**Evaluating Hybrid Winding Technologies for Enhanced DFIG Operation in Wind Turbines**

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**Abstract:** Based on an analytical and systematic approach, prospects of wind energy development in Uzbekistan were studied in the present study. It demonstrates that when incorporated as a component during the modern wind power conversion process, DFIGs would present various operational and economic benefits. These benefits consist of enhanced active and reactive power management, lower converter ratings requirements, and better general system flexibility. Furthermore, the proposed study suggests hybrid (combined) stator windings as an alternative to traditional stator windings in the design of DFIG-type wind turbines. Implementing such enhanced winding designs should lead to enhanced electromagnetic properties of the generator (power factor improvement, reduction of electrical and thermal losses, and energy conversion efficiency), in order to better its electromagnetic behavior. Scientific modeling and performance assessment techniques for the comparative study of hybrid vs conventional winding configurations will be performed to validate the effectiveness of those configurations in optimizing the operational performance of DFIGs in wind energy applications.

**Keywords:** DFIG, hybrid winding, wind energy, harmonic reduction, electromagnetic performance, energy efficiency, variable speed.

**INTRODUCTION**

The electricity from wind power has become a key part of the global energy portfolio, increasingly a relevant renewable energy resource in a growing number of countries. Not only is installed generation capacity growing at a fast pace but the contribution of wind is also growing towards the total yearly production of electricity. Over the past decade or so wind power has transformed from being an extension of energy options to an increasingly important part of sustainable energy strategies in much of the world. The installed capacity of wind turbines worldwide has been steadily increasing and has increased around 100–200% since 2010 (Figure 1). This massive increase demonstrates advancement in power generation technologies for turbines as well as a growing worldwide focus on carbon-reduced energy solutions, energy security, and diversified energy sources. The acceleration of large wind farms also shows the growing requirement for high efficiency and high reliability generator systems that can maintain the wind output in a range of conditions. Thus, research efforts have progressively concentrated on generating technologies improvement and optimization, particularly generator technologies which are more controllable with respect to the energy conversion efficiency as well as the reduced operating losses, to promote continuous growth of the wind energy sector.



**FIGURE 1.** The graph of the development of installed wind energy (GW) since 2010   
(Indicators from left to right: Worldwide, EU, Germany, America)

The strategic priority for the 2020–2030 period has been the development of energy production based on renewable sources. Particular attention is also devoted to raising the share of electrified energy produced from renewable sources, such as by quickly spreading solar power. Such projects are carried out exclusively via investments by independent power producers. Build 3 GW of wind-power facility and 5 GW solar-power facility in relation to the 2020-2030 national renewable energy goal. Targeted parameters for the annual commissioning of renewable energy plants have also been proposed [1-5].

**EXPERIMENTAL RESEARCH**

According to the elementary theory of electrical machines, rotational speed depends on a generator rotor. Hence, when the speed of the rotor changes, the generator produces voltage, the amplitude, frequency, and phase of which also change. On the other hand, GOST 32144-2013 emphasizes the importance of strict regulations of the quality of electrical energy. Hence, because the wind force and flow direction vary, different electrical parameters need to be transformed into standardized output values.

The wind flow instability is typically mitigated by yaw control systems for horizontal-axis wind turbines, or by vertical-axis turbines that are inherently insensitive to wind direction.

To facilitate configuration design of wind, we proposed a novel representation of the current distribution, the Discretely Specified Spatial Function (DSSF). Based on this, the DSSF method is derived [3].

There are two major technical approaches to stabilizing the output voltage frequency.

Mechanical regulation, performed by altering the wind turbine rotational speed: often via blade pitch control.

Electric conversion, in which non-standard electricity output is converted into standard electricity.

Overview of Wind Turbine Generators

Wind electricity systems generally use three key types of generators:

Asynchronous (induction) generators.

Synchronous generators.

DC generators.

The asynchronous generators themselves are a kind of three sub-category: Direct-start induction generators, Full-converter induction generators, Doubly-fed induction generators (DFIGs).

Each of these machineries has certain advantages and disadvantages:

1. Direct-power induction generators (“the Danish Concept”). Such generators are appreciated for their simplicity and high dependability of installation [4]. To maximize operating performance with regards to the power-to-speed ratio, variable-pole induction generators are employed. But it is efficient on limited operational areas and could introduce short-term power output variations and mechanical vibration in severe wind gusts.

2. Full-converter induction or synchronous generators. This technique allows to utilize the entire speed range of the generator but often without a gearbox. It enables continuous active and reactive power control over the network with dynamic power. However, since the system needs a fully rated power converter, it is a more expensive technology.

3. Doubly-fed induction generators (DFIG). When operating DFIGs, the speed of DFIGs is generally within the ±30% speed range of the synchronous speed in a normal speed frame. By operating at variable speeds, they keep active and reactive power stable—just like full-converter systems and at vastly lower converter costs, being that only a fraction of the total power passes through a converter.

Maintaining high quality electrical output is essential for autonomous power supply systems that operate at industrial frequency. Stabilizing electrical parameters under variable rotor speed is tricky because the mechanical energy comes from one of the more unstable sources, a wind turbine.

One excellent solution is based on doubly-fed induction generators, where the mechanical energy is converted to electric energy, and frequency control, voltage control, and reactive power is provided separately. As such, engineering and research interests in DFIG technology have surged, as this provides a promising means of achieving a stable and efficient operation within autonomous wind energy systems. This is most important for the autonomous generators using changes in the number of rotations (ω), electrical frequency (f), and output voltage (U) in the given range [6-11].

**RESULTS**

A model of a DFIG with hybrid stator winding. Different designs have been proposed for doubly-fed induction generators (DFIGs), including brushless configuration, multipole gearless system, or rotor-side multiphase (e.g., five-phase) DFIG construction. All of these designs are promising in a certain technical sense and are being investigated in practice in the context of current wind energy conversion systems. Although there is increased enthusiasm for advanced generator design, the modeling, electromagnetic characterization, and practical application of DFIGs with hybrid stator winding systems is inadequate in the scientific literature. Hybrid stator winding—defined as a stator winding designed using a combination of alternating/reverting phases rather than a conventional stator winding arrangement—outperforms the conventional winding schemes. One of the major advantages of it is to achieve better electromagnetic performance, such as better flux distribution, lower harmonic distortion, and greater active volume utilization of the machine. Consequently, hybrid-wound DFIGs display the utmost technical attributes as against several available alternative generator architectures. Furthermore, the hybrid winding structure is responsible for a major enhancement of the quality of the voltage waveform generated. By minimizing the space-harmonic constituents and optimizing the distribution of winding, the output voltage of a hybrid DFIG achieves a wave that is considerably nearer to an ideal sinusoid to decrease total harmonic distortion (THD) and improve compatibility with power electronic converters and grid-connected systems. These benefits suggest that the hybrid stator winding arrangement can realize significant advantages in the performance and reliability enhancement of the wind turbine generator system. However, thorough mathematical models, simulation methods, and experimental validation methodologies pertaining to hybrid DFIG architectures are still scarce in the literature, highlighting the need for further research in this subject to enable a better evaluation of the performance of such different DFIG architectures in actual wind farm environments.

**TABLE 1.** Assignment of the phases in the slots



|  |  |  |
| --- | --- | --- |
|  |  |  |
| *a)* | *b)* | *c)* |

**FIGURE 2.** Vectors of electromotive force (EMF). *a) classical EMF distribution; b) shifted EMF vectors; c) ombined vector system with 30° displacement, improved harmonic characteristics.*

This image shows the winding vectors by position. From this, it is visible that each vector is displaced by 30 electrical degrees, resulting in a more uniform magnetic field distribution. This angular displacement is able to enhance the general operational efficiency and electromagnetic performance of the machine. An application of Görges polygons is also suggested to more clearly show the effects of voltage distribution and increasing the number of coil sides. A Görges polygon is implemented for a classical open-loop winding setting (case in point) in a stator core with 36 slots per pole pair. Such representation enables visualization of the spatial distribution of MMF vectors and qualitative inspection of the harmonic structure of the winding. The harmonic content in a winding is reduced dramatically when the coils' starting and ending points are close to the locus of the circle generated by the fundamental magnetic wave [5, 6], which is well established. In other words, that well-shaped coil sides reduce space harmonics providing a voltage waveform closer to the ideal sinusoidal shape, leading to an enhanced electromagnetic quality of the machine.



**FIGURE 3.** Görges polygon for the " combined winding" scheme with Z = 36 and y = 12, p =3

Motors equipped with those windings have unique characteristics and are superior to all similar products existing on the market around the world. The combined windings also have other advantages:

-Smaller pendulum moments

-Lower noise emissions

-More sinusoidal voltages and currents.

|  |  |
| --- | --- |
| *a) (standard winding)* | *b) (combined winding)* |

**FIGURE 4.** Spectra of higher harmonics

|  |  |
| --- | --- |
| *a) (standard winding)* | *b) (combined winding)* |

**FIGURE 5.** Starting current of the stator

**CONCLUSIONS**

Combined (hybrid) stator winding, in DFIG model, produces a large improvement in the overall energy performance of the machine compared to a regular winding configuration in DFIG model. Notably, the hybrid winding enhances the power factor and efficiency which enhance the electrical energy conversion performance of the wind turbine systems. Based on these findings, some very significant advantages of hybrid stator windings in electric devices include. Enhanced operating frequency capacity. Hybrid windings enable an electric machine to operate at high voltage frequencies using the common electrical steels appropriate for an initial operation at 50 Hz. Now this greatly expands the operational flexibility of the apparatus. Better mechanical properties. The hybrid arrangement enhances the electromagnetic torque profile so that the starting torque power increases and the torque ability advances over a larger range. This translates to better consistency of operation in windy conditions. Reduced copper losses. At increasing winding factor and more of the magnetic field in the winding, the loss of copper within the stator winding will decrease by 7–13%, therefore a direct increase in the machine efficiency results and the heat stress on the winding diminishes. Less harmonic distortion and less mechanical load. Harmonic suppression not only decreases torque ripple but also lowers redundant rotor losses and electromagnetic interference. This results in an efficient functioning, better performance, and the machines have long service life as well. High efficiency under loads from very low to very high-speed data. The good electromagnetic properties of hybrid windings allow the machine to work without interference on different loading conditions, which is suitable for the context of wind power applications with different working states.

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