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Analysis of Power System Stability of a Hybrid Microgrid for On-grid and Off-Grid Operation by using ETAP software

Análisis de Estabilidad del Sistema de Potencia de una micro-red Híbrida para Operación Conectado y No-conectado a la red Utilizando el Software ETAP

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Abstract— In this article, we worked under a hybrid microgrid design that includes photovoltaic generation and electrical network to perform a stability analysis of the microgrid response considering off-grid and on-grid operation scenarios. The methodology used for stability analysis was developed using the ETAP software, from the modeling and simulation of 4 cases corresponding to different operating scenarios of a 400 kW concentrated electrical load micro-grid, in which possible stability failures were identified. Finally, the worst type of failure that occurred was tested and resolved, determining that the photovoltaic system does not influence the stability in off-grid operation, assigning the instability to the auxiliary devices of the network, and to the speed of their response to the failures. It was concluded that the critical clearance time and the critical clearance angle of the fault are crucial to know if an electrical power system will be able to return to a stable condition or become unstable.

***Keywords*— Power System Stability, Hybrid Microgrid, ETAP, Fault clearance, Prosumer**

Resumen— El este artículo se trabajó bajo un diseño de micro-red híbrida que incluye generación fotovoltaica y red eléctrica para realizar un análisis de estabilidad de la respuesta de la micro-red considerando escenarios de operación aislada y conectada a la red red. La metodología de análisis de estabilidad se desarrolló utilizando el software ETAP, a partir del modelado y simulación de 4 casos correspondientes a distintos escenarios de operación de la micro-red de carga concentrada de 400 kW, en los que se identificó las posibles fallas de estabilidad. Finalmente se probó y resolvió el peor tipo de falla ocurrida, determinando que el sistema fotovoltaico no influye en la estabilidad en operación aislada, adjudicando la inestabilidad a los dispositivos auxiliares de la red, y a la rapidez de respuesta de los mismos a las fallas. Se concluyó que el tiempo de despeje crítico y el ángulo de despeje crítico de la falla son cruciales para saber si un sistema de energía eléctrica podrá volver a una condición estable o volverse inestable.

***Palabras Clave*— Estabilidad de Sistema de Potencia, Microrred Híbrida, ETAP, Despeje de Falla, Prosumer.**

I. Introduction

It is well known that "Power System Stability" has become an important and trendy topic used in the generation and transmission of power, according to [1]. here is a field that has gained notoriety in electrical generation systems called microgrids which allow bidirectional power flow (from suppliers to consumers, and vice versa), using digital technology and encouraging the incorporation of renewable generation sources [2].

Microgrids are on-site generation and storage resources that serve a localized electrical load and also can be con-nected/ disconnected from a larger electrical grid in cases of outage or instability [3]. Hybrid systems incorporate gen-eration assets, often in the form of renewable energy like wind generation, photovoltaic generation and battery-based energy storage [4]. The implementation of a Smart grid and microgrids need the development of electrical equipment such as, smart meters, protection relays, special transformers and so on. For instance [5] proposed a novel transformer which permits the integration of renewable sources direct to the grid avoiding the cost of high-power converters, as well as allowing the bidirectional power flow.

Keeping the balance between power supply and load has become problematic for usability in recent years [5]. Microgrid implementation improves the control of the power supply-load balance by offering storage and generation services to the main grid [6]. Therefore, it is imperative to study and

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evaluate the behavior and stability of these systems to identify failures, elements of the network that cause them and predict future results and implement new technologies that serve as improvements to guarantee the optimal functioning of the system in terms of reliability. and stability [7]. This type of analysis is carried out in the present work through the modeling and simulation of a microgrid using the ETAP software, in which a hybrid microgrid between photovoltaic and electrical generation with a configured load of 400 kW is considered.

The parts of the paper are organized as follows: in section II Power System Stability. Section III brief description of the Modeling and Simulation used. Section IV the details of the methodology while in section V the performance assessment of methodologies is reported. Conclusions are given in section VI.

II. Power System Stability

The power system is a highly nonlinear system that operates in a constantly changing environment; generator outputs, operating parameters, and loads mutate continually. When disturbances occur, the stability of the system depends on the initial operating condition and the nature of the disturbance [8].

Power system stability is the capacity of an electric power system, for a given initial operating condition, to recover equilibrium of operation after being exposed to a large disturbance (sudden load changes, switching operations in power electronic devices, faults in the system, etc.) with most operation variables controlled, so, practically the entire system remains undamaged [9,10].

According to the literature, the power system stability is classified into Steady State, Transient and Dynamic Stability.

- Steady State Stability studies are constrained to small and gradual changes in the system operating conditions. The attention here is limiting the bus voltages close to their nominal values. At the same time guaranteeing that phase angle between two buses are not too large and performing evaluations for the overloading of the equipment and branches. These evaluations are usually performed by power flow studies [11].
- Transient Stability involves the study of the power system following a major disturbance. Following a large disturbance a synchronous generator response to fast changes in electromechanical swings and during these changes the rotor angle stabilizes at a new value or the rotor angle gradually increases which may lead the system to a loss of synchronism [12].
- Dynamic Stability is the capacity of a power system to keep stability under continuous small disturbances because of unplanned fluctuations in loads and generation levels [13].

A. The Swing Equation

Under normal operating conditions, the relative position of the rotor axis and the resultant magnetic field axis is fixed. The angle between the two is known as the power angle or torque angle. During any disturbance, the rotor will decelerate or accelerate with respect to the synchronously rotating air gap Mmf, and a relative motion begins [14,15]. The equation describing this relative motion is known as the swing equation, represented as follows:

$$M\frac{d^2\varrho}{dt^2} = Pa = Pm - Pe \tag{1}$$

Where,

$$M = \frac{2H}{\omega s} \tag{2}$$

Pa is the accelerating power,
Pm is the mechanical power,
Pe is the electrical power output,
ωs is the synchronous angular velocity of the rotor, δ is the synchronous machine rotor angle,
M is the inertia constant coefficient.
H is the inertia related constant.

B. The Power-Angle Equation

The simplest form of the power angle equation and is basic to an understanding of all stability problems. The relation shows that the power transmitted depends upon the transfer reactance and the angle between the two voltages [16-18].

$$Pe = \frac{\left|E^{'}\right||V|}{X} sin\delta \tag{3}$$

Where,
Pe is the electrical power output,
$E^{'}$ represents the transient internal voltage of the generator.
V is the voltage at the receiving end and is regarded as that of an infinite bus or as the transient internal voltage of a synchronous motor whose transient reactance is included in the network.
X is the transfer reactance between $E^{'}$ and V.

C. Equal-area criterion

This method is a graphical explanation of the energy stored in the rotating mass and help to know the keeping of the stability of the machine after a disturbance. The colored areas Al and A2 must be equal, and similarly.

From Figure 1, a critical clearing time could be calculated, which is the maximum elapsed time from the initiation of the fault until its isolation such that the power system is transiently stable. Also, the critical clearing angle can be found through the following expression:

$$\delta_{cr} = cos^{-1}\left[(\pi - 2\delta_0)\, sin\delta_0 - cos\delta_0\right] \tag{4}$$

Where,

δ_0 is the generator power angle pre-fault condition.

The critical clearing time is:

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_0)}{\omega s}} \tag{5}$$

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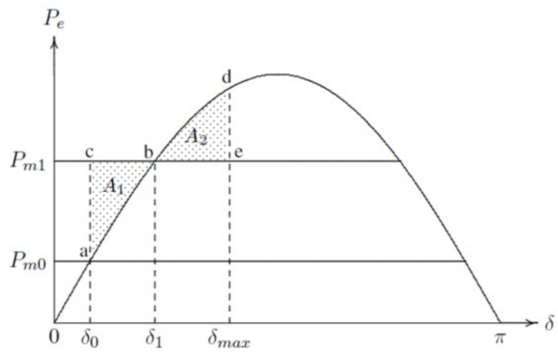

Figure 1. Equal-area criterion- sudden change of load [12].

Where,

ωs is the synchronous angular velocity of the rotor, δ_0 is the generator power angle pre-fault condition, δ_{cr} is the critical clearing angle.

III. Modeling and Simulation

In order to perform a power system stability analysis, it is necessary to develop an adequate model of a hybrid microgrid, with capabilities to operate off-grid and also on-grid. The hybrid system designed consists of six buses, the power grid, a diesel generator, and a photovoltaic plant as power sources connected at a main distribution bus, along with four power transformers servicing 40 users represented by a static load with power factor of 1. A simplified diagram of the system is shown in Figure 2 and Figure 3.

The input data regarding all the elements that comprise the system is detailed in the following tables:

IV. Methodology

A stability analysis of the diagram shown in Figure 2 was conducted by ETAP software based on the next conditions:

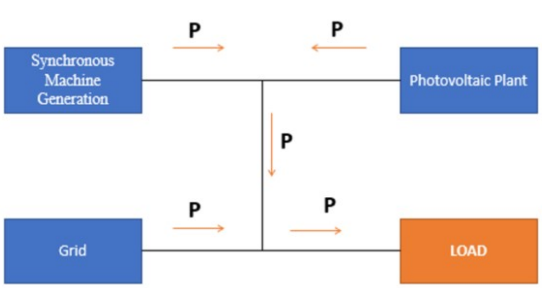

Figure 2. Box Diagram of the System.

Table I
Power grid.

ID	Rating		%Z 100MVA Base		
	MVAsc	KV	R	X	X/R
Grid 1	1000	34.5	0.99504	9.95037	10

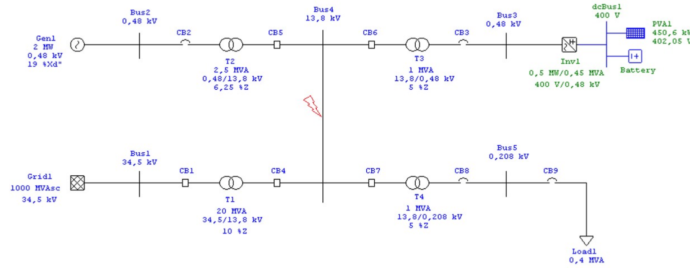

Figure 3. Case of study 1: Hybrid microgrid single line diagram.

Table II
Generator.

ID	Rating		%Z	%P.F.	RPM	Poles	H
	MW	KV	Xd"				
Gen 1	2	0.48	19	80	1800	4	0.384*

*Value automatically calculated by ETAP

Table III Photovoltaic panels.

ID	Rating		
	KW	V	A
481.1	450.6	402.05	1120

Table IV
Inverter.

ID	DC Rating			AC Rating		
	MW	V	A	MVA	kV	A
Inv 1	0.5	400	1250	0.45	0.48	541.3

Table V
Transformers.

ID	Rating					Vector group
	MVA	Prim. kV	SeckV	%Z	X/R	
T1	20	34.5	13.8	10	20	Dyn11
T2	2.5	0.48	13.8	6.25	6	Dyn11
T3	1	13.8	0.48	5	3.5	Dyn11
T4	1	13.8	0.208	5	3.5	Dyn11

Table VI
Buses.

ID	kV
Bus 1	34.5
Bus2, Bus3	0.48
Bus 5	0.208
Bus 4	13.8
DC Bus 1	0.4

Table VII
Circuit Breakers.

ID	kV
CB1	34.5
CB4, CB5, CB6, CB7	13.8
CB2, CB3	0.48
CB8, CB9	0.208

From the diagram depicted in Figure 2, four cases will be analyzed. Case 1 (Figure 3) consists about the system in normal operation, all circuit breakers closed, Grid1 in swing

![t]

Table VIII
TRANSIENT STABILITY PARAMETERS.

Method of solution	Newton-Raphson
Maximum number of iterations	99
Precision of the solution System	0.00010000
frequency	60
Units	metric

operation, Gen1 in voltage control operation and Inv1 in voltage control operation, load1 at 100% and all transformers operating.

Case 2 (Figure 4) consists in the system in operation with only two sources, CB1 and CB4 open, Grid1 out of service, Gen1 in swing operation and Inv1 in voltage control operation, load1 at 100%, T2, T3 and T4 transformers operating, T1 out of service. Case 3 (Figure 5) consists in the system in operation with only one source of power. In this case we consider the system is operating in off-grid mode. The photovoltaic plant is the prime source of power. CB1, CB4, CB2 and CB5 open, Grid1 and Gen1 out of service, Inv1 in swing operation, load1 at 100%, T3 and T4 transformers operating, T1 and T2 out of service.

Finally, in case 4 (Figure 6) consists in the system in operation with only two sources, CB2 and CB5 open, Gen1 is out of service, Grid1 in swing operation and Inv1 in voltage control operation, load1 at 100%, T1, T3 and T4 transformers operating, T2 out of service.

In each of the proposed cases, a 3-phase fault and subsequent clearance events are introduced in Bus4 in order to determine the behavior and stability of the system. The events are as follows:

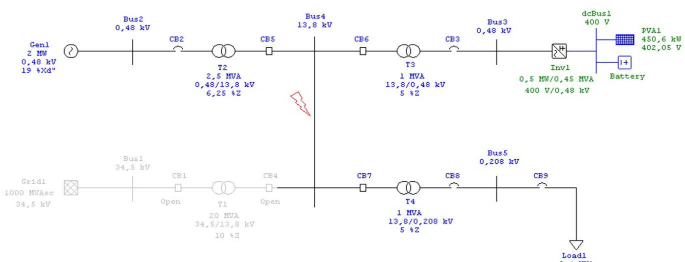

Figure 4. Case of study 2: Hybrid microgrid single line diagram without the Public grid.

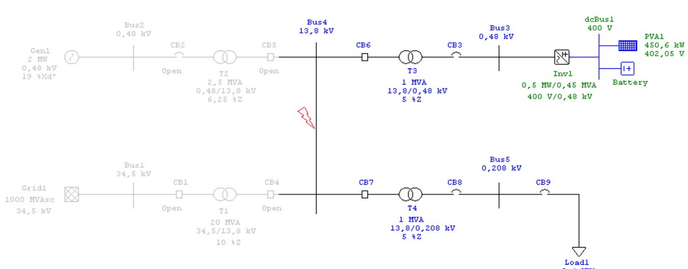

Figure 5. Case of study 3: Hybrid microgrid single line diagram with only photovoltaic generation.

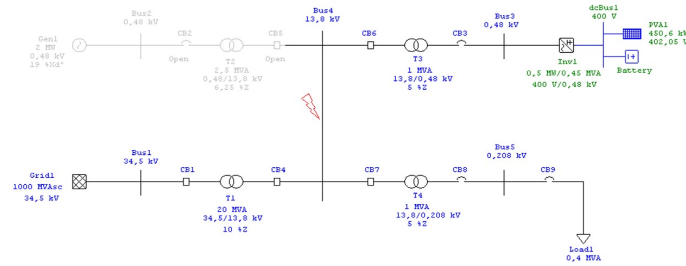

Figure 6. Case of study 4: Hybrid microgrid single line diagram without synchronous machine generation.

Table IX
TRANSIENT STABILITY PARAMETERS.

ID	Time (s)	Device	Action
Event 1	1.0	Bus 4	3 phase fault
Event 2	1.5	Bus 4	clear fault

Some performance curves of the following elements were plotted:

- For the Generator Gen1: Power angle (relative), Power Angle (absolute), Speed, Mechanical Power (MW) and Electrical Power (MW).
- For the buses Bus1, Bus2, Bus3, Bus4 and Bus5: Voltage, Voltage Angle and Frequency.

V. RESULTS

A. Case 1

When the 3-phase fault occurs in 1.0s, both the relative and the absolute angle of the Gen1 begins an oscillatory process, the speed increases and the electrical power decreases, as in the case of simulation, the control element (governor) for the mechanical power is not considered and this value remains constant.

At the moment of clearing the fault, the relative angle of the Gen1 rotor remains in oscillation but manages to quickly stabilize at 2.0s at its pre-fault values. The same happens for the values of speed and electrical power delivered.

In the case of Bus1, Bus2, Bus3, Bus4 and Bus5, they recover the voltage, angle and frequency almost immediately when the fault clears in 1.5s, the bus that represents the greatest variation until it recovers its initial condition is Bus2 corresponding to the connection point of Gen1 and followed by Bus3, connection point of Inv1 and the photovoltaic plant system, it presents an angle compensation due to its voltage control operation. In general lines, the system represented in case 1 remains stable after the events introduced after 2.0s, meaning for Gen1 that the clearance angle (δ_c) in 1.5s is within the initial angle (δ_0) and the critical clearance angle (δ_{cc}), under the criterion of equal areas, the area A1 would be equal to the area A2 and therefore Gen1 returns again to its initial state.

B. Case 2

In this case, after the failure in 1.0s and its clearance in 1.5s, the rotor angle of the Gen1 and its speed begin a steep

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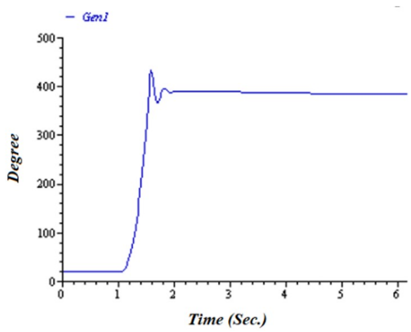

Figure 7. Gen1 absolute power angle.

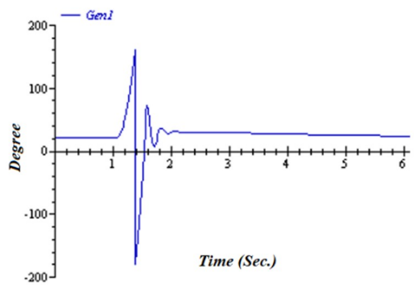

Figure 8. Gen1 relative power angle.

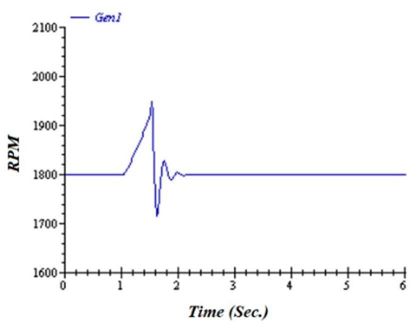

Figure 9. Gen1 speed.

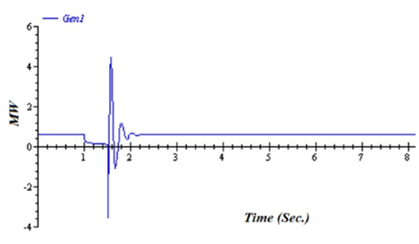

Figure 10. Gen1 electrical power.

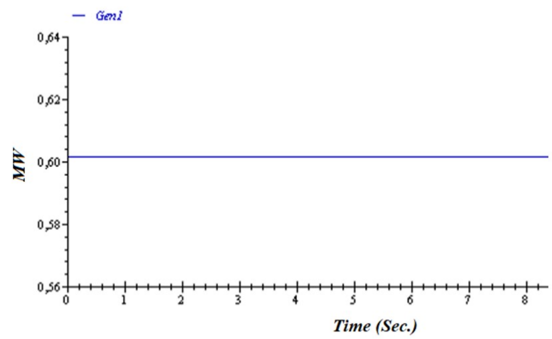

Figure 11. Gen1 mechanical power.

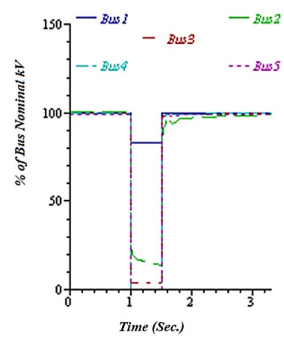

Figure 12. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage.

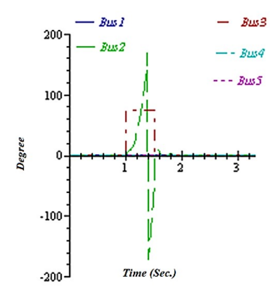

Figure 13. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

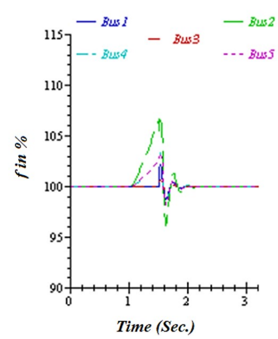

Figure 14. Bus1, Bus2, Bus3, Bus4 and Bus5 frequency.

decline that cannot be reversed, therefore causing instability in the delivery of electrical power to the system, in addition to the consequent collapse of the constant mechanical power and exit of the unit after approximately 5.5s.

At the time of the exit of the Gen1 unit, the frequency on the buses stops at its oscillation and stabilizes 100% immediately; however, the voltage magnitude cannot recover and stabilizes around 68% of its nominal value. Bus3 corresponding to the connection point of Inv1, and the photovoltaic plant presents a drastic variation in its voltage angle at the moment of failure; after its clearance, it begins an oscillatory process in conjunction with the angle of the rest of the buses during the period of instability of the Gen1 unit, after its exit, the angle of all the buses stabilizes at similar values. After several simulations, at any fault clearance time, the system remains

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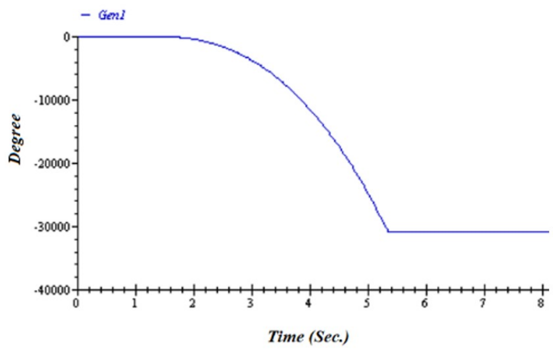

Figure 15. Gen1 absolute power angle.

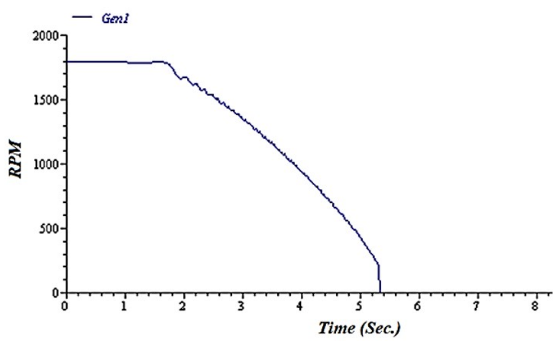

Figure 16. Gen1 speed.

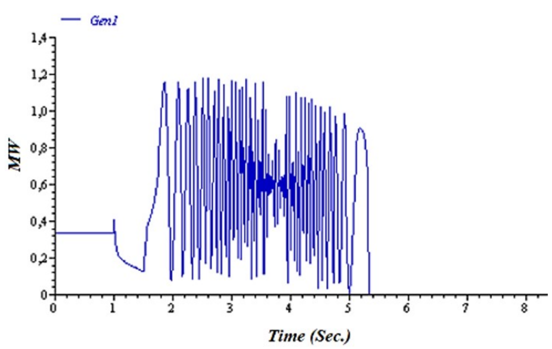

Figure 17. Gen1 electrical power.

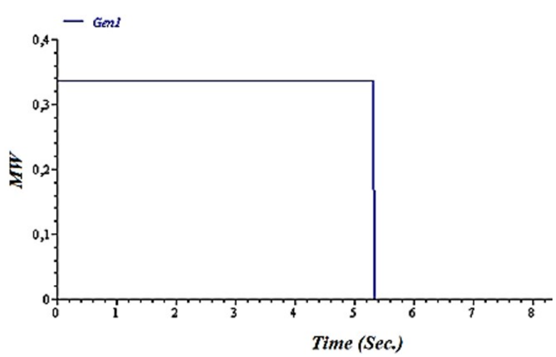

Figure 18. Gen1 mechanical power.

unstable, and the generator stops and the voltages in all buses never recover to their pre-fault values.

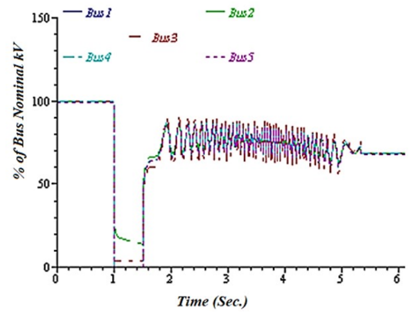

Figure 19. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage.

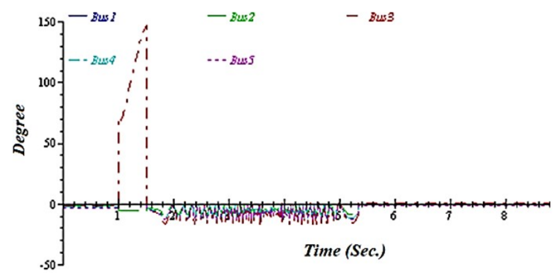

Figure 20. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

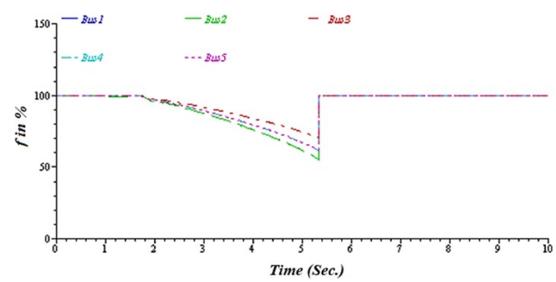

Figure 21. Bus1, Bus2, Bus3, Bus4 and Bus5 frequency.

C. Case 3

In this case the system shows a better response than previous cases and regains stability almost immediately after the fault clearance. Bus3 increases its voltage angle as it is in voltage control operation. The frequency remains invariable, during and after the events introduced. In overall the system is stable.

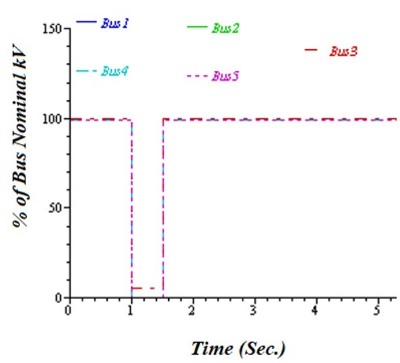

Figure 22. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage.

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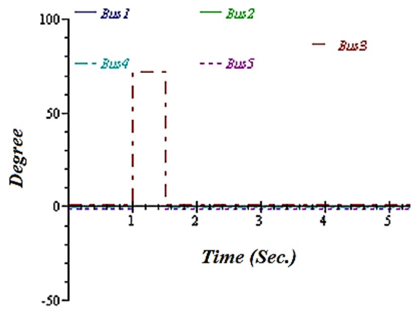

Figure 23. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

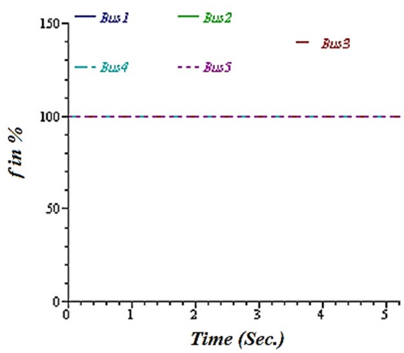

Figure 24. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

D. Case 4

In this case the system shows a better response than previous cases and a similar behavior from Case 3. In overall the system regains stability almost immediately after the fault clearance. Bus1 maintains its voltage magnitude above the 80% level during the fault while other buses instantaneously go to zero during the fault. Bus3 increases its voltage angle as it is in voltage control operation. Frequency remains invariable, during and after the events introduced. In overall the system is stable.

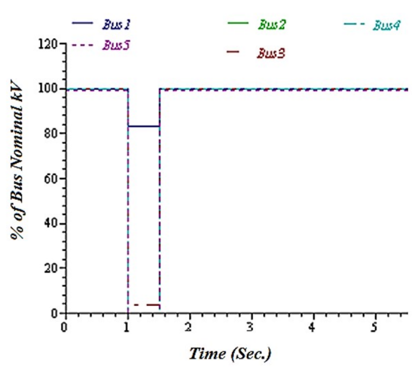

Figure 25. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage.

VI. Conclusions

The results indicate that the photovoltaic system is more stable while in off-grid mode or on-grid mode and it has no negative impact on the stability of the system. However, while in off-grid mode with the local generation unit connected, there is an element of instability introduced into the system that needs to be addressed by means of the use auxiliary devices such as power system stabilizers (PSS) and/or adjustments in the exciter elements and governing system of the synchronous generator unit/s.

The system under all these scenarios has several limits in its performance. The worst condition for stability would be when the power grid utility Grid1 fails or is not available; in this case the system relies on the operation of Gen1 and/or the PV array with all the synchronizing requirements considered. The best condition regarding stability, are all sources operating including the power grid and photovoltaic arrays, reducing the rotating elements which introduces instability situations that need to be resolved.

The critical clearance time and critical clearing angle are crucial in whether an electric power system will be able to return to a stable condition or turn unstable. If the disturbance or the fault takes a longer time to be cleared than the critical clearance time, the system will become unstable.

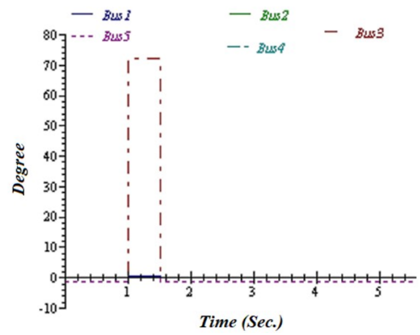

Figure 26. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

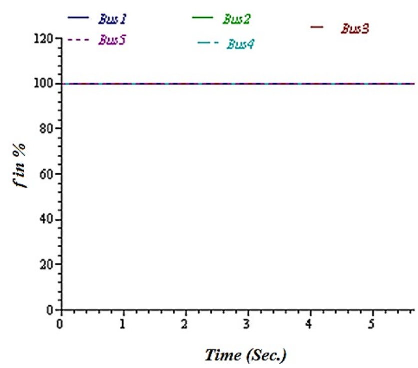

Figure 27. Bus1, Bus2, Bus3, Bus4 and Bus5 voltage angle.

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