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The Impact of Adding Solar Panels on The Wind Turbine Performance During Transient Disturbances

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ABSTRACT. *Recently electrical engineers look forward to replace the conventional power grid with a smart grid. This replacement requires massive changes, one of them is the integration of distributed generations and renewable energy sources in the distribution networks of the grid. These changes may affect the transient stability of the grid. In this paper, IEEE 9-bus system is used to perform transient stability analysis for a three-phase fault contingency. A 20 MW wind turbine was installed to study its performance and impact on the transient stability of the system. Then, a 3.6 MW PV station was added to study its impact on the wind turbine performance during the contingency. ETAP® 2016 software is used for simulation. The results show that the critical clearing time (CCT) of the system increases when the wind turbine is added and decreases when the PV station is installed. The impact of PV station on the wind turbine performance is not significant and it mainly affects the reactive power of the wind turbine generator after the fault is cleared.*

Keywords: Critical clearing time, IEEE 9-bus system, Photovoltaic panels, Rotor angle, Solar system, Transient stability, Wind turbine.

1. Introduction. Any power system is prone to disturbances during its operation such as; faults, large generation loss, load variations, and loss of critical branches [1]. These disturbances may lead to system instability under some circumstances [2]. Therefore, it is important to analyze the stability of the system during planning stage in order to prevent; huge economical losses, and service disconnection.

One of the important types of power system stability is the transient stability. Transient stability means the ability of the power system to regain its steady-state operation after being subjected to a large disturbance such as faults [2]. In order to analyze the transient stability of any power system, two terms are needed to be studied and they are; the rotor angle (or load angle), and the critical clearing time. The rotor angle (delta) means the P-V generator rotor angle with respect to the swing generator angle. The critical clearing time (CCT) means the maximum allowable time for the fault to be stayed before the system becomes unstable.

However, by moving towards a smarter grid, the distributed energy resources (DERs) become the point of interest. The DERs are small generators that are installed in the distribution networks in order to support the main conventional generating units economically and operationally. One of the important types of the DERs are the renewable energy sources (RES) such as; wind turbines and solar panels.
In this study, the performance and impact of a 20 MW wind turbine on the transient stability will be studied.
The impact of a 3.6 MW PV station on the wind turbine performance during a transient contingency will be studied. The impact of wind turbine and PV panels on the critical clearing time will be analysed.
Eftekharnejad, S., et al. have studied the effect of large-scale penetration of PV panels on both the transient stability and the steady-state operation of the system [3]. Simulations were done and their results show that by increasing the penetration of the PV panels in the system, the voltage dips that follows the disturbance will be larger [3].
On the other hand, Munkhchuluun, E., and L., Meegahapola have studied the impact of PV panels on the voltage stability [4]. Simulations were done and their results show that the integration of PV panels in the system enhanced the voltage stability especially when the grid is stressed [4].
Moreover, Tamimi, B., et al. have studied the impact of PV panels on the power system stability [5]. Simulations were done and their results show that there will be no changes on the transient stability of the system when the PV panels have reactive power control [5].
Furthermore, Achilles, S., et al. study the impact of large penetration of PV panels on a power system under real circumstances [6]. Simulations were done and their results show that by increasing the penetration of PV panels, the risk of transient instability will become greater [6].
Acharya, S., and M., Ramezani have done a study on the performance of a 100 MW wind turbine during a transient contingency [7]. The simulations were done using ETAP® software and their results show that the wind turbine support the system by injecting reactive power at the point of connection during the occurrence of the fault [7].
Nunes, M., et al. have studied the impact of doubly-fed induction generators (DFIG) wind turbines on the transient stability margins [8]. Simulations were done and their results show that the DFIG wind turbines positively affect the transient stability of the system compared to the fixed-speed wind turbines [8].
Meegahapola, L., et al. have studied the impact of high penetration of wind turbines on the transient stability of the system [9]. Simulations were done on the IEEE-14 bus system and their results show that by increasing the penetration of wind turbines to 50%, the system stability will be decreased due to the high reactive power absorbed by the wind turbines from the system [9].
Gautam, D., et al. have studied the impact of high penetration of DFIG wind turbines on the transient stability of the system [10]. Simulations were done and their results show that the high

penetration of wind turbines will negatively affect the system stability due to the lack of inertia problem [10].

2. Methodology:

2.1. The swing equation and the equal area criteria

In order to analyze the system dynamic behavior during a transient disturbance, a very important term must be taken into account and it is called the synchronous machine dynamics [1].

The synchronous machine normally consists of a rotational masses which give us the very important mechanical feature that is called the moment of inertia. Usually, we need the inertia in the system in order to mitigate the damage that caused by the disturbance in the system. Hence, the inertia helps in increasing the boundaries of the stability in the system [11-13].

In order to represent the electrical and mechanical features of the synchronous generator mathematically, then, we need the swing equation:

$$\frac{2H}{\omega_{synch}}\omega_{pu}(t) * \frac{d^2\delta(t)}{dt^2} = P_{mp.u.}(t) - P_{ep.u.}(t) - \frac{D}{\omega_{synch}\frac{d\delta(t)}{dt}} = P_{ap.u.(t)} \tag{1}$$

Where,

H : The inertia constant in (pu.s).

ω_{synch} : The synchronous angular velocity of the rotor in (rad/sec).

ω_{pu} : Rotor angular velocity in (pu).

δ : Rotor angle in (deg.)

As shown in equation (1), the swing equation mainly consists of two parts; electrical, and mechanical. The left-side of the equation shows the acceleration of the rotor multiplied by the inertia constant. The right-side of the equation shows the acceleration power which is the result from subtracting the damping part and electrical power from the mechanical power of the turbine.

There is an analytical method for studying the transient stability especially in the single machine – infinite bus (SMIB) system. This method is called the equal – area criteria. In this method, the swing equation is used in order to determine; the stability state, and the critical clearing time of the system. Figure (1) shows the equal area criteria.

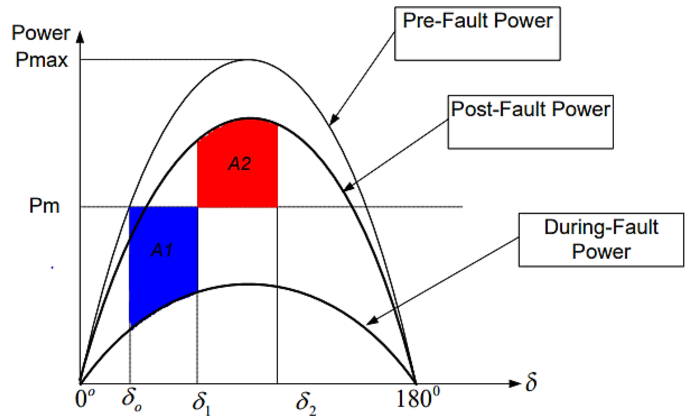


FIGURE.1. The equal area criteria

The two areas A1 and A2 in figure (1) represent the accelerating and decelerating areas for the synchronous machine respectively. in order to have a stable system, the accelerating area of the machine must be equal to the decelerating area, this is achieved by making the swing equation equals to zero. The following equation explain this criteria:

$$\int_{\delta_0}^{\delta_1}(P_{mp.u.} - P_{ep.u.})\, d\delta = \int_{\delta_1}^{\delta_2}(P_{mp.u.} - P_{ep.u.})\, d\delta \qquad (2)$$

As shown in equation (2), the left – side represents area 1 (accelerating area), and the right – side represents area 2 (decelerating area). By looking at figure (1), if A1 is greater than A2, then the system is unstable, if A1 equals or less than A2 then the system is stable.

From the equal area criteria, the critical clearing time (CCT) of the system can be found. When a large fault occurs within the system, the electrical power goes to zero, and by implying this case to the swing equation, the CCT can be calculated by the following equation:

$$CCT = \sqrt{\frac{4H}{\omega_{synch} P_{mp.u.}}(\delta_{cr}(t) - \delta_0)} \qquad (3)$$

Where,

δ_{cr} : Critical clearing angle in (dig.).
δ : Initial rotor angle in (dig.).

All of the above calculation can be solved without using any software, but, in the case of multi-machine system, the mathematical solution becomes more complex and requires specialized software to judge system stability and find the CCT.

2.2. Building the system

The IEEE 9-bus system was built using ETAP® 2016 software. The system was tested using power flow analysis. After that, a contingency case of a three-phase fault on bus 5 was added to the system in order to study the transient stability of the system and find the critical clearing time. A 20 MW wind turbine was added to the system through bus 4 to study its performance during the same contingency that was applied in the previous section.

A 3.6 MW solar station was added to the system through bus 4 to study its effect on the performance of the wind turbine during the same contingency that was applied before.

3. Results and Discussion:

3.1. The normal system without adding PV or wind

The power flow analysis of the built IEEE 9-bus system is shown in figure (2). Bus 1, bus 2, and bus 3 are working on 100% of their voltage. From bus 3 to bus 9 the percentage of the operating voltages ranges between 99% and 96%. The power flow from the generating units to the loads is seem to be very good. Hence, it is verified that the system is working correctly without any problem.

A case study of a three-phase fault was added to the system. The fault was applied on bus 5 at 1 second firstly without clearing the fault. The transient stability of the system were analyzed and the results of buses voltages, buses frequencies, and generators data are shown in figures (3) and (4).

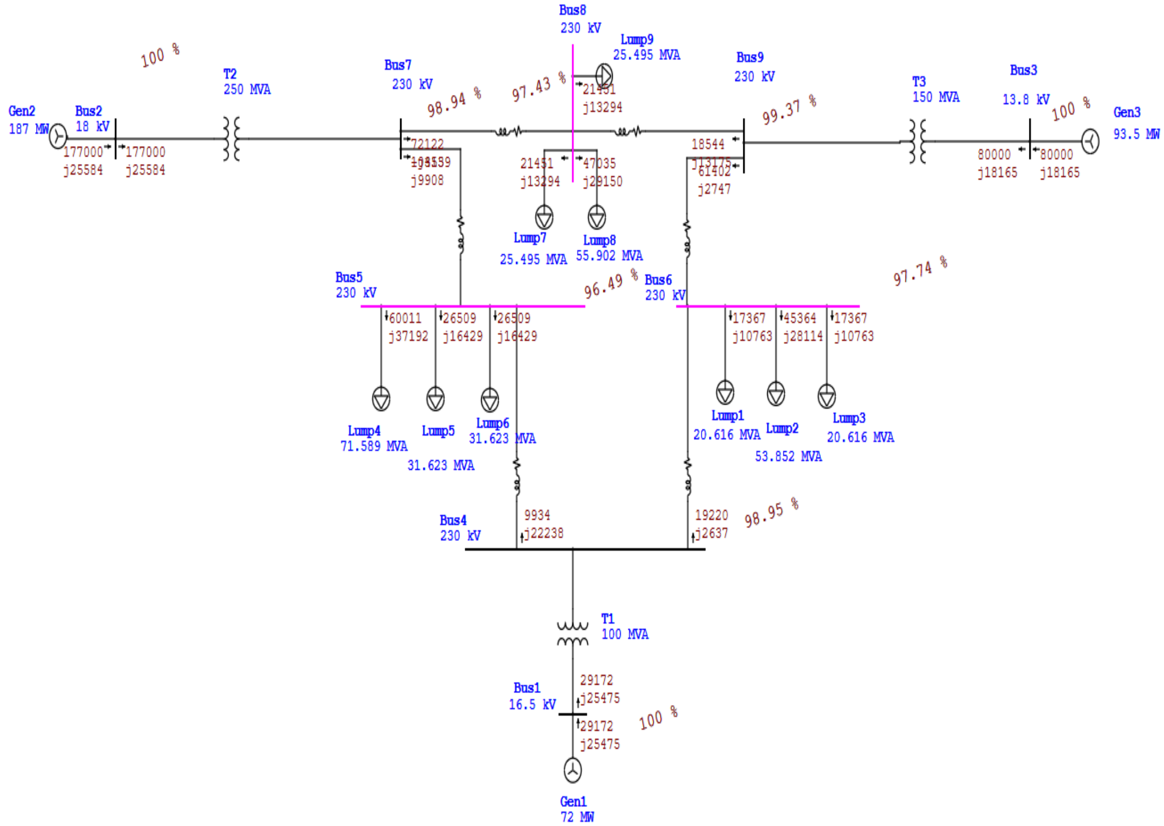
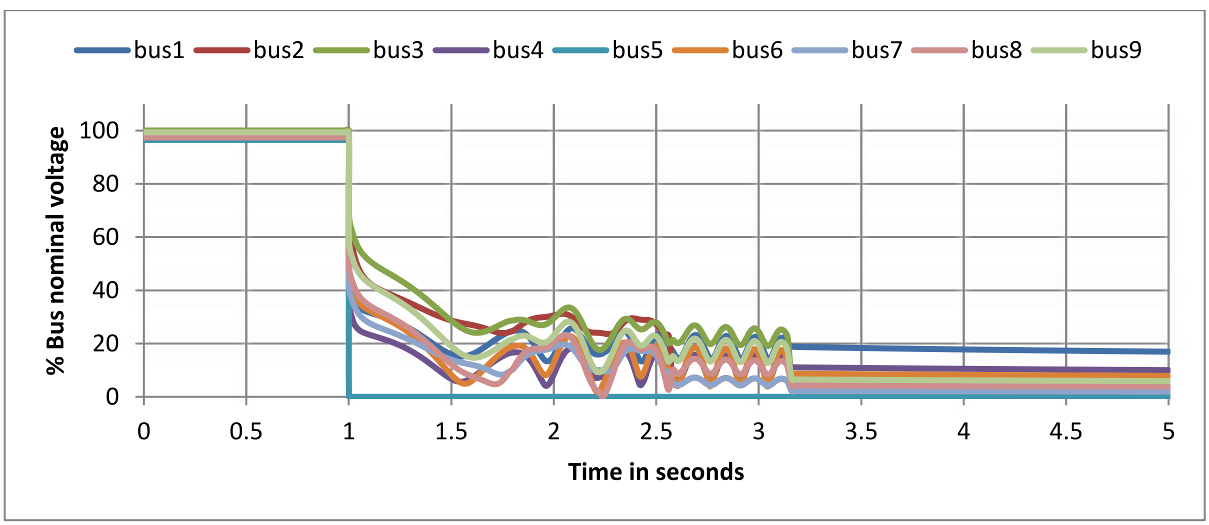


FIGURE.2. Power flow analysis for the normal system



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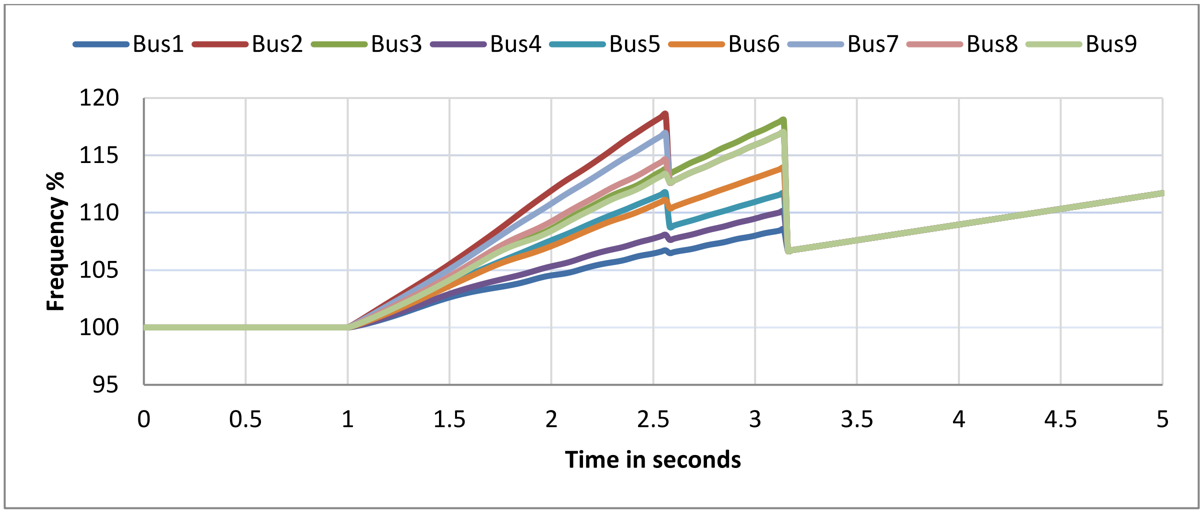
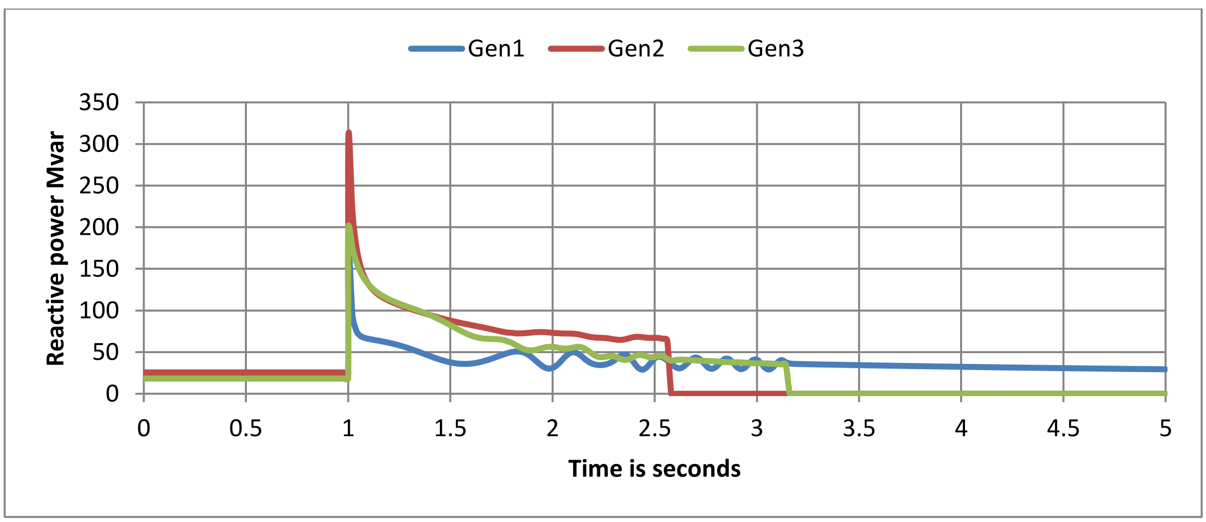


(b)

FIGURE.3. All buses voltages, (a) percentage of buses nominal voltages, (b) buses frequencies.

As shown in figure (3-a), before second one, all of the voltages were in steady-state. After second one, the voltage of bus 5 became zero and all of the voltages became unstable and decrease to a very low values.
From figure (3-b), before second one, the frequencies of all buses were the same (60Hz). After second one, the frequencies of all buses lost synchronism, and around second three, the system became unstable.



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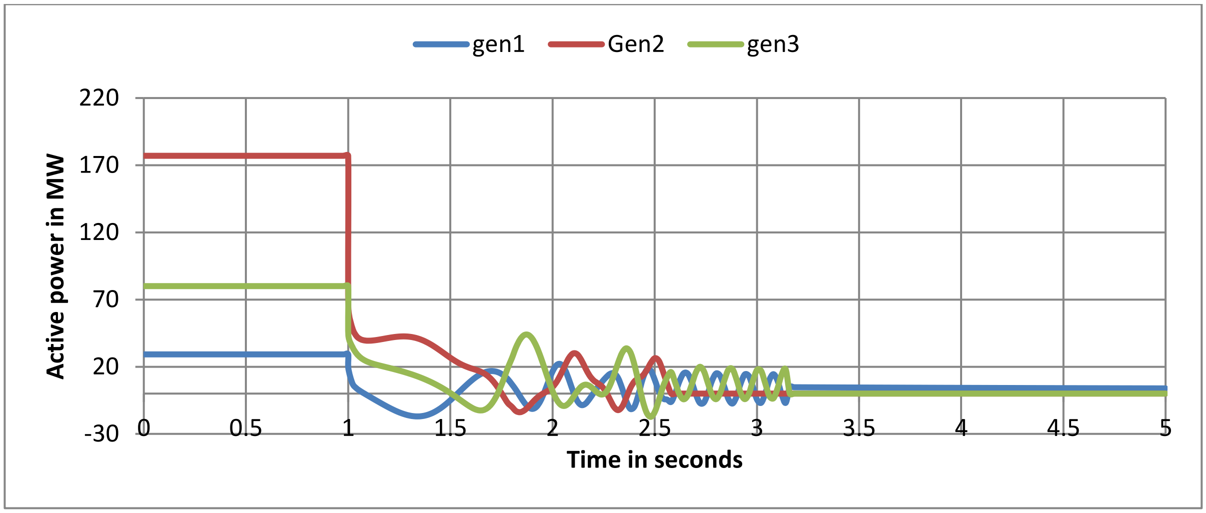

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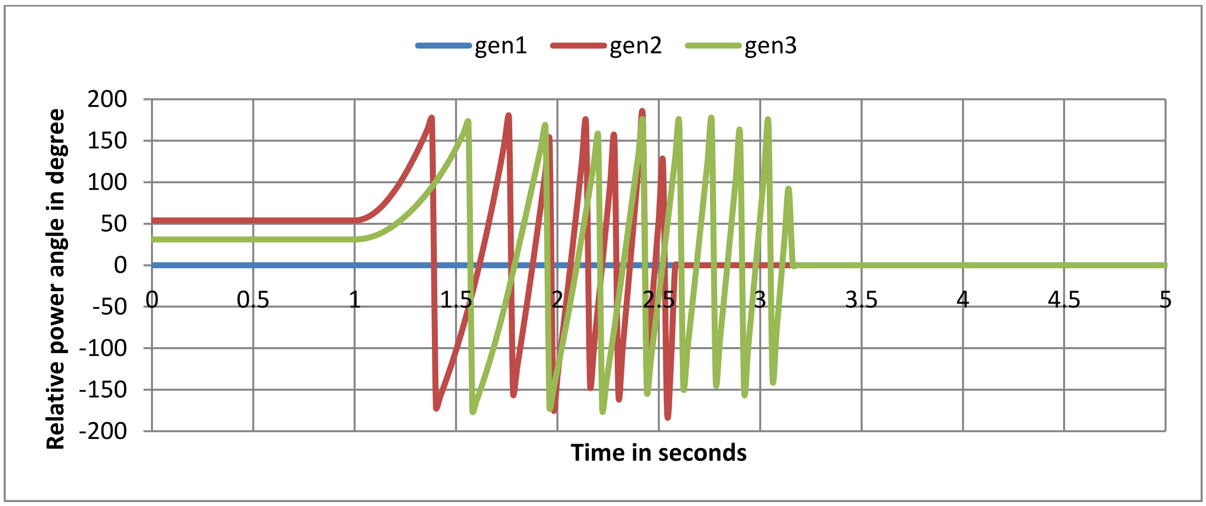


(c)

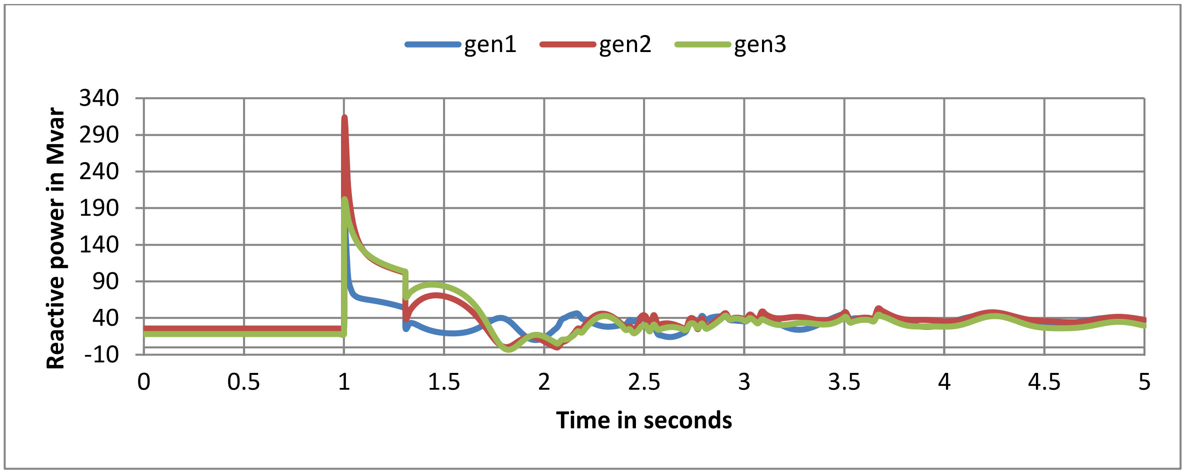
FIGURE.4. Generators status during contingency without clearing the fault, (a) generators MVAR, (b) generators MW, (c) generators relative power angles

From figure (4-a), before second one, all of the generators were producing MVARs and the system were stable. After second one, all of the three generators increase the production of the reactive power especially generator 1 (the swing generator) in order to support system's voltage collapse during the contingency. About the second three, the system lost synchronism and became unstable.

From figure (4-b), after one second, the active powers of the generators began to oscillates and at three seconds, the system lost synchronism and all active powers became zero.

As shown in figure (4-c), the relative power angles of the generators become to oscillate between 200 and -200 after one second which indicate that the system became unstable.

After that, the critical clearing time of the system was calculated based on the swing equation and the equal area criteria. The critical clearing time of the system was found to be 307 ms. The fault was cleared at the critical clearing time of the system. Figure (5) shows the generators MWs, MVARs, and relative power angles after the fault is cleared at 1.307 sec.



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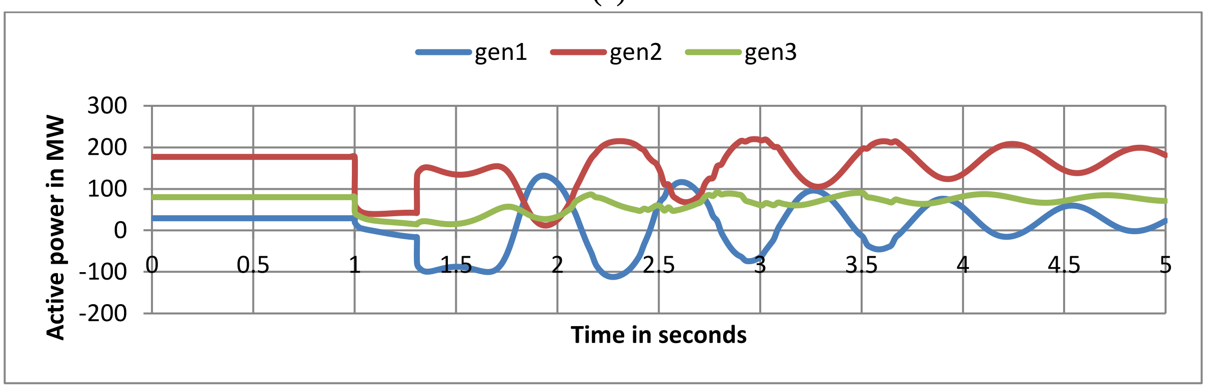

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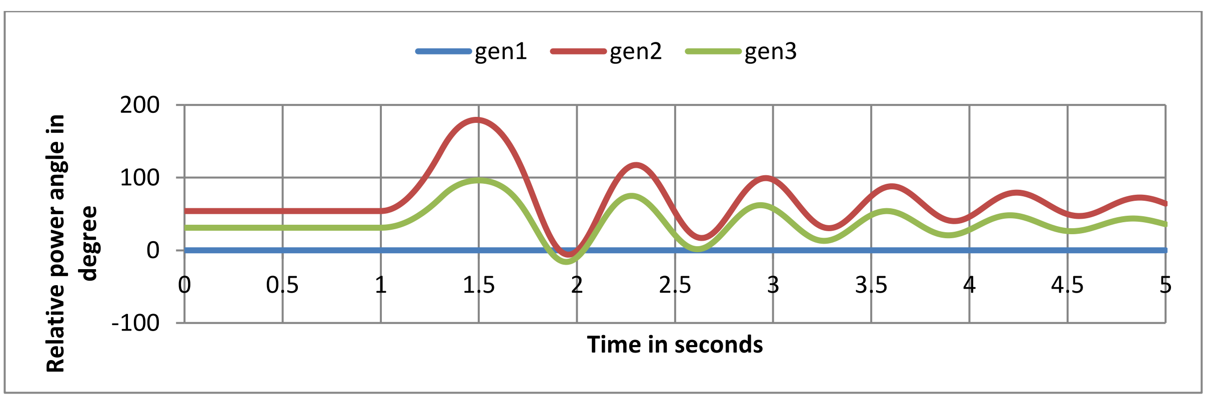


(c)

FIGURE.5. Generators status during contingency with clearing of the fault at 1.307 sec, (a) generators MVAR, (b) generators MW, (c) generators relative power angles

As shown in figure (5-a), the reactive powers of the generators increased at 1 sec, and after the fault is cleared, the reactive powers came back to the steady-state operating values as before. From figure (5-b), the huge oscillations in the active powers at 1 sec can be noticed, but, after the fault is cleared, the active powers came back to the steady-state operating values as before. As shown in figure (5-c), the power angles of the generators oscillate at 1 sec, then, the oscillation is decreased due to the fault clearance, and the power angles came back to the initial steady-state operating values.

3.2. Adding wind turbine to the system

A 20 MW wind turbine was added to bus 4 in the system. The power flow analysis for this system is shown in figure (6). Bus 1, bus 2, and bus 3 are working on 100% of their voltage. From bus 3 to bus 9 the percentage of the operating voltages ranges between 99% and 96%. The power flow from the generating units to the loads is seem to be very good. Hence, it is verified that the system is working correctly without any problem.

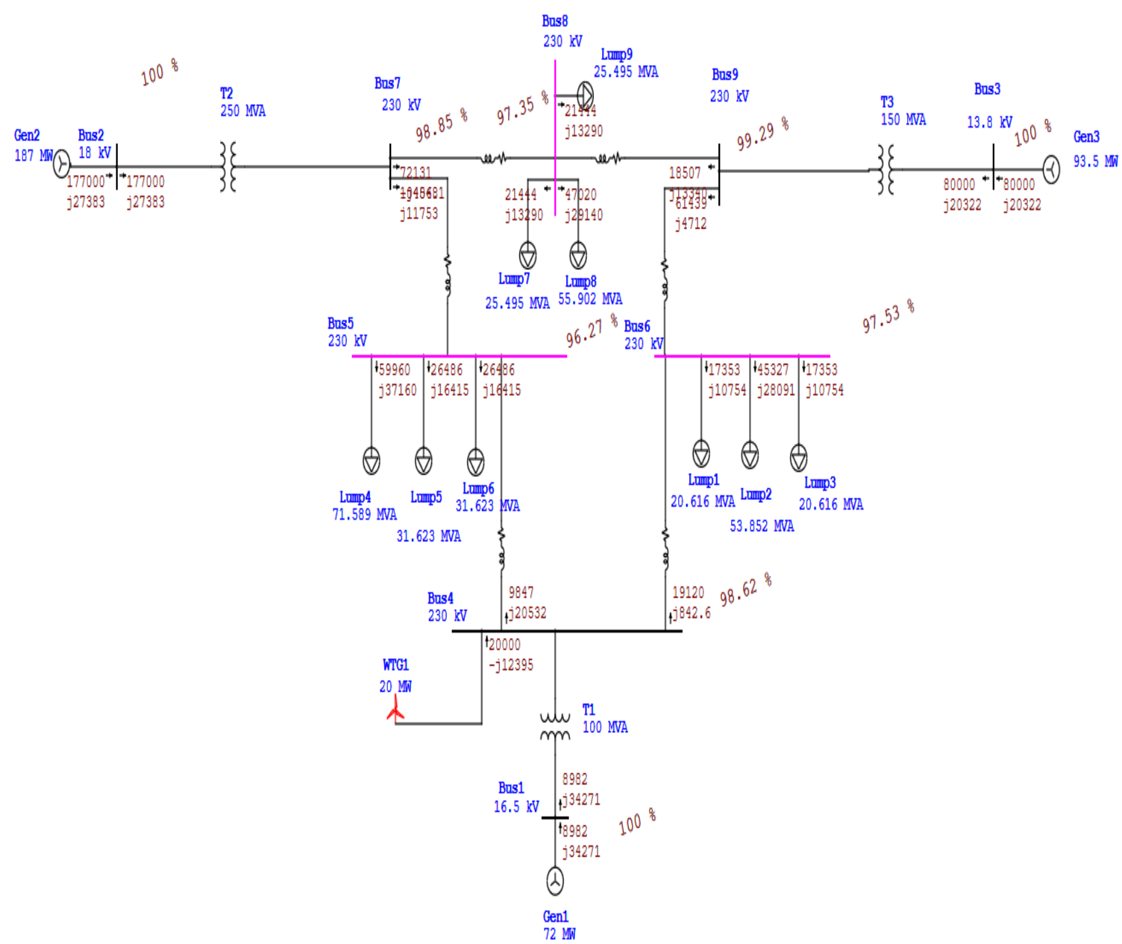
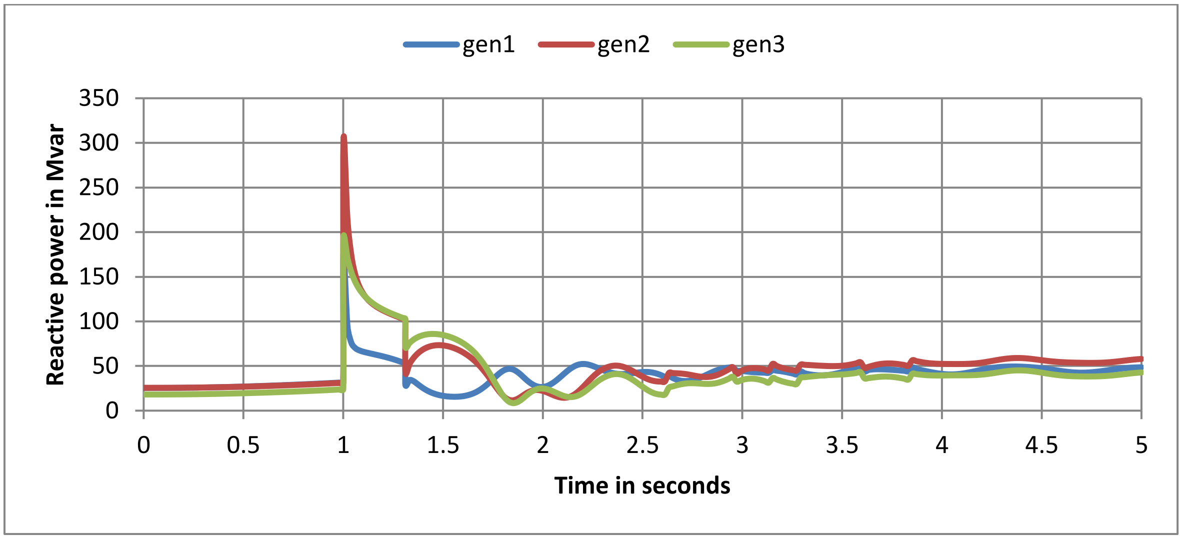


FIGURE.6. Power flow analysis for the system with wind turbine

The same contingency case was added to this system (three-phase fault on bus 5 at 1 sec). The critical clearing time for this system was calculated based on the swing equation and the equal area criteria and it was found to be 311 ms. The fault was cleared at this CCT. The generators active powers (MW), reactive powers (MVARs), and relative power angles (degrees) are shown in figure (7). The wind turbine's active power (MW), reactive power (MVAR), and mechanical power (MW) are shown in figure (8).



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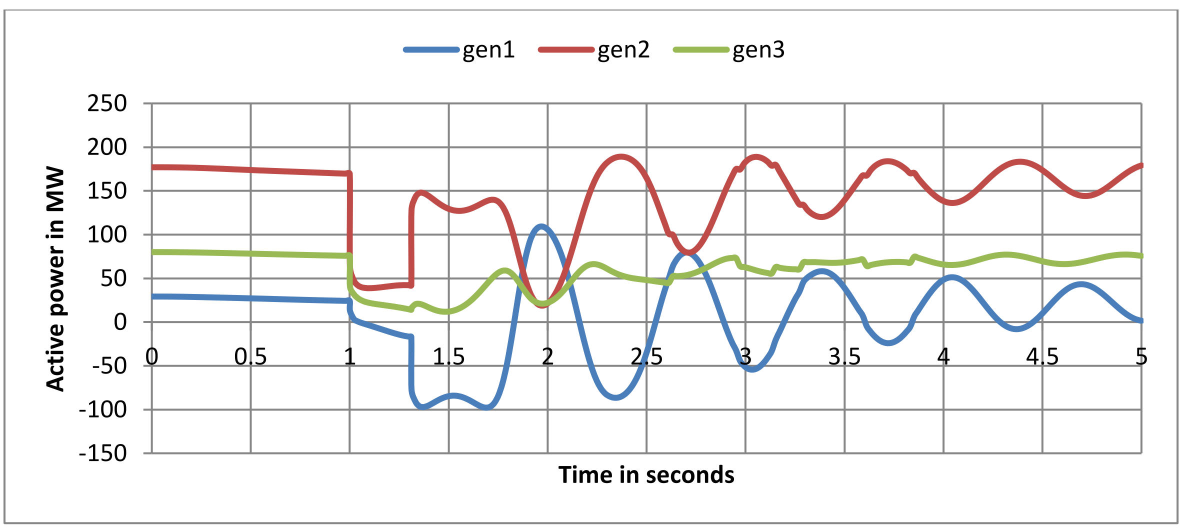

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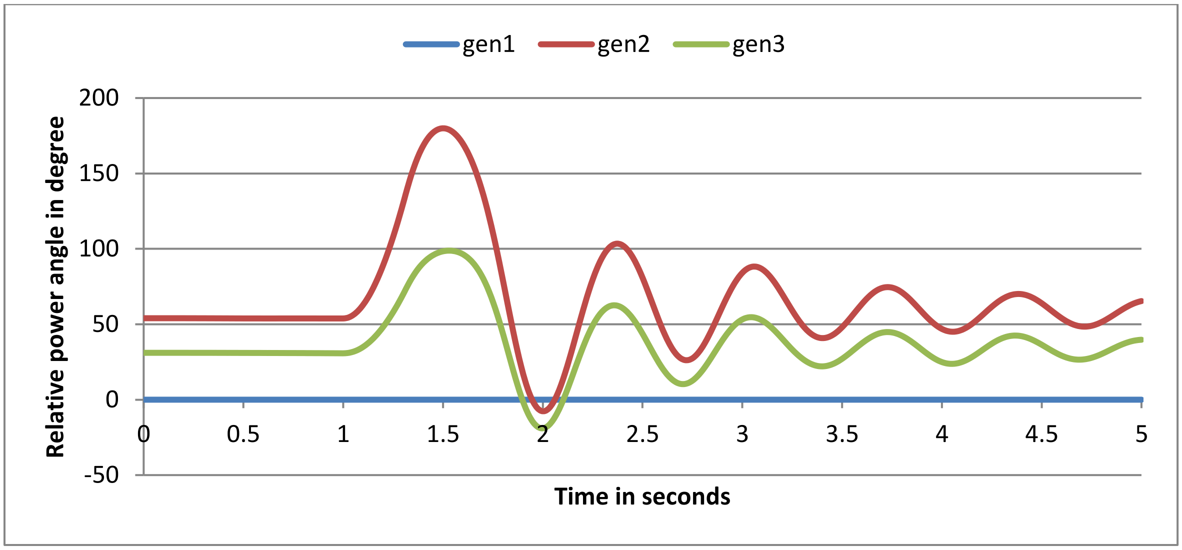
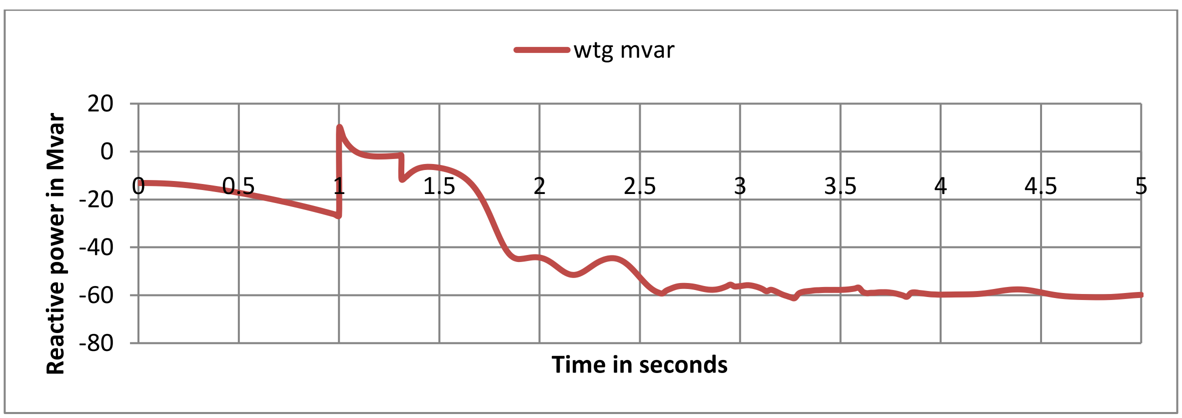


(c)

FIGURE.7. Generators status during contingency with clearing of the fault at 1.311 sec, (a) generators MVAR, (b) generators MW, (c) generators relative power angles

From figure (7), the generators MVARs in this system increased at 1 sec and came back to the normal operating values just like the normal system, but, the difference here is that there is a small increasing in the generators MVARs before 1 sec (during the steady-state).

The generators MWs acts just like the normal system's performance, but, the difference here is that there is a slight decreasing in the MWs during the steady-state operation (before 1 sec). the relative power angles acts like the ones in the normal system; they oscillate at 1 sec, then came back to the normal steady-state initial values.



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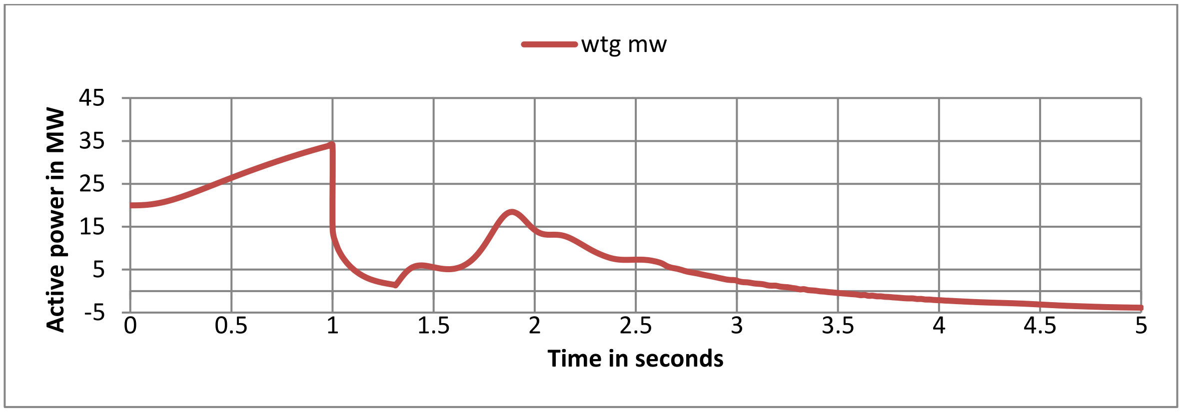

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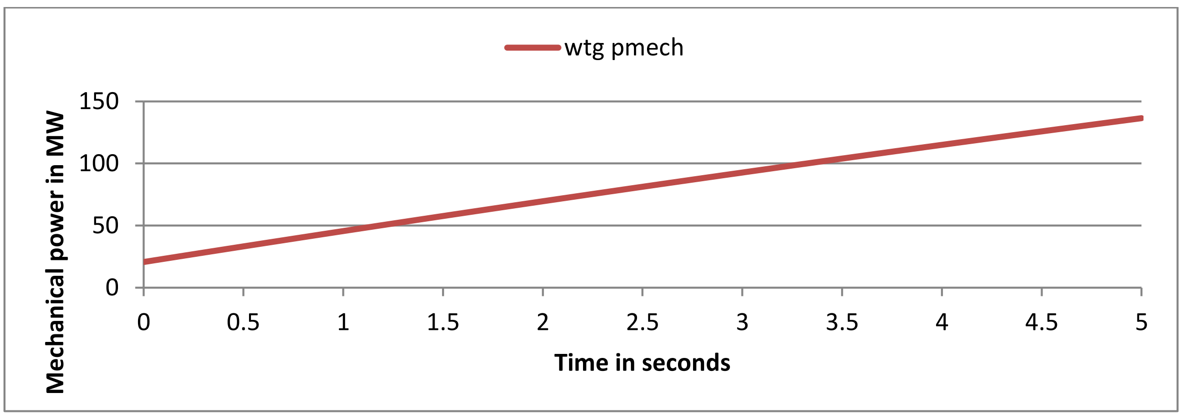


(c)

FIGURE.8. WTG status during contingency with clearing of the fault at 1.311 sec, (a) WTG MVAR, (b) WTG MW, (c) WTG mechanical power

From figure (8), the wind turbine generator (WTG) performance during the transient contingency summarized in supporting the system with MVARs when a transient disturbance occurs in order to stay connected to the system as long as possible. Figure (8-a) shows that the wind turbine producing MVARs at 1 sec instead of consuming it, and after the fault is cleared, the WTG came back to consume even more MVARs from the system.

Figure (8-b) shows that the WTG increase the production of active power during the steady-state operation (before 1 sec), and when the fault occurs, the active power decreased from 35 MW to 1 MW, and after the fault is cleared, the active power increased again to 19 MW at 1.9 sec, then, start to decreasing (i.e. it oscillates in order to find the new stable conditions).

Figure (8-c) shows the mechanical power of the wind turbine generator, this power starts at 20 MW (initial value) and continue to increase during the next 5 seconds (as expected).

3.3 Adding PV station to the system

A 3.6 MW PV station was added to the system through bus 4. Figure (9) shows the power flow analysis of the system.

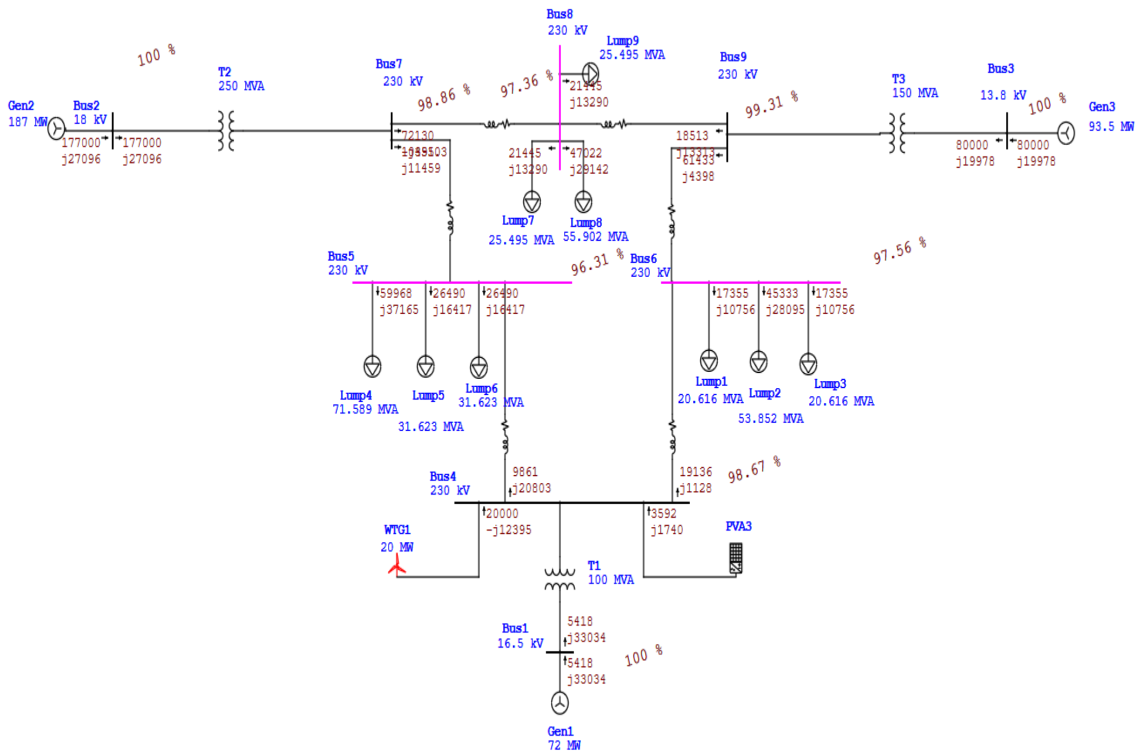
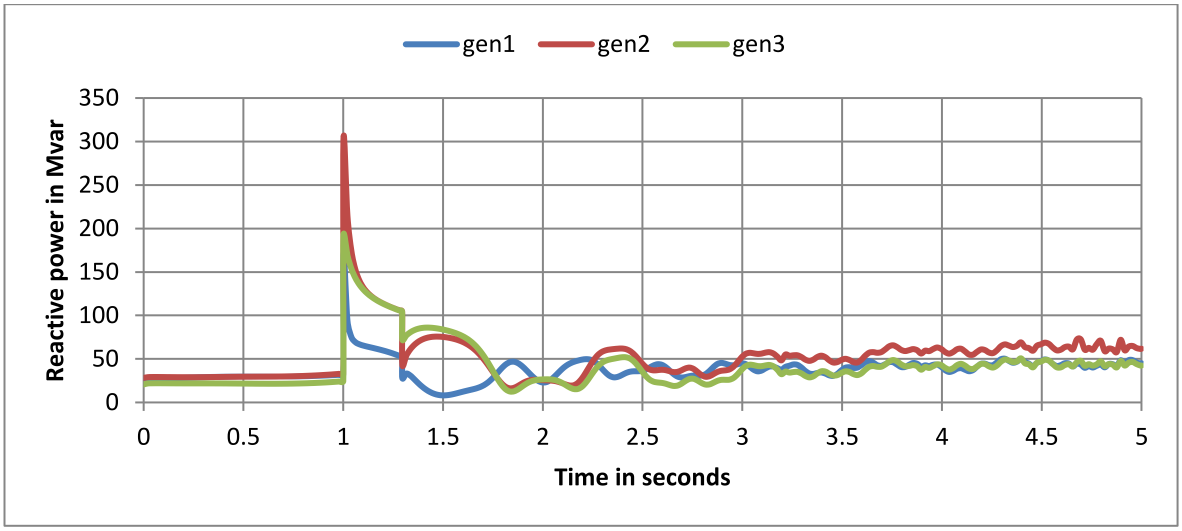


FIGURE.9. Power flow analysis for the system with PV and wind

Bus 1, bus 2, and bus 3 are working on 100% of their voltage. From bus 3 to bus 9 the percentage of the operating voltages ranges between 99% and 96%. The power flow from the generating units to the loads is seem to be very good. Hence, it is verified that the system is working correctly without any problem.

The same contingency case was added to this system (three-phase fault on bus 5 at 1 sec). The critical clearing time for this system was calculated based on the swing equation and the equal area criteria and it was found to be 295 ms. The fault was cleared at this CCT.

The generators active powers (MW), reactive powers (MVAR), and relative power angles (degrees) are shown in figure (10). The wind turbine's active power (MW), reactive power (MVAR), and mechanical power (MW) are shown in figure (11).



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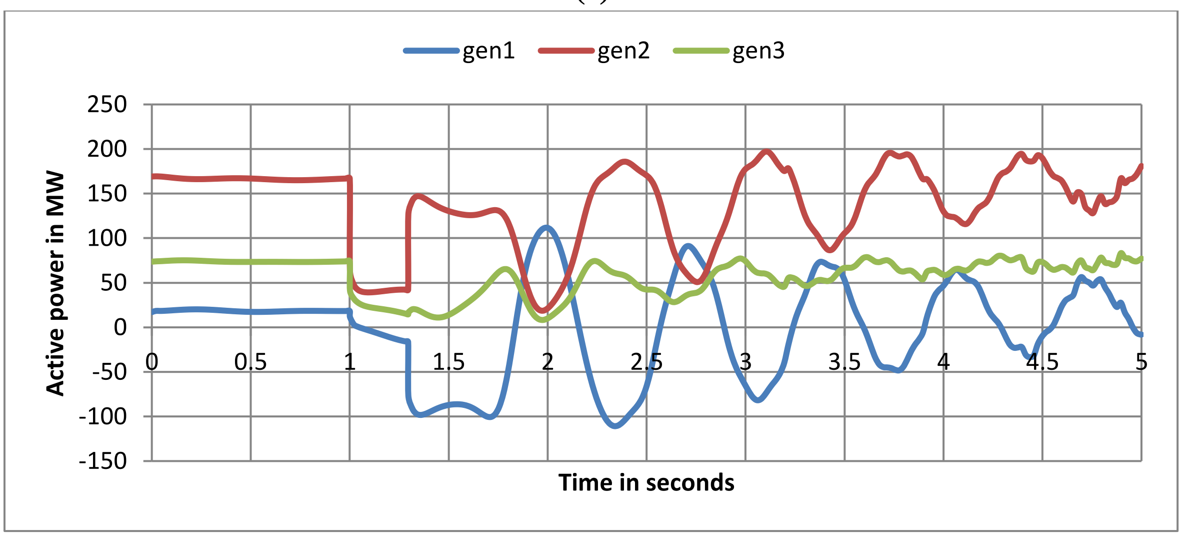

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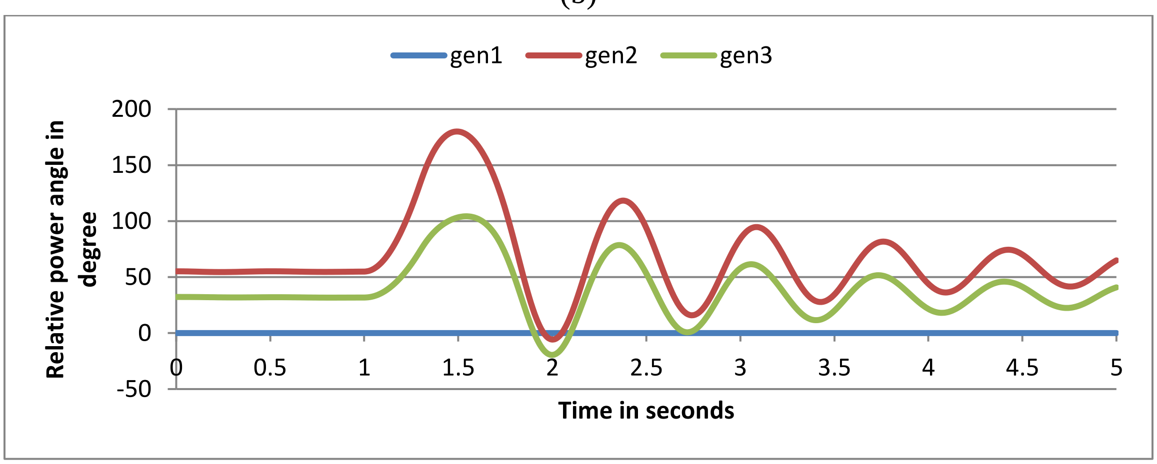


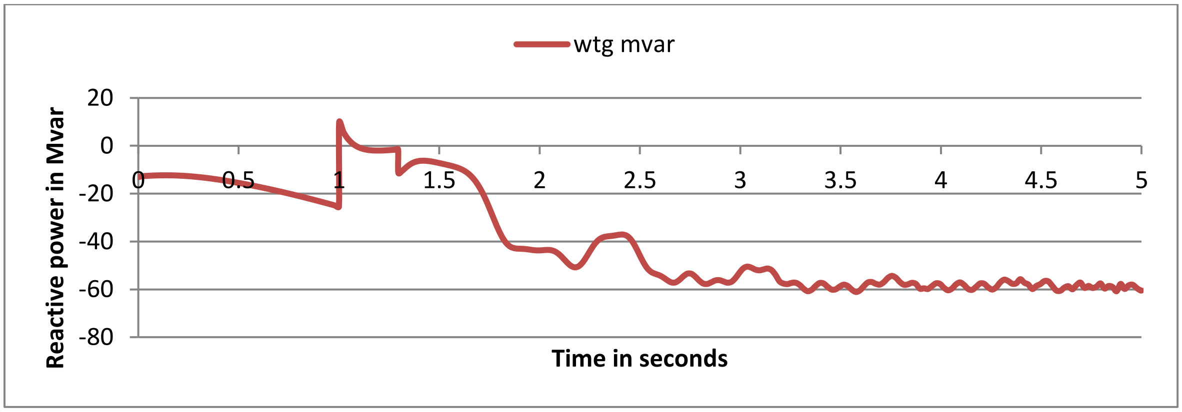
(c)

FIGURE.10. Generators status during contingency with clearing of the fault at 1.295 sec, (a) generators MVAR, (b) generators MW, (c) generators relative power angles

As shown in figure (10-a), the reactive powers of the generators increased at 1 sec to support the system's voltage, but the difference here is that after the fault is cleared, the MVARs return to steady-state values but with a noticeable oscillations around these values.
The same effect appears at figure (10-b), the generators active powers start to oscillate at 1 sec, and after the fault is cleared, an extra oscillations appear on the generators MWs when they try to reach a new steady-state operating values.

From figure (10-c), the relative power angles oscillations of the generators do not affected by the installation of the PV panels in the system. The relative power angles starts to oscillate at 1 sec, and after the fault is cleared, the oscillation of these angles decreased in order to reach an new steady-state operating values.

Hence, it can be noticed that the addition of photo voltaic panels in the system affects both of the reactive and active powers of the real synchronous generators by adding extra oscillation to the signals after the fault is cleared. This result appears due to the absence of rotational masses in the conventional inverter-based photovoltaic panels which will make the overall moment of inertia in the system, and the transient stability margins to be decreased.



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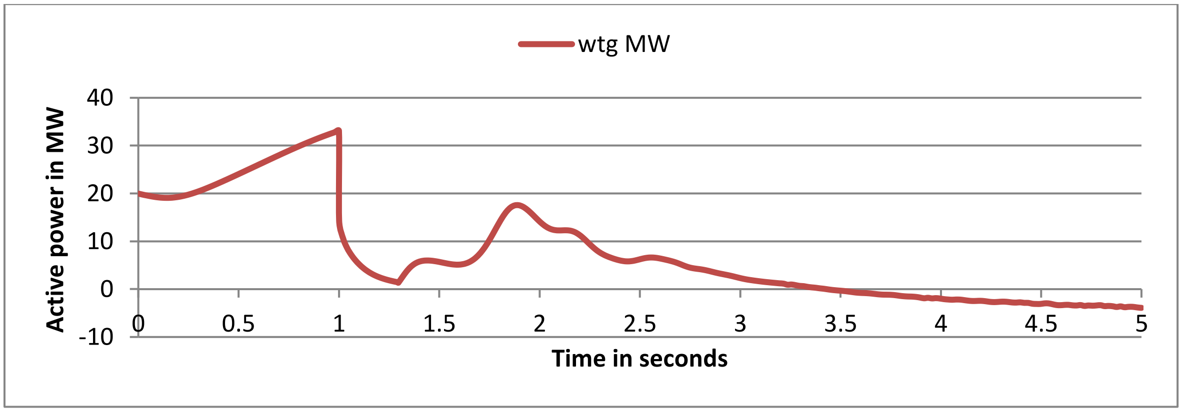

(b)

(c)

FIGURE.11. WTG status during contingency with clearing of the fault at 1.295 sec, (a) WTG MVAR, (b) WTG MW, (c) WTG mechanical power

As shown in figure (11-a), the wind turbine generator start producing reactive power to the system at 1 sec instead of consuming it to support the system voltage during the contingency, and to stay connected with the grid. This behavior of WTG is similar to the one that obtained in the previous system (system with only WTG), but, the difference here is that the installation of PV panels in the system affects the MVAR behavior of the WTG after clearing the fault. This effect appears as an extra oscillations of the MVARS at around 3 sec.

From figure (11-b), the active power decreased to almost zero at 1 sec, then, it starts to increase after the fault is cleared just like the previous system. Hence, the PV station does not affect the MW behavior of the WTG.

As shown in figure (11-c), the mechanical power of the wind turbine generator starts at 20 MW (initial value) and continue to increase during the next 5 seconds (as expected). Hence, the PV station does not affect the mechanical power behavior of the WTG.

3.4 Comparison of the three systems

From the above results it can be noticed that the critical clearing time changed for each of the three systems; normal system, system with only wind turbine, and system with PV and WTG. The CCT of the normal system was 307 ms. When only wind turbine was added to the system, the CCT increased to 311 ms. But, when the PV station was added to the system, the CCT decreased to 295 ms. This means that the wind turbine has a small positive impact on the system stability compared to the large negative impact of PV panels. This is due to the absence of rotational masses (moment of inertia) in the stationary PV panels and the small inertia in the wind turbines.

By comparing the two systems; system with only WTG, and system with both PV and WTG, it can be noticed that the impact of adding PV panels on the wind turbine performance is small. The PV panels do not affect the MVAR behavior during the fault period. It affect the behavior after the fault is cleared by producing an extra oscillations on the MVAR signal when it tries to reach stability after the disturbance diminishes. This is due to the lack of inertia in the stationary PV panels.

4. Conclusion

Based on the above results and discussion, it can be concluded that:

- The impact of PV panels on the wind turbine performance during transient contingencies appears in the reactive power signal of the wind turbine generator. It does not affect the reactive power behavior during the fault period, however, it affects the behavior of the reactive power after the fault is cleared by introducing extra oscillations to the signal.
- The WTG slightly increase the critical clearing time of the system whereas the PV panels significantly decrease it. This is because the WTG support the system’s voltage by producing reactive power.

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