Dynamic Stability Enhancement of Wind Power Generation with Static VAR Compensator using Multiobjective Optimization Algorithms

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Received: 3 May 2024 | Revised: 20 May 2024 and 23 May 2024 | Accepted: 26 May 2024

ABSTRACT

Renewable energy, particularly wind energy, is expected to contribute significantly to the overall power generation. Induction machines are extensively used as generators in wind power generation because of their multiple benefits, such as robustness, reliability, and low cost and maintenance. However, due to the reactive power demand from the system to which they are connected, this type of generator brings new problems related to power quality, generally consisting of voltage regulation and reactive power compensation. These problems may cause voltage drops and dynamic instability. This study presents a metaheuristic method to attain a microgrid system with an optimal distribution based on its different constraints. The numerical model of an induction generator constructed in MATLAB/Simulink was used, and the simulation results obtained demonstrate the efficacy of the proposed metaheuristic technique.

Keywords-induction generator; optimization; voltage regulation; reactive power; wind energy

I. INTRODUCTION

Today, the development of renewable energy technologies continues to assert itself in the world due to its character, economics, and inexhaustibility [1]. The increase in industrialization of wind turbines has prompted researchers to investigate this area to improve energy conversion efficiency and quality. Wind generators provide the energy required with acceptable costs [2]. These generators generally use induction machines due to their robustness and low maintenance cost. However, using these machines in autonomous operation introduces a major problem: the control of frequency, voltage, and self-starting [3]. On the contrary, due to their reactive power demand from the system to which they are connected, this type of generator introduces new power quality problems, generally consisting of voltage regulation and reactive power compensation. For these reasons, reactive power compensation systems must be used. These devices, called Flexible Alternative Current Transmission Systems (FACTS) and characterized by high reliability and flexibility, regulate reactive power and stabilize voltage within allowed limits [4].

The Grasshopper and Particle Swarm Optimization (PSO) algorithms are used to solve the problem of optimal reactive power flow. In [5], an overview of the optimization objectives to control reactive power using FACTS devices was presented. These problems can be reduced, and more reliable integration of wind power into a Microgrid (MG) system can be ensured by using cutting-edge control algorithms and energy storage technologies. Many studies have introduced novel methods to ensure the dynamic stability of wind power generation [6]. One probable approach is to use smart MG technologies to better balance and adjust the unpredictability of wind power generation. Operators can improve the stability of an MG system by preventing variations and adjusting electricity generation, merging predictive modeling with real-time data analytics. The combination of large-scale sporadic renewable energy resources, including wind energy, into electricity grids has increased in recent decades. However, this integration poses numerous operational and control problems that hinder the reliable and stable operation of MG systems [7]. Wind energy is growing in popularity as a renewable energy source, but one of the main obstacles is keeping the MG system dynamically steady. Wind generation is unpredictable, introducing fluctuations that result in power generation instability. In [8], multiple techniques were introduced to address the voltage instability challenges of wind power systems.

Static VAR compensators are indispensable for enhancing the system's stability by maintaining voltage levels, reducing the effects of wind power dissimilarities, and assisting the MG with reactive power. Consequently, in the field of power system operation and renewable energy integration, they act as a valuable resource to handle the intricacies and challenges related to voltage instability in wind-integrated power systems [9]. The significance of determining stability challenges in weak AC grid-connected Doubly Fed Induction Generator (DFIG) wind energy structures throughout Low-Voltage Ride-Through (LVRT) events cannot be overlooked, assuming the collective acceptance of wind power-based MG systems. The development of generation loss and post-fault fluctuation within an MG due to grid faults has also developed a notable apprehension [10].

The renewable energy sector has seen extraordinary progress, with innovations in photovoltaic materials, energy storage, and efficiency improvements [11]. By adopting a proactive approach, wind power systems can withstand their competitiveness and sustainability in the long term [12]. This contributes to environmental protection by reducing carbon emissions and reducing long-term costs for consumers. Energy is at the heart of the operation of all industrial societies. Access to energy at reasonable prices and without limits appeared as a necessary condition for economic development and individual comfort. However, the use of non-renewable energies depletes fossil and fissile resources, causing a progressive degradation of the environment and threatening public health. Rapid and major climate change, due to the increase in the greenhouse effect, requires a reasonable and harmless use of energy as part of a sustainable development model. Therefore, there is a correlation between energy, environment, and development [13]. The development of wind turbines continues to assert itself worldwide, as wind power generation is clean and inexhaustible. The proliferation of wind turbines has led research to increase the efficiency of electromechanical conversion and improve the quality of energy that can be distributed to different consumers [14].

II. LITERATURE REVIEW

Three-phase induction machines are widely used as energy-generating devices in wind turbines. These induction machines are widely used to provide electrical energy to individual and technical sites. In [15], three strategies were compared to control the uncertainties of wind power generation. Reactive power is either shunt-generated or absorbed by static reactive power compensators. Introducing an active or reactive current can regulate the voltage at their linked locations [16]. Static VAR compensators consist of thyristor-controlled capacitors and inductors and are used to improve the dynamic performance of electrical systems [17]. Figure 1 shows the block illustration of this approach [18]. This study presents a wind power prediction model that addresses these boundaries through feature improvement and autoregressive error compensation. The model highlights the relationship between six wind power variables collected in the field and utilizes bidirectional long short-term memory to capture bidirectional time series characteristics. The attention mechanism assigns different weights to these features, enhancing their representation and reducing computational complexity. To overcome frequent local fluctuations in wind power, an autoregressive error compensation model is integrated to further improve prediction accuracy [19]. Previous studies have explored the use of advanced technologies, such as smart grid systems and microgrid topologies, to improve the efficiency of wind power systems. The static var compensator improves the transmission capacity of the transmission line [20]. The static reactive power compensator improves the transient stability of the system. Static VAR compensators control steady-state and temporary overvoltage. By integrating precise meteorological predictions, innovative energy storage technologies, and sophisticated grid designs, renewable energy sources can be optimally utilized for sustainable electricity production [21].

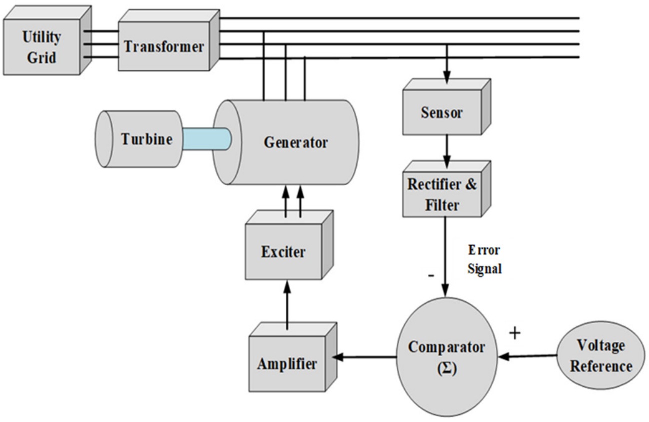

Fig. 1. A simple arrangement of the VAR system.

Several control approaches focus only on static synchronous compensator (STATCOM) control design without any coordination mechanism to regulate the STATCOM and wind/PV plant cooperatively. They also do not establish any reactive power sharing or hierarchical coordination between them or with other VAR-regulating devices. For this purpose, different coordination control frameworks have been presented, classified as decentralized, centralized, and distributed. These systems can facilitate the storage of surplus energy generated during peak periods and its subsequent release when wind availability is low, hence decreasing dependence on conventional backup power sources. In summary, integrating improved voltage regulation and energy storage technologies can greatly increase the overall performance and efficiency of wind power systems. By efficiently managing fluctuations in power generation, these developments can support greater integration of renewable energy sources [22, 23].

The analysis of optimization techniques used in power systems is essential for designing power systems that effectively utilize renewable energy sources such as wind power. By employing such techniques, engineers can optimize the efficiency of energy storage systems and guarantee a more sustainable and reliable grid system for the future. These optimization techniques also enable more efficient planning and control of grid activities, enhancing overall system performance and cost efficiency [24]. PID controllers are constructed using PSO-based optimization, which results in fewer overshoots than controllers built with the conventional Ziegler-Nichols (Z-N) approach. Moreover, all PSO-based PID controllers, except for the Integral of Time-Square Error (ITSE) optimized controllers with their long settling times, perform similarly when optimized using different performance indices. However, PID values are a good place to start using the conventional method [25]. Through the optimized use of renewable energy sources, the dependability and robustness of the power grid are enhanced, guaranteeing a steady and protected power supply. This can reduce dependence on traditional fuels and create a strong power infrastructure in the future. Emerging optimization approaches in the power industry can pave the way for a more sustainable and environmentally friendly power sector.

III. METHODOLOGY

A wind power generation system harnesses the power of the wind to produce electricity, providing a clean and renewable energy source. A static VAR compensator helps stabilize the grid's voltage levels, improving overall system efficiency and reliability. Combining these technologies enhances the integration of renewable energy into the microgrid system while maintaining stability and resilience. This method allows for efficient wind power utilization while ensuring a reliable and stable energy supply. Integrating wind power and static VAR compensators offers a promising solution to address energy stability and environmental concerns. Figure 2 presents a schematic diagram showing the components of the system. Equations (1) to (5) mathematically describe the dynamics and relationships within this system, providing a quantitative framework to understand the interactions between the various elements.

$$G_A(s) = \frac{K_A}{1+sT_A} \tag{1}$$

$$G_E(s) = \frac{K_E}{1+sT_E} \tag{2}$$

$$G_G(s) = \frac{K_G}{1+sT_G} \tag{3}$$

$$G_S(s) = \frac{K_S}{1+sT_S} \tag{4}$$

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \tag{5}$$

Figure 2 shows the AVR block diagram. The optimization approach aims to maximize the benefits of wind power generation by strategically incorporating static VAR compensators to improve grid stability and efficiency. By combining these technologies, the system can better manage fluctuations in wind power output and improve the overall MG system performance, ultimately contributing to a more sustainable and reliable energy infrastructure. This approach not only increases the efficiency of wind power generation but also helps decrease the reliance on conventional fossil fuels, leading to a decrease in greenhouse gas emissions. In general, this optimization strategy is crucial in advancing a cleaner and more sustainable energy future.

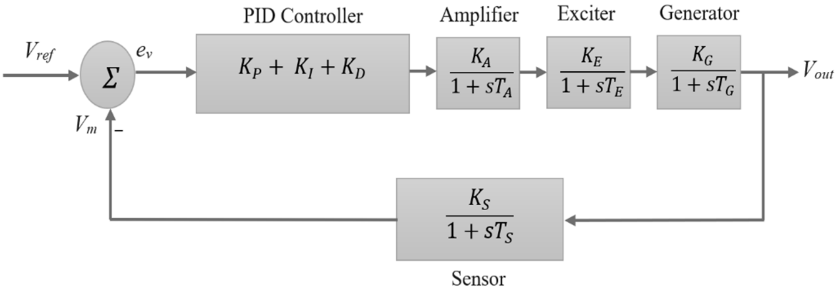

Fig. 2. VAR block diagram.

The complete Transfer Function (TF) model, taking its output against the input ratio, is:

$$G(s) = \frac{G_{PID}(s).G_A(s).G_E(s).G_G(s)}{1+G_{PID}(s).G_A(s).G_E(s).G_G(s).G_S(s)} \tag{6}$$

where $G(s)$ represents the TF of the complete AVR system. Integrating energy storage solutions can enhance the effectiveness of grid stability measures by storing excess energy during periods of low demand. This comprehensive approach ensures a more resilient and flexible energy system that is capable of meeting the demands of a rapidly evolving energy landscape while minimizing the risk of blackouts and disruptions. By incorporating energy storage solutions, grid operators can better manage fluctuations in supply and demand, ultimately improving the overall reliability of the energy system. The simulation setup and parameters are important factors to consider in accurately assessing the impact of these optimization strategies on grid stability. Collaboration between various stakeholders in the energy industry is crucial to effectively implement these optimization strategies. Effective communication and coordination can also help address potential challenges or barriers during implementation. By encouraging a collaborative approach, stakeholders can work together to overcome obstacles and achieve long-term sustainability goals for the energy sector. This collaborative effort requires open dialogue, transparency, and a willingness to compromise to find solutions that benefit all parties involved. Furthermore, regular feedback and evaluation of optimization strategies are necessary to ensure that they meet the desired outcomes and have a meaningful impact on the industry.

Simulations were carried out on a PC with an Intel Core™ i7@2.77 GHz CPU using Matlab/Simulink version 2018a. The number of search agents and the iterations were set to 50 each.

IV. RESULTS AND DISCUSSIONS

The ability of a system to withstand specific changes in its characteristics without compromising stability is known as robustness. The response of the system is evaluated under uncertainties in time constants for the amplifier, exciter, generator, and sensor components (given in Figure 1) from -50% to +50% with a step size of 25%. Figures 3 through 6 show the robustness of the simulation findings. The comparison of results with and without the compensator highlights the positive impact of the solution implemented, showcasing the potential for continued progress and success in improving the efficiency and effectiveness of energy systems. By continuing to invest in research and development, energy infrastructure is improved and addresses challenges such as voltage fluctuations. Figures 3-6 show that the system can handle changes in parameters to ensure stable operation even during variations, demonstrating the robustness of the proposed method.

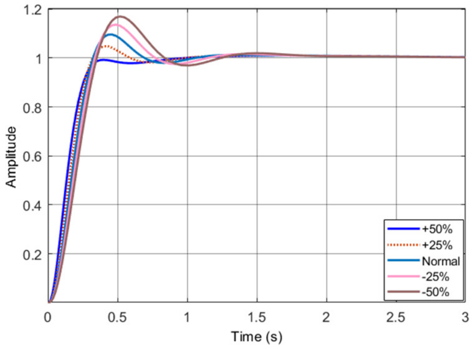

Fig. 3. Amplifier gain variations.

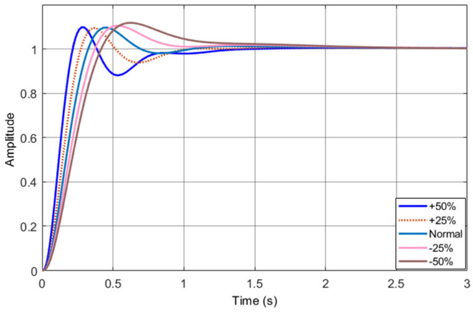

Fig. 4. Exciter gain variation.

Analysis of the dynamic stability enhancement with the static VAR compensator reveals a significant improvement in system performance, with a noticeable reduction in voltage fluctuations and increased overall reliability. These results demonstrate the importance of utilizing advanced technologies to achieve optimal results. Implementing a static VAR compensator is a successful solution to improve system stability and reliability. Moving forward, continued monitoring and adjustment of these optimization strategies will be crucial to maintaining these positive results in the long term.

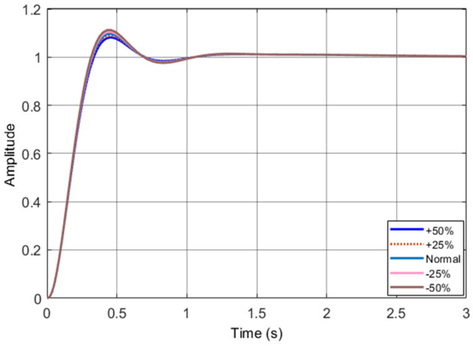

Fig. 5. Generator gain variation.

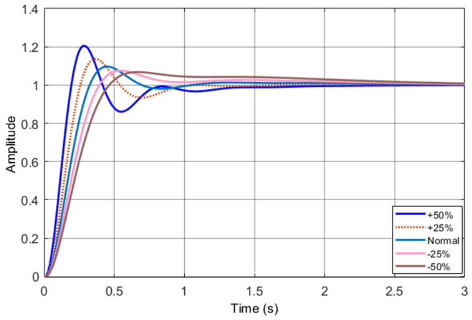

Fig. 6. Sensor gain variations.

The results demonstrate the potential of current developments to enhance the efficiency of power systems through the latest state-of-the-art techniques. This technique successfully addresses the challenges posed by renewable energy fluctuations, voltage variations, and the burden of growing loads. However, the success of this solution paves the way for reducing losses due to stochastic variations. These diversifications encourage more improved methods to mitigate fluctuations and variations in wind turbines. Future studies may emphasize the integration of static VAR compensators into MG systems to improve stability and dependability. Static VAR compensators have real-world applications in wind power systems to improve voltage regulation, reduce power dissipation, and increase grid capacity. These profits can result in more advances and renewable energy systems that will ultimately be conducive to a more sustainable energy future.

V. CONCLUSION

This study presented the integration of a static VAR compensator in an MG to produce optimal results by enhancing its reliability. This strategy increases the efficiency of the MG. Employing static VAR compensators in wind power systems brings tangible benefits. Future research should prioritize more cost-effective static VAR compensators in power systems to gain more benefits from MGs. Deep learning-based techniques can achieve optimal results and solve the dynamic stability of complex power systems.

ACKNOWLEDGMENT

The authors gratefully acknowledge the approval and the support of this research study by grant no. ENGA-2023-12-2020 from the Deanship of Scientific Research, Northern Border University, Arar, K.S.A.

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