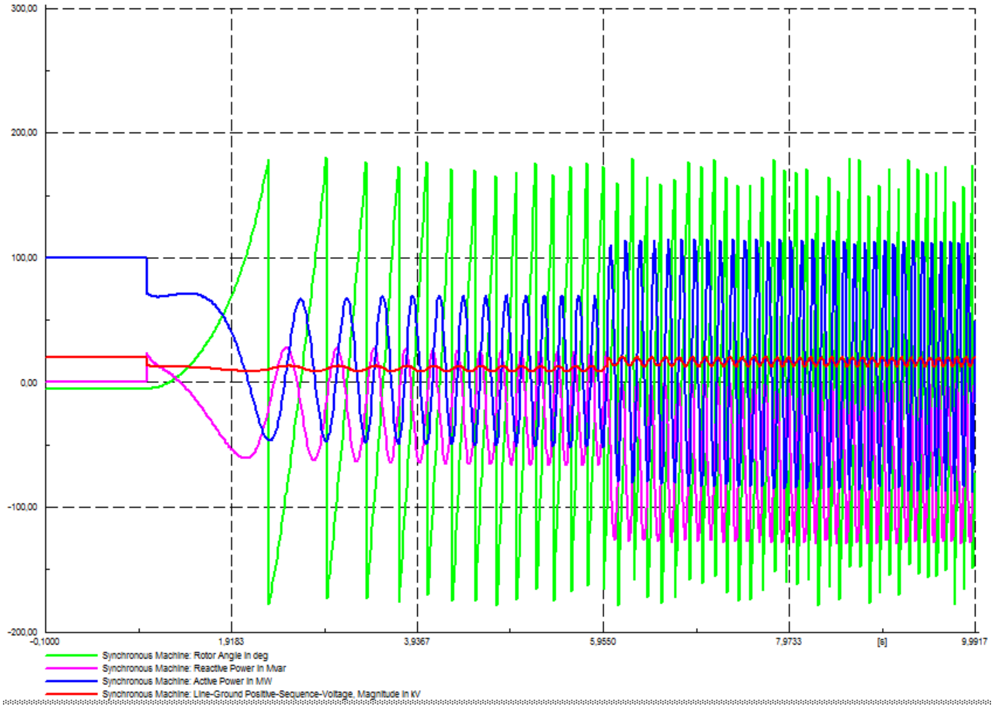


**Figure 7**. All analyzed characteristics of the 250 MW generator for the 5 seconds fault

Figure 8 represents the system when the protection works for 0.05 seconds. As it was mentioned earlier the system should return to the stable state after the quick action of the protection, but in this case the grid is heavily loaded and the generator delivers the maximum amount of power for N-1 criterion. The protection could not help generator to return to the normal state. It can be seen from Figure 7 that the protection quickly reacted at the first second but the system did not return to the stable state.

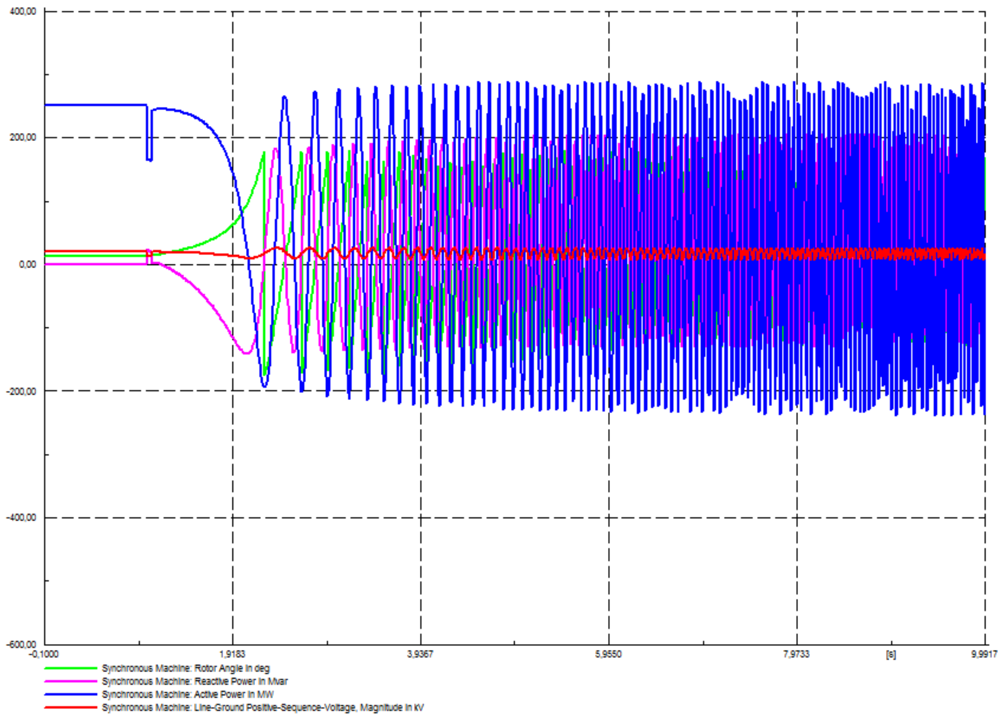


**Figure 8**. All analyzed characteristics of the 250 MW generator for the 5 seconds fault

Journal of Natural Sciences and Engineering, Vol. 2, (2020)
DOI number: 10.14706/JONSAE2020212

**5.3 The case II – Action of protection on the optimal installed power of 75 MW in 0.2 s and 5 s**

In the case II the power delivered to the system by the generator amounts 75 MW. This is the optimal amount of power for the analysed system to work properly. The fault is simulated in the first second and it lasts for five seconds. Then, the protection starts working and it disconnect the line affected by the short circuit. Since the duration of the fault is very long the system could not return to the normal state, which is visible in Figure 9. The voltage, rotor angle, active and reactive power were varying during and after the fault. This case relates to the theory of transient stability where it is said that one of the conditions for the system to return to the stable state is the time of the switch operation. Chances for the system to return to the stable state grow with the quicker response of the switch. This can be seen from this case where the switch operates for too long and the system is not stable.

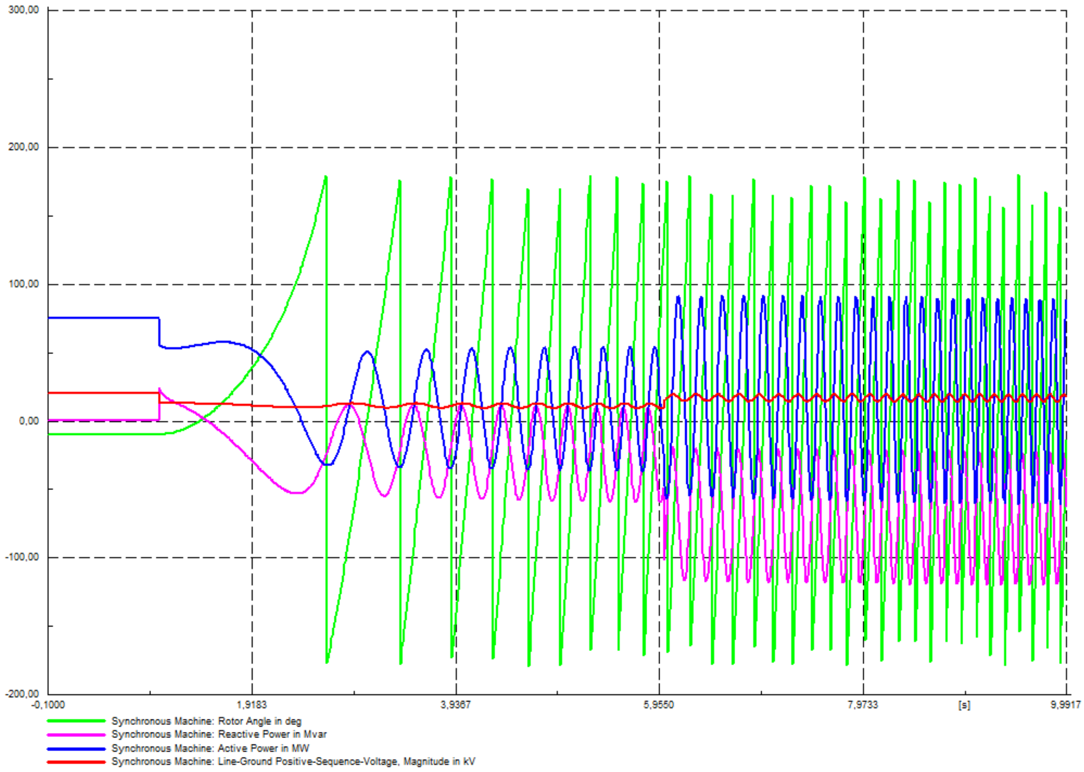


**Figure 9**. The action of the switch after 5 seconds fault

Figure 10 shows the active power after the fault happened at the line 6-11. The fault is happening in the first second and the significant drop of the power is visible. The protection acts after 0.2 seconds after the fault happened. This enables the generator to return to the stable state and to start generating approximately the same amount of power as it was generating before the fault i.e. the system has returned to the stable state.

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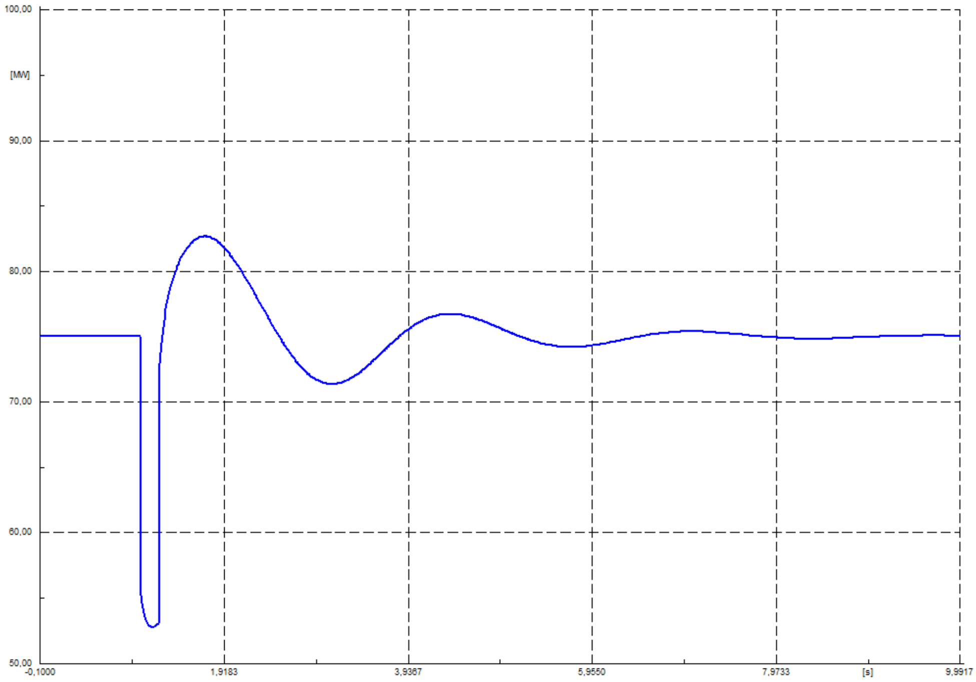


**Figure 10**. Active power of the 75 MW generator

Figure 11 demonstrates the voltage before, during and after the fault. The fault that happened at the line 6-11 is followed by the huge voltage drop. The return of the voltage to the value similar to the one before the fault was due to the quick response of the switch (0.2 s), disconnection of the line 6-11 and the allocation of the power to the other lines. This means that the system has returned to the stable state.

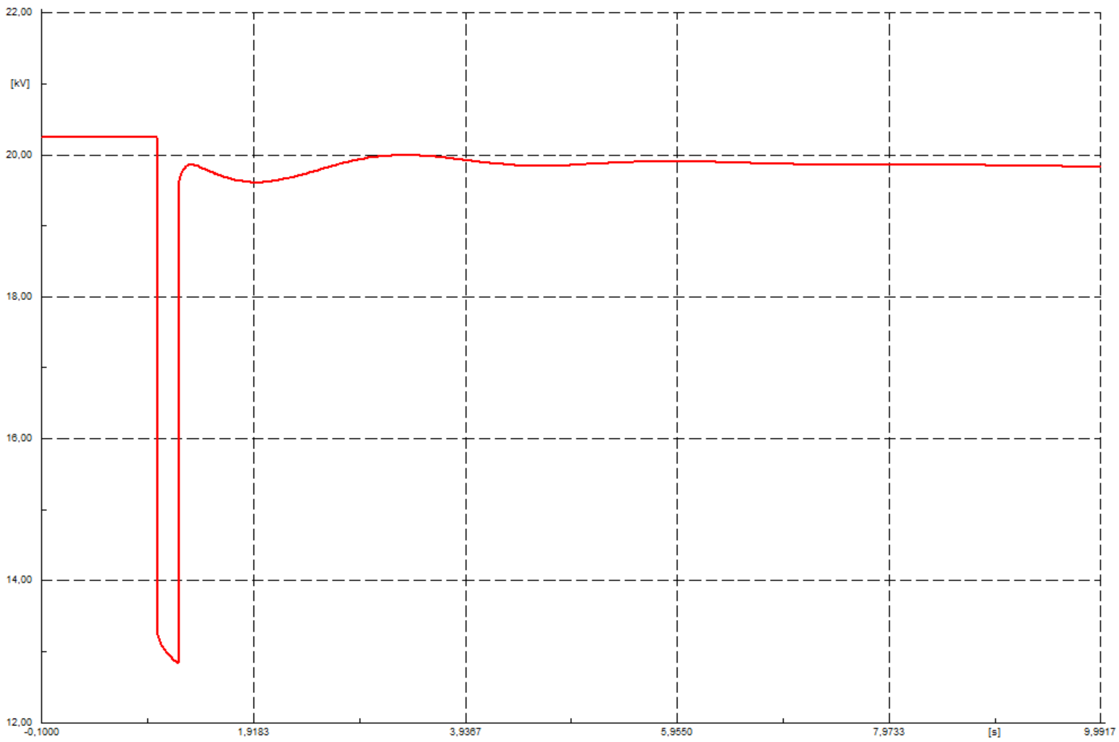


**Figure 11**. Voltage of the 75 MW generator

Journal of Natural Sciences and Engineering, Vol. 2, (2020)
DOI number: 10.14706/JONSAE2020212

Before the fault the generator was producing 0.5 MVAr of reactive power and it was delivering it to the network. The fault at the first second has made the system unstable. During the fault the reactive energy was accumulated in the rotor. It is visible from the Figure 12 that the reactive power was almost constant after the quick response of the switch i.e. the system is again stable. The system would not be stable if the changes in value of reactive power were greater because that reactive power could not be substituted.


**Figure 12**. Reactive power of the 75 MW generator

Before the fault the generator had the rotor angle of approximately -10 degrees. The generator cannot have the same value of the angle even if it returns to the stable state. It can be seen from the Figure 13 that even if the rotor angle is not the same (around 0 degrees) as it was before the fault the system returns to the stable state due to the quick response of the protection (0.2 s).

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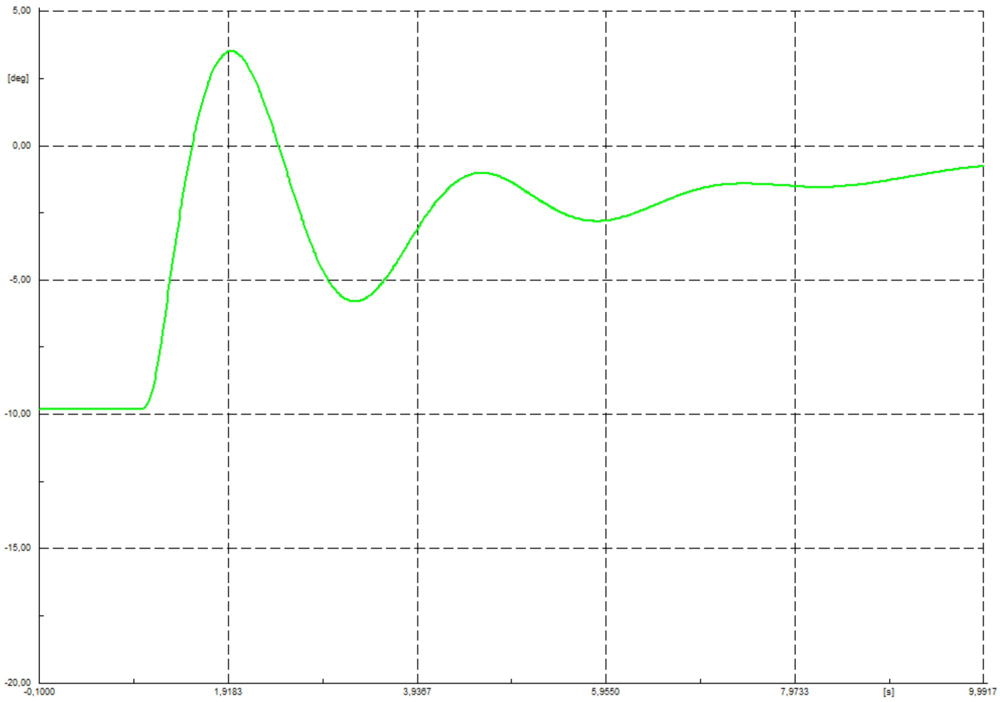


**Figure 13**. Rotor angle of the 75 MW generator

Figure 14 presents the clear overview of all basic parameters during and after the fault. The protection acted quickly after the fault happened, the network is strong and the system remains stable. The fault in the network is followed by the new value of the rotor angle. It is interesting to compare the reactive power from the Figure 9 and Figure 14. It can be seen from Figure 9 that the reactive power drops to almost -80 MVAr while it reaches -15 MVAr in the second case (Figure 14). For the cases similar to the second STATCOM devices are used in order to deliver the reactive power to the network or the protection has to act quickly so that the huge accumulation of the reactive power at the rotor of the generator is stopped. Otherwise, the system will be unstable.

Journal of Natural Sciences and Engineering, Vol. 2, (2020)
DOI number: 10.14706/JONSAE2020212

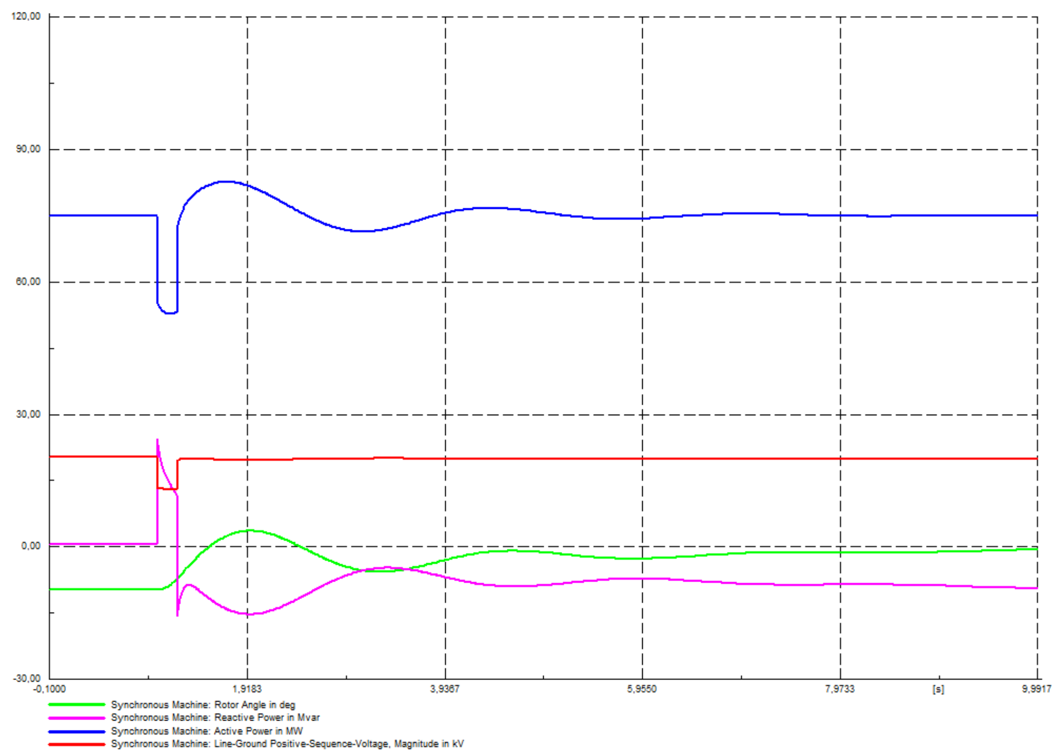


**Figure 14**. All analyzed characteristics of the 75 MW generator

### 5.4. Future research

One of the biggest disadvantages of the test network is the usage of only one generator with the maximum installed power of 250 MW without the return to the normal state. This maximum installed power is limited due to the line cross section. The distribution of electrical energy through the system would be better with more installed generators. It would reduce the loading of the lines and at the same time more power could be installed. Therefore, the occurrence of the short circuits at the vulnerable lines would not cause the serial line outages since lines would not be overloaded. The current system with the 75 MW generator can return to the normal state whenever fault occurs, but the problem would be the addition of new consumers. The system would not be able to return to the normal state with the power greater than 75 MW. This paper could be expanded for future research with the addition of devices that deliver reactive power to the network (STATCOM) in order to increase the optimal power of a generator. The topics of system stability are always important because with the improved network there is less chance for consumers to be without power supply if fault occurs. Therefore, power suppliers would have less or no expenses at all towards consumers since blackout would not happen or its duration would be reduced to minimum.

## 6. Conclusion

The goal of this paper is to present the transient stability analysis for the grid connection of the generator with the maximal installed power and the optimal installed power to the IEEE 14-Bus system. The N-1 criterion was used to determine the maximum power of the generator that can be connected (250 MW). The transient stability analysis demonstrated that the 250 MW generator remains in the instable state whenever the protection system clears the fault, as it was shown in Section IV for case A, when the switch acts once after the 0.05 seconds and once after 5 seconds. The reason is large power of the generator being supplied to the weak network. The generator of 75 MW (the optimal power) is connected to the network in the case II. The protection reacts after 0.2 and 5 seconds. The system returns to the stable state when the protection reacts after 0.2 seconds due to the installed power not being too big for the network and the quick reaction of the protection. The rotor angle then has new value and the system continues with the proper work. The system cannot return to the stable state when the protection acts after 5 seconds. The reactive power is becoming negative (the accumulation at the rotor of the generator) and the system lacks the devices that would stop the accumulation or devices that will deliver reactive power to the network. This paper showed that the system can work properly with the maximum power of the generator installed at the specific network, but it showed as well that the generator cannot maintain the stable state of the system when fault occurs. The connection to the grid of the generator with the optimal amount of power along with the properly designed protection will enable generator to work properly in the stable state since the system will disconnect the faulted lines.

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