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Improving Distribution System Voltage Stability Using DFIG-Based Wind Farms

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ABSTRACT

This study investigates the impact of doubly fed induction generator (DFIG)-based wind farms on distribution system voltage stability. A modified 61-bus distribution network is simulated in PowerWorld Simulator using the voltage collapse proximity indicator (VCPI) to evaluate voltage stability under different wind penetration levels. A method for calculating the voltage collapse proximity indicator when reactive power limitation of wind generators is taken into consideration and a system reaches maximum loading, was developed in our previous work. DFIG-based wind generation is connected at a strong bus and operated in voltage-controlled mode. Simulation results for 10%, 20% and 30% wind penetration levels show that the doubly fed induction generator improves the distribution system voltage stability and increases the voltage collapse margin. The improvement becomes more significant as wind penetration increases, with the 30% case providing the best performance. These results demonstrate the potential of DFIG-based wind farms to enhance voltage stability in distribution network.

تحسين استقرارجهد نظام التوزيع باستخدام مزارع الرياح القائمة على المولدات الحثية ثنائية التغذية

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الكلمات المفتاحية

شبكات التوزيع
استقرار الجهد
مؤشر انهيار جهد الدائرة (*VCPI*)
دمج طاقة الرياح
توربينات الرياح القائمة على المولدات الحثية مزدوجة التغذية (*DFIG*)

الملخص

تبحث هده الدراسة في تأثير مزارع الرياح المعتمدة غلي المولدات الحثية مزدوجة التغذية (**DFIG**) على استقرار الجهد في شبكات التوزيع. وقد اجريت محاكاة لشبكة توزيع مكونة من 61 ناقلا (**bus**) باستخدام برنامج **PowerWorld** مع الاستعانة لمؤشر الاقتراب من انهيار الجهد (**VCPI**) لتقييم استقرار الجهد في ظل مستويات متفاوتة من دمج طاقة الرياح في الشبكة . وتستند الدراسة الي طريقة تم تطوير ها في عمل سابق لنا لحساب مؤشر الاقتراب من انهيار الجهد القرب من انهيار الجهد مع مراعاة قيود القدرة الغير فعالة (**Reactive Power**) لمولد الرياح عند وصول النظام الي اقصى حمل تشغلي له . ويتم توصيل نظام توليد الرياح (القائم على تقنية **DFIG**) عند ناقل قوى (**Strong bus**) وتشغيله في وضع التحكم في الجهد. اضهرت نتائج المحاكاة عند مستويات دمج لطاقة الرياح بنسبة<**30%** , **20%**, **10%** ان المولد الحثي مزدوج التغذية يحسن استقرار الجهد في نظام التوزيع ويزيد هامش الامان ضد انهيار الجهد .وقد لوحظ ان هدا التحسن يصبح اكثر وضوحا مع زيادة نسبة طاقة الرياح حيت حققت حالة الدمج بنسبة **30%** افضل اداء . وتبرز هده النتائج قدرة مزارع الرياح التي تعتمد علي تقنية **DFIG** علي تعزيز استقرار الجهد في شبكات التوزيع.

Introduction

At present, as environmental concerns continue to increase, the use of renewable energy resources and related technologies has expanded widely. Wind power generation has experienced a rapid increasing in penetration levels worldwide [1]. Wind power development has become an important component as part of governmental initiatives aimed at reducing carbon dioxide output. Many countries have introduced energy targets aimed at substituting specific percentages of conventional power generation capacity with renewable energy resources in contrast to conventional power generation, renewable energy sources generate electricity with minimal environmental emissions and without fuel-related costs. Nevertheless, their incorporation into the grid may affect the operational performance and stability characteristics of power system [2]. Wind power has emerged as a leading renewable energy solution for electricity generation. As

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wind turbines and wind farms increase in scale, the impact of wind power generation on power system stability has become a critical area of concern. The cumulative installed wind power capacity worldwide reached approximately 1,300 GW in 2025 [3]. Consequently, increasing wind penetration may influence power system operation, power flow distribution, node voltage profiles, dynamic performance and overall system [4]. Electric power systems represent a critical foundation of modern society and are widely regarded as among the most extensive and complex systems developed by humans. Generally, electric power systems are composed of three primary components: power generation, transmission and distribution systems. The continuous development of power systems has resulted in extensive generation sources and transmission lines designed to serve a wide range of electrical loads. Maintaining power system stability requires a constant balance between electricity generation and load demand. There is a growing trend toward integrating wind power generation into distribution networks, which may lead to greater impact from wind generation integration. The geographical distribution, wind penetration level and type of wind generator. The negative impact of wind integration can be mitigated by carefully considering the geographical placement, penetration levels, and the specific technology of the wind generators [5]. Voltage stability within distribution system is a critical factor that must be addressed during the design phase of wind power generation projects. Doubly fed induction generators (DFIGs) are the most common technology utilized by wind farms integrated into distribution networks. This specific wind turbine model is the most popular technology due to their advantages over other wind turbines. This study focuses on evaluating the effect of DFIG-based wind generation on distribution-system voltage stability for a fixed connection point at a strong bus, considering different wind-penetration levels. The study considers a single wind farm connection point; therefore, the effect of alternative DFIG siting locations, particularly weak buses, is outside the scope of the present work. This research examines how the integration of doubly fed induction generators (DFIGs) at strong bus locations influences voltage stability within distribution network. To assess how varying levels of wind penetration affect voltage stability, this study utilizes the voltage collapse proximity indicator (VCPI), which is derived from network loadability. However, the impact of DFIG-based wind farms on distribution-system voltage stability, particularly their effect on voltage collapse proximity under different wind penetration levels, has not been sufficiently quantified using a VCPI-based loadability assessment.

DFIG-Based Wind Turbine System

By leveraging advanced power electronics and sophisticated control frameworks, contemporary wind turbines are capable of regulating both active and reactive power output [6], [7]. As demonstrated in Fig. 1, the DFIG is the most prevalent generator configuration utilized in variable-speed wind turbine systems. The back-to-back converter system is designed to handle only a fraction of the total power generated by the generator. The system achieves variable speed operation by regulating the rotor voltage at slip frequency via slip rings, which facilitate the necessary current flow into or out of the rotor. Figure 1 displays the configuration of the doubly fed induction generator, which is managed via converters C1 and C2. The system's terminal voltage or power factor. The main role of converter C2 is to regulate the DC-link voltage, manage bidirectional rotor power flow between the generator and AC grid and maintain operation at unity power factor. By adjusting the d-axis components of the rotor voltage while maintaining synchronous speed ($\omega_s = 2\pi f_s$), it becomes possible to independently regulate two distinct generator variables [8]. DFIG-based wind farms can pro

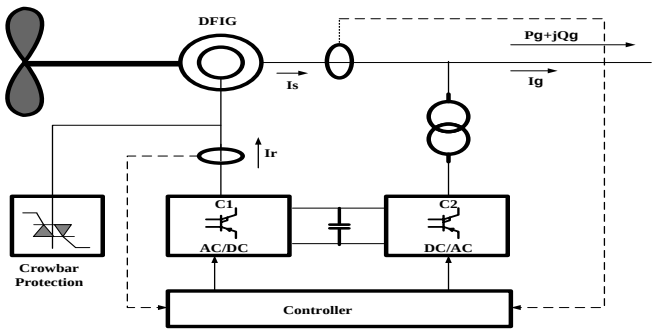


Fig. 1: Configuration of the DFIG wind turbine

Voltage Control

Figure 2 illustrates the fundamental design of a DFIG voltage controller. Within this system, the d-axis rotor current reference is derived from the magnitude. Discrepancy the difference calculation between the actual terminal voltages (V_s) and the reference set point $(V_{s_{ref}})$. The actual d-axis rotor current $(i_{dr_{ref}})$ is evaluated against its reference value(i_{dr}). To produce an error signal, which serves as the input for standard PI control loops. The necessary rotor voltage (V_{dr}) is calculated by summing the output generated by the PI controller, incorporating a custom-designed compensation term [9].

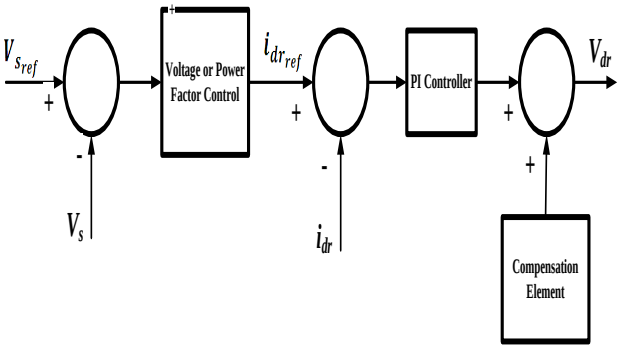


Fig. 2: Schematic of the DFIG voltage regulation feedback loop.

Reactive Power Capability of the DFIG

Reactive power plays an important role in the operation of power systems, especially in the case of wind energy integration [10]. A voltage-source converter is incorporated into the doubly fed induction generator system. Consequently, the converters C1 and C2 can inject or absorb reactive power as required, enabling effective voltage control at the grid terminals. Figure 3 illustrates the P-Q operating envelope, demonstrating the reactive power capability of the DFIG [11]. The reactive power regulation capability of the DFIG is constrained by the operational boundaries of converters C1 and C2. These operational boundaries are primarily determined by induction machine load current and magnetizing requirements. The reactive power absorption limit of the wind turbine generator in under-excited operation exceeds the maximum Mvar output achievable under over-excited conditions. The wind turbine generator is capable of providing reactive power support even when no active power is being produced,

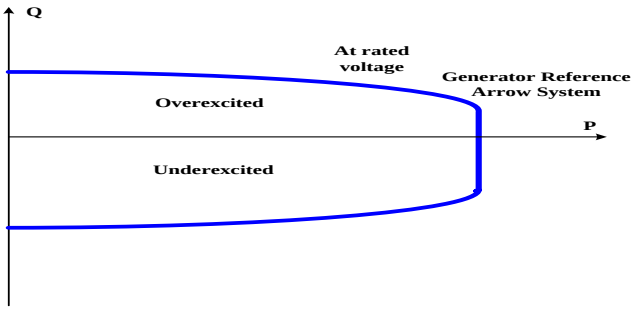


Fig. 3: P-Q capability curve for the DFIG

Voltage collapse proximity indicator (VCPI)

Within the existing suite of approaches for assessing voltage stability. A variety of voltage stability indices have been proposed to provide rapid indicators of proximity to collapse. [12]-[13]. One of these studies developed an enhanced voltage stability index (EVSI) from two port π line model that explicitly retains line impedance active and reactive power terms, and voltage angle difference between sending and receiving ends [14]. To gauge the influence of the doubly fed induction generator and distribution network voltage stability, a load ability-based VCPI is adopted as the primary evaluation index in this network [15]. A comprehensive simulation study is required. To evaluate how DFIG-based wind generation influences voltage stability within distribution network under a variety of operating conditions. The methodology presented is evaluated across a range of simulation scenarios that incorporate diverse wind speed profiles and varying levels of DFIG penetration. In contrast to systems where wind generators hit their reactive power capacity constraints. The voltage collapse proximity indicator (VCPI) for a specific bus is defined as the ratio of the equivalent system impedance to the equivalent load impedance at that location [15].

Adequate reactive power support from wind generation achieves higher power transfer and voltage stability margins. Compared with systems in which the reactive power capability of wind generators has reached its operational limit. After the wind generator attain its reactive power limit, no further reactive power support can be supplied to satisfy the system demand. The voltage collapse proximity indicator (VCPI) for a bus is calculated as the ratio between the equivalent system impedance and the equivalent load impedance at that bus.

$$\text{VCPI} = \frac{Z_{ie}}{Z_L}$$

As the VCPI measurement nears zero, the grid's capability to maintain stable operation decreases. As VCPI approaches unity, the power system reaches a marginally stable operating condition, signalling that the system is nearing the point of voltage collapse.

Case Study

To investigate how different levels of DFIG integration influence the system voltage integrity of the distribution network. The modified 61 bus distribution network [16], was utilized for modelling purposes. The system supplies power to 18 distinct load nodes, stepping down voltage from 132 kV to 33 kV via a primary substation, and the load buses operate at a normal voltage of 11 kV with a total system load of 58 MW. The system has a rated generation capacity of 80 MW. The DFIG was represented as a PV bus within the simulation model. Wind farm is installed at the stronger bus 12, and each turbine within the farm has a power rating of 1.5 MW. The collected data is analysed to ascertain the maximum power output corresponding to each level of wind penetration. Table 1summarizes the DFIG penetration levels and bus 12, the corresponding connection. For this analysis, the DFIG was represented as a PV node in the simulation and configured to operate between a ,maximum loading power factor of 0.95 (capacitive AVR support)and a minimum lagging power factor of 0.95 (inductive AVR absorption).

Table 1: Evaluated wind power penetration levels for the 61-bus test system.

Penetration level of wind (%)	10%	20%	30%
Wind generation output (kW)	8 MW	16 MW	24 MW

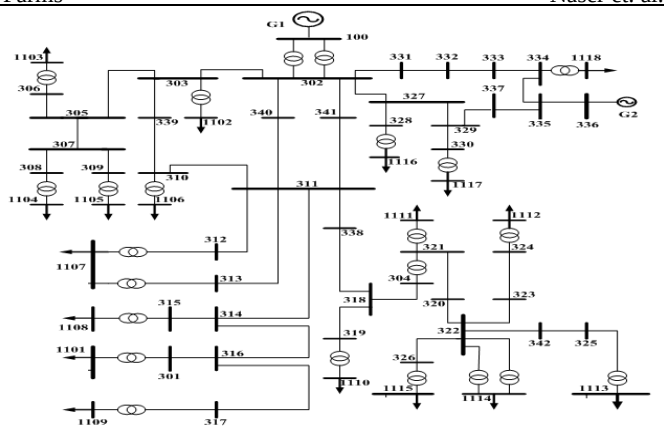


Fig. 4: Schematic representation of the modified 61-bus distribution network

Simulation Analysis and Discussion of Results

This section examines the influence of varying wind power penetration levels on distribution network voltage stability. The network loadability index is utilized to evaluate the DFIGs' contribution to maintaining voltage stability within distribution system. The VCPI is calculated across multiple wind penetration scenarios (10%, 20% and 30%) and compared against the baseline case, which represents the system without wind energy integration. In this case, the wind generation data is analysed to determine the maximum output at each wind penetration level. The wind speed is considered constant during the selected time step. The load bus is progressively increased at a single bus until the voltage collapse proximity is reached. Meanwhile, the load at all other buses in the system remain constant. The VCPI is evaluated at the selected time step. To assess voltage stability, buses 45, 51, and 58 of the 61 bus distribution system are selected due to their critical operating conditions and increased risk of voltage instability. The results present the VCPI profile of buses 45, 51 and 58, respectively, for a wind generator connected to strong bus 12 at wind penetration levels of 10 %, 20 % and 30%. The results indicate that the VCPI value rises with increasing load at the selected bus. As a result, the VCPI approaches the voltage collapse point. Figures 5,6 and 7 illustrate the VCPI behaviour at buses 58, 51 and 45 under different wind penetration levels. For bus 58, the VCPI reaches the critical value of the bus at maximum loading of 0.0883 p.u. for the base case, 0.093 p.u. for 10% wind penetration,0.0981 p.u. for 20% penetration and 0.105 p.u. for 30%. Similarly, at bus 51, the critical VCPI value is reached at loading levels of 0.480, 0.496, O.544 and 0.584 p.u. for the base case, 10%, 20%, and 30% wind penetration, respectively. At bus 45, the corresponding loading levels are 0.079, 0.085, 0.088 and 0.092 p.u., respectively. These results indicate that increasing the DFIG-based wind penetration increases the maximum loadability of critical buses and, consequently, improves the voltage stability margin of the distribution system.

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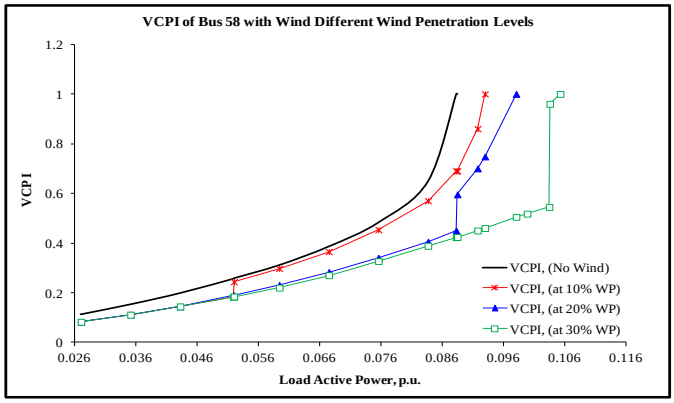


Fig 5: VCPI values for bus 58 across various wind power penetration levels

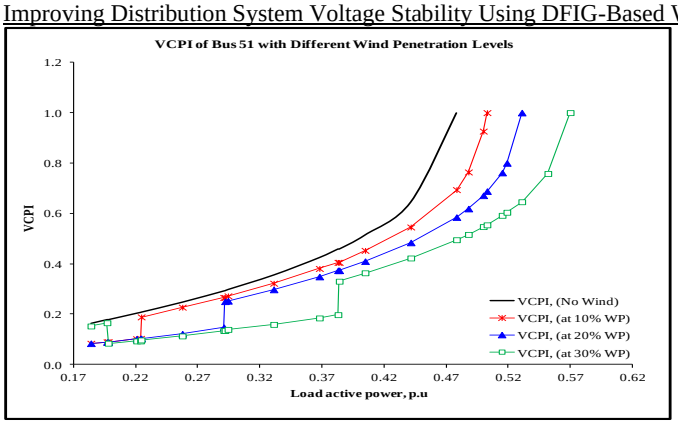


Fig 6: VCPI values for bus 51 across various wind power penetration levels

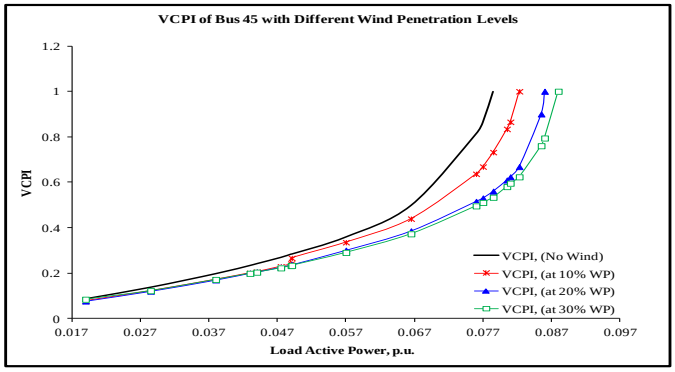


Fig. 7: VCPI values for bus 45 across various wind power penetration levels

Conclusion

This study demonstrates the positive impact of DFIG-based wind generation on distribution system voltage stability. A variable-speed DFIG operating in voltage-controlled mode was modelled as a PV bus and evaluated using load flow simulations and the voltage collapse proximity indicator (VCPI). Wind penetration levels of 10%, 20% and 30% were investigated for connection to a strong bus. The results show that DFIG integration improves voltage stability and increases the system loadability margin, with greater benefits achieved at higher wind penetration levels. These findings confirm that appropriate DFIG integration can enhance the voltage stability of distribution system.

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