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A Single Machine Brushless DFIG for Grid-Connected and Stand-Alone WECS

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Authors' contributions

This work was carried out in collaboration between the two authors. Author MAS designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Author MNE managed the literature searches. Both authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

In this paper a new design for brushless doubly fed induction machine for operation as generator in wind energy systems is proposed. This machine, named single machine-brushless doubly fed induction generator (SM-BDFIG) is composed of three main components; a regular three phase wound rotor induction machine, a power electronic converter, and a pack of rechargeable Lithium-ion batteries. The converter is mounted on the outer surface of a web reinforced hollow metallic (aluminum) or fiber glass cylinder. The battery packs are embedded in the inner part of the cylinder between the webs. The hollow cylinder is mechanically coupled with the induction machine on the same shaft. Therefore, all the three main components of the SM-BDFIG rotate with the same angular speed. A brief description and analysis of the proposed machine merits, parameters, and characteristics are given. The authors could provide the detailed designs of SM-BDFIG and the required testing facilities to the manufacturer who is ready to fabricate the first product of SM-BDFIG and facilitate their testing.

Keywords: WECS; DFIG; double-sided converter; Li-ion battery.

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1. INTRODUCTION

Wind energy is poised to become a major player in the global energy scene. Wind energy installations totaled 318 GW by the end of 2013 and are expected to reach 596 GW by 2018 [1]. The international energy agency (IEA) New Policies scenario [2] suggests that the total installed capacity of wind energy conversion systems (WECS) would reach 587 GW by 2020 according to the moderate scenario and may reach 1100 GW by 2020 according to the advanced scenario. WECS are expected to supply11.7%-12.6% of global electricity by 2020. Both scenarios show that in the coming six years, not less than 270 GW of WECS will be manufactured and installed. Accordingly, the WECS industry will invest more than $400 bn in the coming six years. Research and development Institutions should work hard to find the best designs for the different components of WECS. The electromechanical energy converter (generator), the power electronic converter and its associated controller, represent a major part of the WECS components.

The main trend is to use doubly fed induction generator (DFIG) in recently manufactured WECS, due to the significant reduction in the rating of the associated converter, which was proved to be not more than 10% of the DFIG rating [3].DFIG has also the advantage of variable speed operation and the possibility of power factor improvement [4]. It is interesting to refer to the statement of General Electric (GE) executive product manager [5], that GE, which is a major WECS manufacturer, is to return to DFIG ten years after ditching the technology for permanent magnet generators (PMG). GE assumption that PMG has reduced mass and DFIG is unable to meet future grid connection codes, proved to be wrong. First, DFIG technology is more cost effective compared to PMG. Secondly, substantial progress has been made in DFIG technology that made it capable of meeting grid codes, and finally the electrical conversion losses proved to be substantially less compared to PMG losses.

The benefits of DFIG are undeniable; however, the presence of copper slip rings and carbon brushes to transfer electrical energy to /from the rotating winding of the generator from/to the stationary electronic converter creates the need for frequent inspection and maintenance. Also, the transfer of electric current between the rotating slip rings and the stationary carbon brushes may generate sparks which forbids the WECS installations near explosive environments. The need for frequent maintenance due to the presence of brushes increases sharply the operating costs of WECS especially in remote areas and offshore installations.

In the last few years, the brushless doubly fed induction generator (BDFIG) has made the first steps in its way to replace the regular DFIG to avoid all the adverse effects due to the use of carbon brushes. Great efforts are being done to develop alternative designs for BDFIG based on wound rotor induction machine. Two cascaded wound rotors induction machines were proposed and investigated [6-8] as a first alternative for DFIG. A single frame self cascaded induction machine was proposed and investigated as another alternative for DFIG [9-10]. The third version of the BDFIG proposed and analyzed by M. Ruviaro et al. [11-12], is the DFIG with rotary transformer. It is composed of 3-phase induction machine with its stator winding directly connected to the grid, and its 3-phase rotor windings rigidly connected to the secondary winding of a transformer. The secondary winding rotates on the same shaft of the induction machine. The primary winding of the transformer is fixed and electrically connected to the grid via a power electronic converter. The primary and secondary windings of the transformer are magnetically coupled through an air-gap. This configuration allows controlling the torque, power factor, and current of the induction machine by the converter.

The fourth alternative of the BDFIG is with a rotating power electronic converter (RPE-BDFIM), which is proposed and investigated by M. R. Malik et al. [13]. The RPE-BDFIG employs two machines; the main generator, which is a 3-phase induction machine with its stator directly connected to the grid, and the control machine, which is a synchronous machine handling the slip power. The rotors of both machines are electrically connected via a rotating power electronic converter mounted on the same shaft with both machines. This configuration differs in handling the slip power compared to the versions mentioned before. The RPE-BDFIM converts the slip power to mechanical power via the synchronous control machine and adds it to the shaft at the super-synchronous range of operation of the main machine. When the main machine operates in the sub-synchronous range of operation, the control machine extracts mechanical power from the shaft, converts it to electrical power, and adds it to the induction machine via the converter to provide the necessary slip power to the rotor of the main machine. In all the above mentioned alternatives of the BDFIG, a second machine (induction, synchronous, or transformer) is used in addition to the main generator.

In this paper a new version of the BDFIM is proposed. It is the single machine brushless doubly fed induction generator (SM-BDFIG), which is composed of three main components; a regular three phase wound rotor induction machine, a power electronic converter, and a pack of rechargeable Lithium-ion batteries. The converter is mounted on the outer surface of a web reinforced hollow metallic (aluminum) or fiber glass cylinder. The battery packs are embedded in the inner part of the cylinder between the webs. The hollow cylinder is mechanically coupled with the induction machine on the same shaft. Therefore, all the three main components of the SM-BDFIG rotate with the same angular speed. The batteries are connected together partly in series and partly in parallel, ending with output terminals carrying the full dc voltage of the whole battery pack. These two terminals are electrically connected to dc terminals of back to back converter. The ac terminals of the converter are connected to the rotor winding of the induction machine. A lower voltage terminal from the batteries may be needed to feed the rotor of the induction machine directly when it is running at synchronous speed. Since all the three main components of the SM-BDFIG are mounted on the same shaft, i.e. all rotate with the same angular speed, then the connections between them are rigid electrical connections without any sliding contacts, slip rings, or brushes.

When the SM-BDFIG operates in the super-synchronous speed range, the excess slip power is transferred from the rotor of the induction machine to the converter. This power is converted to dc power which is used to charge the batteries. When the SM-BDFIG operates in the sub-synchronous speed range, the charged batteries supply dc power to the converter, hence converted to a 3-phase ac power at the required voltage magnitude, phase and frequency with the aid of the well designed controller. This ac power is fed to the rotor of the induction machine to operate as a generator, transferring this slip power in addition to the shaft mechanical input power. The sum of these two power components represent the air gap power transferred from the rotor to the stator of the induction machine, which is the output power of the SM-BDFIG fed to the grid or the load plus the stator copper losses and the iron losses. When the induction machine runs at synchronous speed, its rotor is fed by dc power, either directly from the battery packs or from the converter. The machine then will run as a synchronous machine with dc excitation in the rotor side.

In addition to the known merits of the previously mentioned BDFIG such as the provision of recovering slip power without slip rings or carbon brushes, employing partially rated converters power for variable speed operation, and higher power quality since most of the power injected into the grid is unprocessed by the power electronic converters, the SM-BDFIG has the following advantages: a) It uses only one machine, (b) It is able to generate power when the main machine runs at synchronous speed, (c) the input mechanical power provided by the wind turbine is converted to electrical power only by the main induction machine, and finally (d) it can operate with grid connected as well as stand-alone WECS.

2. THE MAIN COMPONENTS OF THE SM-BDFIG

The SM-BDFIG is composed of three main components, namely; the induction machine, the power electronic converter, and the rechargeable battery bank. All the three components are driven by the same shaft and therefore rotate by the same angular speed. The converter and controller are mounted on the outer surface of the web-reinforced hollow cylinder and the rechargeable batteries are embedded in the cavities of the hollow cylinder.

In what follows, the basic configurations of the different components are briefly described and a general analysis of their performance is given.

2.1 The Induction Machine

The corner stone component of the SM-BDFIG is the generator which is a regular three-phase wound rotor induction machine. The optimized geometrical dimensions and weights of wind-driven doubly fed induction generators of power rating in the mega-watt range (0.75-10MW) are given in Table 1A [14]. The prime importance of the data collected in this paper is to compare the sizes and weights of the converter, controller, battery banks, and the carrier cylinder of the SM-BDFIG with the generator size and weight in order to ensure that the driving shaft and outer casing will be of reasonable sizes.

Table 1A. DFIG

Power MW	0.75	1	1.5	3	5	10
Air gap diameter-m	0.58	0.61	0.68	0.75	0.84	0.86
Stator outer diameter-m	0.65	0.7	0.8	1	1.1	1.15
Stator length-m	0.41	0.45	0.53	0.8	1.15	1.97
Stator total length-m	1.0	1.05	1.2	1.6	2	2.6
Total weight-tons	5	8	15	35	55	155

The wind is naturally a time-varying phenomena, therefore the wind power delivered to the wind turbine and consequently the wind turbine speed of rotation will be changing with time. The wind turbine driven SM-BDFIG, therefore will have a wide range of rotating speed variations. This range of variations is divided into three operating ranges for the SM-BDFIG, namely; the sub-synchronous ($\omega < \omega_s$), the super- synchronous ($\omega > \omega_s$), and the synchronous ($\omega = \omega_s$) ranges of operation, where ω is the rotating angular speed of the machine and ω_s is the synchronous speed of the induction generator.

Each of the operating ranges will be briefly analyzed separately, since each range of operation has its own specific analytical tools. Nevertheless, some basic concepts are discussed in the following paragraphs.

When WECS operate under steady state conditions, the angular speed ω of the generator rotor is constant, therefore the mechanical torque Tm driving the machine shaft is equal to the electromagnetic torque T_e resulting from the interaction of the stator and the rotor magnetic fields of the generator :

$$T_m = T_e \quad (1)$$

$$\omega T_m = \omega T_e = (1\text{-}s)\ \omega_s T_e \quad (2)$$

$$P_m + sP_g = P_g \quad (3)$$

Where Pm= T. ω =input mechanical power to the induction generator
$P_g = T\ \omega_s$ = electromagnetic power transferred through the machine air gap
sP_g = slip power

When the generator is operating at sub-synchronous speed with positive slip ($s = (1- \omega/ \omega_s)$, then the input mechanical power to the rotor of the generator is converted to electrical energy and supplemented by the slip power sP_g to form the electromagnetic power transferred through the machine air gap. The battery bank of the SM-BDFIG will be responsible for providing via the electronic converter (at the proper frequency, amplitude, and phase of its output voltage), the slip power in addition to the rotor copper losses of the machine**.** It goes without saying that the output power of the generator will be air gap power Pg less the stator copper losses and the iron losses.

When the machine runs at a speed higher than the synchronous $\omega > \omega_s$, the slip s will have a negative value. The input mechanical power will be converted to electrical power ($P_m = P_g – (-s)\ P_g$), partly P_g transferred via the gap to the stator then to load deducting the stator copper and iron losses. The other part is slip power sP_g which (after deducting the rotor copper losses and the losses in the converter) is converted to dc power via the electronic converter and is utilized in recharging the battery bank.

When the machine runs at synchronous speed ($\omega = \omega_s$ and $s = 0$), the generator operates as a non-salient synchronous generator in which all the input mechanical power is converted to electrical and transferred to the stator through the air gap. However, in this case a small amount of dc energy is needed from the battery bank to feed the rotor winding of the machine in order to create the necessary magnetic field in the generator air gap, i.e. the rotor winding in this set-up replaces the excitation winding of the regular synchronous machine.

2.1.1 Sub-synchronous range

When the induction machine runs at a speed less than its synchronous speed, i.e. $0<s<1$, the voltage induced in the rotor circuit is sE_2 at a frequency sf_1, where,

E_2 = voltage induced in the rotor circuit at standstill
f_1 = frequency of stator current

Under this condition the wind turbine provides the mechanical power while the battery bank supplies electric power to the rotor circuit of the generator via the power electronic converter. The converter output voltage $V_s = V_s\ e^{j\gamma}$. The voltage magnitude (V_s), phase angle (γ), and frequency (sf_1) are all adjusted such that the air gap power P_g transferred from the rotor to the stator attains its maximum value. Using the power flow approach [4], these values can be easily obtained as:

$$\gamma = \arctan(s.\beta) \tag{4}$$

$$\alpha = s/ \sqrt{(1+ s^2.\beta^2)} + s_n (1-s).\sqrt{(1+ s^2.\beta^2)} \tag{5}$$

where, $\alpha = (V_s / E_2)$ and $\beta = X_2/ R_2$
γ = the electrical angle by which V_s leads the rotor induced voltage sE_2
R_2 = rotor resistance per phase
X_2 = rotor leakage reactance per phase at standstill
s_n= nominal slip

Fig. 1 plots the relation between γ and slip at different values of β. While Fig. 2 shows the relation between the minimum value of α which sustains the generation mode of the induction machine and the slip at different values of β for rated slip s_n =0.02. From these figures it is concluded that as β increases, the dc voltage required at synchronous speed decreases while the angle by which the stator voltage lead the induced rotor voltage decreases. This fact assists in designing the machine for certain operation range.

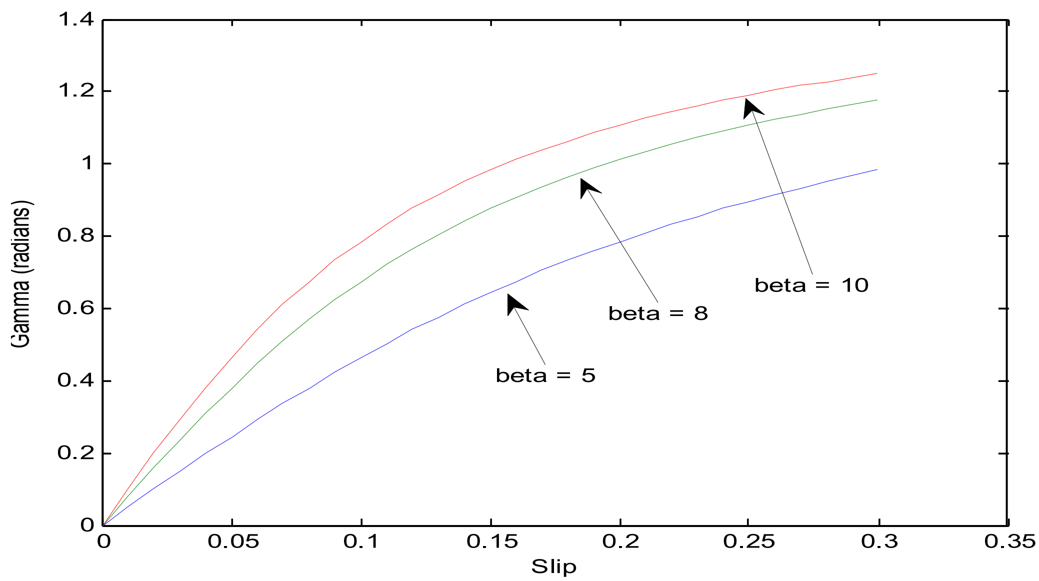

Fig. 1. The relation between γ and slip for different values of β

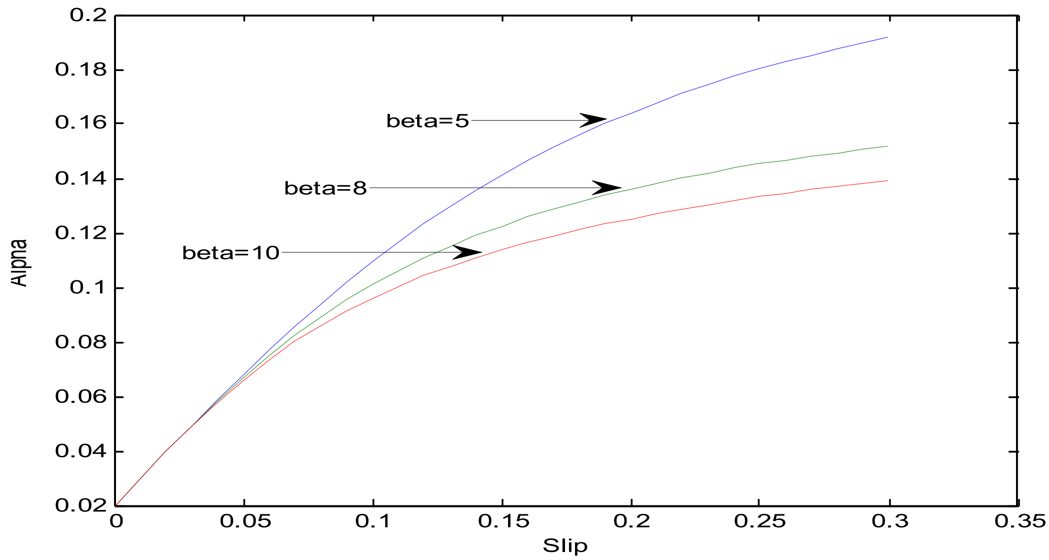

Fig. 2. The relation between α and slip at different values of β for nominal slip s_n =0.02

2.1.2 Super-synchronous range

When the machine runs at a speed higher than its synchronous speed ($\omega > \omega_s$ and $s<0$), the power flow will be different than in the sub-synchronous range. Part of the mechanical power transferred to the rotor shaft from the wind turbine, will be transferred to the stator of the machine via the air gap (P_g), and the other part (sP_g), which is the slip power minus the rotor copper losses will be fed to the electronic converter, which acts in this range as a rectifier converting the ac slip power into dc power recharging the battery bank.

2.1.3 Synchronous range

If the machine runs at its synchronous speed, its rotor should be fed by dc current to create a rotating magneto-motive force (MMF) to interact with the stator rotating MMF to convert the shaft mechanical power into electrical power to be transferred to the stator via the air gap. The machine operates in this range as a synchronous machine with the rotor winding acting as the excitation winding of a regular synchronous machine.

The rotor winding is either star or delta connected. If star connected, the dc voltage is applied between the terminals of one phase and the common terminal of the two other phases. The current flowing in one phase is I_d, while current flowing in other two phases is $I_d/2$.

If rotor windings are delta connected, then the dc voltage is applied between the two terminals of the first phase. If the current flowing in this phase is I_d, then current flowing in the other two phases is $I_d/2$.

In both cases of star and delta connections, the dc current flows in the first phase in a direction opposite to its flow in the other two phases.

The fundamental component of the MMF is obtained using Fourier analysis as follows:

$$(MMF)_{fd} = (6/\pi)\ N_2\ I_d \tag{6}$$

Where N_2 is the number of turns of rotor winding per phase

When the machine is operating as an induction machine, the amplitude of the fundamental component of the pulsating MMF per phase assuming balanced 3-phase currents is:

$$\begin{aligned}(MMF)_A &= (4/\pi)\ N_i\ I_{2max} \sin(p\omega t)\\ &= (4/\pi)\ N_i\ \sqrt{2}\ I_2 \sin(p\omega t)\end{aligned} \tag{7}$$

Where, p is number of pole pairs of the induction machine.

The amplitude of the rotating MMF wave resulting from the three pulsating MMFs of phases is given by:

$$\begin{aligned}(MMF)_{fac} &= (3/2)(4/\pi)\ \sqrt{2}\ \ I_2\\ &= (6/\pi)\ \sqrt{2}\ I_2\end{aligned} \tag{8}$$

This means that the rotor winding should be fed by a dc current $Id = \sqrt{2}\ \ I_2$ to produce a rotating MMF wave, in the air gap of the induction machine, with a magnitude equal to that produced by a rotor current I_2 when the machine runs at sub or super synchronous speed.

The dc current I_d flowing in the rotor winding should not exceed the rotor current at rated speed to avoid overheating the rotor windings. Hence, the amplitude of the MMF due to the dc current will not exceed $1/\sqrt{2}$ of MMF produced by rotor current at rated speed, i.e.

$$(MMF)_{dc} = (0.707)\ (MMF)_r \tag{9}$$

Since the electromagnetic torque and consequently the air gap power of the induction machine is proportional to the product of the amplitudes of the stator and rotor MMFs, therefore;

$$P_g \propto (MMF)_2 \tag{10}$$

$$P_{gdc} \leq 0.707 P_{gr} \tag{11}$$

The wind turbine power input to the induction machine rotor is a quadratic function of the turbine angular speed or the generator angular speed ω, i.e.

$$\begin{aligned}P_m &= K\ \omega^2\\ P_m &= (\omega^2 / \omega_r^2)\ P_{mr}\end{aligned} \tag{12}$$

When the machine runs at synchronous speed, all the input mechanical power (P_m) is converted to electrical power $(P_g)_{dc}$, then from equations 8 and 9:

$$(P_m)_s = (P_g)_{dc} \leq\ 0.707\ P_{gr} \tag{13}$$

$$(P_m)_s \leq\ 0.707\ P_{mr} /(1\text{-}s_r) \tag{14}$$

or

$$(\ \omega_s^2\ /\ \omega_r^2)\ P_{mr} \leq 0.707\ P_{mr} /(1\text{-}s_r) \tag{15}$$

Since $1-s_r = \omega_r / \omega_s$

Therefore $\omega_s / \omega_r \leq 0.707$ (16)

The induction generator is to be designed to produce its rated output at a speed about 1.41 times the synchronous speed which is higher than the normal practical values.

As an alternative, the rotor winding could be designed to endure 20% more current than the rated rotor current for a limited time when the wind drives the rotor shaft with the synchronous speed, which is a normal practice for the electric machine designer.

Therefore $(P_g)_{dc} \leq$ will be equal or less than 0.85 P_{gr} and then the rated slip $s_r \leq -0.18$.

Normally the DFIG operates in the range $-0.2<s<0.3$ which is almost appropriate for the operation of SM-BDFIG

The dc voltage applied to the rotor terminals at synchronous speed V_{dc} can be easily obtained by equating the dc current flowing in the rotor winding to the dc rated current flowing in the rotor winding when the generator runs at its rated speed. Therefore,

$$\alpha_{dc} = V_{dc} / E_2 = 1/\sqrt{(1/s_r^2)} + \beta^2 \quad (17)$$

This relation is plotted in Fig. 3 for two values of rated slip; namely, s_r=-0.2 and s_r=- 0.4

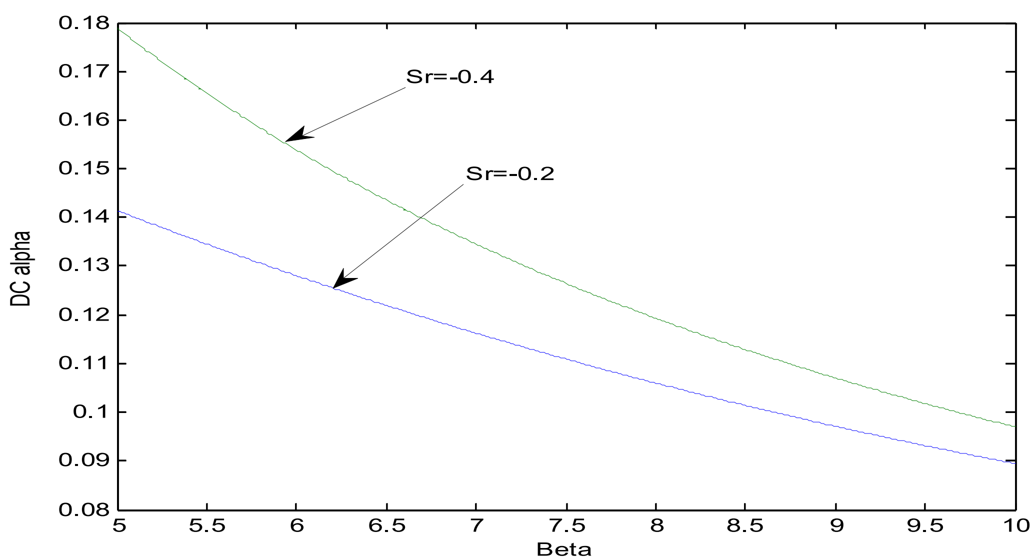

Fig. 3. The relation between α_{dc} and β

2.2 The Converter

The compact electronic converter with the digital controller, speed sensor and advanced meters compose together an intelligent device constituting the second major component of the SM-BDFIG. This device operating in a real time situation converts the battery bank d.c. voltage to an a.c. voltage of certain magnitude, frequency and phase according to a specified function of the induction machine rotor speed(see equations1 & 2) in the sub-synchronous range of operation ($\omega < \omega_s$). On the other hand, in the super-synchronous range of operation ($\omega > \omega_s$), this device will act as a rectifier converting the a.c. slip power into d.c. power charging the battery bank. When the induction machine runs at synchronous speed ($\omega = \omega_s$), this device will actuate a 3-pole power switch fixed to the rotor shaft to connect the battery bank directly to the rotor winding of the induction machine. The battery terminals connected to the rotor in this case should be such that the applied d.c. voltage to the rotor winding terminals is equal to the values given by equation (17). The battery bank in this case will supply the magnetizing current to the rotor winding to act as the non salient poles of a regular synchronous machine.

This device with all its components is mounted on the outer surface of a reinforced hollow metallic (Aluminum) or fiber glass cylinder coupled to the same shaft of the induction machine. The geometrical dimensions (outer and inner diameters and length), the volume and the weight of this device are estimated in Table 1B for different powers of the converter (75-1000 kW) or for the induction machine (0.75- 10 MW). This power range of the converter is the appropriate size of the converters that can handle the slip power in the whole range of operation of the induction generator.

Table 1B. Compact converters and controller and sp. sensor

Power (kW)	75	100	150	300	500	1000
Weight (kg)	8	10	15	30	50	100
Volume (lit)	16	20	30	60	100	200
Outer diameter (cm)	40	45	60	85	112	150
Inner diameter (cm)	20	25	30	42	56	75
Length (cm)	20	30	45	92	150	300

It is clear from the estimated values in Table 1B that both the volume and weight of this device are much smaller than the corresponding values for the induction machine. Therefore, the additional mechanical stresses on the shaft will be in acceptable range.

2.3 The Batteries

Large scale electrical energy storage batteries have been under development for several decades. Renewable energy systems such as WECS and PV may require electrical energy storage, either to store excess electrical energy from the PV or WECS, or to feed electrical energy to some components of the renewable energy system, or for both functions.

The utilization of batteries in renewable energy systems usually fall into two broad categories; energy application and power applications. Energy applications involve storage system discharge over periods of hours (typically one discharge cycle per day) with correspondingly long charging periods. Power applications involve comparatively short periods of discharge (seconds to minutes), short recharging periods, and often require many cycles per day.

The SM-BDFIG operating in WECS require power application of the associated battery banks due to the intermittent nature of the wind resource and its frequently changing speed. Consequently, the speed of the wind-driven generator changes over short time periods.

When running with super-synchronous speed, the rotor slip power will be converted to dc power via the converter to charge the battery storage system. At sub- synchronous speed, the battery will discharge part of its energy to the rotor circuit via the converter, which converts it to ac energy at the appropriate frequency, voltage magnitude, and phase. When the generator runs at synchronous speed, the battery will supply the rotor circuit directly with dc energy.

Various battery technologies have been and are being proposed and developed for electrical energy storage applications. Developers are seeking lower cost, flexible designs, reliable performance, lower maintenance cost, higher efficiency, and ensuring the possibility of controlling large battery banks.

The authors believe that the most suitable type of the commercially used batteries for the proposed SM-BDFIG is the Lithium-ion polymer type. These batteries were first introduced by Sony Corporation in the early nineties. The Lithium polymer battery has merits compared to other types. These merits can be summarized as follows: no leakage due to using solid electrolyte, can be made into thin batteries with different shapes, can attain high voltage, and has high volumetric energy density.

A reasonable efficiency should be maintained such that the final delivery of energy to the power converter is sufficient to maintain the SM-BDFIG generating energy when running at sub-synchronous speed.

The fast development in Li-polymer technology can be monitored through, the large increase in its rating and decrease in cost during the last few years. For example, on 2013 the cost reached $400-500/kWh, capacity 130-140Wh/kg, and power density 3500W/kg .It is expected that by the year 2015, the cost will reach $200-200/kWh and capacity 250-300 Wh/kg, and energy density 3500W/kg [15].

Recently, an American company [16] manufactured Li-ion Polymer cells that offer 490Wh/L total volumetric energy density and 207Wh/kg total gravimetric energy density, significantly outperforming today's lithium-ion pouch (soft-packaged) solutions with 50% more energy density in Wh/L, and 20-30% more in Wh/kg. (This also represents twice the gravimetric energy density available with lithium-iron phosphate solutions). Also, another company invented a new thin-film construction for Lithium-metal-polymer batteries allowing the batteries to be embedded in printed circuit boards or integrated circuit chips. The batteries are postage-stamp size and about 1/10 mm thick, and contain "micro-energy cells". The batteries demonstrate near zero self-discharge. The micro-energy cells are ideally suited for use with all forms of energy harvesting techniques for recharging, such as solar, thermal, RF, magnetic and vibration energy.

Lately a Seattle-based company manufacturing advanced nano-structured materials for next-generation energy storage breakthroughs, today announced that it has extended its product lines to further boost lithium-ion battery capacity and power performance. These improvements, designed to harness the benefit of silicon in Lithium-ion batteries, leverage EnerG2's unique polymer chemistry-based approach and come less than year after launching production of hard-carbons tailored for Li-ion anodes. This development allows the Li-ion batteries to be the optimum choice for storing excess energy generated by single machine brushless doubly fed induction generators (SM-BDFIG) in wind energy conversion systems.

As in the case of employed converters, described in the last section, it is clear from the estimated values in Table 1C that both the volume and weight of the battery are much smaller that the corresponding values for the induction machine. Therefore, the additional mechanical stresses on the shaft will be in the acceptable range.

Table 1C. Lithium ion batteries

Power (kw)	75	100	150	300	500	1000
Volume (liter)	7.5	10	15	30	50	100
Weight (kg)	21	29	43	86	143	286

3. CONCLUSION

A novel single machine-brushless doubly fed induction generator (SM-BDFIG) is proposed and analyzed. The (SM-BDFIG) is composed of three main components; a regular three phase wound rotor induction machine, a power electronic converter, and a pack of rechargeable Lithium-ion batteries.

All the mechanical energy delivered to the shaft from the wind turbine is converted to electrical energy in the induction machine. The slip power flows from the rotor to the converter then to the battery pack and vise-versa. The power electronic converter, which is the main source of harmonics, is neither connected to the grid nor to the output terminals of the generator. Therefore, the output power quality is higher than in the regular DFIG.

The SM-BDFIG can generate electric power within wide range of rotor speeds including synchronous speed. It has neither slip rings nor brushes. Hence, it is more adequate for offshore wind turbines or in remote areas, since it does not need frequent inspection and consequently lower maintenance cost.

The SM-BDFIG can operate safely near explosive environments due to the absence of rotating slip rings and stationary brushes which may generate sparks.

The SM-BDFIG can be connected to the grid or operate in stand-alone WECS.

DFIG technology is more cost effective compared to PMG. The cost of an induction machine is less than the cost of a permanent magnet synchronous machine of the same power. Secondly, the converter size connected to the DFIG is less than 10% of that connected to PMG which leads to an additional cost reduction, and finally the electrical conversion losses in the DFIG proved to be substantially less compared to PMG conversion losses.

This paper presents the general description of the different components of the SM-BDFIG, and a brief analysis for each of them. The authors are looking for feedbacks from the research and development institutions and manufacturers about the technical viability of the SM-BDFIG and are ready to provide the detailed designs and analysis of the different components if any of them is interested in developing such machine.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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