The Impact of Renewable Energy Integration on Stability of the Jordanian National Grid

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ABSTRACT
The electrical power demand is increasing due to the high population growth rate, industrial investments expansion, and modern lifestyle requirements. Renewable Energy Sources (RES) have been taken into account to cover the highly increase in power demand. In this thesis, the impact of the integration of the RES on the electrical power system stability in Jordan has been studied. Load flow analysis, including voltage and electrical power losses, has been measured for minimum and maximum loading of the system. The dynamic behavior of the electric power system with and without RES for minimum and maximum loading has been proposed. The dynamic behavior of rotor angle, frequency and voltage stability has been studied. The simulated response curves have been presented for several cases. The results show that adding RES to the conventional power system affects the frequency stability in the case of minimum loading. Rotor angle stability curves show a good response with RES. The voltage profile of the integrated electrical power system has been improved as the penetration of RES increased. The case studies have been simulated using DIgSILENT Power Factory simulation software.The components and parameters used in DIgSILENT software are the same as the actual system under different operating conditions.

Keywords
Power System, Renewable Energy. Rotor angle Stability, Frequency Stability, Voltage Stability.

1. INTRODUCTION
Highly demand for energy makes the electrical power systems to grow day by day rapidly, so thinking of establishing new power sources will be the persistent need.

A rapid increase in the cost of fossil fuel, which is used in conventional energy sources, make the decision makers employ a new kind of energy sources with lower cost and a friend of the environment. Alternative Energy (AE) sources such as wind farms, photovoltaic PV technology, biomass, hydropower and many deferent new power alternatives are used. The geometrical region, environmental issues, natural sources and weather conditions should be taken into account before establishing any type of AE source.

The use of renewable energy sources adds additional complexity to power systems and makes them more challenging to the operator, the renewable power generation sources can be divided into two categories, the sources which have similar characteristics to conventional power generation facilities in that they are predictable and controllable, such as hydroelectric generation and biomass and the variable and intermittent sources, such as wind and solar.

The effect of wind and solar renewable sources on power system stability is different from that of the conventional power sources. Wind and solar are depending on variable conditions such as weather conditions, like wind speed and solar irradiance, site dependence, types of generators used.

Today's power system is already complex and poses many challenges for system operators to ensure grid stability and reliability. The increasing integration of variable renewable energy sources, such as wind and solar power, adds further complexity and operational difficulties to the overall system [1, 2, 3].

The expected peak load for the years from 2017 to 2020 is shown in Figure 1.

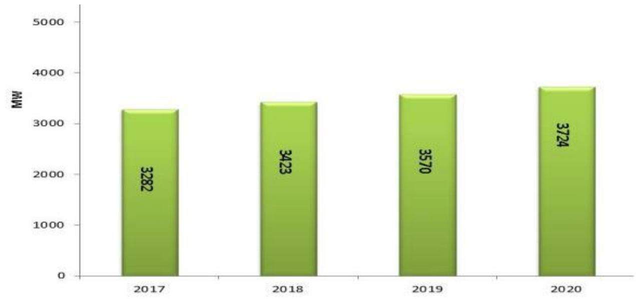


Fig 1: National grid expected peak load (2017.2020)

The impact of renewable generation on the Jordanian national electrical power system stability is investigated, in order to review related risks and to propose mitigation measures for ensuring a secure and reliable power system.

Generally, the electrical power system consists of many individual elements connected together to form a large, complex system capable of generating, transmitting and distributing electrical energy over a large geographical area [4,5,6]. It can be described as a highly nonlinear system since its dynamic performance is affected by a high number of devices with different response rate and characteristics. This will affect the stability of power system.

Stability is a necessary condition to operate all machines in synchronism which is influenced by the dynamics of generator rotor angles and power angle relationship. The stability issue is also affected by the stability of the voltage and frequency of a power system which must be in an accepted range [6, 7].

1.1 Frequency Stability
Frequency is the parameter of a power system that indicates if there is an imbalance between active power generation and consumption. Therefore “Frequency Stability” refers to the ability of a power system to balance generation and load.

The simplest electrical power system consists of a single electric generator and a load. An electric generator converts rotational kinetic energy to electric energy. The law of energy conservation requires that, at any instant, the power demanded by the load is supplied by the generator and/or by energy stored within the system. If the consumption in the load increases, the extra energy demand is initially supplied by the rotational inertia of the generator through a decrease of its speed. The frequency of the voltage in an electrical generator is directly proportional to the rotational speed of its rotor. All the alternators connected to an electrical system rotate with the same electrical angular speed, according to the relation:

$$f = \frac{pn}{60}$$

Where f is the frequency, p the number of poles in the alternator and n the rotational speed of the rotor in rpm (revolutions per minute). Consequently, the decrease in rotational speed will be accompanied by a proportionate decrease in the frequency of the voltage generated by the generator. Frequency instability can occur within different time frames. A frequency stability problem can be resolved by load shedding or tripping generation [8-10].

1.2 Voltage Stability

The core of voltage instability problem is the drop in voltage magnitude which occurs by active and reactive power flow through transmission reactance. This drop may occur due to the increase in active or reactive power of the load, decrease in reactive power delivered by compensating devices/transmission lines or increase in the reactive power consumed by transmission lines. Assuming that the three-phase system is balanced, the transmission line can be simplified to the single-line circuit in Figure 2.

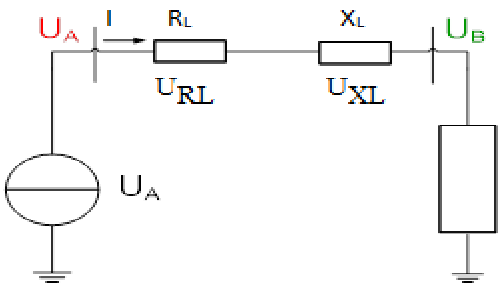


Fig 1: Single line radial system

Both the line resistance RL and the line reactance XL have been included. Figure 2 shows the voltage drops across the elements of the transmission line. due to the presence of an inductive element the current I is not going to be in phase with the voltage UA. The voltage drop in the line resistance $UR=R_L I^*$ will be in phase with the current I, while the voltage drop in the line reactance XL will lead the current by 90°.

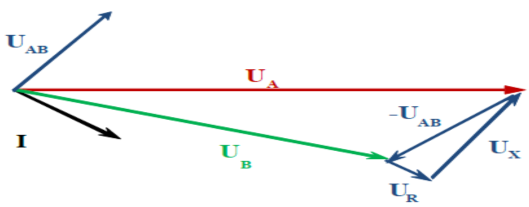


Fig 3: Voltage drops for different elements of the transmission line

1.3 Rotor Angle Stability

Rotor Angle Stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. From the simple power system shown Figure 4 shows the relationship between the interchange power and the angular position of the rotor of synchronous machines. Figure 5 shows the phasor diagram of voltages between generator and motor [15-20].

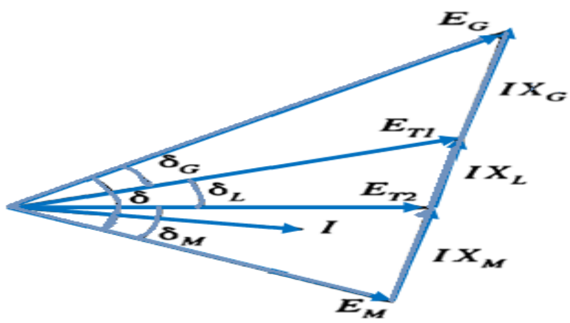


Fig 5: 1Phasor diagram of voltages

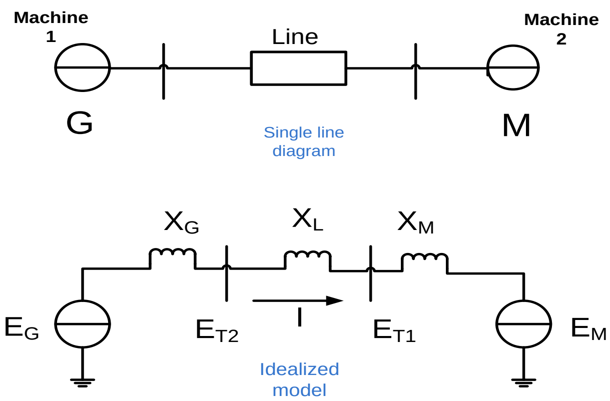


Fig 4: Simple power electrical system

The power transfer from the generator to the motor equation is given by:

$$P = \frac{E_G E_M}{X_T} \sin \delta$$

Where $X_T = X_G + X_L + X_M$ and $\delta = \delta_G + \delta_L + \delta_M$

Figure 6 below shows the electrical system stability issue, due to the relationship between the highlighted areas A1 and A2

[11-14]:

- If A1 is less than A2 then the system is stable.
- If A1 is equal to A2 then the system is critically stable.
- If A1 is more than A2 then the system is unstable

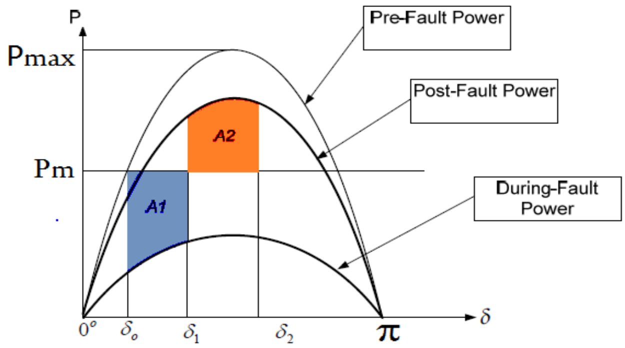


Fig 6: Electrical and mechanical power relationship in synchronous generator

2. EXPERIMENTS AND SIMULATION

2.1 Software

This paper is based on real electrical system data simulated using the DIgSILENT Power Factory software. The calculation program DIgSILENT Power Factory is a computer-aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to the electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

"DIgSILENT" is an acronym for "**Dig**ital **SI**mu**L**ation of **E**lectrical **N**e**T**works". Power Factory is primarily intended to be used and operated in a graphical environment. That is, data is entered by drawing the single line diagram network elements, and then editing and assigning data to these objects. Data is accessed from the graphics page by double clicking on an object. An input dialog is displayed and the user may then edit the data for that object.

The DIgSILENT Power Factory software has been used in a number of related researches for both static and dynamic power system analysis It provides a user-friendly interface and set of tools to perform beside the normal load flow analysis contingency, stability, reliability, power quality and other analysis.

2.2 Operation scenarios

The National Power System stability will be studied by the assumption of two main operation conditions, without Renewable energy sources (RES) and with to RES.

Case 1:

The system will be studied for load flow and dynamic stability analysis without RES, a three-phase fault will be applied at Qatranah substation then the stability of the system according to the rotor angle, voltage and frequency values will be observed.

The rotor angle will be measured on three generators at three different substations also the voltage and frequency will be measured in two substations one in the north and the other in the South of the Jordan. In this case, two operating conditions minimum and maximum loading will be taken into account.

Case 2:

Stability analysis of case I will be repeated but with RES and two deferent faults at Qatranah and Tafila S/S with the same operating conditions in case I.

The electric power system consists of three main parts: generation, transmission, and distribution, the transmission voltages in Jordanian power system are 400 kV,132 kV, and 230kV.

Figure 7 shows the plan of the electrical power system stability analysis.

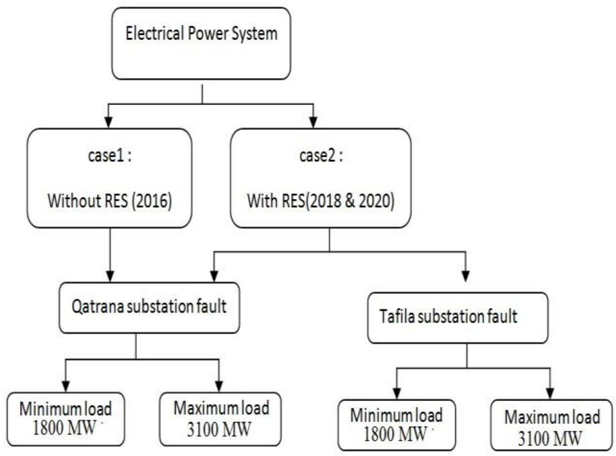


Fig 7: Electrical power system stability analysis flow chart

Nine conventional generating units in Jordan were distributed geographically from South to North;

Table 1 shows generation station with its capacity and generation technology

Table 1. Conventional generating units in Jordan without RES \2016

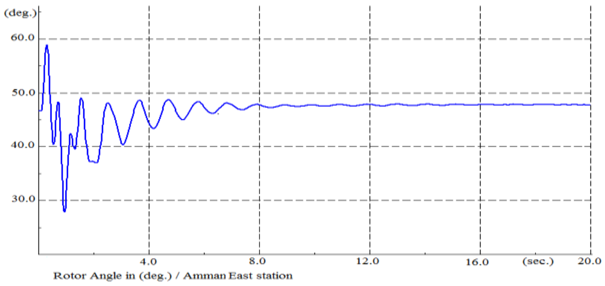
Power station	Capacity in MW	Generator type
Aqaba thermal	650	Steam
Amman South	30	Gas turbine
Rehab	360	Combined cycle gas turbine
Resha	150	Gas turbine
Samra	1020	Combined cycle gas turbine
Amman East (IPP1)	420	Combined cycle gas turbine
Qatrana (IPP2)	420	Combined cycle gas turbine
IPP3	570	Diesel Generator
IPP4	240	Diesel Generator

2.3 Dynamic Analysis results without RES

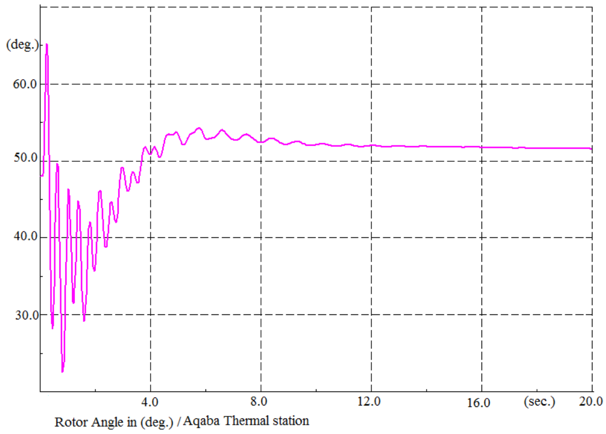
In this section, a dynamic analysis study will be simulated when a three-phase fault occur at Qatranah substation in two simulation experiments; Experiment I system with minimum loading and Experiment II system with maximum loading.

Experiment I:

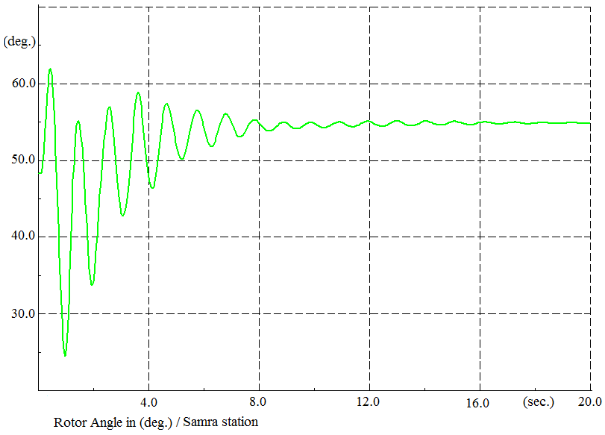
A three phase fault has been applied at Qatranah substation then the response curves for rotor angle, frequency and voltage of the electrical power system with minimum loading at stations Amman, Aqaba, and Samra are shown in Figures 8, 9, and 10.



a. Amman



b. Aqaba



c. Samra

Fig 8: Rotor angle response curves for stations Amman, Aqaba, and Samra of experiment I

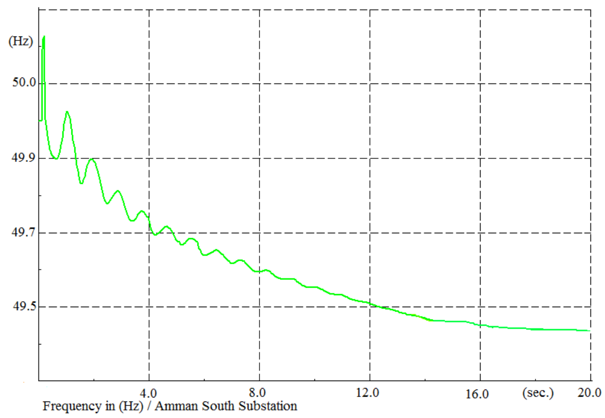


Fig 9: Frequency response curves for experiment I-Amman station.

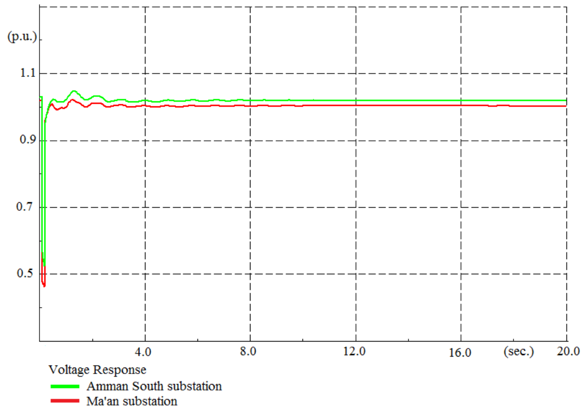
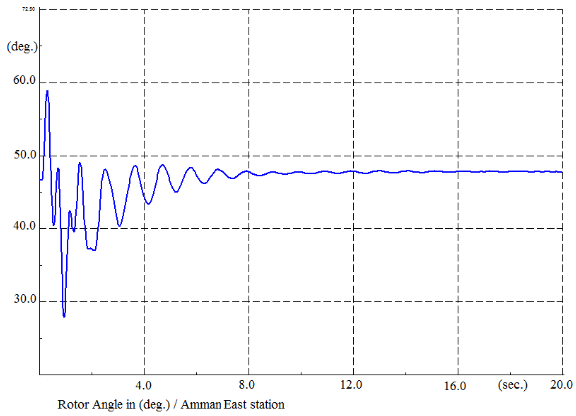


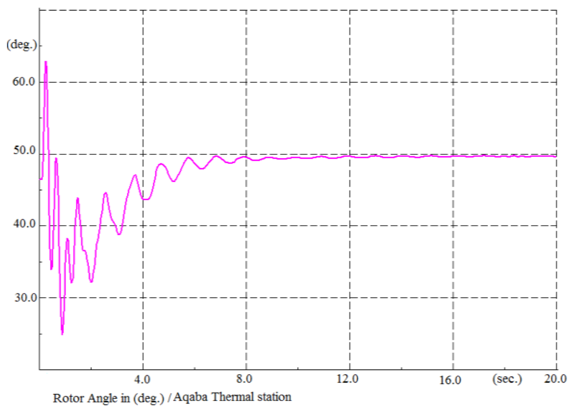
Fig 10: Voltage response curve of Amman South and Ma'an S/S for Experiment I

Experiment II:

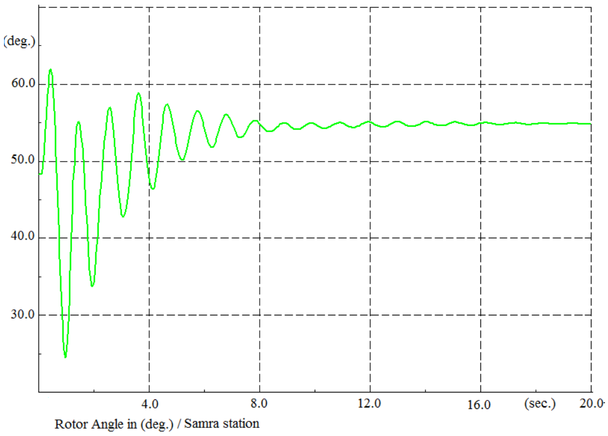
A fault has been applied at Qatranah substation then the response curves for rotor angle, frequency and voltage of the electrical power system with maximum loading at three stations shown in Figures 11,12 and 13 show the performance characteristic parameters of the electrical power system for rotor angle, frequency and voltage.



a. **Amman**



b. Aqaba



c. Samra

Fig 11: Rotor angle response curves for Experiment II

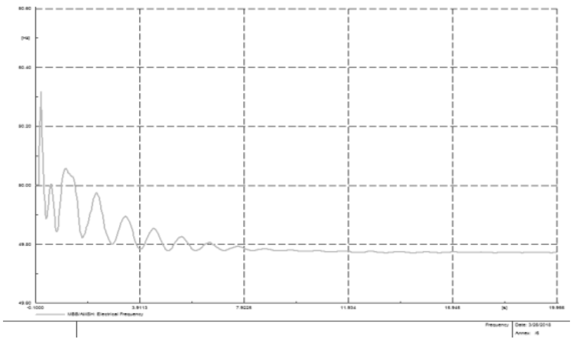


Fig 12: Frequency response curves for experiment II

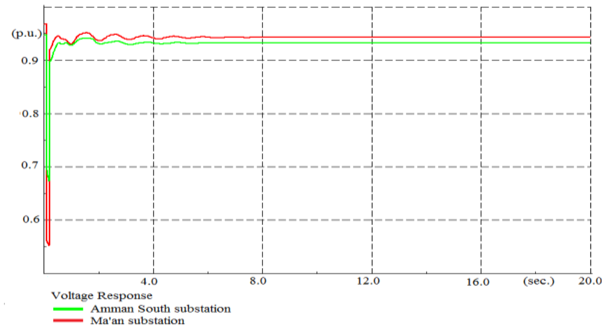


Fig 13: Voltage Response Curve of Amman South and Ma'an S/S for Experiment II

2.4 The National System with RES

The renewable energy sources were started to couple with the Jordanian electrical power system at the beginning of2017.In this section, stability of the electrical power system will be studied with the existence of RES for the years 2018 and 2020. In 2017 and 2018 a new renewable energy sources projects connected to the national grid, Table 2 illustrates the RES which added to the system at the end of 2018 and the type of each of them (wind or PV).

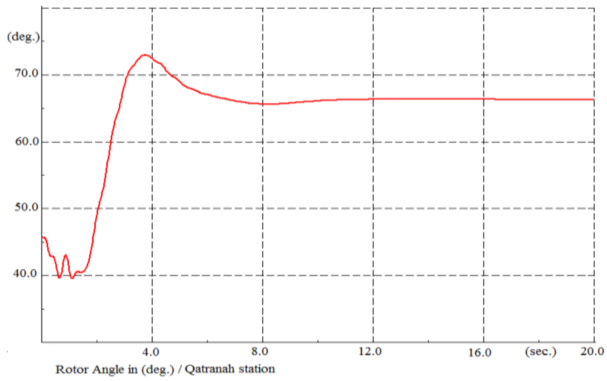
Table 2: RES added to the electrical power system at the end of 2018

Power Station	Capacity in (MW)	Type
Tafila	117	Wind
Ma'an Development Area (MDA)	160	PV
Quara	75	PV
Shamsuna	10	PV
Alazraq	4	PV
Jo Solar\HIE	20	PV
Scatec\Ma'an	10	PV
Ma'an Wind \King Husain	75	Wind

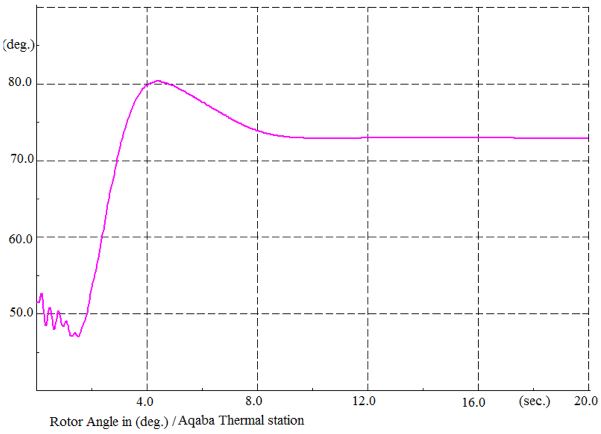
Experiment III:

A fault has been applied at Tafila substation then the response curves for rotor angle, frequency and voltage of the electrical power system with minimum loading at three stations mentioned in section 2.2 are shown in Figures 14,15,16 show the performance characteristic parameters of the electrical power system for rotor angle, frequency and voltage.

Note that in experiment III both of Samra and Amman East generation stations are not operated because of the economic dispatch operation for the generation station which is issued by the Monitoring and Control Center (MCC) this specific order is called operation merit order which is depend on the cost of MWH of each generation station. This order assists to supply the required load with the lowest financial cost.

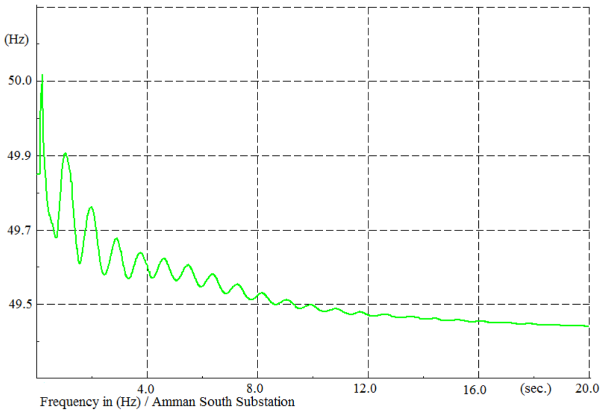


a. Qatranah

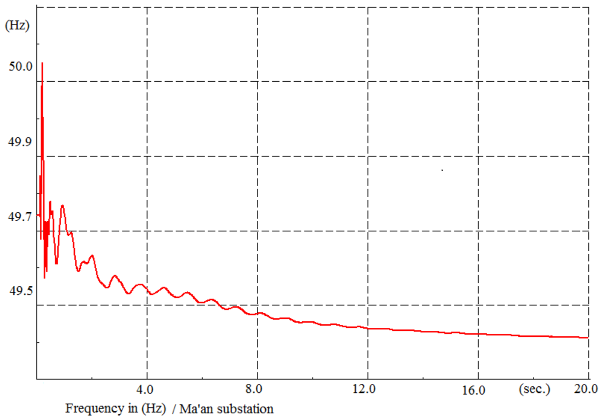


b. Aqaba

Fig 14: Rotor angle response curves for experiment III



a. Amman



b. Ma'an

Fig 15: Frequency Response Curves for Experiment III

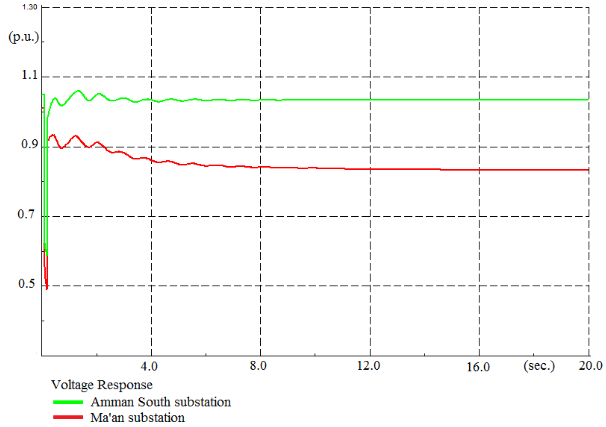
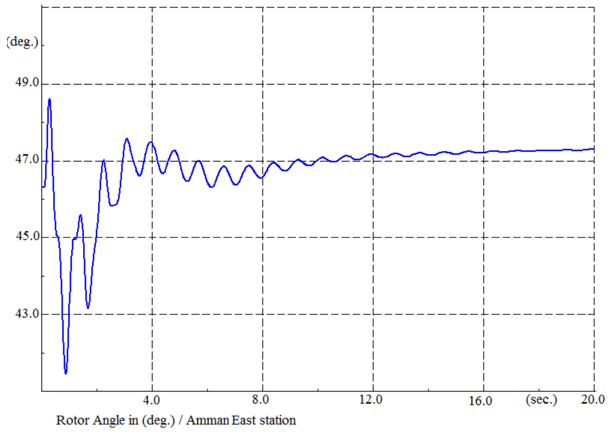


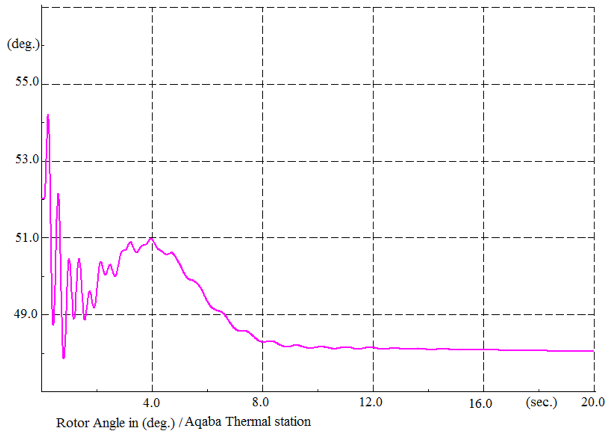
Fig 16: Voltage Response Curve of Amman South and Ma'an S/S for Experiment III

Experiment IV:

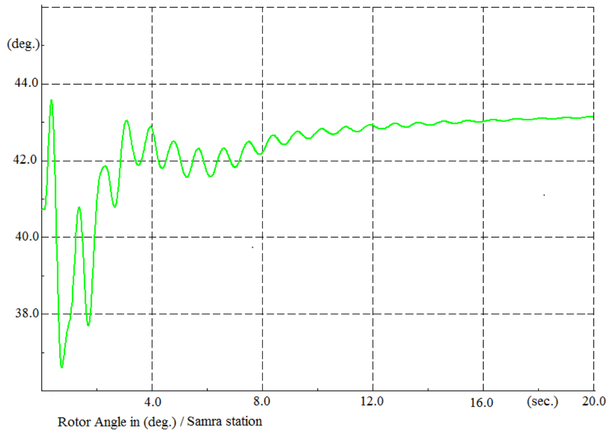
A fault has been applied at Tafila substation then the response curves for rotor angle, frequency and voltage of the electrical power system with maximum loading at three stations mentioned in section 2.2 are shown in Figures 17, 18 and 19 show the performance characteristic parameters of the electrical power system for rotor angle, frequency and voltage.



a. Amman

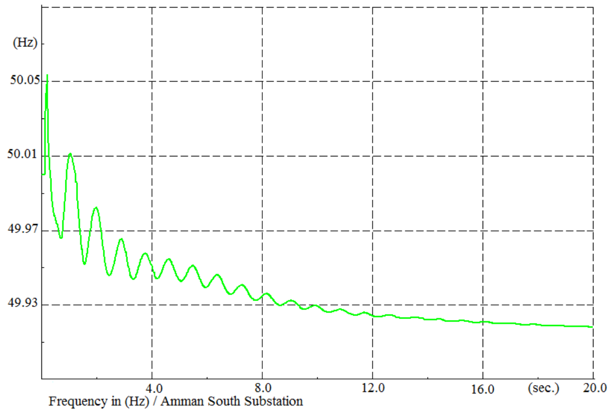


b. Aqaba

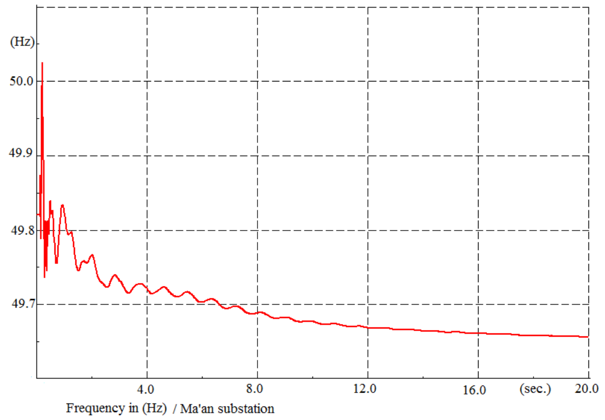


c. Samra

Fig 17: Rotor angle response curves for Experiment IV



a. Amman South S/S



b. Ma'an S/S

Fig 18: Frequency Response Curves for Experiment IV

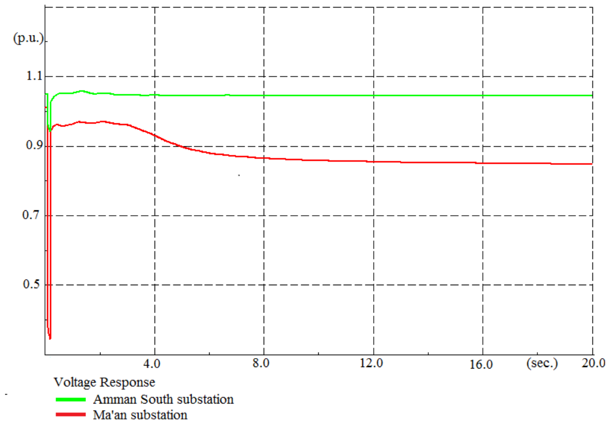


Fig 19: Voltage Response Curve Amman South and Ma'an S/S for Experiment IV

Experiment V:

A fault has been applied at Qatranah substation then the response curves for rotor angle, frequency and voltage of the electrical power system with minimum loading at three stations mentioned in section 2.2 are shown in Figures 20, 21 and 22 show the performance characteristic parameters of the electrical power system for rotor angle, frequency and voltage.

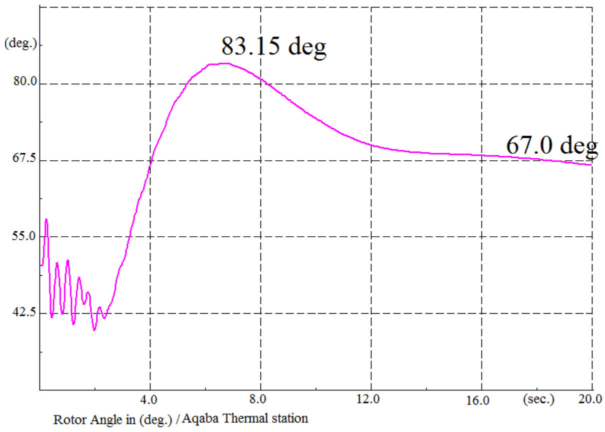
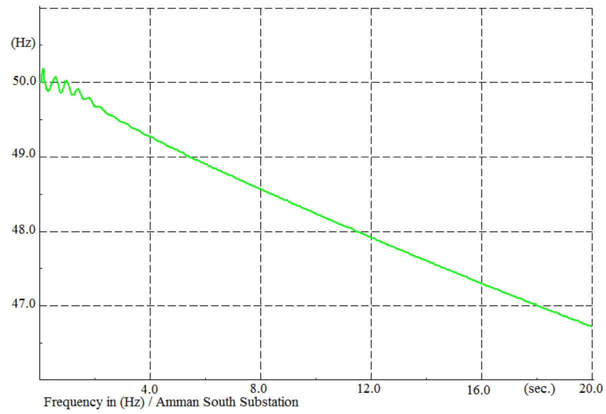
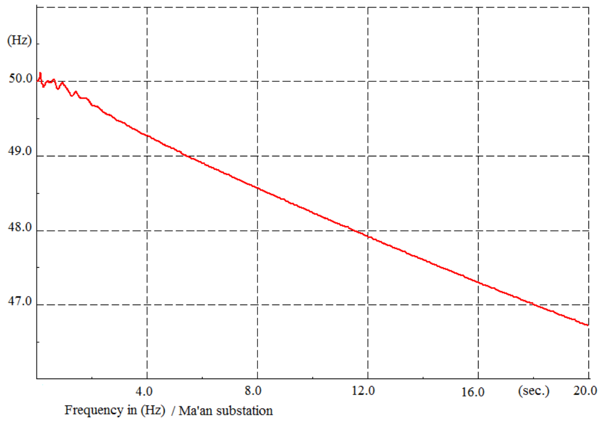


Fig 20: Rotor angle Response Curves for Experiment V for Aqaba



a. Frequency at Amman South S/S



b. Frequency at Ma'an S/S

Fig 21: frequency Response Curves for Experiment V

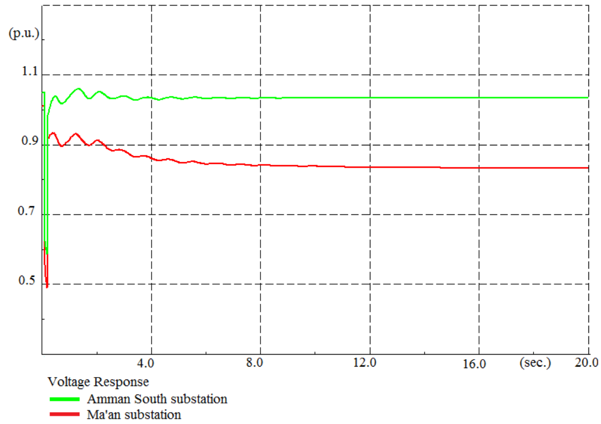


Fig 22: Voltage Response Curve of Amman South and Ma'an S/S for Experiment V.

2.5 Results and Discussion

Table 3 shows that the rotor angle didn't change by changing the system loading, this indicates that the power system generators can feed the predicted maximum load without losing its synchronism.

Table 3 Rotor Angle in (deg.) for Both Minimum and Maximum Loading

	Without RES		With RES/2018		With RES/2020	
	Minimum loading	Maximum loading	Minimum loading	Maximum loading	Minimum loading	Maximum loading
Amman East	46.8	46.8	46.8	46.8	46.8	46.8
Aqaba Thermal	52.8	52.8	52.8	52.8	52.8	52.8
Qatranah	52.19	52.19	52.19	52.19	52.19	52.19
Samra	36.7	36.7	36.7	36.7	36.7	36.7

Tables 4 shows the total losses in the electrical power system, which had a small increased when the RES connected to the system. This can be explained due to the increase in losses across transmission lines since most of the RE stations are located in far south of Jordan while the center of the loadis located in middle and north of Jordan, this makes the distance between the generation station and loads longer.

Table 4 System Losses(MW)

Without RES Load of 3000MW	With RES/2018 Load of 3330MW	With RES/2020 Load of 3330MW
46.8	56.2	71.9

Tables 5 and 6 demonstrate that the rotor angle showed a stable behavior in all experiments. In most cases, the maximum overshoot decreases with the increase in the RES. Also, the steady state time with renewable energy is higher than that without RES.

Table 5 Rotor Angle in (deg.) / Fault at Qatranah

			Without RES(I,II)	With RES 2018(V,VI)	With RES 2020(XI,X)
AE	Min	Overshoot (%)	31.5	Not economic at minimum operation	Not economic at minimum operation
		Ts	8		
	Max	Overshoot (%)	30	34	24
		Ts	8	12	8
Aqaba	Min	Overshoot (%)	9	24	12
		Ts	9.5	16	16
	Max	Overshoot (%)	11	20	20
		Ts	8	11	8
Samra	Min	Overshoot (%)	17.7	Not economic at minimum operation	Not economic at minimum operation
		Ts	10		
	Max	Overshoot (%)	12	18	21
		Ts	12	14	10

Table 6 Rotor Angle in (deg.) / Fault at Tafila

			With RES 2018(III,IV)	With RES 2020(VII,VIII)
AE	Min	Overshoot (%)	Not economic at minimum operation	Not economic at minimum operation
		Ts		
	Max	Overshoot (%)	3	2
		Ts	16	12
Aqaba	Min	Overshoot (%)	10	2
		Ts	12	11
	Max	Overshoot (%)	13	7.5
		Ts	12	14
Qatranah	Min	Overshoot (%)	10	3
		Ts	10	9
	Max	Overshoot (%)	8	6
		Ts	14	9
Samra	Min	Overshoot (%)	Not economic at minimum operation	Not economic at minimum operation
		Ts		
	Max	Overshoot (%)	1	0.01
		Ts	16	13

Table 7 shows a decrease in frequency in all experiments with and without RE sources. Without RE the frequency still stable in both cases minimum and maximum loading.

Table 7 Frequency in (Hz) / Fault at Qatranah

			Without RES(I,II)	With RES 2018(V,VI)	With RES 2020(XI,X)
Amman South	Min	Steady state	49.4	Unstable	Unstable
		Ts	6	Unstable	Unstable
	Max	Steady state	49.78	49.65	49.75
		Ts	6	6	6
Ma'an	Min	Steady state	49.75	Unstable	Unstable
		Ts	6	Unstable	Unstable
	Max	Steady state	49.78	49.66	49.7
		Ts	6	12	6

But when the system operated with minimum loading and with the existence of the RES it can be seen that its lost the stability on frequency when a fault applied at Qatranah power station, this can be explained by the unavailability of the primary reserve due to lowering the number of the conventional power stations

Table 8 clarify the aforementioned instability situation where a fault was applied at Tafila power station as we can see that the frequency still stable after fault because the majority of the remaining power stations is conventional power stations which increase the primary reserve in the system and keep its frequency in its boundary limits.

To overcome this drop in frequency, load shedding in multiple stages should be programmed and utilized to stabilize the decrease in the system frequency.

Table 8 Frequency in (Hz) / Fault at Tafila

			With RES 2018(III.IV)	With RES 2020(VII,VIII)
Amman South	Min	Steady state	49.92	49.83
		Ts	8	6
	Max	Steady state	49.9	49.9
		Ts	8	12
Ma'an	Min	Steady state	49.93	49.83
		Ts	8	8
	Max	Steady state	49.9	49.9
		Ts	8	8

Table 9 and 10 show that the voltage response curves still stable with and without renewable energy for both cases minimum and maximum loading Also, the maximum overshoot with RE is highly decreased as the RE sources increased. thisdecrease is due to adding RE units especially PV which behave like voltage controllers and enhance the total reactive power of the whole system.

Table 9 Voltage / Fault at Qatranah

			Without RES(I,II)	With RES 2018(V,VI)	With RES 2020(XI,X)
Amman South	Min	Voltage dip (%)	49	44	13
		Ts	0.8	0.8	0.8
	Max	Voltage dip (%)	35	9	12
		Ts	0.8	0.8	2
Ma'an	Min	Voltage dip (%)	52	40	29
		Ts	0.8	0.8	4
	Max	Voltage dip (%)	53	49	29
		Ts	0.8	0.8	2

Table 10 Voltage / Fault at Tafila

			With RES 2018(III.IV)	With RES 2020(VII,VIII)
Amman South	Min	Voltage dip (%)	41	14
		Ts	0.8	0.8
	Max	Voltage dip (%)	9	12
		Ts	0.8	0.8
Ma'an	Min	Voltage dip (%)	40	30
		Ts	0.8	8
	Max	Voltage dip (%)	45	30
		Ts	0.8	0.8

3. CONCLUSION

In this paper the impact of integration of the RES to the electrical power system stability in Jordan has been studied. Voltage profile of the whole electrical power system has been enhanced due to the increase in RES penetration. Load flow analysis, including voltage and power system electrical losses has been measured for minimum and maximum loading of the system. Several experiments with different specifications were done to measure the stability of the system. The results show the dynamic behaviour of rotor angle, frequency and voltage stability. Adding RES to the conventional power system affects the frequency stability; the frequency of electrical power signal decreased and shows instability in case of minimum loading. This decrease in frequency is due to the increase of the electronic based generation plants which is substitute other conventional generating units, and the overall system inertia is reduced. Load shedding shall be taken in to account to stabilize the system frequency after the loss of generation fault. Rotor angle stability curves show good

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