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*Original Article*

# The Impact of Large Wind Farms on the Transient Voltage Stability Using Different Control Techniques-Jordan as a Case Study

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***Abstract -*** *In this paper, an overview of the major problems caused by connecting wind farms to conventional electrical networks is given. Then, the characteristics and impact of doubly-fed induction wind generators on the voltage stability of the network are discussed. This work is applied to the electrical grid in Jordan as a case study, using a detailed 40-BUS network model to represent the southern part of the Jordanian transmission system. This model is employed as a tool to study the system stability by illustrating the network response to a three-phase fault applied to the wind farm connection bus. The Electrical Transient and Analysis Program is used to perform various simulation cases of operational techniques of voltage and reactive power control. The study is done for different production levels of wind plants to achieve the goal of voltage stability assessment and to investigate the size of the system portion, which the introduction of the wind farm might correctly enhance. Finally, the current work reveals that with adequate reactive power support and a proper application of voltage control, the wind farm's performance during the fault can approach the same level as that of the conventional one.*

***Keywords -*** *Doubly Fed Induction Generator, Reactive power, Voltage stability, Wind power, RER.*

## 1. Introduction

Since the beginning of this century, modern power systems have started to rely on Renewable Energy Resources (RERs) to enhance their energy potential and to reduce the detrimental pollution impact. Despite the difference in achievements of this goal in various countries, a remarkable global growth in solar and wind energy adoption was noticed in the last two decades. This evolution is attributed to several reasons, such as the abundance, cheapness, and cleanliness of renewable energy resources.

However, this significant opportunity is faced with several challenges, which directly affect the existing electrical transmission and distribution grids. The nature of these challenges comes from the fact that the behavior of conventional generating stations is completely different from that of renewable plants during normal and abnormal operating conditions. In addition to that, there are other barriers facing the integration of renewable energy into conventional networks, such as weather and climate changes, thermal and stability limits of loaded transmission lines, weak environmental protections, and the debate among researchers about the prioritization of profit over sustainability associated with a deregulation process.

To reliably employ the available renewable energy resources, several extensive studies were carried out to identify the effects of these new sources on the power system performance. Voltage stability is considered one of such vital studies, which have found a significant concern in determining the system's reliability and security during contingencies. Traditionally, voltage stability is classified into steady-state and transient stability based on the value of change in the system voltage.

Steady-state voltage stability, or as it is sometimes called the small signal stability, is defined as the power system's ability to keep the voltages under normal conditions, whereas transient stability is the ability of the power system to maintain synchronism when it is subjected to a severe transient disturbance. In all related studies, the main concern is to maintain a set of acceptable voltage values at system buses and to employ the system response as an indicator of stability after the occurrence of a three-phase fault [1-3].

Although the wind is the second fastest-growing source of renewable energy in the world, the increase of its penetration level is faced by a number of hard conditions. These conditions are applied to the wind generation units when the power system is subjected to severe disturbances, including faults [4]. The interest in this subject is attributed to the fact that Wind Farms (WFs) were assumed to play a significant role in post-fault system recovery, especially with the development of new technologies, which must facilitate rapid power restoration after experiencing severe disturbances [5].

Doubly Fed Induction Generator (DFIG) is characterized by a topology, which allows it to enhance system voltage during and after the fault occurrence by changing its reactive power output. This goal is achieved by using power electronic inverters to control the waveform of the rotor voltage. These inverters carry part of the power delivered by the generators, allowing for higher MVA ratings of Wind Turbines (WTs) to be used [6]. This privilege clearly explains the widespread of DFIG units in most wind farms nowadays.

In the last two decades, a large plan for wind energy development was introduced in Jordan. Therefore, several wind energy plants were already built and connected to the grid or are still under construction. The latter will be connected to the Jordan transmission system in the next few months. Since Jordan is one of the pioneering countries in renewable energy in the Middle East area, a significant development in clean energy projects is clearly noticed [7]. Therefore, a typical large wind farm with tens of DFIGs is selected to perform the current study.

In this paper, different scenarios of network structure were proposed to determine the penetration limit of wind energy and to calculate the amount of reactive power support needed to reduce the security limits of the power system under certain operating conditions. Then, the impact of DFIGs on the voltage stability of the network was verified, using the southern part of the electrical grid in Jordan as a case study. Therefore, a detailed 40-BUS network model was built and applied to perform the current study.

Additionally, the Electrical Transient Analysis Program (ETAP) was employed here to make various simulations for voltage and reactive power control operational techniques. The study was done at different production levels of wind plants to achieve the goal of voltage stability assessment and to investigate the size of the system portion, which needs to be correctly enhanced by the introduction of the wind farm.

The present work is of great significance to the researchers in this area because the number of wind farms in Jordan is continuously increasing compared to the neighboring countries. Although such wind farms are owned by international companies, they are operated by the National Control Center (NCC), which suffers from load fluctuation during the day. Jordan is one of few countries, which spends almost half of its energy on residential load. Therefore, the voltage and reactive power control modes are changed here at least three times per day, namely in the early morning, in the afternoon, and the evening peak. This problem is one of the main reasons for performing the current research work. Despite the remarkable development in the exploitation of renewable energy resources in Jordan, the achievements are still below the required target. The main hurdles are the high initial cost of renewable energy equipment, the instability of issued regulations, and the need for large financial investments.

## 2. Literature Review

Although there is a significant increase in wind energy potential nowadays, the research works in this vital field are still not adequate. The study in [8] shows that large-scale integration of wind generation may be reduced according to the operation modes associated with slip and shaft stiffness.

In [9], it was shown that a fault rides through of the DFIG can be enhanced by a modulated series dynamic braking resistor control strategy that employs a Pulse Width Modulation (PWM) switching technique. In [10], it was demonstrated that a bridge-type fault current limiter was a very effective device in attaining better stabilization of the DFIG and outperforming the series dynamic braking resistor.

One of the important topics discussed by researchers in this field is the assessment of the correct decision about the operation of wind turbines during a fault in the grid. The main debate was whether to keep the wind turbines running or disconnect them upon the occurrence of the fault. The initial attempts to develop a specific operational strategy for wind farms were not adequate because the early number of wind turbines connected to the grid was very limited.

The policy followed by several power system operators at that time was simply to disconnect the wind turbines from the grid once the fault had been noticed to cause a voltage drop at the point of common coupling with the grid. However, several researchers think that if the wind farm is to be disconnected during the fault, wind turbines should withstand the impact of voltage dip for a certain duration and should be allowed to feed local loads during the fault.

In light of the above debate, several research works with various approaches have clearly discussed this topic. In [11], for instance, a method that sustains DFIGs synchronized after clearing a fault was proposed so that the turbines can be reconnected to the grid very quickly after faults, whereas in [12], the researchers have made a review of fault current limiting devices to enhance the fault ride through capability of the DFIG based wind turbines.

In [13], the problem was approached from the controller’s point of view using adaptive dynamic programming. However, in [14], the researchers have proposed a robust composite wide-area control of a DFIG wind energy system for damping inter-area oscillations. Generally, most of the research works and applied techniques were directed toward improving the transient stability of the DFIG systems.

One of the important topics studied by several power system researchers was the stability index. Therefore, critical stability indices for performance evaluation were proposed by some workers such as that shown in [15]. Here, a generic model of DFIG was used to analyze transient voltage collapse caused by singularity-induced instability.

The paper has also highlighted a novel interaction between the grid and the wind farm. On the other hand, the authors in [16] have introduced a modern voltage stability index for the prediction of voltage collapse and the estimation of maximum load-ability for weak buses and critical line identification. In contrast, the authors in [17] have presented a survey on the effect of high penetration of wind energy systems on transient stability.

One of the important topics in this field is the relationship between fault location and voltage stability. In [18], a voltage collapse proximity indicator based on network loading was employed to investigate the contribution of wind generator location to voltage stability. The authors in [19] have used a method based on mathematical calculations to obtain the optimal reference value of reactive power. They have demonstrated the effectiveness of the proposed method via simulations performed by MATLAB/Simulink software.

Despite the intensive work in this field, the impact of large-scale wind energy on transient voltage stability is not completely disclosed because different systems have different structures and different experiences in this field. Therefore, the significance of the current work is attributed to the special topology of the Jordan network, where all large wind farms are installed in the southern region of the country. In contrast, the heavy load centers are located in the middle and northern areas. This pattern of non-uniform geographical distribution of wind farms will add a singularity to the obtained results of the current study.

The present paper is organized so that section 3 provides a brief description of the studied wind farm and the configuration of the investigated portion of the power system. Section 4 discusses several cases describing the response of the power system when a three-phase fault hits the grid. Different scenarios were illustrated in this section, considering both reactive power and voltage control operation modes. Finally, several conclusions are presented in Section 5.

## 3. Investigated System

The current study was performed using a simplified model, applied to the southern part of the Jordanian power system. The national grid of Jordan is considered one of the most reliable networks in the Middle East area. The installed capacity of the Jordan power system exceeds 5000 MWs, whereas the maximum peak load recorded in the last year was 4010 MWs. This system is characterized by a large number of high-voltage substations connected through several 132 kV and 400 kV overhead transmission lines. These transmission lines are fed from a number of thermal power plants in addition to the electrical interconnection with Egypt through a 400kV submarine cable.

One of the stability problems facing the Jordanian electric grid is the large distance between the generation and load sites. The main load centers are located in the middle area (Amman and Zarqa) and the northern regions of Jordan (Irbid and Mafraq). In contrast, the majority of the renewable generation stations are located in the southern part of the country (Maan, Shobak, and Tafila) (see Figure 1). These areas are rich in wind and solar radiation, but they do not have industrial activities or enough population density.

By the end of the year 2022, the total installed capacity of renewable energy in Jordan was 2577 MWs, 614 MWs of which were produced from wind farms. The capacity of such wind farms ranges from 50 MWs to 217 MWs. Therefore, it is worth mentioning here that the current renewable energy contribution exceeds 28% of the total consumed energy in Jordan.

In addition to this development, the early assessment of the wind energy potential in Jordan has indicated that a capacity of more than 1000 MWs may be generated from new wind farms in the future. This additional energy will be readily transmitted by the enhanced existing and future high voltage lines within the so-called “Green Corridor” project, linking renewable energy plants in the southern part of Jordan with the load centers in the middle and north. The project is not limited to the reinforcement of the existing grid but also includes the construction of future transmission lines and several high-voltage substations.

To perform the current study, the 40-bus Jordanian test system was proposed (see Figure 2). Fourteen of these buses (19-32) are considered load buses, with a total active and reactive power of 594.49 MW and 195.65 MVAr, respectively. This network also has eight generation buses (33-40) with a totally active and reactive power of 1055 MW and 100.2 MVAr, respectively. Bus No. 1, with an active power of 8859.09 MW, was selected as a swing bus. This bus is connected to the Jordan network, whereas Bus No. 2, with an active power of 980.34 MW, linking Jordan and Egypt grids, was modeled as a PV bus.

There are five levels of voltage in the studied system, specifically 400, 132, 33, 15, and 6 kV. The first two levels are transmission voltages, whereas the rest ones are classified as distribution voltages. The loads were modeled in the same way as that specified in the IEEE-14 BUS test system.

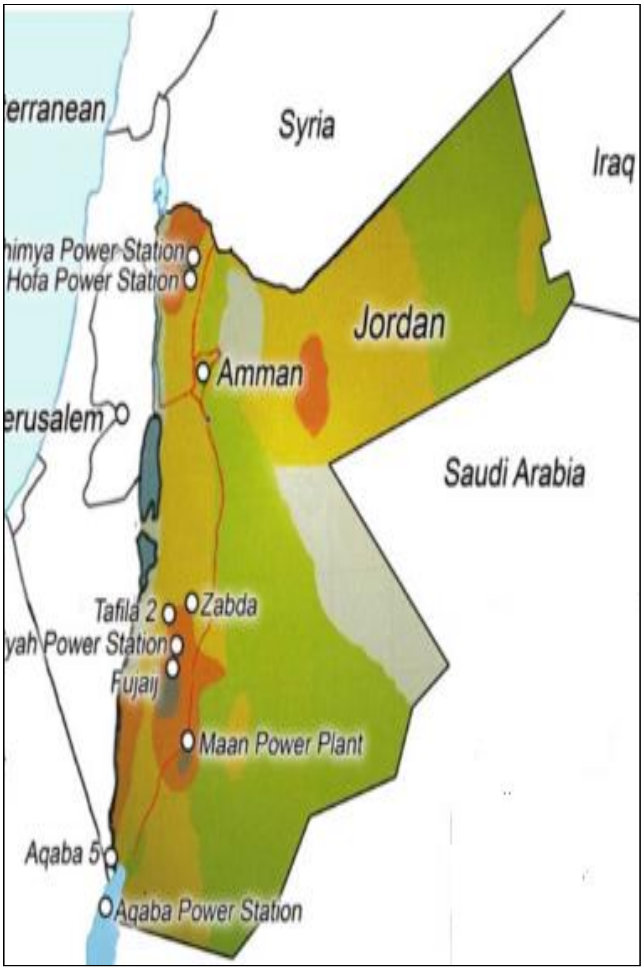

**Fig. 1 Map of Jordan with wind farm sites**

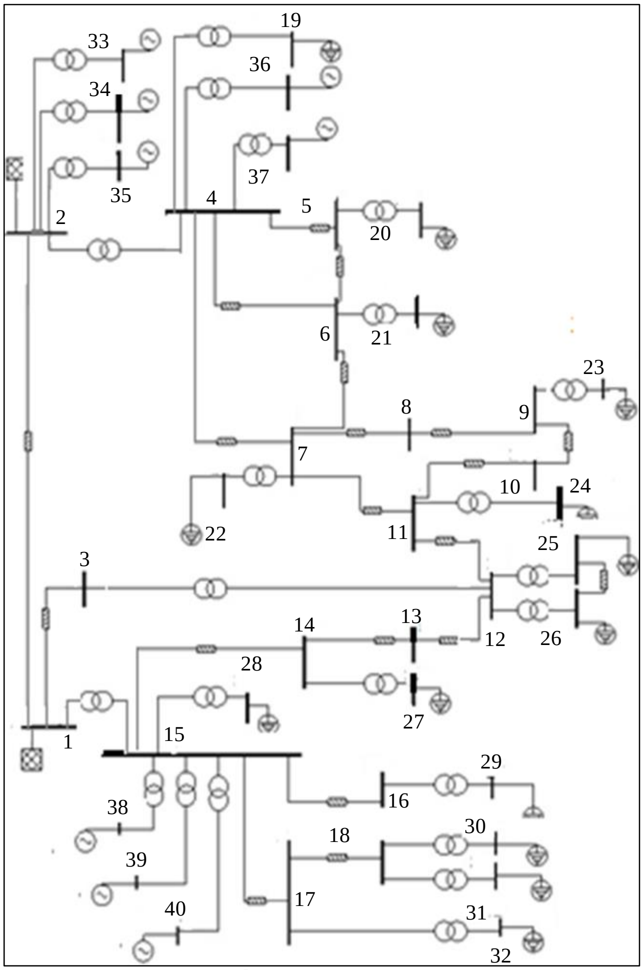

**Fig. 2 Jordanian 40-BUS test system**

In this study, it is important to model both the active and reactive power loads. Active power loads have been considered as constant current loads, whereas reactive power loads were treated as constant impedance loads according to the recommendations reported in [20].

To perform the required study, a wind farm with a total capacity of 81 MW, connected to the system at bus 14, was considered. The main configuration and components of this wind farm are arranged to match the wind directions, land terrain, and farm dimensions. This plant has 3 main buses, 47 branches, and 45 wind turbine generators distributed within the area of this plant in the form of identical arrays. (See Figure 3).

The selected model for the wind turbine representation in this study is based on using Vestas V90-1.8 MW. This turbine is a production of Vestas Wind Systems A/S, a manufacturer from Denmark. All sets of information related to this model and to the machine data are precisely specified in the manufacturer's document.

[21-23] For modeling of DFIG-based wind energy conversion system in the synchronously rotating frame of reference, it is necessary to characterize the two-phase system of the stator and that of the rotor in a synchronously rotating (d-q) frame of reference. The power rating of each wind turbine is 2 MVA with a generator terminal voltage of 0.69 kV.

The step-up transformers are selected with a power rating of 2.107 MVA to connect the wind turbine generators to the medium voltage collector at a 30 kV voltage level. Each transformer has a short circuit impedance value ($V_{sc}$) of 8.62% and an (X/R) ratio of 11.33. At the main substation, the wind farm was connected to the 132kV transmission system on bus 14 via a 100MVA step-up transformer that has a short circuit impedance value of 8% and an (X/R) ratio of 34.1.

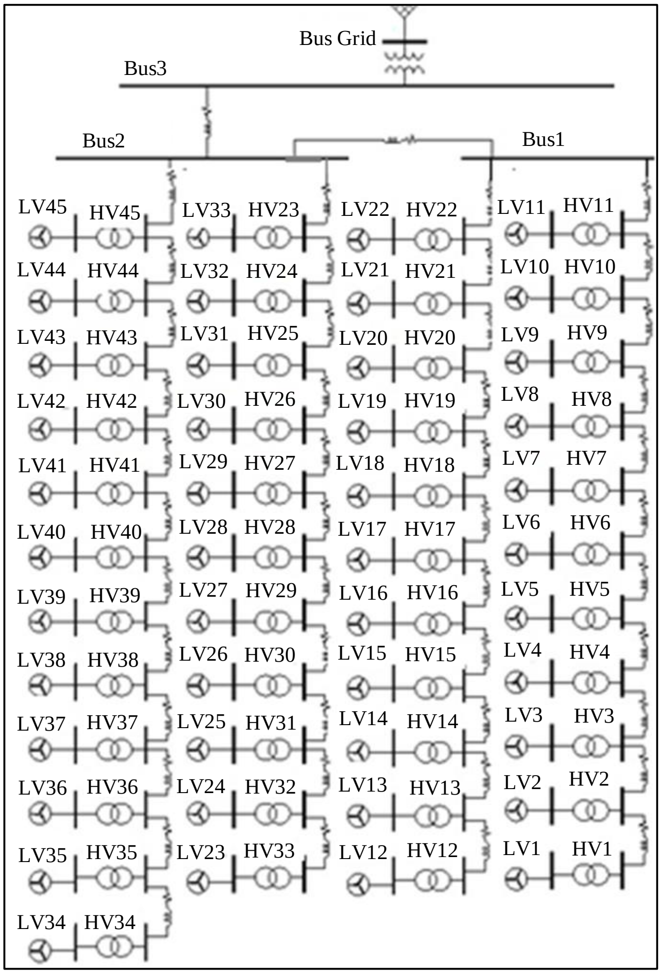

**Fig. 3 Wind farm configuration**

## 4. Results and Discussion

### *4.1. System Response to Faults*

One of the important aspects of voltage stability is the assessment of the system’s ability to recover after experiencing a large disturbance. Therefore, the system under consideration was initially modeled using the ETAP transient stability analysis program to study the dynamic response of the grid to a three-phase fault. Such a fault is commonly used in dynamic and transient studies because it is the most severe one. Therefore, before modeling the wind farm, a 0.5s duration three-phase short circuit with an 80% voltage dip was applied.

According to the grid code applied to the Jordanian power system, the wind farm must withstand the above-mentioned abnormal event without causing any negative effect on the rest of the network. [24] In this study, it is attempted to illustrate that it is not enough for the wind turbines to stay connected to the power system. However, they also must provide reactive power compensation to support the voltage profile during the fault occurrence. Initially, it was necessary to test the voltage response to the three-phase fault at Bus 14 before replacing the existing synchronous generators with the proposed wind energy ones. (See Figure 4). After placing the wind farm in the selected model, the present study was performed for both reactive power and voltage control operation modes. The wind speed mainly determines the amount of electricity generated by the wind turbine. The higher wind speed leads to a faster rotation of blades and more generation of power. The amount of power output of the wind generator is directly proportional to the cube of the wind speed as shown in Equation (1) [25].

$$P=0.5\rho_a A_T V^3 \tag{1}$$

Where P is the output power of the wind turbine in kW, $\rho_a$ is the density of the air in kg/cm$^3$, $A_T$ is the swept area of the blades formed during their rotation in space, measured in m$^2$, V is the wind speed in m/s. Therefore, an average wind velocity of 8 m/s, at which the wind turbine generates 812 kW, was considered as a first production level, whereas a wind velocity of 12 m/s, corresponding to a generation of 1800kW, was set as a second production level.

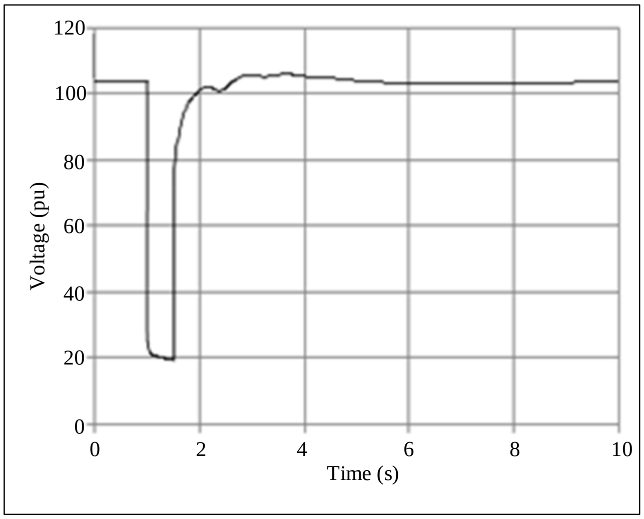

**Fig. 4 Voltage at BUS 14 during three three-phase faults without wind energy**

### *4.2. Reactive Power Control Mode*

Initially, it is important to mention that the DFIG scheme is not only based on simplicity, but it also represents a highly controllable way to transform the variable speed mechanical energy into a fixed frequency electrical supply. One of the important characteristics of DFIG is the limited absorption of reactive power. Therefore, this type of power is controlled to maintain the power factor at an acceptable value at the point of common coupling of the wind farm to the power system.

The control of reactive power and voltage must be a coordinated strategy. Therefore, the reactive power capability must be sufficient to bring back the voltage when a severe voltage dip occurs in the grid; otherwise, it is necessary to install reactive power compensation devices. In reactive power control mode, the selected wind turbine generators were designed to give a constant amount of reactive power, approximately equal to 20 kVAr. This value can be achieved by correctly setting the converter control limits for each wind generator. The study results concerning voltage and reactive power control modes for the same three-phase fault are also presented in this paper. (See Figures 5 and 6).

The results of the current work illustrate that the production level of the wind farm has a minor effect on the fault current at the average wind speed (around 8m/s). Therefore, only the wind speed values of 12 m/s and above will be considered for the rest of the studied cases. In this operating mode, the voltage was significantly dropped due to the reduction in reactive power support. At the wind speed of 8 m/s, the wind farm has produced 5 MVAr, whereas at 12 m/s, it has absorbed 1.8 MVAr. At higher production levels, this difference can be minimized by switching to more compensation devices, such as capacitor banks or Static VAR Compensators (SVCs).

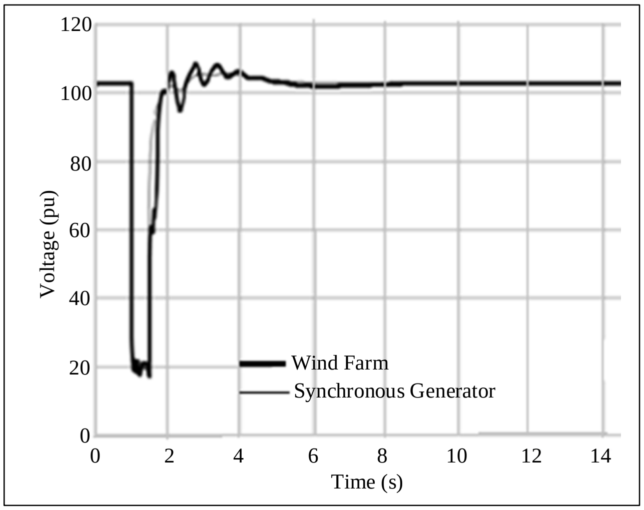

**Fig. 5 Voltage at BUS 14 with MVAr operation mode at 3-phase fault**

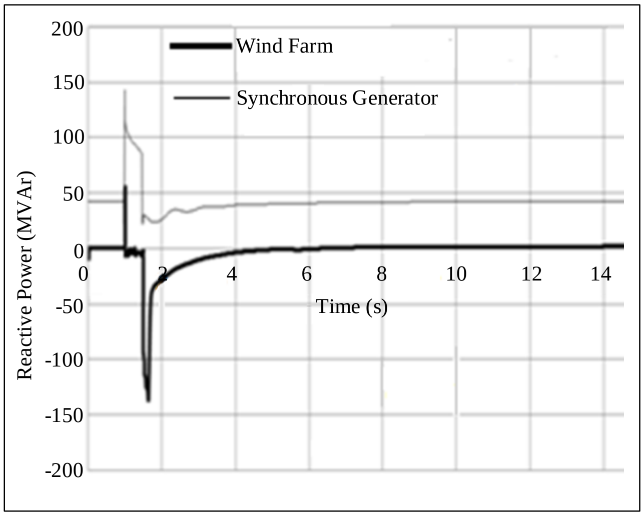

**Fig. 6 WF reactive power with MVAr operation mode at 3-phase fault**

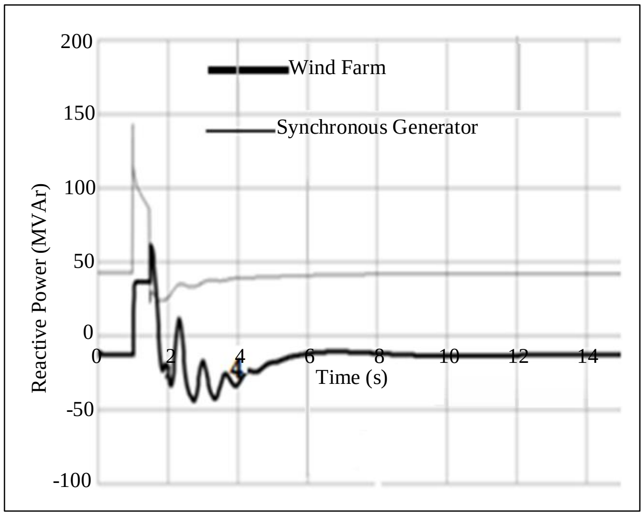

**Fig. 7 Output reactive power at 3-phase fault**

With this fault, the wind farm was able to regain its active power production in 3.3 seconds after fault clearance, which was within the grid code requirements. The reactive power output of one of the nearby synchronous generators (generator at bus 38) was also examined (see Figure 7). It is worth mentioning here that at a rated wind speed of 12m/s, the power of the wind farm represents 7.1 % of the total generation.

### *4.3. Voltage Control Operation Mode*

In voltage control mode, wind energy systems are designed to give reactive power support to maintain the voltage in the range from 0.95pu to 1.05pu. It is reasonable to consider a maximum limit of reactive power support equal to 20% of the WT rating. The voltage profile has shown an improvement with a slight increase at the same fault conditions (see Figure 8). It can also be noticed that the voltage during the fault is smoother and closer to the initial case, which existed before inserting the wind farm.

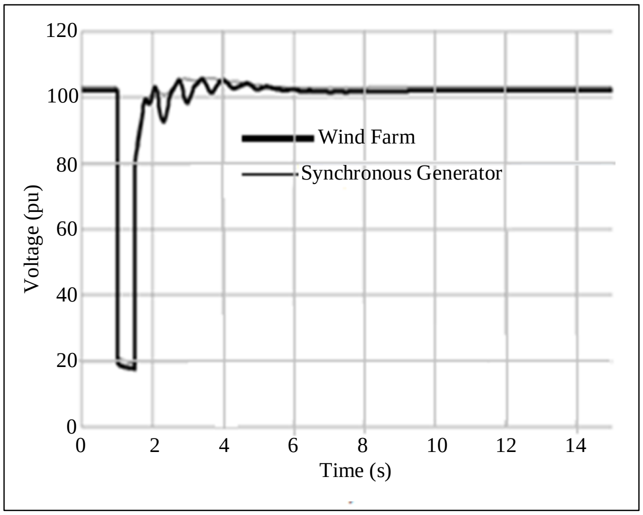

**Fig. 8 Voltage at wind farm connection bus for voltage control operation mode at 3-phase fault**

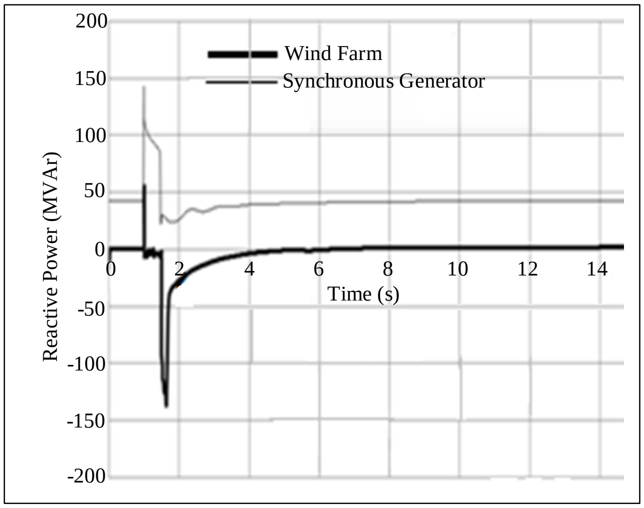

**Fig. 9 Output reactive power at both operational modes for a 3-phase fault**

From the voltage stability point of view, there was no problem with a higher penetration level of wind energy into the grid at this operating mode when the plant acts very close to the thermal unit. Therefore, it was necessary to illustrate the results of reactive power support for both operational modes (see Figure 9).

Here, it is easy to notice that this support for reactive power operation mode is less stable during the fault and, therefore, it is the reason for having voltage oscillations during the fault. The shape of oscillation, depicted after the fault clearance, is similar to that of the delivered reactive power for both operational modes.

The technique used in this work to study the voltage and reactive power operating modes is simple and does not need complex mathematical tools. Unlike other related works, the results are readily explained and agree well with other similar works. In addition to that, the present work can be easily developed to involve several wind farms connected to different parts of the Jordanian power network.

## 5. Conclusion

The present study was performed for two cases, before and after connecting a wind farm to the southern part of Jordan's electric grid. The time variation curves of voltage and reactive power control modes were obtained using the ETAP software. The study was performed for two different scenarios of wind farm operation. One scenario was considered at a high production level, whereas the other one was done at a low production level.

Different operational patterns of DFIGs were tested. The production level of the wind farm has shown a minor effect on the fault current at the average wind speed compared to that at high wind speed. It was found that the wind farm operating with a voltage control mode acts closer to that of synchronous generators during the fault.

This result raises the significance of this mode of operation and makes it more suitable for systems with a high density of wind farms. The reactive power support at the reactive power operation mode was much lower during the fault and less stable than that of the voltage control operation mode. After connecting the wind farm to the transmission grid, the high level of reactive power support becomes responsible for the higher voltage levels during the fault. Finally, this inevitably improves the voltage stability of the considered power system.

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