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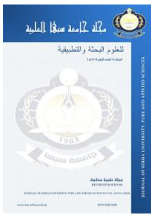

Impact of Wind Farm Location on Voltage Stability

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ABSTRACT

Recently, the use of wind farm in power systems is increasing rapidly it is having a more noticeable impact on the manner in which these power systems operate. When large wind farms are connected to a power system network, voltage stability is a concern as it affects system operation. This paper investigates the impact of wind farm location on voltage stability in power system network when the reactive power limitation of wind generators is taken into consideration and a system reaches its maximum loading. An IEEE-14 bus test system was modified by connecting wind farms to the system at different buses, with different connection scenarios at different wind penetration levels, and the wind farm consists of several variable speed doubly fed induction generator (DFIG) wind turbines. In addition, a voltage collapse proximity indicator (VCPI), based on network loadability, is employed to investigate the contribution of wind generator location to voltage stability. The results of this paper show that system voltage stability is affected positively or negatively depending on the location of wind farm.

تأثير مواقع طاقة الرياح على استقرار الجهد الكهربائي

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الكلمات المفتاحية:
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مولد الحث تغذية مضاعفة
استقرار الجهد
مؤشر القرب انهيار الجهد

الملخص

في الآونة الأخيرة، يتزايد استخدام مزارع الرياح في أنظمة الطاقة بشكل سريع وله تأثير أكثر وضوحًا على الطريقة التي تعمل بها أنظمة الطاقة هذه. عندما يتم توصيل مزارع الرياح الكبيرة بشبكة الطاقة الكهربية، يكون استقرار الجهد مصدر قلق لأنه يؤثر على تشغيل النظام. يبحث هذا البحث تأثير موقع مزرعة الرياح على استقرار الجهد في شبكة نظام الطاقة عندما يؤخذ في الاعتبار الحد من الطاقة التفاعلية لمولدات الرياح ويصل النظام إلى أقصى حمل له. تم تعديل نظام اختبار باص IEEE-14 عن طريق ربط مزارع الرياح بالنظام في باصات مختلفة، مع سيناريوهات اتصال مختلفة بمستويات اختراق مختلفة للرياح، وتتكون مزرعة الرياح من عدة توربينات رياح متغيرة السرعة ذات تغذية مزدوجة (DFIG). بالإضافة إلى ذلك، يتم استخدام مؤشر قرب انهيار الجهد (VCPI)، وبناءً على قابلية تحميل الشبكة يتم التحقق من مساهمة موقع مولد الرياح في استقرار الجهد. تظهر نتائج هذا البحث أن استقرار جهد النظام يتأثر سلباً أو إيجاباً حسب موقع مزرعة الرياح.

1. Introduction

In the past, the main power supply for the electrical industry came from conventional thermal power plants. These plants are mainly based on the combustion process of fossil fuels such as oil, coal and natural gas. Use of these primary fuels is not sustainable in the long

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term and also leads to the production of pollution such as CO_2[1].There is increasing interest in the production of electricity using renewable resources due to the ability of these resources to reduce greenhouse gases[2]. Wind energy plays a major role in the generation of electricity from renewable energy resources. In the last 25 years, the total global wind generation installed capacity has increased almost 150 times. The world wind energy total capacity has increased from 24 GW in 2011 to 733 GW in 2021 which is enough to cover 3% of the world's electricity demands [3] The impacts of wind power on power systems can be divided into local impacts and system-wide impacts [4], taking into account the electrical aspects of wind turbines and the characteristics of the wind. Moreover, the connection of wind power challenges the planning and operation of the grid. In local impacts, as an individual small-scale wind power generator connected to distribution network, the impact of wind power generator mainly depend on network condition and the connected wind turbine type. System-wide impacts are largely results of the variability and limited predictability of the wind and mainly depend on a number of factors, including wind power penetration level, intermittent nature of wind generation, geographical dispersion of wind generation and the size of the electrical network [5]. As more wind power generations are installed in power system, the possible impacts wind generation increase. A geographical dispersion of wind generator may reduce some of these impacts, however, especially if these are related to wind generation fluctuation. The objective of the paper is to investigate the impact of wind generation location on voltage stability in power system network when the reactive power limitation of wind generators is taken into consideration and a system reaches its maximum loading. An IEEE-14 bus test system was modified by connecting wind generation to the system at different buses, with different connection scenarios at different wind penetration levels, and the wind farm consists of several variable speed doubly fed induction generator (DFIG) Furthermore, a voltage collapse proximity indicator (VCPI), based on network loadability, is employed to investigate the contribution of wind farm location to voltage stability.

Voltage Stability Problem

Special attention has been given to voltage stability especially in weak long lines and heavy loads. Voltage stability is considered to be the cause of recent blackouts in many electric utilities around the world [6]. The problem of blackout has been associated with system loadability and/ or credible contingencies such as loss of transmission lines or main generating equipment. Power system loadability is becoming increasingly important as the overall system load demand increases. When large wind farms are connected to the power system network, voltage stability is one of the concerns, which affects system operation.

Wind generators may affect system voltage stability in two ways. The first because of its intermittency; the second is wind generator instability due to a disturbance on power system network may lead to system instability.

Voltage stability is another problem because of wind farm reactive power consumption. A number of researched methods are used to estimate the proximity to voltage instability [7-8-9].

Doubly Fed Induction Generator (DFIG)

Today new wind turbine technology integrates power electronics and control, making it possible for wind power generation to participate in active and reactive power control. The typical generator configuration for a new variable speed turbine is the doubly fed induction generator (DFIG) shown in Figure 1. This configuration consists of a wound rotor induction generator where the stator windings are directly connected to the grid and the rotor windings are connected to a back-to-back power converter. This back-to-back power converter is dimensioned for partial generator power and is able to operate bi-directionally. It uses a wound rotor induction generator with slip rings to take current into or out of the rotor winding, and variable speed operation is obtained by injecting the controllable voltage into the generator rotor at slip frequency [10]. As shown in Figure 1, the rotor winding is fed through the variable frequency power converter, typically based on two AC/DC insulated gate bipolar transistor (IGBT) based voltage source converters (VSC) linked by the DC bus. The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling the variable speed operation of the wind turbine. The voltage source converter (VSC) produces an AC voltage that is controllable in magnitude and phase, similar to the synchronous generator or synchronous compensator. The VSC commutates independently of the AC-side voltage and consequently it can be used on the load-only system. This makes the VSC useful for rotor connection, wind farm connection and so forth.

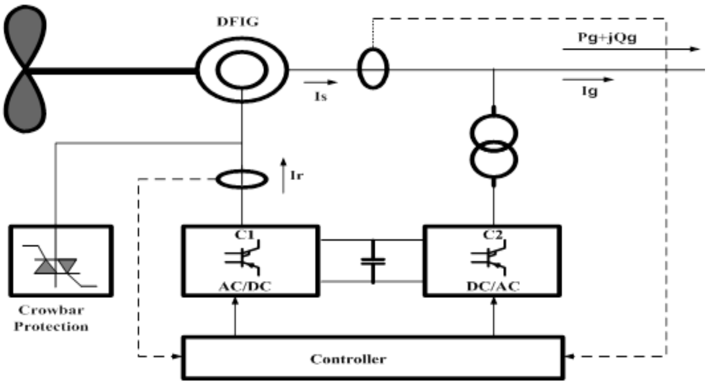

Fig. 1: Typical Configuration of the DFIG Wind Turbine.

Converters (C1) and (C2) in Figure 1 are used to control the doubly fed induction generator wind turbine. A number of manufacturers use converter (C1) to provide torque/speed control, together with terminal voltage or power factor control for the overall system. Converter (C2) is used to maintain the DC link voltage and provide the path for power to flow to and from the AC system at unity power factor. The wind turbine generator model in this paper is based on the DFIG model as a PV bus, which is operated in voltage controlled mode.

Voltage Collapse Proximity Indicator (VCPI)

In this paper, a voltage collapse proximity indicator (VCPI) based on network loadability is used to investigate the contribution of wind generation location to voltage stability. The VCPI calculation procedure takes into consideration the reactive power limitation of wind generators in the system was presented in [11]. The wind generator is assumed to be a doubly fed induction generator (DFIG), which has a reactive power control capability. DFIG can be used as a reference to PQ buses when it operates within its reactive power capability. Due to the reactive power limitation of wind generators, system impedance is not a constant. The bus voltage collapse proximity indicator is defined as the ratio of the system equivalent impedance to the load equivalent impedance of that bus.

$$\mathrm{VCPI} = \frac{\mathrm{Z_{ie}}}{\mathrm{Z_i}} \qquad (1)$$

When VCPI is approaching zero it means the system is stable. The system becomes marginally unstable when VCPI approaches unity (the critical point). Beyond this point the voltage of the bus may collapse, and as a consequence the system may become unstable.

Test System

A single line diagram of the IEEE-14 bus system is shown in Figure 2 and detailed data of the system are shown in [12].The system consists of five generators which supply power to 11 loads through a 69/13.8 kV. The total generation capacity is 1300 MW and peak load is 935 MW. The modified test system was analyzed using AC Optimal Power Flow (OPF). All simulations were carried out in the Power World Simulation. The test system was modified by connecting wind generation to the system at different buses, with different connection scenarios at different wind penetration levels, and the farm consisted of several variable speed doubly fed induction generator (DFIG) wind turbines, each of 1.5 MW. The DFIG was modelled as a PV bus and operated with maximum and minimum power factors of 0.95 leading (capacitive VAr) and 0.95 lagging (inductive VAr).

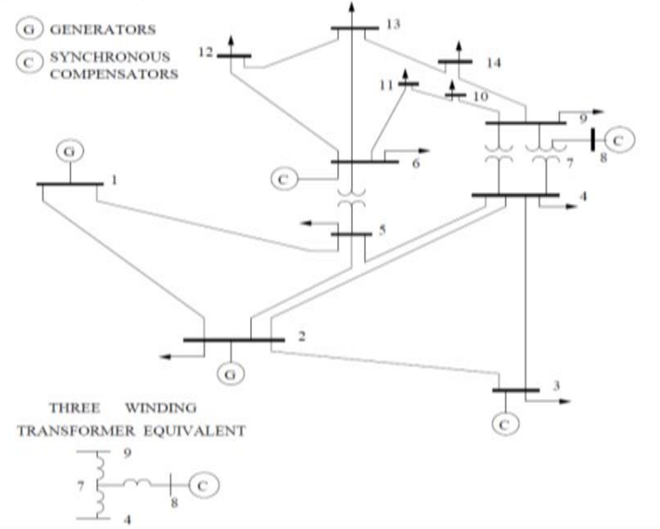

Fig.2: One-line diagram of IEEE-14 bus system.

Simulation Results and Discussion

The reason for connecting the wind farm at different buses is to show the effect of wind farm location on voltage stability from different areas in the network, and also to choose a suitable connection point bus for the wind farm which can improve the voltage stability. As mentioned in this paper, variable speed wind turbines equipped with voltage source converters have the capability of generating or absorbing reactive power and can be used as reactive power sources to control the voltage at grid terminals. A voltage collapse proximity indicator (VCPI), based on network loadability, is used to study the impact of wind farm location on voltage stability. In this section, , results for 3 wind generation connection scenarios are considered and compared to the base case when no wind generator is connected to the network. One wind farm is located at bus 4 in the first connection scenario, and then the same wind farm is connected to bus 12 in the second scenario. In the third connection scenario, the wind farm is connected to buses 4 and 12 simultaneously with a combination wind penetration level. The simulation will be processed under 20% and 30% penetration level of wind generation. Table 1 shows the wind penetration level and locations connected at these buses.

Table.1: Different wind penetration levels and different locations for IEEE-14-bus system.

% Wind Penetration (WG4)	% Wind Penetration (WG12)	% of Combination Wind Penetration (WG4, WG12)
20% (260 MW)	20% (260 MW)	10% (130 MW), 10% (130 MW)
30% (390 MW)	30% (390 MW)	15% (195 MW), 15% (195 MW)

The penetration level percentages refer to the value of wind generation as a function of total conventional generating capacity. The conventional generators are assumed to be thermal; their capacities and the buses to which they are connected are given in Appendix A. The total installed capacity is 1300 MW, which is used as the reference value for calculating the penetration percentages of the wind generator. The system voltage stability was analyzed and VCPI calculated from different standpoints. These were the level of wind penetration (WP) (i.e. 20% to 30%), the dispersion of wind generation (i.e. one location at strong bus, one location at weak bus and two locations as a combination). By using the proposed method, the voltage collapse proximity indicator is calculated for a certain load bus for the maximum output of each wind penetration level at a specific time step simulation. Buses 14 and 10 are selected separately for investigating each scenario of wind penetration and wind location. The results are presented here to assess the impact wind farm location has on system voltage stability. Figures 3, 4, 5 and 6 show the variation of the VCPI of buses 14 and 10 with load at 20% and 30% wind penetration levels. Wind farms are connected to the network according to the three different connection scenarios defined previously and compared to the base case (i.e. when no wind is connected to the system). It can be seen from Figure 3 that the VCPI of bus 14 reaches the value 1.0 as the load at bus 14 reaches maximum loading at 1.308 p.u for the base case (no wind), 1.334 p.u for 20% wind penetration when wind generation is connected at bus 4 (strong bus), 1.201 p.u for the same wind penetration when wind generation is connected at bus 12 (weak bus), and 1.304 p.u for 20% combination wind penetration when wind generation is connected to buses 4 and 12. Compared to the base case, the voltage stability is improved only when wind generation is connected to a stronger bus. The reverse is true when wind generation is connected to a weaker bus or multiple locations of wind farms at the same wind penetration level. FACTS devices such as SVC and STATCOM are required to support voltage stability when DFIG is located at a weaker bus.

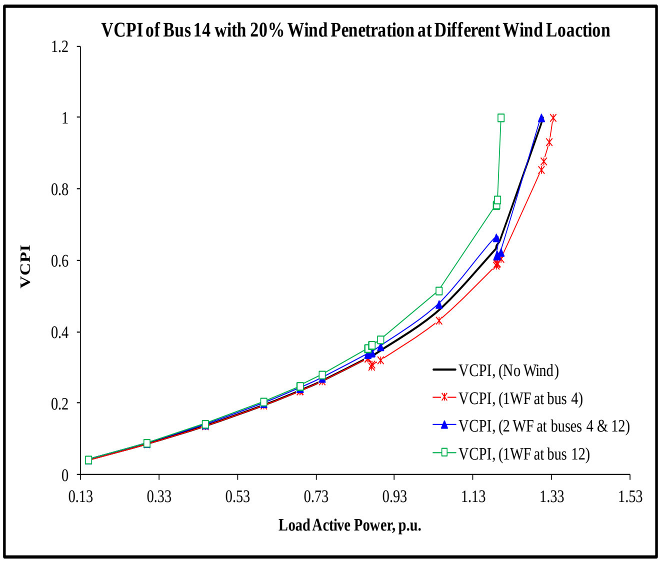

Fig.3: The VCPI of bus 14 at 20% wind penetration level for different wind connection scenarios

Figure 4 shows that the variation of the VCPI with load at bus 10 with 20% penetration level. The VCPI reaches the value of 1.0 when the load at the bus reaches maximum loading at 1.638 p.u for the base case, 1.725 p.u when the wind generator is at bus 4, 1.571 p.u when the wind generator is at bus 12, and at 1.68 p.u when the two wind farms are connected at buses 4 and 12 with a combination of wind penetration levels. The results show that, from the voltage stability point of view, the doubly fed induction generator being connected to a stronger bus (bus 4) is a better option and will improve system voltage stability more than when the wind generator is connected to other buses, as shown by the VCPI.

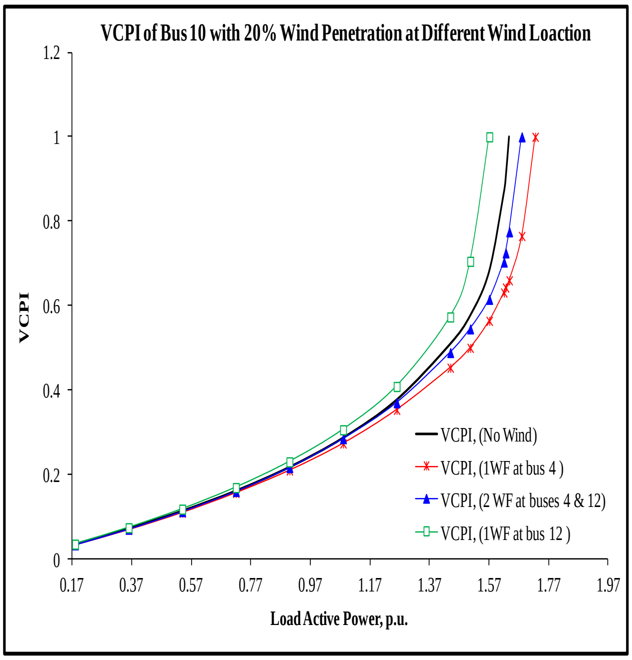

Fig.4: The VCPI of bus 10 at 20% wind penetration level with different wind connection scenarios

Figures 5 and 6 show that at the high wind penetration level, the system voltage stability is better for one connection location when the wind farm is connected to a stronger bus compared to other location scenarios according to the VCPI point at maximum loading for buses 14 and 10. Reactive power compensation (e.g. SVC) may still be necessary, especially if a large penetration of DFIG is connected to a weak area.

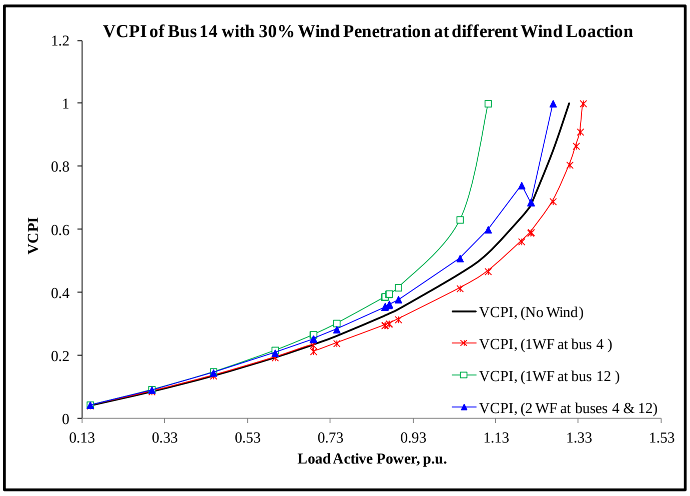

Fig.5: The VCPI of bus 14 at 30% wind penetration level with different wind connection scenarios

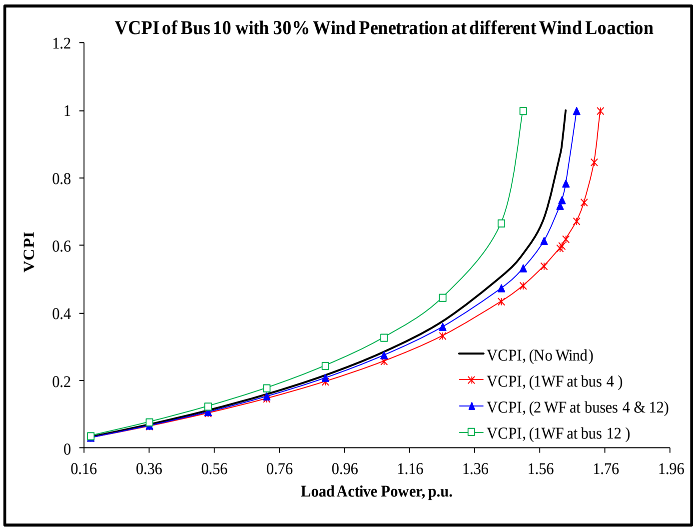

Fig.6: The VCPI of bus 10 at 30% wind penetration level for different wind connection scenarios

Conclusion

The integration of wind farms into existing electricity networks and the impact on networks has been presented in this chapter. Furthermore, case study results have been presented regarding the impact of wind farms location on system voltage stability. The type of wind generator used was of variable speed with a doubly fed induction generator (DFIG) which was modelled on load flow studies as a PV bus and operated in voltage controlled mode. In this paper, a voltage collapse proximity indicator was also calculated and employed to investigate the contribution of wind generation to voltage stability. Different penetration levels from 20% to 30% were used and different wind connection scenarios were used in the network to analyse the impact of wind generation. From the results presented in this paper, it can be concluded that voltage stability is affected positively or negatively depending on location of wind generator connection. When wind generation was connected to a stronger bus it was able to improve system voltage stability and the higher the penetration level the better. The reverse was found to be true when wind generation was connected to a weaker bus, in which case reactive power compensation (e.g. SVC) may still be necessary, especially if a large penetration of DFIG is connected to a weak area. The results obtained show that system voltage stability was better for a single wind farm connection location connected to a stronger bus compared to multiple locations of wind farms for the same amount of wind penetration level. Developers and system operators can decide on the location and penetration levels of new wind farms to be connected to existing systems based on the proposed methodology used here, which calculates the system proximity to voltage collapse using the voltage collapse proximity indicator, which considers location, penetration level of wind generators.

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