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The impact of the wind farm on the voltage stability of the western Algerian power system

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Abstract. A recent analysis shows that the mean reason for some major blackouts and failures of a power system is the voltage-instability problem. The wind-farm power generation has received a considerable attention for its significant impact on the power system voltage stability. The paper discusses the impact of integrating wind farms using doubly-fed induction generators (DFIG) on the western Algerian power-system operation for this proposes. The wind farms have been installed at different buses to determine their best location and to optimize their power. The maximum loading factor in the power system is determined based on the P-V curves. The simulation results obtained by using the Power System Analysis Toolbox (PSAT) show that the wind farms can be effectively used to enhance the static-voltage stability and increase the network loadability margin.

Keywords: Voltage stability, P-V curve, Doubly-Fed induction generators (DFIG), wind power, best location

Vpliv vetrnih elektrarn na napetostno stabilnost zahodnoalžirskega elektroenergetskega sistema

Zadnje analize so potrdile, da je napetostna nestabilnost eden glavnih razlogov za izpad elektroenergetskega omrežja. Pridobivanje električne energije z vetrnimi elektrarnami in njihov vpliv na stabilnost omrežja sta predmet številnih študij. V prispevku obravnavamo vpliv integracije vetrnih elektrarn v zahodnoalžirsko elektroenergetsko omrežje. Vetrne elektrarne so bile priključene na različnih mestih z namenom optimalnega prenosa moči. Največji faktor obremenitve v omrežju je določen s krivuljami P-V. Rezultati simulacij, pridobljeni s programskim orodjem PSAT, potrjujejo, da vetrne elektrarne pomembno prispevajo k napetostni stabilnosti omrežja in omogočajo večjo obremenitev.

1 INTRODUCTION

The voltage stability is a subset of the global power system stability and presents the ability of a power system to maintain steady acceptable voltage values at all buses under normal operating states and after being subjected to a disturbance [1]

The voltage stability problem is now a serious concern to the power generation industry. Many large interconnected power systems are increasingly experiencing abnormally high or low voltages and voltage collapses. These voltage problems are associated with the increased loading of power transmission lines, insufficient local reactive power supply, and of power transmission over long distances. The spirit of the voltage stability problem is the voltage drop that occurs when a power system experiences a heavy load [2].

The traditional power generation is insufficient when it comes to a high load demand; hence, the call for other sources of energy has become paramount, such as renewable energy in order to boost production in several cases.

The wind power is one of the most competitive renewable technologies and, in developed countries with good wind resources, the onshore wind is often competitive with the fossil fuel generated power. The wind-power generation has experienced a tremendous growth in the past decade, and has been recognized as an environmental friendly and economically competitive means of electric power generation. The size of wind turbines and wind farms is increasing quickly; a large amount of the wind power is integrated into the power system [3].

As the wind power penetration into the grid increases quickly, the impact of wind turbines on the power quality and voltage stability is becoming more and more important [4].

Generally, these wind turbines can either operate at a fixed speed or a variable speed. There are several reasons for using a variable-speed operation of the wind turbines; among those there is a possibility to reduce stresses of the mechanical structure and acoustic noise and to control the active and reactive power [5, 6]. An important type of the variable speed wind turbine is the wind turbine with a Doubly-Fed Induction Generator

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(DFIG) which can contribute to an improved voltage stability.

There are two types of the voltage stability based on the time frame of simulation: dynamic voltage stability and static voltage stability. Various approaches have been proposed for analyzing the static voltage stability. One of the main approaches, the continuation power flow (CPF), has a wide range of applications. CPF is one of the most important methods to find a complete PV curve starting at the base load and leading to the steady-state voltage-stability limit (critical point) [7].

The paper studies the impact of the wind farm operation with DFIG connected to the power system at different buses in order to get the best location. The important characteristics, such as voltage profile, load bus PV characteristic and active-power losses, are studied for a connected and unconnected wind-farm operation. Simulations are performed on the western Algerian power system using the Matlab-based toolbox (PSAT). The simulation results show that using DFIG improves the power-system voltage stability.

2 VOLTAGE STABILITY AND P-V CURVE

The voltage is an integral part of a power system and is an important aspect in the system stability and security. In recent years, the problem of the voltage instability has been paid a considerable attention because of many voltage collapse incidences [8].

The voltage stability is the ability of a power system to maintain steady voltages at all its buses when subjected to a disturbance. It is the ability of maintaining the voltage so that when the load is increased, the load power also increases and the voltage and power are controlled. The voltage instability occurs in the form of a progressive fall or rise of voltages of some buses [9].

The voltage stability can be classified as small or large based on the disturbance type. A small voltage stability refers to the ability of the system to control the voltage at an occurrence a small perturbation, such as a change in the load. A large voltage stability refers to the ability of the system to control the voltage after being subjected to a large disturbance, such as, a load outage, fault and large-step change in the load [10].

There are two types of the voltage stability based on the time frame of simulation: static voltage stability and dynamic voltage stability. The static analysis involves only the solution of algebraic equations and therefore is computationally less extensive than the dynamic analysis [11]. The static voltage stability analysis is commonly performed on a system and the results are indicative in determining the voltage-stability condition of a system [12].

The static voltage stability analysis is traditionally done using power-flow methods. The conventional static voltage stability analysis techniques usually detect saddle-node bifurcations, or voltage collapse points, in order to determine the loadability limits of the power system [13]. Several methods have been used in the static voltage stability analysis such as the P-V and Q-V curves, model analysis, continuation load flow method, etc.

In the steady-state voltage stability analysis, The CPF method [14, 15] is widely used for its tracking the power-flow solution at a critical voltage point. The CPF method is applied to get the critical point by tracing the P-V curve (see Fig. 1). This curve is also called the nose curve by the system planning engineers.

As shown in Figure1, the abscissa of the P-V curve is Loading parameter λ and the vertical axis is the voltage amplitude corresponding to the load. The P-V curve inflection point is the critical point of a stable operation. Loading parameter $\lambda_{\max}$ corresponding to the inflection point is the ultimate loading factor, and the voltage V_{cri} corresponding to the inflection point is the limit voltage of a stable operation.

The difference between the ultimate loading factor and loading factor of an actual operating point, as well as the voltage difference between the limit and actual voltage operating point can be integrated to reflect the static voltage stability margin of the node.

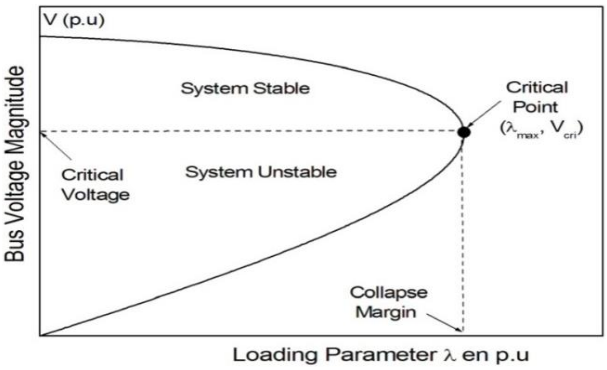

Figure 1. P-V curve.

3 MODELING THE WIND FARM

3.1 Wind model

The wind kinetic energy can be converted into the mechanical energy by the wind turbine. The wind energy takes the form of the kinetic energy. The energy produced by the wind turbine is determined by various factors, such as the wind speed and the turbine size and turbine type. The amount of the power generated by the wind is calculated by using this formula [16, 17]:

$$P = 0.5 \times \rho \times C_p(\lambda) \times S \times V^3 \tag{1}$$

where P is the aerodynamic power extracted from the wind turbine (W), C_p is the coefficient of the power control of the wind turbine $(C_p < 1)$, ρ is the air density (kg/m^3), V is the average wind speed (m/s), λ is the tip-speed ratio and S is the sweeping area of the rotor blades (m^2).

The power coefficient (C_p) measures the amount of the energy obtained by the rotor of the wind turbine [18].
The tip-speed ratio is given by the expression

$$\lambda = \frac{\omega \times R}{V} \tag{2}$$

where R is the radius of the wind-turbine rotor in (m) and ω is the angular velocity of the rotor in rad/s.

3.2 Turbine model

There are many different types of the wind turbine in use worldwide, each having its own list of benefits and drawbacks [19]. In the paper, a variable-speed wind turbine with a wound rotor induction generator (Fig. 2) – DFIG is taken into consideration.

DFIG is an induction generator with both the stator and rotor winding. DFIG is nowadays widely used in variable-speed wind energy applications with a static converter connected between the stator and rotor. As shown in Figure 2, its stator circuit is directly connected to the grid while the rotor circuit is connected to the grid via slip rings and a three-phase converter [20].

DFIGs can be included in load-flow studies as PQ or PV buses, as they can operate in either power-factor-controlled or voltage-controlled modes. When modeling DFIG as a PQ bus, it is assumed that DFIG operates in a power-factor-controlled mode, meaning that the specified reactive power is zero. In a voltage-controlled mode, DFIG can be represented as a PV bus with Q limits applied [21].

This basic DFIG structure offers the benefits of an improved efficiency, reduced converter size, minimized costs and losses, easy implementation of the power-factor correction, variable speed operation, and four control quadrants of the active and reactive power [22].
To sum up, using DFIG instead of an asynchronous generator in wind turbines offers the following advantages [23]:

- Operation at a variable rotor speed while the amplitude and frequency of the generated voltages remain constant.
- Complete control of the amount of the power generated as a function of the wind available up to the nominal output power of the wind-turbine generator to optimize the power exchange with the grid.
- Virtual elimination of sudden variations in the rotor torque and generator output power.
- Power generation at a lower wind speed.
- Control of the power factor (to maintain the unit power factor).

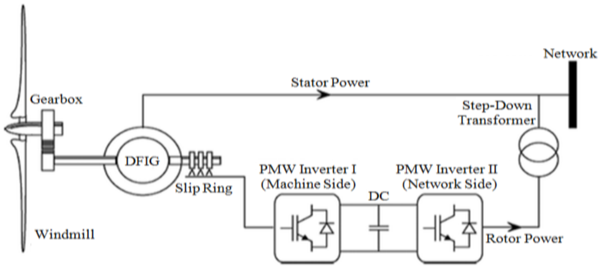

Figure 2. DFIG model.

In DFIG modelling, the full scale model is represented by four equations, considering the generator variables in the d-q synchronous reference frame. The equations for the stator and rotor winding can be written as follows [24, 25, 26]:
For the stator winding:

$$V_{ds} = -R_s \times i_{qs} + (X_s + X_m) \times i_{qs} + X_m \times i_{qs} \tag{3}$$

$$V_{qs} = -R_r \times i_{qs} + (X_r + X_m) \times i_{ds} + X_m \times i_{dr} \tag{4}$$

For the rotor winding:

$$V_{dr} = -R_r \times i_{dr} + (1-\omega) \times (X_r + X_m) \times i_{qr} + X_m \times i_{qs} \tag{5}$$

$$V_{qr} = -R_r \times i_{qr} + (1-\omega) \times (X_r + X_m) \times i_{dr} + X_m \times i_{ds} \tag{6}$$

V_{ds}, V_{qs}, V_{dr} , V_{qr}: d and q axes stator and rotor voltages, i_{ds}, i_{qs}, i_{dr}, i_{qr}: d and q axes stator and rotor currents, R_s, R_r: stator and rotor resistances, ω : synchronous speed, X_s, X_r: stator and rotor self-reactances and X_m mutual reactance.

The structures of the most widely used DFIGs to produce electricity in wind turbines are very complex [27]. They can be operated in two different control modes: constant power factor and voltage control. In the power-factor control mode, the reactive power from the turbine is controlled to match the active power production at a fixed ratio. When the terminal-voltage control is employed, the reactive-power production is controlled to achieve the target voltage at a specified bus [28]. In the load-flow studies, DFIG is represented as a PV bus for the voltage control mode. The PQ mode refers to the DFIG generation at a fixed MW and MVAr. When modeling DFIG as a PQ bus, DFIG is assumed to operate in the power-factor-controlled mode, meaning that the specified reactive power is zero. In the voltage-controlled mode, DFIG is represented as a PV bus with the Q limits applied [29, 30, 21].

Though being, considered satisfactory when first integrated in the Power Flow studies, such modeling techniques are clearly inadequate to accurately represent the generator behavior [27].

In the paper, DFIG is modeled as a PV bus and its stator is directly connected to the ith bus via a step-up transformer.

4 WIND POTENTIAL IN ALGERIA

Algeria is generally quite windy. The Algerian wind map, drawn in 2006 for the height of 10 m, above the ground level by Kasbadji-Merzouk (see Figure 3) [31], shows that the highest wind speeds are distributed in the south while the north is generally less windy.

The annual mean speed obtained vary from 1 to 6 m/s. One may conclude that outside the coastal region (the exception being Bejaia and Oran), i.e Tassili and Beni Abbes, the mean wind speed in the rest of the region is higher than 3 m/s.

In fact, the central part of Algeria is characterized by the wind speed varying from 3 to 4 m/s and it increases toward the south-western region [32].

The south-western and the north-western regions have a great potential with the speed exceeding 6 m/s for the site of Adrar (south-western region) and the site of Tiaret (north-western region). The wind map shows that the average wind speed on 50% of the country surface is considerable.

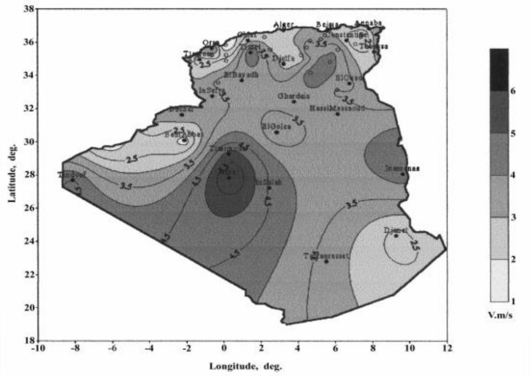

Figure 3. Algerian wind map.

Figure 4 shows the annual average wind velocities in the seven wilayas of Algeria: Adrar, Tiaret, El Kheiter, Ain Salah, Bejaia, Oran and Bordj Bouariredj. Therefore, the maximum average wind speed is about 6.37 m/s and 6.19 m/s for Adrar and Tiaret, respectively. For Ain Salah, Bejaia, Oran and Bordj Bouariredj, the average wind speed is about 5.22, 4.98, 4.95, 4.58 and 4.37 m/s, respectively.

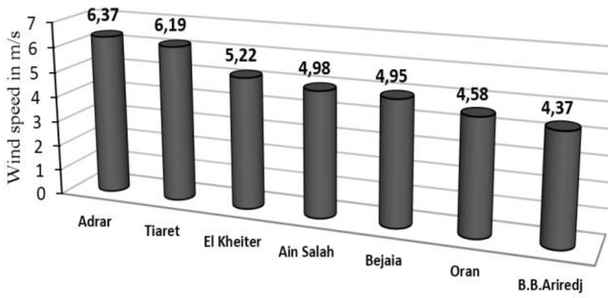

Figure 4. Average wind speed.

5 SIMULATION AND RESULTS

5.1 Test system set-up

To investigate the wind-power impact on the voltage stability, the western Algerian 220 KV electric power system is used. The single-line diagram of this system is shown in Figure 5 and the detailed data are given in Reference [33]. The system has six generators at bus 2 (Hassi Ameur), bus 3 (Mersat Centrale), bus 4 (Relizane), bus 5 (Tiaret) and bus 6 (Naama) injecting their power supply system to 17 loads over 33 transmission lines. In the test system, bus number 1 (MARSAT H) is considered as the slack bus and the base MVA of the system is 100 MVA. The voltage low limit at all buses is set to 0.95 p.u and the upper limit to 1.05 pu.

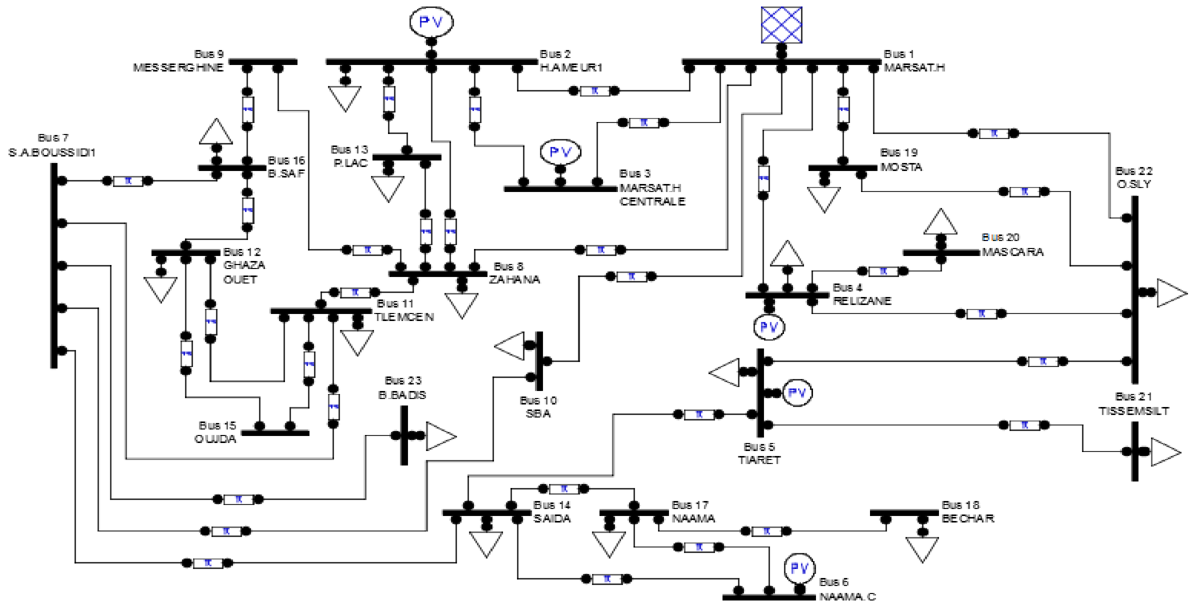

Figure 5. Western Algerian 220 KV electric power system (2016).

Figure 6 (August 01, 2016) represents the daily load curve, showing the power-system load variations, during different hours of the day. The maximum daily load is 720.24 MW at 3 p.m.

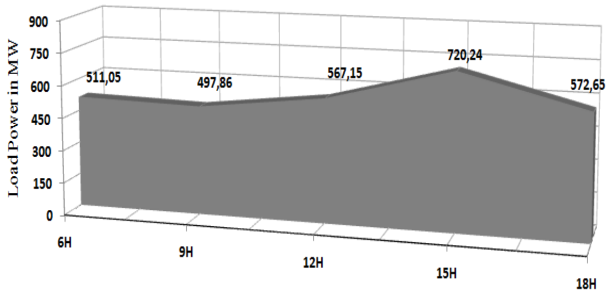

Figure 6. Daily load curve.

5.2 *Simulation results*

Simulations are carried out using PSAT [34]. PSAT is a power-system analysis software, which has many features including CPF feature of PSAT, the voltage stability of the test system is investigated.

To demonstrate the wind-power impact on the voltage stability, three cases are studied: a) voltage stability with no wind farm; b) stability impact of a wind farm connected to different buses; c) differently noted wind farms. The three cases are discussed below:

5.2.1 *With no wind-farm integration*

Fig. 7 shows three dimensional voltage profiles obtained by a load-flow calculation at a critical state before adding a wind farm. The simulations are taken at 3 p.m (rush hour).

It can be seen that when the system reaches its maximum loadability point ($\lambda_{max} = 1.8242\, p.u$), bus voltages 10, 11, 12, 14, 15, 16 and 23 greatly decrease.

Figure 8 shows the P-V curves of all buses of the western Algerian power system. Calculated by using the CPF method, these curves show the bus-voltage level as the loading factor increases. The loading factor is zero and it gradually increases, in each system bus bar reaching until the maximum loading point.

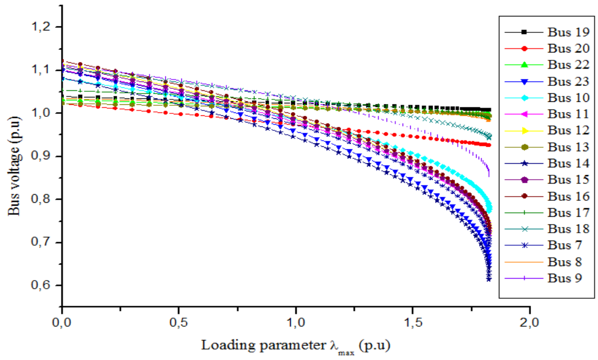

Figure 8. P-V curves of all load buses.

As observed from the P-V curves (Fig. 8) as the load increases from the no-load state until the receiving voltage starts dropping form the initial no-load voltage state to the point where λ 1.8242 p.u that is the critical point of the system. After this point, the system collapses.

It appears that bus 14 is the weakest. The next weakest one is bus 23. This is due to the steepness of the graph for both buses; it is the most precipitous.

The voltage sensitivity index (VSI) [35] can be also used to identify critical nodes. Figure 9 shows with the voltage sensitivity factors of the buses.

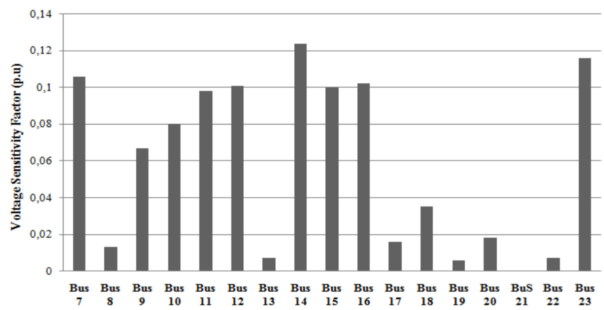

Figure 9. Voltage sensitivity factor (VSF).

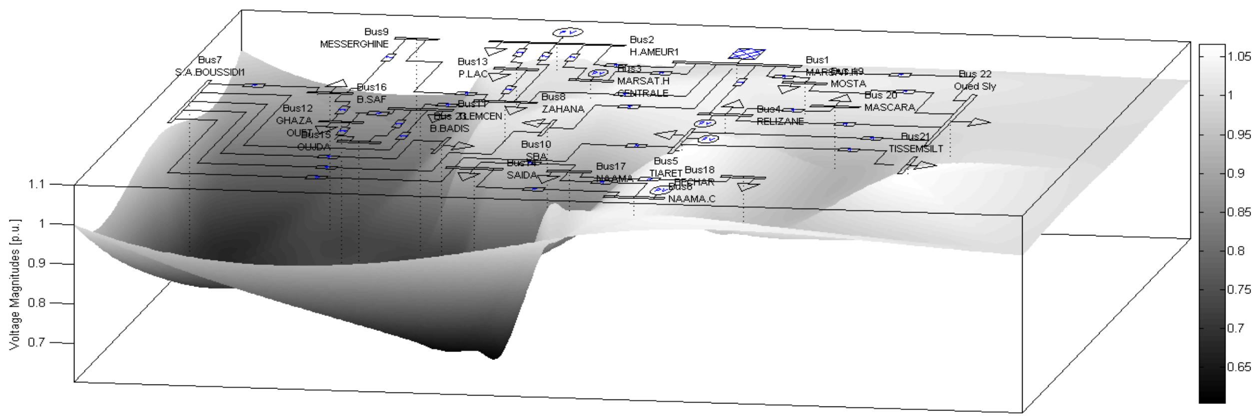

Figure 7. Three-dimensional voltage profiles before adding the wind farm.

The bus with the highest voltage sensitivity factor can be considered as the weakest bus in a system. The weakest bus is more sensitive to the load variations. In other words, the load connected to this bus is affected more than other loads in case of an unexpected load increase. Thus, in Figure 9, bus 14 (Saida) is the weakest bus in the western Algerian power system with the highest voltage sensitivity factor of 0.124. Bus 14 is the most vulnerable to voltage collapse and is followed by buses 23, 7, 16, 12 and 11.

Figure 10 shows the P-V curves for buses 14 and 23. that are the most sensitive to the load increase. As seen from this figure, the voltage decreases rapidly at the knee point which is indicative for the instability. This nose point or knee point indicates the stability limit at which the power system should never operate as this may lead to a large-scale black-out. As bus 14 at Saida has the minimum voltage level (0.62415 p.u.), it is the weakest bus in the western Algerian power system.

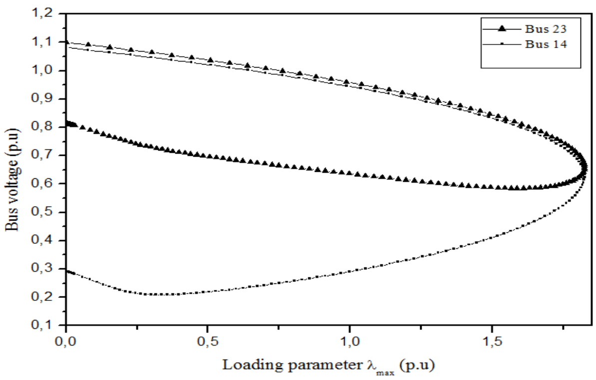

Figure 10. PV curve for critical nodes.

5.2.2 *Impact of the wind-farm location on the voltage stability level*

In this scenario, the simulation is performed by changing the location of the wind farm composed of 30 wind turbines. The blade length of each wind turbine is 75 m.

The wind farm is installed at different buses (bus 5, bus 14 and bus 23) via a step-up transformer (25/220 kV) in order to get the best location as illustrated in Figure 11.

The wind farm is connected to the system at buses 23 (Ben Badis), 14 (Saida) and 5 (Tiaret). The Saida and Ben Badis buses are considered to be the most sensitive buses to the load increase and the Tiaret bus is considered to be the windy region as shown in Figure 3. The daily mean wind speed varies between 4 an 8 m/s.

Figure 12 shows the daily mean wind speed for these three regions [36].

The bus voltages are observed for the western Algerian power system at the base case and with the integration of a wind farm.

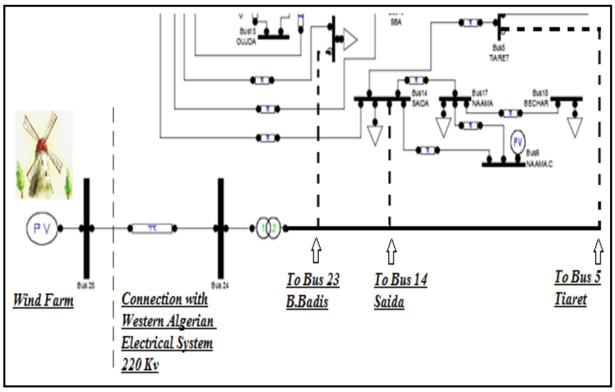

Figure 11. Connection of the wind farm with the electric power system.

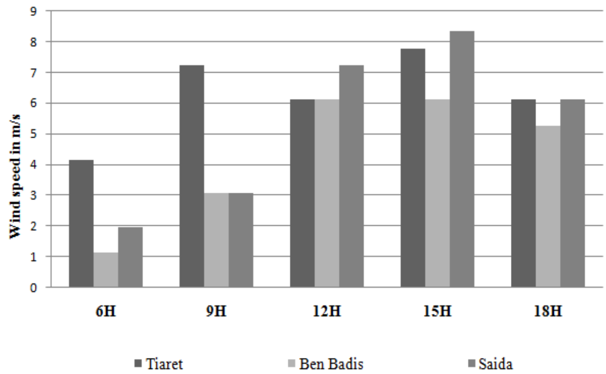

Figure 12. Daily mean wind speeds (01/08/2106)

Figure 13 shows that the voltage at each bus is improved after inclusion of a wind farm. The voltage of bus 14 is improved from 0.9441 p.u in the base case (with no wind farm) to 0.9711 p.u with a wind farm inclusion. Similarly the voltage of bus 23 is improved from 0.9584 p.u in the base case to 0.98 p.u with a wind farm inclusion. It is observed that the buses near the wind farm show a better voltage improvement compared to remote buses.

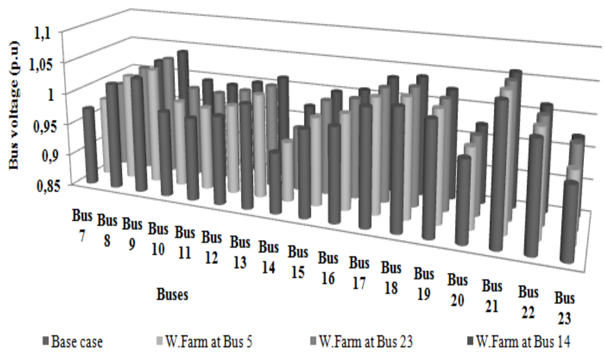

Figure 13. Bus voltages in the base case and with the integration of a wind farm.

As shown in Figure 13, the voltage profile at all buses is improved with the integration of a wind farm.

The relationship between the maximum load factor, location of the wind farm and daily load can be expressed in a three-dimensional graph (Figure 14).

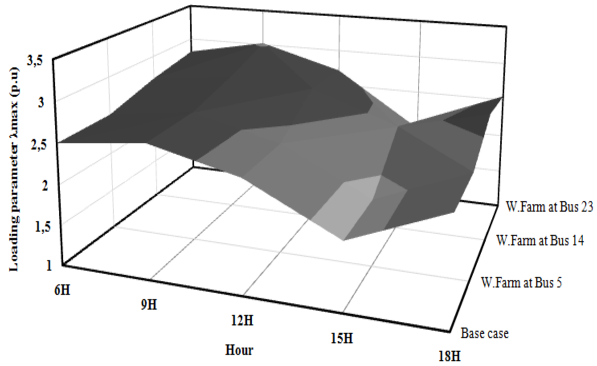

Figure 14. Relationship between the wind farm location, (λ_{max}) and daily load.

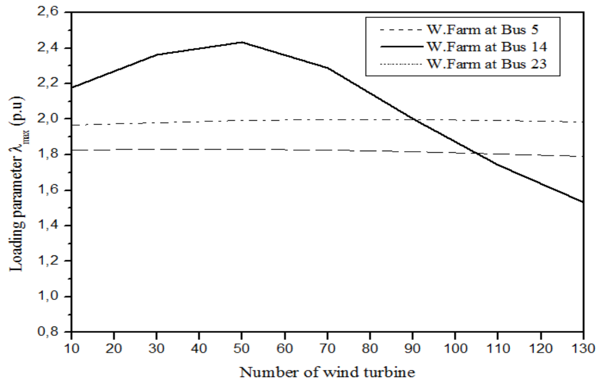

Figure 15. Maximum loading parameter (λ_{max}).

To allow for a better comparison of the values of the maximum loading parameter obtained when the wind farm is installed at different buses, these values are given in Table 1.

Table 1. Relationship between the wind farm location, (λ_{max}) and daily load.

Hour	With no wind farm	Location of the wind farm		
		Bus 5 (Tiaret)	Bus 14 (Saida)	Bus 23 (B.Badis)
	Loading parameter (λ_{max}) (p.u)			
6H	2.507	2.51	2.6882	2.8092
9H	2.6376	2.6503	2.8138	3.0217
12H	2.3759	2.3832	2.7565	2.7122
15H	1.8242	1.8316	2.363	1.9819
18H	2.2997	2.3061	2.6416	2.5484

As seen, adding a wind farm, improves the loading parameter (λ_{max}). λ_{max} increases by adding a wind farm at the locations Tiaret, Saida and Ben Badis. However, bus 14 (a critical node of Saida) exhibits the greatest values of λ_{max}.

5.2.3 *Wind-farm output-power variations*

In this scenario, the simulation is performed by varying the wind farm-power generation level.

The wind farm is connected to the system at buses 23 (Ben Badis with a critical node), 5 (Tiaret being the windiest region), and 14 (Saida with a critical node). Figure 15 shows the variation in λ_{max} for the location of the wind turbine and the wind-farm output power.

Figure 15 shows that λ_{max} increases with an increase in the wind power at the three locations. However, bus 14 exhibits the greatest values of λ_{max}. Figure 15 shows that to enhance the voltage stability, the best location of the wind turbine is the weakest bus which contains the largest load. In this case, it is bus 23. The optimal number of the wind turbines is 50, after which λ_{max} decreases.

5.3 Comparison between the system with and with no wind farm

The effectiveness of the equivalent model representing a collective response of the wind farm is determined by comparing the simulation results of equivalent and complete model during a normal operation and at a grid disturbance.

The impact of the wind farm on the power-system voltage stability is demonstrated by comparing the simulation results obtained, with and with no wind farm installed at an optimal location and generating an optimum power.

The voltage profiles obtained by a load-flow calculation at a critical state before and after inclusion of a wind farm are shown in Figure16.

It can be seen that the voltage profiles increase at all the buses in the system after a wind-farm inclusion.

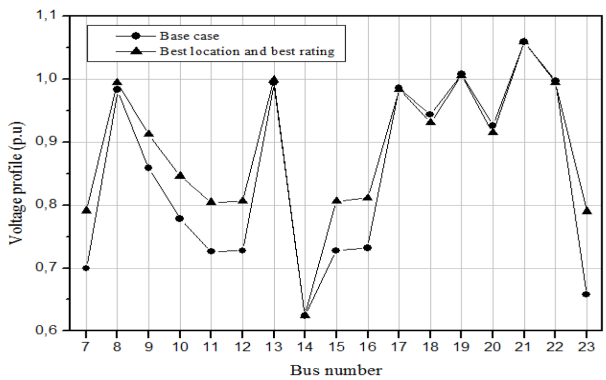

Figure 16. Bus voltages at a critical state before and after a wind farm inclusion.

Figure 17 shows the P-V curves for buses 14 and 23 for the base case and the case with a wind farm.

The maximum loading margin is increased from 1.8242 p.u in the base case to 2.4317 p.u after a wind farm inclusion. This suggests that a wind farm can improve the voltage stability of an electric power network.

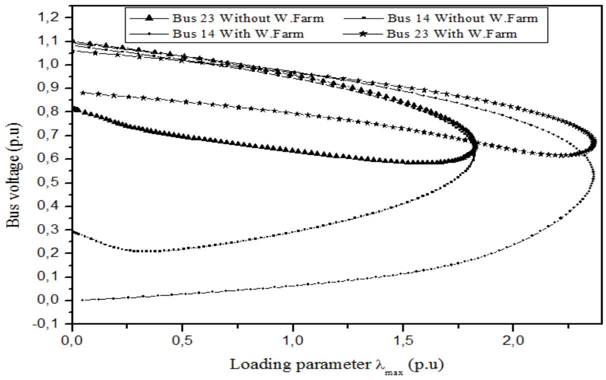

Figure 17. P-V curves for bus 14 and 23 for the base case and after a wind farm inclusion.

The impact of the wind farm on the system losses is evaluated. The active-power losses of the system with a wind farm are also evaluated by using CPF to demonstrate the impact of the wind farm on the system losses. Figure 18 shows the variation in the active-power losses as a function of the loading parameter *(λ)*.

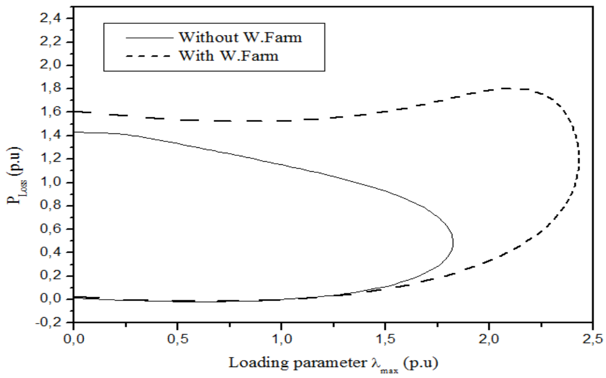

Figure 18.Variation in the active-power losses as a function of the loading parameter *(λ)*.

It is observed that by increasing the loading factor (λ), the power losses increase (Figure18). By integrating a wind farm in the power system, the power losses are considerably decreased.

When $\lambda_{max} = 1.8242\, p.u$, the total power losses are decreased from 0.5344 p.u in the base case to 0.2185 p.u after a wind-farm inclusion.

6 CONCLUSION

The main issue investigated in this paper, is to determine the effect of the wind farms composed of variable-speed wind turbines on the voltage stability of a power system. To get the answer, the steady-state voltage stability of the western Algerian power system with and with no remote DFIG-based wind farm is analyzed. The analysis is made by using the PSAT program based on the PV curves.

The optimal location of the wind power and its impact on the voltage stability are thoroughly analyzed. Different locations and wind-power values are tested using a DFIG wind turbine at different load buses.

The simulation results indicate that bus 14 (Saida) is the weakest bus of the system and that locating a wind turbine at this bus would be a better choice in terms of the power-system voltage stability.

Using this scenario considerably improves the bus voltages due, to the integration of a wind farm in bus 14 (Saida) compared to bus 5 (Tiaret) which is considered the windyest region on the network.

Integration of a wind farm improves the bus voltages at all the system buses. The buses in the vicinity of a wind farm show a higher increment in the bus voltages. The analysis of the P-V characteristics shows that integrating a wind farm enhances the maximum loading margin of all the buses. Moreover, the integration of a DFIG-based wind turbine in the system reduces the power losses.

Following the above, integration of a wind farm in a power system improves its voltage stability provided that the wind turbine location is optimally selected and that the wind power is of an adequate capacity.

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