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Published in:
IEEE Access

DOI (link to publication from Publisher):
10.1109/ACCESS.2021.3101907

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 29, 2021, accepted July 26, 2021, date of publication August 2, 2021, date of current version August 31, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3101907

Fractional kVA Rating PWM Converter Doubly Fed Variable Speed Electric Generator Systems: An Overview in 2020

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This work was supported in part by the Excellent Youth Fund of Shandong Natural Science Foundation under Grant ZR2020YQ40, in part by the fund from Science, Technology and Innovation Commission of Shenzhen Municipality under Grant JCYJ20190809101205546, and in part by the Fundamental Research Funds for the Central Universities of China under Grant 2021XXJS002.

ABSTRACT Variable speed generator systems (VSGs) are at work in the now 600 GW installed wind power plants (parks). Also, they are used as vehicular and on ground stand-alone generators. VSGs imply full kVA rating PWM converters in permanent magnet (PM) or in electrically excited synchronous or in cage rotor inductance generators. But, to reduce cost in absence of PMs at a reasonable initial cost (weight) and efficiency, the fractional kVA PWM converter doubly fed induction generators (DFIG) cover now about 50% of all installed power in wind generators. The present paper reviews recent progress in DFIG and various forms of brushless DFGs (doubly fed generators) characterized in terms of topology, design, performance and advanced control for healthy and faulty load conditions in the hope of inspiring new, hopefully ground breakings, progress for wind and hydro energy conversion and in vehicular and on the ground stand-alone generator applications.

INDEX TERMS Variable speed generator system, double fed induction generator, brushless double fed induction (reluctance) generator, dual stator winding cage rotor induction generator, dual rotor bidirectional flux-modulation permanent magnet machine.

I. INTRODUCTION

With more than 600 GW wind energy installed power and 10 times more installed hydro energy power, the renewable energy conversion makes already a notably contribution to the world energy consumption and is on the rise for the near and distant future [1], [2].Variable speed generator systems (VSGs) are today extensively used for wind energy conversion and on board of vehicles/aircraft, marine ships, railroad vehicles and on-ground stand-alone applications, but with even greater potential for hydro energy conversion too, for more energy yield at higher efficiency and superior control flexibility in modern power systems.

The associate editor coordinating the review of this manuscript and approving it for publication was Inam Nutkani.

VSGs, today in operation in wind energy conversion, are of 4 types (PM synchronous-PMSG (1), electrical excited synchronous-EESG (2), double fed induction-DFIG (3) and cage induction-CRIG (4)). Types (1), (2), (4), cover about 50% of all installed wind power and require full kVA power rating PWM converters that offer rather complete control but are rather expensive in the MVA range, with constant ac voltage and frequency or dc output constant voltage control, for up to 1.3 to 0.7 p.u. speed control range. To reduce initial costs, VSGs with fractional kVA power ratings as cascaded DFIG with max. 50% PWM converters have been introduced since previous years [3], fed through mechanical brushes, while slip-rings wound rotor of induction generators (DFIGs or WRIGs), that are also capable of regulated constant ac voltage and frequency, for the speed range of 1.3/0.7 p.u. [1]–[8],

TABLE 1. Classifications.

Configuration	With PM or PM-less	Brush or brushless	Single or dual stator winding	With or without rotor winding	Single or dual rotor
DFIG	PM-less	With brushes or brushless (swapped rotor to stator) or cascade configuration	Single 3Φ stator winding, p pole pairs	Single 3Φ rotor winding, p pole pairs	Single rotor
BDFIG + BDFRG*	PM-less	Brushless	Dual stator winding p_m pole pairs (main) p_c pole pairs (control)	With rotor nested cage winding p_r=p_p+p_c poles *p_r salient pole rotor	Single rotor
DSW-CRIG	PM-less	Brushless	Dual stator winding $p_p = p_c$	With cage rotor	Single rotor
DR-DSWBG	With PM inner rotor	Brushless	Dual stator winding (with different pole pairs): p_p, p_c	With variable reluctance outer (reactive) rotor $p_{fm}= p_p+p_c$ pole pairs	Dual rotor
BFM-PMM	With outer active PM	Brushless	Dual stator winding (with different pole pairs): p_{w1}, p_{w2}	With PM load rotor $p_{fm} = p_{w2}- p_{w1}$ flux modulated second rotor at stand still but with servo-regulated position for control	Dual rotor

represent 50% of all installed wind generators power. The control attributes are a bit weaker than for full rating PWM converter VSGs but are apparently satisfactory. So for DFIG up to 6.4MVA/unit [2] with 3 stage mechanical transmission are in operation while even a direct drive 10rpm 10MVA DFIG (with unity power factor in the stator) has been designed (but not yet experimented) in an effort to promote PM less VSGs at reasonable costs with fractional kVA PWM converters [9]. In view of the above this over review of DFGs recent progress with a perspective refers to the following subjectively selected issues:

- DFIG advanced modeling, design and constant voltage and frequency output control for healthy and faulty conditions, power quality and increased reliability.
- Recently proposed DFIG with variable stator frequency control using only a full power 3 phase/6 phase voltage boost transformer and diode rectified full power output, as a fully decentralized lower cost sending interface of M(H) Vdc power transmission with DFIGs in parallel on dc. The same diode rectified output solution is recommended in vehicular and on ground dc bus generator systems.
- The brushless twin wound rotor and stator cascaded induction generators (BDFIGs). Only the second stator winding is fed from a fractioned PWM converter (up to 50%).
- DFIG turned brushless by swapping stator with rotor roles at high (above 150-300 Hz) primary constant or variable frequency, to reduce size and costs) [1].
- Brushless DFIG with dual stator winding (a 3-phase power winding with pp pole pairs and a 3-phase ac (in general) control winding with pc pole pairs) with a nested cage, or/and a salient pole rotor of pp+pc poles, with ac or dc output controlled only through the fraction rating (max 30-35% in general) PWM converter that feeds the control winding. The power winding frequency is kept rather constant or may be made variable to yield more flexibility in ac or dc output controller better efficiency.
- Brushless dual stator winding (pp = pc) cage rotor induction generators (DSW-CRIG) with only the control winding fed from a fractional kVA PWM converter (30-35% maximum). Ac or dc output control is feasible.
- Brushless dual rotor DBR DFG with a segmented salient pole outer rotor with NFM poles (as flux modulator) and an inner PM freewheeling (excitation) rotor of pm pole pairs. The stator hosts two 3-phase ac windings: the power windings with pp = pm pole pairs and the control windings with pc = NFM - pm pole pairs acting as a Vernier machine. Again, only the control winding is fed from fractional kVA rating PWM converter with the power stator winding operation at constant or even variable frequency.
- A novel bidirectional flux-modulation permanent magnet outer active rotor (BFMPMM) machine with fixed PM inner rotor for standalone dc wind power generation has been proposed very recently. The key is to control the inner rotor position with a small servo motor, and with bidirectional flux modulation effect, the resultant induced voltage in two sets of stator windings even series connected can be adjusted accordingly. Consequently, in wide wind speed range, the various -speed constant-amplitude voltage operation is realized.
- As the recent progress in R&D related to the above solutions was staggering, in an effort to boost performance in energy conversion and control at lower initial costs, the present overview continues by describing main results in some detail, from design to control and from power quality and reliability issues, in the hope of inspiring even more progress in the near future on the route to commercialization.

An illustrative summary of included configurations as a classification is presented in Table 1. It should be noted that only DFIG has brushes and the two rotor configurations both have PMs and the second rotor is not coupled to the load. Also the last configuration DFM-PMM uses only a full power diode rectifier for dc output while the dc voltage (power) control is done with a low power servomotor which adjusts the second rotor position (at standstill).

Note. All configurations have by now constant power winding frequency (with variable control winding frequency) but both frequencies may be variable, especially for diode rectified DC output, though all configurations works routinely with AC output.

The paper continues with DFIG recent progress in Section II, brushless double fed induction (reluctance) generator (BDFI(R)G) recent progress in Section III, DSW-CRIG in Section IV, dual rotor dual stator-winding brushless generator (DR-DSWBG) in Section V, dual rotor bidirectional flux-modulation permanent magnet machine (BFM-PMM) in Section VI and discussion and conclusion in Section VII.

II. DFIG–RECENT PROGRESS

Typical commercial large power wind DFIGs are illustrated in Table 2. Apparently the DFIG for wind energy conversion may be extended, with 3 stage transmission, to 10 MW units, and even a direct drive 10 MW, 9.1 rpm DFIG with large diameter and flexible frame has been proposed, with promising results.

TABLE 2. Typical large DFIG designs.

Manufacturer	Power	Description
VESTAS–SA [6]	2.0 MW 4.2 MW	4 pole 3 stage transmission
GAMESA [7]	2.2 MW	3 stage transmission
G.E. Wind	4.8 MW	Onshore
NORDEX	4.5 MW	3 stage transmission
SENVION [8]	6.3 MW	3 stage transmission (two planetary + one spur gears)
Proposed in [9]	10 MW, 9.1 rpm	Direct drive

In general, DFIG for given power and speed is slightly heavier than PMSG and CRIG but lighter than EESG, while not using PMs.

The DFIG has been applied also in industrial sites (so far) at 400 MVA [10] respectively 300 MVA and 230 MVA [11] with a maximum +/−10% of speed control range in pump storage hydro energy power plants.

With the availability of up to 100 (2∗50) MVA multilevel PWM (ac-dc-ac) converters, the DFIG power range or the speed range may be extended further, dramatically.

The generic control system in Fig. 1, includes double fed IG with the fractional kVA rating (30%) PWM converter connected through mechanical brushes to the wound rotor but adds the other commercial generators (PMSGs, EESGs and CRIGs), where the full kVA rating (100%) PWM converter is connected to the stator winding.

Though by now DFIG is a mature technology with main design and control issues treated in dedicated chapters or entire books [11]-[14], optimal design [15] and advanced control issues such as related to asymmetric voltage sags [16], [17], stability analysis, low and high frequency oscillations, sub synchronous resonance are far from worldwide

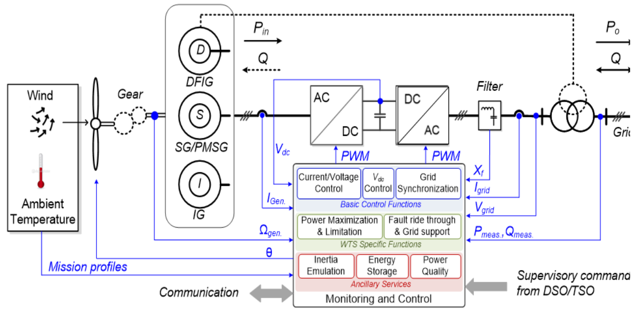

FIGURE 1. Generic control of main types of variable speed generators with ac output (after [1]).

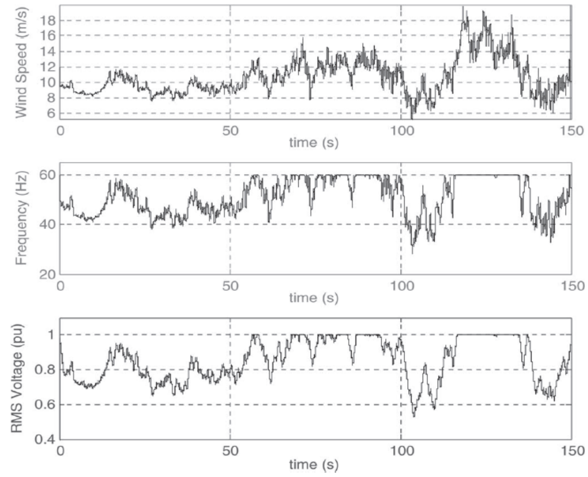

FIGURE 2. Voltage deficit in a DFIG with constant stator V/f control and low (5%) fractional rating PWM converter [20].

acceptance, despite of recent dynamic worldwide R&D effort [18], [19]. So far, rather constant stator frequency control (with implicit), variable rotor slip frequency is the norm.

In an attempt to reduce the fractional kVA ratings of the PWM converter connected to the wound rotor of DFIG, variable stator frequency control was proposed. A reduction of kVA ratings of the PWM inverter to 5% for a +/-20% speed range has been proposed with an output voltage deficit at low speeds, Fig. 2, [20] to be handled by the voltage boosting of the full PWM rectifier that represents the sending end of the M(H) Vdc transmission line. Further on, to decentralize totally and simplify the DFIG control and its interfacings with a dc voltage transmission line, the fractional kVA rating of PWM converter may be kept at around 30%, but to be used in a scheme which adds a voltage boosting 3/6-phase full power transformer and a diode rectifier as the sending end, with the prospect of laminating both the ac paralleling of wind generators and the PWM high voltage rectifier as sending end of HVDC transmission line [21], [22]. Variable stator frequency with speed also provides better (optimal) efficiency opportunities [21], as shown in Fig. 3.

The reactive power need at stator unity power factor with a transformer and diode rectifier has to be considered when designing the grid-side dc-ac PWM converter of DFIG, to maintain constant dc output voltage at variable speed. Quite

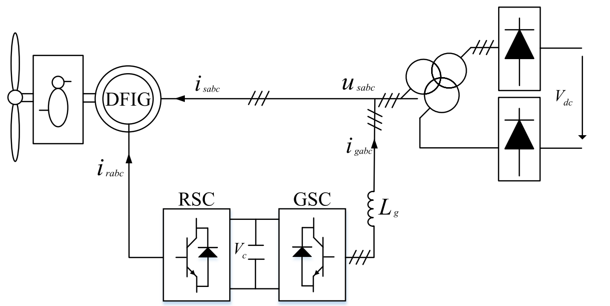

FIGURE 3. Fully decentralized control of a DFIG connected to a HVdc link by a full power 3/6-phase transformer and diode rectifier (after [21]).

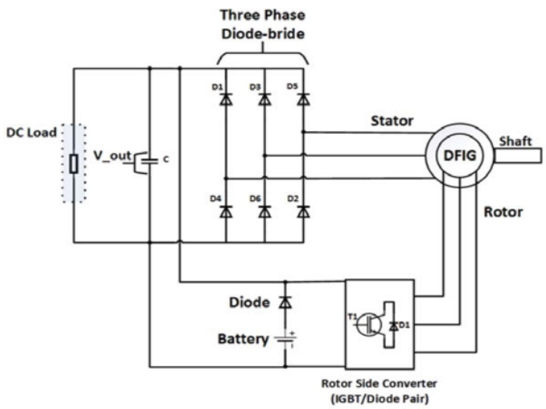

FIGURE 4. Standalone dc output DFIG scheme [22].

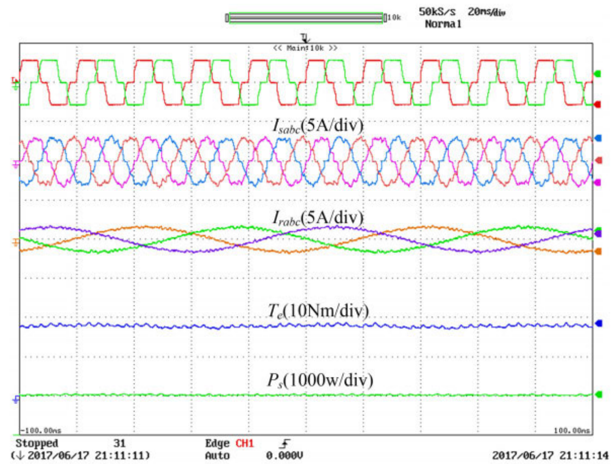

FIGURE 5. DFIG with rotor harmonic voltage compensation to produce rather sinusoidal stator currents Isabc [26].

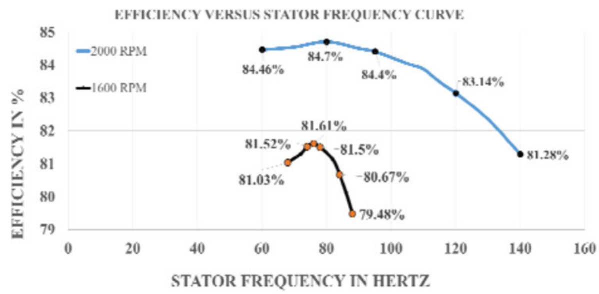

FIGURE 6. Maximizing efficiency of DFIG variable stator frequency control in DFIG with diode rectifier output [22].

a few other issues like voltage handling, encoder-less control of dc output voltage, self-excitation, dc paralleling, stator (not only slip) frequency variation, are to be solved before such a simplified decentralized solution is brought to the markets.

For vehicular or on-ground applications, standalone dc output variable speed DFIGs have been proposed since 2001 [23] and relaunched recently [24] due to the control simplicity, lower weight at acceptable efficiency and, finally, lower cost via a single dc-ac fractional (20%) kVA rating PWM converter, as shown in Fig. 4, for a speed range of 2.5/1 and a frequency range of 2/1.

A rich literature investigated recently the DFIG with dc output [23]–[27], especially its control to reduce torque pulsations and stator current harmonics in presence of a 6 pulse (diode) rectifier. The typical experimental results can be seen in Fig. 5.

When variable stator frequency control in DFIG with diode rectifier output is performed, it is possible to use it for maximizing the efficiency at different speeds. In general, the efficiency can be increased by 3-5% [22], as shown in Fig. 6.

As the power goes up or the environment is sensitive, the brush-slip rings transmission of power to the rotor in DFIG may become a problem. Especially when a higher primary frequency is feasible (f1>150 Hz), swapping the rotor with the stator and using a full power winding rotary f1 frequency transformer in DFIG will turn the latter brushless, with the fractional kVA rating PWM converter connected now to the stator, as shown in Fig. 7.

This novel solution may operate, with an output diode rectifier, as an avionics or marine ships or diesel locomotives or dc output brushless generators. The higher primary frequency will be, the more the transformer size will be reduced, while the inherent larger slip frequency in the PWM converter will reduce the thermal stress on the power switches etc. No test results on this solution are yet available. Finally, another fractional kVA rating PWM converter brushless DFIG is represented by the rather known (and revived recently) cascaded (twin stator and twin wound rotor) induction generator where only the second stator winding is PWM converter-fed [3], [29], [30], as shown in Fig. 8.

As the two stators are identical, it means that the second stator and its PWM converter kVA rating is about 50%, while the two wound twin rotors are connected to each other with different phase sequence such that though (pp = pc pole pairs) the synchronous speed is

$$n_s = (f_p + f_r)/2p_p \tag{1}$$

where the power-winding frequency is donated by f_p, and the rotor-winding frequency is represented by f_r.

It is again feasible to let f_p = constant (and also variable) if the ac output handles frequency insensitive loads or, respectively, if a dc diode rectified output is required. It is argued that the dual machine volume is larger and the efficiency is not

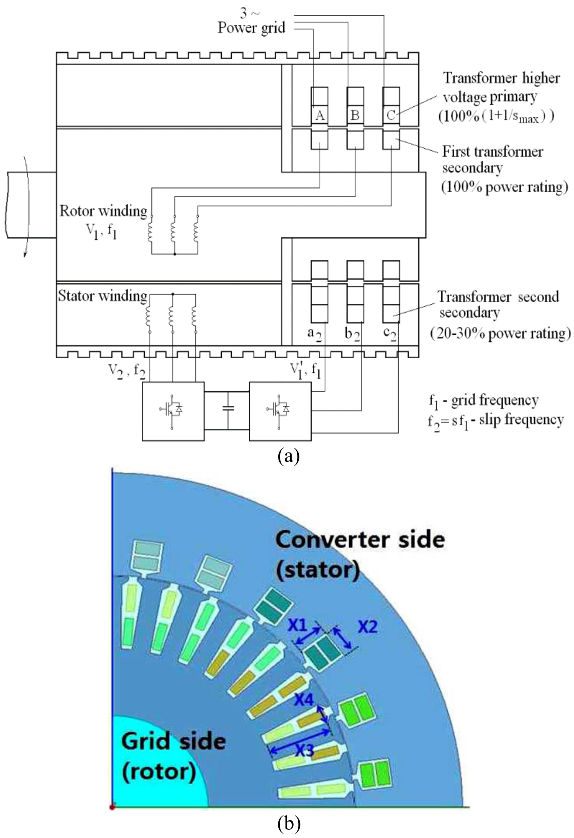

FIGURE 7. Brushless DFIG. (a) With rotary three windings full power transformer [1]. (b) Its cross-section [28].

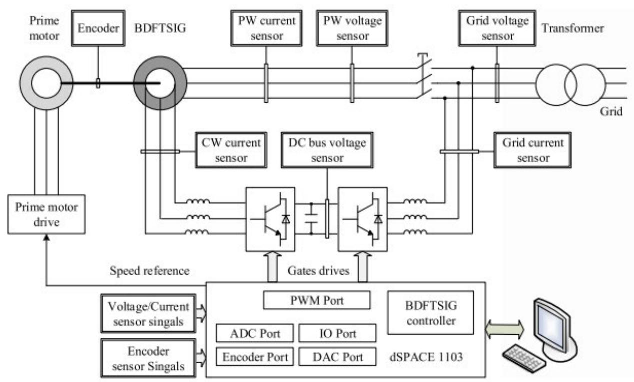

FIGURE 8. Brushless cascaded (twin dual stator, twin dual-rotor) induction generator system, after [3].

high, but the twin 50% kVA rotating machines with a common frame and shaft brushless topology might prevail. It should be kept in mind that the torque density in DFIG is fairly large, being based on fundamental field components interaction.

III. THE BDFI(R)G

The BDFI(R)G (recent progress in [31]) thoroughly investigated since previous years (in cascaded connections) [32] due to its brushless attribute, has two windings on stator (a main one with pp pole pairs and a control one with pc pole pairs). The rotor is provided with a nested cage pr = pp+pc poles [5], as shown in Fig. 9. Again, only the control winding

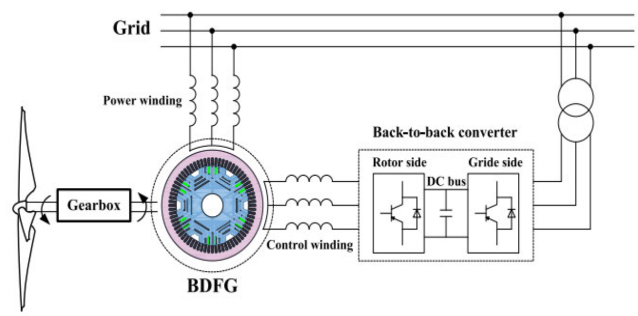

FIGURE 9. BDFI(R)G with dual stator winding (pp, pc poles pairs) and hybrid (nested cage+salient pole) rotor of pr = pp+ pc poles [5].

is fed at variable frequency fc from a fractional kVA rating PWM converter. The synchronous operation speed ns is

$$n_s = \left[f_p + f_{c(\text{variable})}\right] / \left(p_p + p_c\right) \quad (2)$$

The brushless attribute is reflected apparently by the fact that the coupling of the two windings (in BDFRG) through the rotor is produced by the first harmonic of air-gap-permeance leading to a maximum fundamental winding factor of around 0.5, which means, inevitably, low torque density. Also, the machine shows on both winding an additional (leakage) average air-gap-permeance – producing inductance which deteriorates notably the power factor in one or the other winding, but this is useful to limit current transients [31] in BDFRG (not so, apparently, for BDFIG [31]) during voltage sags. Also, for the nested cage rotor, the rotor losses are still larger.

The BDFRG (with flux-barrier rotor poles) shows lower rotor losses (better efficiency), but it may hardly produce good torque density. The combined nested cage + flux barrier poles rotor performed in the middle, in efficiency, between BDFIG and BDFRG.

With a 10 Nm/liter torque density at an outer stator diameter of 0.35 m, the BDFI(R)G has apparently a long way to go to become competitive with the DFIG in torque density (volume and weight). The most recent topologies of control methodologies for the BDFIGs in the standalone systems can be summarized, in depth case study, as follows.

A. ROTOR POSITION/SPEED OBSERVERS

A sensorless position/speed observer is very essential for a high-performance operation of the standalone BDFIG system to improve the control reliability of the applied direct voltage control (DVC) method and reduce the overall cost [33]–[37]. Many procedures for sensorless purpose have been presented in the literature which are based on either model or injection principles [4], [37]–[40].

A simplified approach for the rotor-position observer (RPO) of BDFIGs has been proposed and investigated in [39], [40] with a direct estimation principle without any PI controllers or integral components as shown in Fig. 10. Compared to the other sensorless methods, this proposed observer in [39], [40] can be considered better when compared to

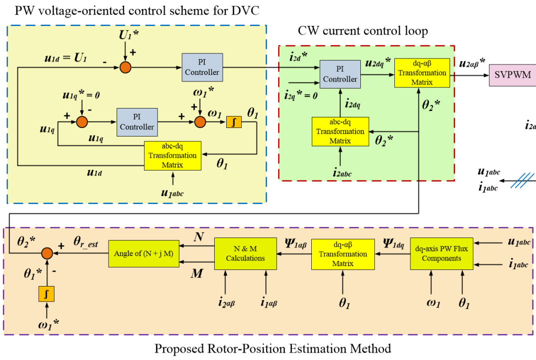

FIGURE 10. Main control structure for the rotor-position detection procedure [39], [40].

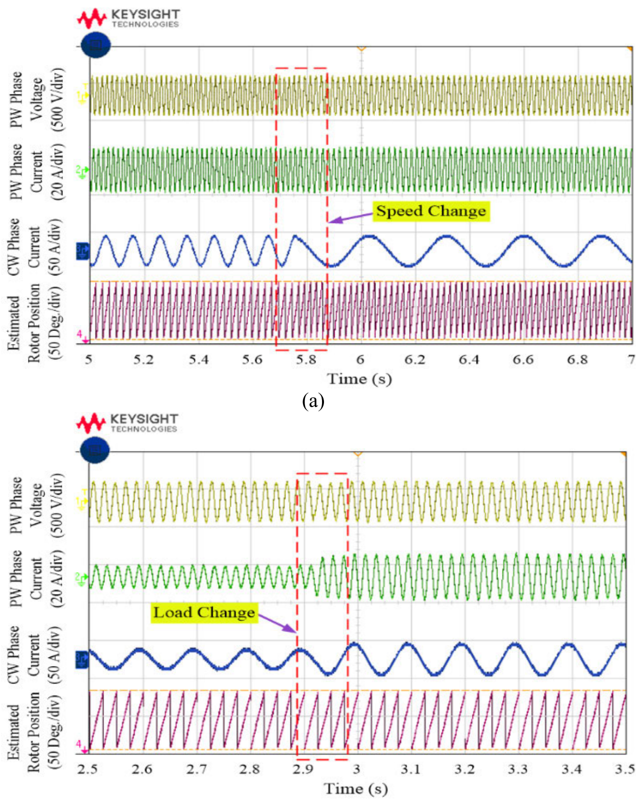

FIGURE 11. Analysis for the presented rotor-position observer in [40] for the standalone BDFIG. (a) Speed change condition (600-700 rpm). (b) Machine parameter variations (30% uncertainties).

the literatures [36]–[38] due to the following merits. The calculation complexity was the lowest and hence, a fast implementation in the DSP chip can be realized. Moreover, no PI controllers has been required in the RPO, and consequently, a better starting performance can be obtained. Furthermore, no integrators have been required in the RPO, which would significantly reduce the cumulative error of the estimated rotor position. Comprehensive results are obtained in [39] and [40] to verify the effectiveness of the DVC system for the stand-alone BDFIGs with the proposed RPO under speed variations, load changes, and parameter uncertainties as given in Fig. 11(a)-(b) which would assure its robustness and strong operation.

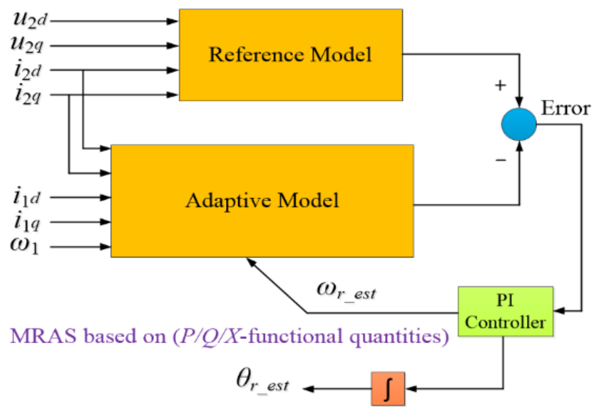

FIGURE 12. Design structure of the proposed P/Q/X-MRAS methods for the BDFIGs [42], [38].

On the other side, the sensorless control methods with the principle of model reference adaptive system (MRAS) have attracted a great attention from researchers in many literatures for its high-performance operation [38]. Different algorithms of MRAS methods have been introduced over the years based on the selected functional quantity [4], [41], [42]. Due to the constraints of calculations for the flux estimation, another improved track to develop the MRAS observer based on the active/reactive/fictitious power quantities ($P/Q/X$-MRAS), shown in Fig. 12, have been recently investigated for the standalone BDFIGs as in [42] and [38] respectively. The proposed methods have confirmed the control simplicity by reducing the required voltage sensors which would ensure the efficacy and superiority of the MRAS observer for the rotor position detection with a good tracking under various operating conditions.

B. IMPROVED ROTOR SPEED OBSERVER FOR STANDALONE BDFIG WITH UNBALANCED AND NONLINEAR LOADS

For the observer-based speed estimation, some literatures have handled this topology for both BDFIG [36], [37]. In [37], an improved rotor speed observer (RSO) has been discussed without analyzing the effect of the unbalanced and nonlinear loads and also the design of parameters has not been developed. In [33], the improved RSO has been studied under the impact of the unbalanced loads, but the effectiveness of the improved RSO under the operation of the nonlinear loads has not been discussed.

In [36], an improved rotor speed observer has been proposed with using both the second-order generalized integrators (SOGIs) and low-pass filters (LPFs) to eliminate the impact of unbalanced and nonlinear loads on the rotor speed observation by achieving the pre-filtering of PW voltage and CW current. In [37], the principles of the RSO have been studied with the main block diagram illustrated in Fig. 13(a), The improved RSO, shown in Fig. 13(b), has been analyzed and investigated under the operation of the unbalanced and nonlinear loads. In addition, the parameter tunning with a

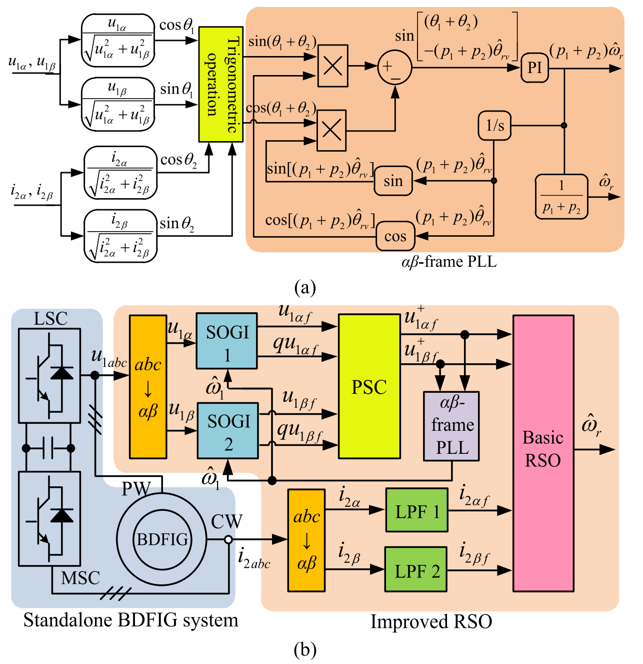

FIGURE 13. Structures of the rotor speed observers (RSO). (a) Structure of the basic RSO [37]. (b) Structure of the improved RSO [36].

complete guideline for the improved RSO has been verified to attain a better dynamic behavior under various operating conditions supported with comprehensive experimental results. The presented analysis in [36] has assured the efficacy of the proposed sensorless observer for the promising BDFIG.

C. UNBALANCED AND LOW-ORDER HARMONIC VOLTAGES REJECTION

The standalone mode is sensitive to abnormal working situations, especially under unbalanced and nonlinear loads which can cause significant unbalance and distortion for PW voltage and current. In PW voltage, the negative sequence component represents the effect of unbalanced loads, and the 3rd, 5th and 7th harmonic components indicate the effect of nonlinear loads. In [43] and [44], the negative sequence voltage compensator, low-order harmonic voltage compensator and the dual-resonant controller (DRC) are proposed to reduce the unbalanced and nonlinear load influences.

In [43], a new control strategy based on DRC has been proposed to minimize the unbalance and nonlinear effects of PW voltage as shown in Fig. 14(a) and confirmed by the experiments shown in Fig. 14(b)-(d). The design methodology of the DRC is easier and the computational burden can be decreased. In addition, the filters to extract the negative sequence or 5th and 7th harmonic components can be removed. Furthermore, the ability of working under unbalanced or nonlinear loads can be achieved.

IV. THE DUAL STATOR WINDING CAGE ROTOR INDUCTION GENERATOR (DSW-CRIG)

The DSW-CRIG with regular cage rotor and $p_p = p_c$ pole pairs in the two windings is inherently brushless and, (again),

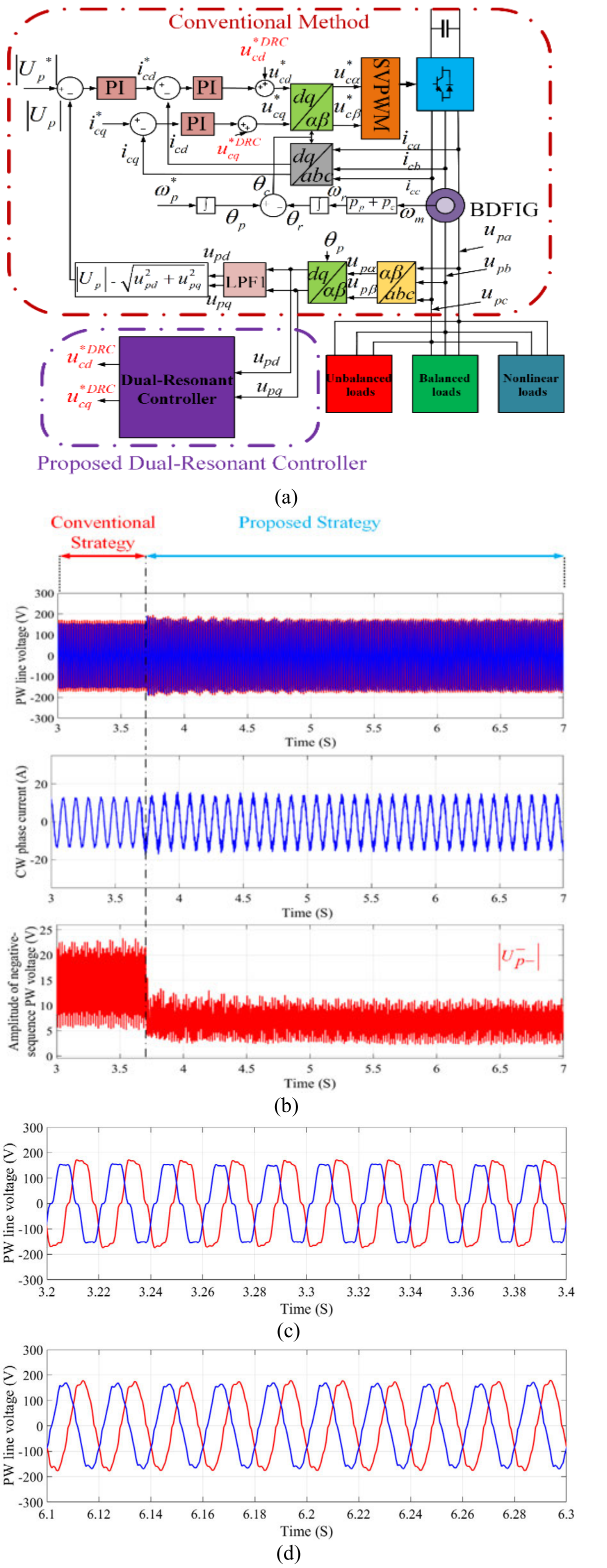

FIGURE 14. The control scheme and experimental results under unbalanced and nonlinear loads in [43]. (a) Overall control system. (b) PW voltage and CW current. (c) Expanded view of PW voltage before compensation. (d) Expanded view of PW voltage after compensation.

uses a fractional kVA rating PWM converter in the control stator winding [45]–[47]. It may be implemented in quite

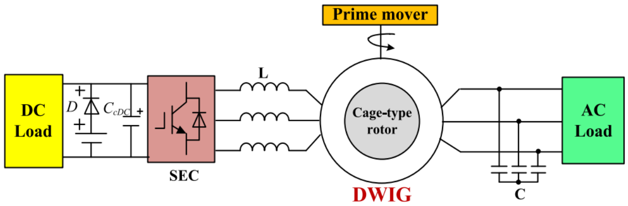

FIGURE 15. DSW-CRIG scheme with dc and ac output [45].

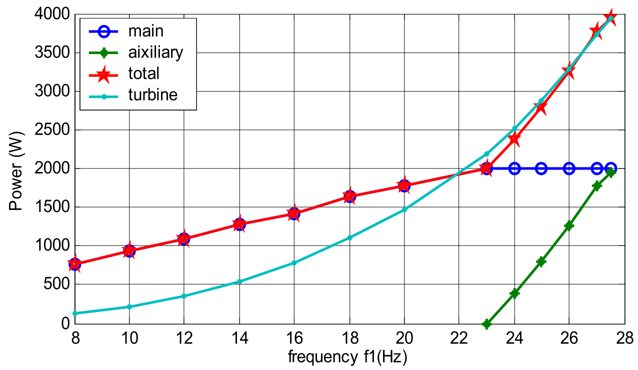

FIGURE 16. DSW-CRIG power contributions versus speed (after [47]).

a few topologies to provide eventually ac and dc output at constant (or even variable) main winding frequency [45]. A typical scheme for vehicular implementation is shown in Fig. 15 [45]–[47]. Total efficiency around 80-85% in the 10th of kW range has been demonstrated in a regular torque density rugged topology.

The cage rotor, flowed by single (slip) frequency currents, provides for reasonable efficiency, especially in wind (or similar power-speed envelope) applications, when the control winding, which is inverter-fed, operates alone at low speed (low power) and together with the main self-excited by capacitors power winding at higher speeds by proper design [47]. Fig. 16 presents the DSW-CRIG power contributions versus speed.

It seems rather strange that this rather practical solution did not meet more attention or/and already industrial use as vehicular or stand alone on ground generator, or in wind energy industry etc.

V. DUAL ROTOR DUAL STATOR-WINDING BRUSHLESS GENERATOR (DR-DSWBG)

The DR-DSWBG has been proposed very recently to increase the torque density and efficiency BDFI(R)G.

The stator seats two 3-phase ac stator windings with pp and p_c pole pairs, while it has inside an inner freewheeling IPM rotor with $p_m = p_p$ pole pairs and an outer segmented ferromagnetic active rotor of n_{FM} poles and inter-poles such that $p_c = n_{FM}$-p_p (Fig.17). The power winding (p_p pole pairs) interacts with the inner PM rotor ($p_m = p_p$) as a synchronous generator (obstructed a bit by the FM flux modulation rotor poles), while the control winding, fed from a fractional kVA rating PWM converter (with p_c pole pairs) interacts with the FM active (load) rotor as in a Vernier machine [48].

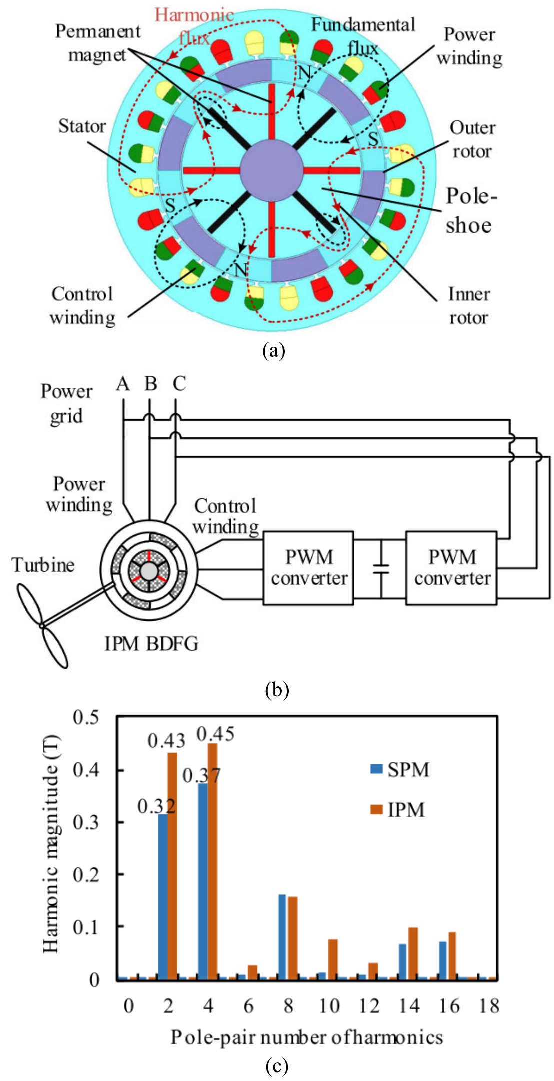

FIGURE 17. DR- DSWBG. (a) Cross-section. (b) General scheme. (c) No load air-gap flux density.

Again, the synchronous speed of outer (active) FM (lower speed) rotor n_{FM} is:

$$n_{FM} = (f_p + f_c)/(p_p + p_c) \quad (3)$$

A reported 20Nm/liter torque density at 0.21 m outer stator core diameter [48] means a 2/1 increase in torque density with respect to the BDFI(R)G at 0.35 m outer stator core diameter.

The PM inner rotor plays the role of dc excitation and runs at speed $n_{ir} = f_p/p_m$, which is large and eventually constant (if f_p = constant). Here, again, f_p may be controlled as variable to further increase efficiency at variable speed (as for DFIG) with diode rectified output. Experimental verification is still due to expose the performance characteristics as well as to develop adequate controls.

VI. DUAL ROTOR BIDIRECTIONAL FLUX-MODULATION PERMANENT MAGNET MACHINE (BFM-PMM)

In an effort to further reduce the PWM converters kVA rating, a dual rotor and dual stator windings in series BDFG

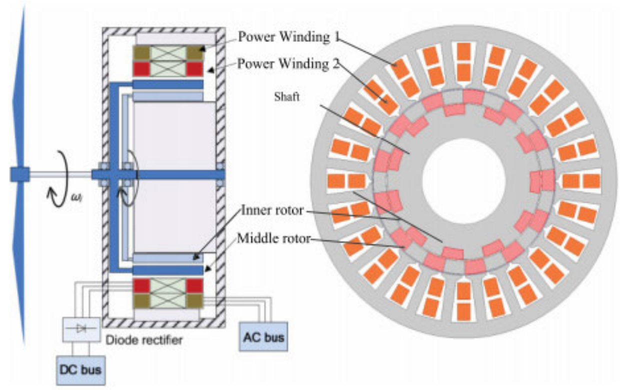

FIGURE 18. Basic configuration of the dual rotor and dual stator structure - BFM-PMM (after [49]).

with diode full power rectifier machine for stand-alone dc wind power generation was proposed in [49], as shown in Fig. 18. The key is to control the inner rotor position with a small servo motor, and with the bidirectional flux-modulation effect, the resultant induced voltages in two sets of stator windings connected in series (and diode rectifier) can be adjusted accordingly. Consequently, in a wide wind speed range, the variable-speed constant-amplitude-voltage operation is realized.

The novel structure has two major merits. First, it has high reliability without the maintenance problems caused by mechanical gearboxes, slip ring assembly, and brushes. Second, the proposed system requires for dc controlled output, only a low-cost uncontrolled diode rectifier, which enhances the reliability and reduces the cost of the system.

The analytical model and operation principle of the BFM-PMM machine are illustrated and the simulation results using a finite-element method are presented [49]. A prototype is optimized and fabricated. The experimental results agree well with the simulation results and verify the correctness of the analytical model and the effectiveness of the proposed structure. Therefore, the novel structure offers a potential solution to provide a stable dc power for standalone conditions, such as remote area or offshore applications. However, both flux modulation consequent pole PM rotors which provide good torque density are rather costly. Also, the inner PM rotor which operates at standstill has its position change and latch controlled, to provide control for the system, by a PWM converter-fed servomotor (with high gear ratio).

The number of pole pairs (for example) of winding 1: $p_{w1} = 2$, winding 2: $p_{w2} = 13$ (both windings have concentrated coils), stator slots $N_s = 24$, inner (PM rotor controlled at standstill) $p_{ri} = 11$, outer (load PM rotor) $p_{ro} = 13$ [49]. A combination of PM synchronous generator/motor operation ($p_{ro} = p_{w2}$) and a bidirectional flux modulation operation takes place also as $p_{w1} = 2 = p_{ro} - p_{ri} = 13\text{-}11$. With inner PM rotor axis angle $\gamma < 90°$ (electrical) at low load rotor speed (p_{ro} pole pairs), both windings generate electric power, while for $\gamma > 90°$ a kind of flux weakening takes place with winding 1 operating as a motor [49].

VII. DISCUSSION

Variable speed generator systems (VSGs) are used extensively with wind turbines, or vehicles (avionics, marine ships etc.) and in stand-alone ground applications to tap more energy, increase efficiency and produce feasible control under healthy and faulty conditions all at affordable initial (USD/kW) and energy costs (USD/kWh).

- Full kVA rating PWM converter (connected to stator) generators refer to PMSG, EESG and CRIG; while providing comprehensive active and reactive power control, they are rather expensive and complex.
- Fractional kVA rating PWM converter (30-35%) VSGs, DFGs, are less expensive and proved, in DFIG implementation, worthy of more than 50% of all installed wind power. Variable stator frequency control of DFIG may further reduce the power converter kVA rating. Besides, ever more robust and reliable control for stability and power quality challenges such an operation under deep voltage sags, reduction of high frequency resonance oscillations. Less expensive more performant interfacings of DFIG wind power

to M(H)Vac or dc power transmission lines, with better optimal Multiphysics design, are steel needed
- DC output DFIGs have been explored heavily for vehicular applications, mainly to eliminate the brush-slip-ring system that transfers the slip power to the rotor winding of DFIG. There is a proposal to swap the rotor with stator and use a full power rating rotary 3 windings transformer at larger primary f_p frequency, (f_p >150 Hz), to reduce the size of later.
- Also, to eliminate brushes, the DFI(R)G has been introduced many decades ago; it is still marred by inherent low torque density and low power factor of the two stator windings which leads to a higher kVA rating of power converter and less efficiency.
- Another brushless dual stator windings ($p_p = p_c$) cage rotor IG (DSW-CRIG), again with partial kVA rating PWM converter feeding the control winding, has recently been investigated thoroughly in the last decade with outstanding results (including good torque density and acceptable efficiency at variable speed).
- A very recent newcomer – the dual rotor (DR-IPM-BDFG) has been proved in theory, so far, capable of doubling the torque density of BDFI(R)G at the price of a more complicated topology, but at reasonable cost for a brushless configuration. The inner PM rotor with small PM pole pair rotates freely at high speed $n_{ir} = f_p/p_m$.
- Design and performance of BDFIG for different rotors (with nested cage and (or) flux barrier) has been scrutinized again recently, with 3-6% more efficiency and 10-15% more power factor and same geometry [5].
- Advanced stable for entire speed range control winding current control in BDFIG has been developed recently [50]. Encoder based control of cascaded BDFIG for asymmetric load was illustrated in [29].
- Novel encoder-less control of BDFIG connected to the grid [4] and standalone (with unbalanced load and nonlinear load) [43], [44] showed notable progress in performance.

TABLE 3. Performance qualitative characterization.

Attribute	DFIG	BDFIG brushless	BDFRG brushless	DSW-CRIG brushless	DR-DSWBG brushless	BFM-PMM brushless
Torque density	High	Low-Medium	Medium	High	Medium-High	Medium-High
Efficiency	High	Medium	Medium +	Medium	Medium-High	Medium-High
Fabrication complexity	High	Medium	Medium -	Medium - -	High	High
Initial system cost	High	Medium	Medium	Medium - -	Medium-High (PMs)	Medium
Fractional kVA converter ratings for +- 30% speed range	30% (50% with cascaded brushless configuration)	30%	30%	30%-50%	30%	Only a full power diode rectifier (with the two stator windings in series)
Suggested power range	Wide	Small to medium	Small to medium	Wide	Small to medium	Small to medium
Reactive power control range	Limited	Very limited	Very limited	Limited	Limited	Limited

• A dual rotor and dual stator windings in series BDFG with diode full power rectifier for machine [49] for stand-alone dc wind power generation was proposed [49].

• References [4], [5], [29], [33], [49], and [50] illustrate the formidable opportunities of progress in fractional kVA rating PWM converter variable speed generators in energy conversion for power systems or for ground or vehicular applications at lower cost but better performance. Better, widely accepted, optimal system designs, considering the cost/kW, cost per kWh (including maintenance), are still needed to discriminate between technical solutions of only academic and those of practical industrial interest.

Table 3 shows a qualitative comparison of various configurations investigated in the paper which all have notable industrial potential though the section should be tied to application.

VIII. CONCLUSION

The present paper summarized recent progress in fractional kVA rating PWM convertor doubly fed variable speed generators in a myriad of brush and brushless topologies, emphasizing their characteristics and performances and suggesting DC output diode rectifier control with both power and control winding at variable frequency, for better efficiency, increased energy yield at low speed and/or wide power-speed envelope.

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