Permanent magnet synchronous generators for regenerative energy conversion – a survey

Andreas Binder, Tobias Schneider
DARMSTADT UNIVERSITY OF TECHNOLOGY
Landgraf-Georg-Strasse 4, D-64283
Darmstadt, Germany
Tel.: +49 / (0) 6151– 16 - 2167
Fax: +49 / (0) 6151– 16 - 6033
E-Mail: abinder@ew.tu-darmstadt.de
URL: http://www.ew.e-technik.tu-darmstadt.de/ew.html

Acknowledgements

The authors acknowledge the support of the following companies for supply of valuable data concerning permanent magnet generators: *VATech, Austria; Siemens AG, Germany; Innowind, Germany; Leitner, Italy; ABB, Sweden.*

Keywords

«Non-standard electrical machine», «Permanent magnet motor», «Renewable energy system», «Windgenerator systems», «Generation of electrical energy»

Abstract

A survey on recently installed or developed permanent magnet (PM) synchronous generators for energy conversion in regenerative and alternative power supply systems is given. Its focus is for low speed machines on geared and gearless PM generator systems for wind power plants and small PM hydro generators in gearless coupling. For distributed co-generation of heat and electrical power by micro gas turbines specially designed PM generators for high speed are necessary. Design example for both low speed wind and hydro generators and high speed generators are given along with application examples.

Introduction

Modern permanent magnet synchronous generator technology offers high efficiency power conversion from mechanical into electrical power. Moreover, it allows for special machine design with very low speed e.g. in gearless wind and hydro application and at very high speed for micro-gas turbines, which is of interest for several regenerative or co-generative power conversion technologies. A survey of already realized prototypes or in use PM generator systems is presented for that purpose.

Wind mill power plants

Design rules for PM low speed gearless wind generators

Wind turbines need due to low operational speed of the turbine itself (typically 10 ... 20/min at rated power of 1.5 ... 5 MW) a low speed **gearless** generator, or a **geared** generator solution at elevated speed, typically 1000/min to 1500/min. Especially for future off-shore applications the geared doubly fed slip ring induction generators will need maintenance due to brush service and due to gear maintenance. Both can be evaded, if directly coupled generators are used. This needs a

- big rotor diameter for the big wind turbine torque and
- a high pole count to get suitable frequency at low speed.

Asynchronous high pole count generators have a low magnetizing reactance, so the power factor is very poor. The magnetising current I_m is proportional to the inverse of phase inductance $L_s = L_{s\sigma} + L_h$, which is dominated by magnetizing inductance $L_h \sim l_{Fe} \cdot \tau_p/\delta$, yielding $I_m \sim U/(2\pi L_s) \sim \delta/\tau_p$ (Fig.1a). At high pole count $2p$ the pole pitch $\tau_p = d_{si}\pi/(2p)$ is rather small, so along with the mechanically necessary minimum air gap δ we get a too small ratio of τ_p/δ and so too big magnetizing current, when compared with a low pole count induction machine. In Table I for a 750 kW windmill application with turbine speed 28/min, the calculated magnetization current for a high pole count gearless induction machine A of 96 poles, operated via an inverter, is compared with a standard cage induction generator B, operating directly at the grid. This one of course needs a gear with ratio 1:50 for that operation. The big amount of magnetizing current explains, why induction generators for direct drive, hence gearless windmill application are not in use.

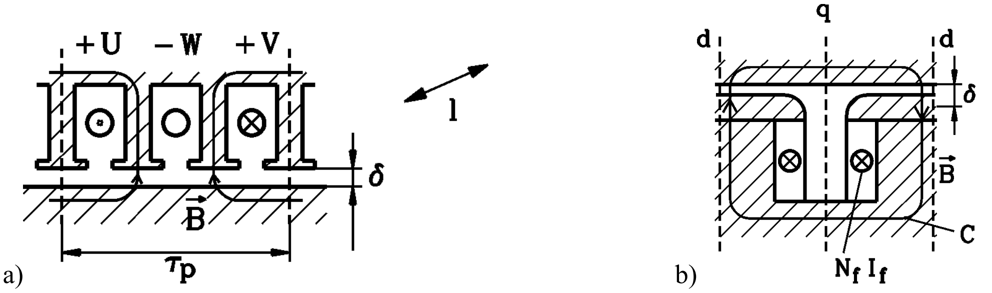

Fig. 1: Basic geometry of high pole count electric AC machines: Air gap field of a) induction machine and b) electrically excited synchronous machine,

Table I: Comparison of design properties of low and high pole count induction machine

Type	P	n	f_s	**$2p$**	d_{si}	τ_p	δ	δ / d	τ_p / δ	l_{Fe}	$\cos\varphi$	**I_m/I_N**
	kW	1/min	Hz	-	m	mm	mm	%	-	M	-	-
A	750	28	22.4	**96**	5	164	5	0.1	32.8	0.35	0.6	**0.8**
B	640	1514	50	**4**	0.45	353	2	0.4	176.5	0.66	0.91	**0.27**

So for low speed operation, **high pole count synchronous generators** are recommended. With electrical excitation also over-excitation is easily possible, so operation at $\cos\varphi = 1$ is utilized to reduce machine side inverter rating to the real power value. This is the generator system of *Enercon* company in *Aurich, Germany*. On the other hand field ampere-turns increase with high pole count, which explains the need to utilize permanent magnets. Taking admissible current loading A and air gap flux density B_δ of the machine, the main dimensions of bore diameter d_{si} and axial stack length l_{Fe} are determined by torque M, which at low speed is high: $M \sim A \cdot B_\delta d_{si}^{2} \cdot l_{Fe}$. As winding temperature rise $\Delta\vartheta$ at low speed is mainly determined by copper losses, and may be expressed with current loading A and winding current density J as $\Delta\vartheta \sim A \cdot J$, for a given torque the flux density in air gap B_δ is fixed. According to *Ampere's* law – neglecting iron m.m.f. – we get for closed loop C (Fig 1.b) $B_\delta = \mu_0 N_f I_f / \delta$. This result is independent of pole count $2p$. So exciting ampere-turns $N_f I_f = \Theta_f$ per pole - with N_f as number of turns of field winding per pole and I_f as DC excitation current - yield an increase of excitation losses $P_f = 2pP_{f,Pol} \sim 2p \cdot \Theta_f^2$ proportional with $2p$. Thus **permanent magnet excitation** yield due to elimination of these losses an increase in efficiency and reduce thermal problems on the rotor side. The design of the permanent magnet circuit has to take into account the demagnetization limit, which may be reached by too big stator current loading (overload condition), which causes opposing stator field on rotor trailing magnet edge. Using *Ampere's* law (Fig. 2a) $H_M \cdot h_M + H_\delta \delta - A \cdot x = 0$, with $B_\delta = B_M$ and $B_M = \mu_0({}_B H_C + H_M)$ according to the linear magnet characteristic in the second quadrant (Fig. 2b), we end up with

$$H_\delta(x) = ({}_{\mathrm{B}}H_C \cdot h_M + A \cdot x)/(h_M + \delta) \quad . \qquad (1)$$

Assuming, that irreversible demagnetization will occur, if H_δ surpasses coercive field ${}_BH_C$, we get the condition for magnet design at hot magnets $H_\delta(x=\tau_p/2) > 0$: ${}_BH_C\cdot h_M > A\cdot\tau_p/2$! So we get the condition ${}_BH_C\cdot h_M > A\cdot d\pi/(4p)$, showing that with increased pole count due to lower flux per pole the danger of demagnetization decreases; hence smaller magnets and thus reduced costs are possible for high pole count machines. Further no brushes and slip rings are necessary, reducing maintenance costs especially for off-shore wind platforms.

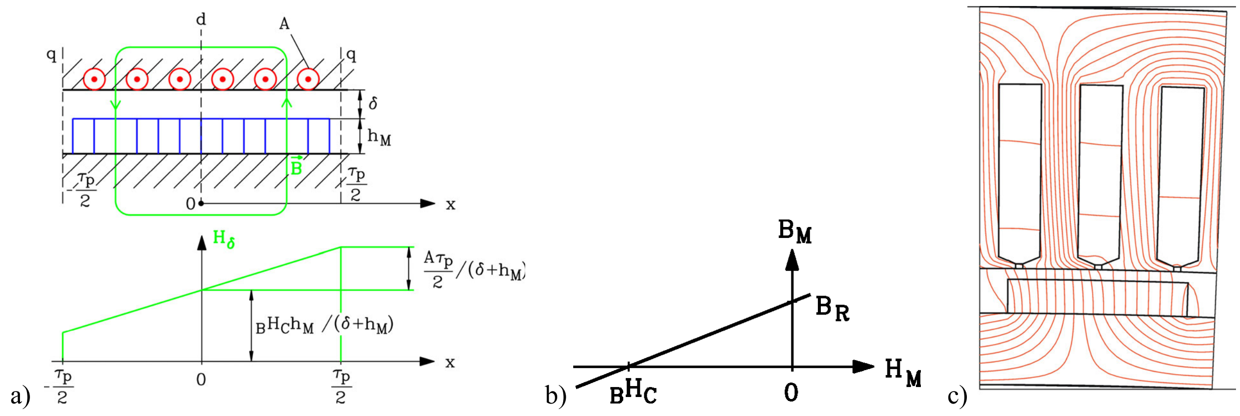

Fig. 2: a) Air gap field of surface mounted PM machine under load, b) PM material magnetization characteristic, c) Calculated magnetic flux pattern at full load of a gearless PM wind generator 1.5MW, 1320 A, 690 V, $\cos\varphi = 0.85$, surface mounted NdFeB magnets

The question arises, if at low speed for given torque M and current I according to $M \sim A\cdot B_\delta d_{si}^{2}\cdot l_{Fe} \sim p\cdot\Phi\cdot I$ = "Flux *x* Current" the dominant I^2R-losses will lead to rather low generator efficiency $\eta = P_{out}/P_{in} \approx 2\pi nM / (2\pi nM+3RI^2)$. Here the elimination of excitation and gear losses show, that in comparison with geared induction generator systems the gearless PM generator solution has comparable results.

Example: (measured values, furnished by *Siemens Company*)
(a) Geared fixed-speed induction generator directly at the grid: 640 kW, $2p = 4$, 1514/min: $\eta_{Gen} = 96.6\%$
two stage gear transfer ratio $i = 50$: $\eta_{Gear} = 97.0\%$ $\Rightarrow$ Full load: $\eta = \eta_{Gen}\,\eta_{Gear} = 93.7\%$
(b) Gearless variable speed PM generator with inverter: 750 kW: $\eta_{Gen} = 95.3$ %, inverter: $\eta_{Inv} = 97.6$ %,
$\Rightarrow$ Full load: $\eta = \eta_{Gen}\,\eta_{Inv} = 93.0\%$

At **partial load** – which is a main operating range of wind mills with so-called "average full load operation hours per year" of typically 1500 ... 1800 h/a onshore, the comparison exhibits even better performance of PM generator due to the lack of excitation and due to variable speed operation.

Design of PM synchronous generators can be optimized by utilizing $M \sim A\cdot B_\delta d_{si}^{2}\cdot l_{Fe}$, having either rather low magnet mass (low B_δ, but of course with obeying demagnetization limit) and big current loading A, or big B_δ and low A. First solution gives a cheap generator, as magnet costs still are a decisive factor in overall generator cost, but a lower efficiency due to higher copper losses, whereas in second case higher costs are combined with increased efficiency. Optimization studies, combining machine design rules with *Pareto*-method for optimization, showed for 1.5 MW gearless PM generator with $2p = 160$ and 5.3 m outer diameter a full load generator efficiency variation 93.7% ... 96.4% for *Pareto*-optimal designs [5] (Fig. 2c). According to these design rules, typical data of low speed PM wind generator are **for example:**

3 MW, 610 V, 3300 A, frequency 13.6 Hz, $\cos\varphi = 0.85$ under-excited, 17/min, calculated efficiency 95.5%, rated torque : 1685 kNm (!), outer diameter of the generator: ca. 5.8 m, overall axial length: ca. 2.3 m. Total generator mass of such a big PM synchronous generator is about 85 t at a high pole count of

typically 90 ... 100 poles. Electric energy has to be transformed to grid frequency 50 Hz via an IGBT low voltage inverters, which have an efficiency of typically 97%. At bigger power up to 5 MW medium voltage inverters are recommended, otherwise inverter losses would be too high. As wind power increases with cube of speed, no field weakening is necessary, so no problems exist in case of inverter failure with voltage overshoot at high speed.

Recently installed wind mills with PM low speed gearless wind generators

Thus, high pole count PM synchronous machines offer many advantages, and are fit for the demands, which modern generators systems require at power of 2 ... 5 MW per unit, i.e. a variable speed generator system for pitch controlled wind turbines to operate at optimum wind turbine speed to maximize efficiency. As PM generator systems are connected to the grid via inverter, fulfilment of the grid demands, published in *Germany* e.g. by *E.on* [1], is accomplished by these inverters. At the moment, PM generator systems are realized in on-shore applications up to power of 3 MW. Examples are the *MTorres* generators in *Spain*, the *Leitner* generators in *South-Tyrol, Italy*, the *Siemens* generators in *Scanwind* design, *Norway* (Fig.3), *Lagerwey* generators, (but this company is no longer active) and generators of *Innowind, Saarbruecken, Germany*. All these generator rotors are designed with surface mounted permanent magnets with distributed stator 3 phase winding, either with inner or outer rotor design. The high pole count leads to small yoke height (Fig. 2b) and lower active masses, which lead to ring shaped generators. If these generators are integrated into a turbine construction with a common turbine and generator main bearing, the inactive mass may be minimized. A good survey on the different geometrical properties of low speed PM generators for wind mill is given in [6]. Most of the PM generators are of inner rotor design. *Innowind* has decided for an outer rotor/inner stator design to increase bore diameter d_{si} for torque production at given constant outer diameter. A total nacelle and wind rotor mass of 81 t, including generator&bearing mass 39 t, was achieved for 1.2 MW output power (Fig. 4). On the generator side, a diode rectifier and a step up converter is used, whereas on the grid side an IGBT-inverter with PWM operates at 50 Hz / 690 V.

Table II: Main data of some pitch controlled wind power systems with gearless PN synchronous generators and inverters

Power	Wind rotor diameter	Hub height	Rotational speed	Company	Max. blade tip speed
P	D_R	h_R	n_R	-	v_{Rmax}
MW	m	m	1/min	-	km/h
1.35	77	65	6 ... 18	*Leitner*	261
1.2	62	69	≤ 21	*Innowind*	245
3.0	90	83	10...20	*Scan Wind*	339

Whereas the *Innowind* uses profiled copper two layer stator winding, the *Leitner* PM generator outer stator is equipped with the cheaper round wire coils. Both generators are cooled by natural air cooling. The total nacelle and wind rotor mass of 79 t of the *Leitner* wind mill comprises 5.5 t for each of the three rotor blades, 13.6 t for the shaft, bearing and hub, 32.5 t for the generator and 16.3 t for the supporting construction. Hence the generator accounts for about 40% of rotor and nacelle mass, which is given due to the large generator diameter of these direct drive systems. Compared to that, gear and induction generator of comparable power, but elevated speed 1200 ... 1800/min have only 21 t. Nevertheless total mass of nacelle and rotor due to clever construction of nacelle are quoted to be about the same (Table III).

Alternatively *Pfleiderer* announced PM synchronous generators at about 400/min, which are operated by a 2 stage gear, transforming speed from about 15/min to 400/min. The advantages are smaller generator dimensions, as torque is reduced by the gear ratio, which is proportional to the square of machine diameter. This *multi brid* system shall also allow for reduced masses, as the reduced mass of the generator outweighs the additional mass of the gear. Nevertheless, gear maintenance has to be taken into account, which for off-shore application is now intensively under discussion.

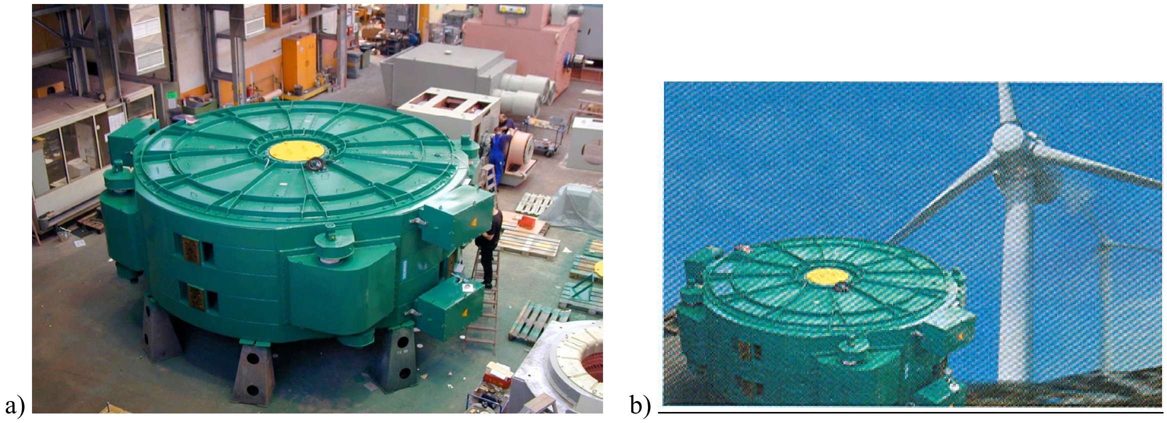

Fig. 3: The 3 MW gearless PM wind generator for on-shore wind mill, *Scanwind, Norway,* built by *Siemens AG, Germany,* a) during final test in shop *Dynamowerk, Berlin,* and b) in front of the completed turbine set

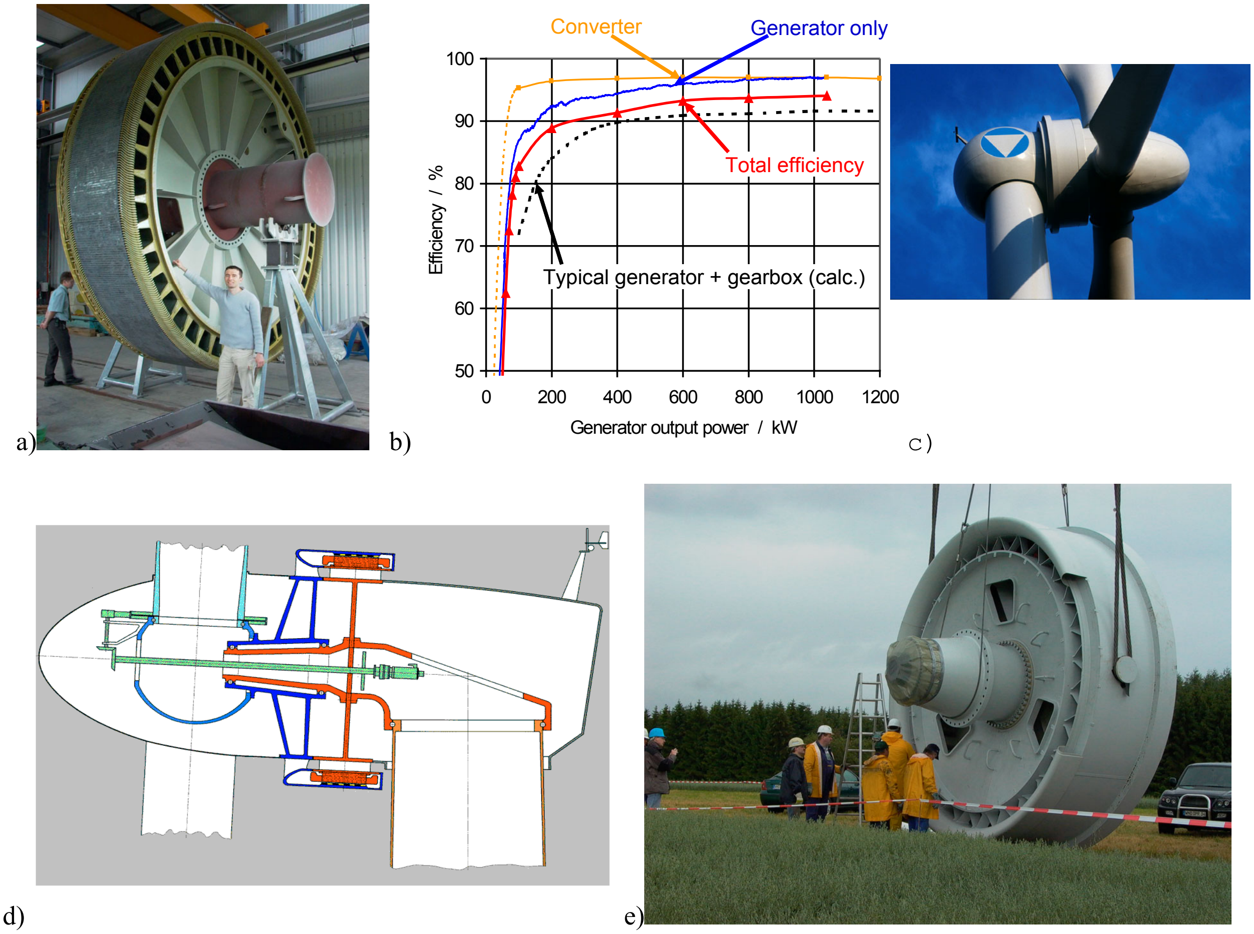

Fig. 4: A 1.2 MW gearless PM wind generator with (a) inner stator design, (b) measured efficiency of PM generator and inverter, (c) generator mounted directly behind the wind turbine, (d) being well integrated on hollow turbine shaft, (e) before mounting. Manufactured by *Innowind, Saarbruecken, Germany.*

Table III: Comparison of masses of geared induction generator systems and gearless PM synchronous generator systems for variable speed wind mill application

Power / Company	3-blade wind rotor / hub	Generator system	Nacelle + wind rotor
1.5 MW *Suedwind*	D_R = 77 m, 5.6 t / blade, hub: 17.2 t	Gear i = 104: 14 t (300 l Oil) Generator: 7 t	84 t
1.35 MW *Leitner*	D_R = 77 m, 5.5 t / blade, hub: 13.6 t	Generator: 32.5 t	78.9 t

Small hydro PM generators

"Small hydro power plants" with power range of typically several hundreds of kW up to 5 MW in smaller rivers are often operated with geared induction generators. PM synchronous generator with variable speed to optimize turbine power at varying water flow allow gearless drive like in wind turbine application, but need an inverter, which gives a rather costly solution [2]. Therefore fixed speed turbine and generator systems are preferred. For large hydro generators in rivers with power range from several MW up to about 30 MW per unit, being directly coupled e.g. to *Kaplan* type turbine, electrical excitation allows for adjusting power factor and voltage amplitude, whereas turbine speed control via pitching of runner and guiding blades allows maximization of efficiency at variable water flow at fixed speed.
Recently, it was proposed to use the rest water flowing over river dams for electric power generation by inserting numerous small *Kaplan* turbines with fixed blades as so-called **propeller turbines** into the barrage. Small turbines of 100 ... 500 kW are short in axial length and can be inserted easily into the barrage. This matrix-like arrangement explains the name **"Matrix turbines".** These turbines are rotating at about 300 .. 500/min with constant speed and directly coupled generators, which are operating directly at the grid via a step-up transformer. In case of use of directly coupled induction generators, which has been done e.g. at river *Danube* at *Freudenau* power station*, Vienna, Austria*, or at the *Nile* river barrage of *Jebel Aulia*, *Sudan* (Fig.5a), the amount of inductive reactive power for magnetiziation is too big (Table I) and is therefore often compensated with capacitor banks in parallel.

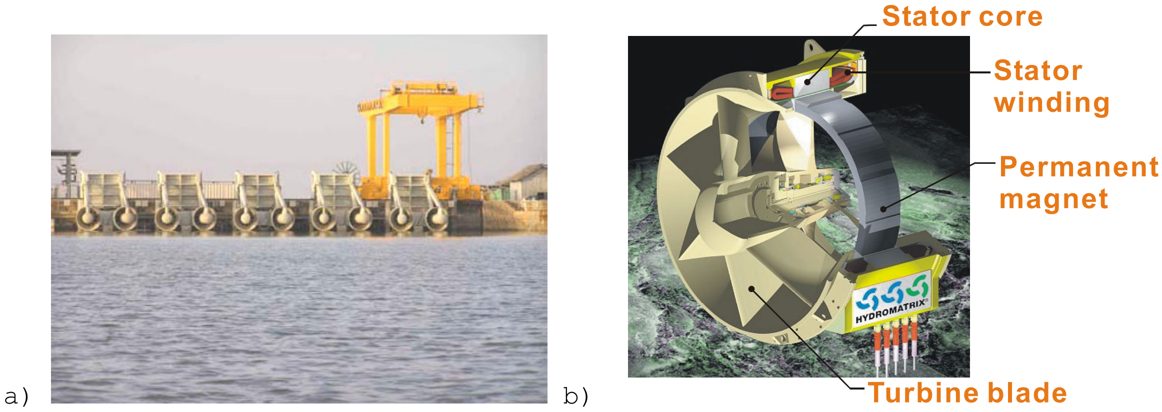

Fig 5: a) Matrix turbine arrangement at *Nile* barrage at *Jebel Aulia, Sudan*, with electrically compensated bulb-type induction generators, b) Alternative concept with straight-flow turbine and ring PM generator *(VA Tech, Hydro, Austria)*

An alternative design with PM generators, also operating directly at the grid, has been presented recently [3]. It showed that - due to the lower losses - a smaller machine with increased efficiency is possible, although due to grid operation, the rotor must contain not only the permanent magnets, but also a damper cage to damp speed oscillations at load steps quickly. With sufficient height of magnets an operation at unity power factor at full load is possible, so no capacitive compensation is needed in that case. The PM machine was designed for the same outer diameter and active length of the induction generator. Due to the big magnetization current the induction machine is loaded thermally in addition to load current losses, giving for the same temperature rise in winding a lower electrical output power at continuous duty by – 26%. The PM machine damper cage is much smaller than the induction machine rotor cage, so – along with the rather small magnet dimensions – rotor mass could be reduced, yielding a reduction of active mass by 15%. The total losses could be reduced likewise due to the lack of magnetizing current, yielding higher full load and partial load efficiency, resulting in a 2% higher energy production per annum, when averaged over the variable water flow during one "standard year".

Table IV: Small bulb type hydro induction and PM synchronous generator for matrix turbine, 690 V, Y, 50 Hz, 16 poles, synchronous speed: 375/min [3]

	Induction generator	PM synchronous generator
Rated power	360 kW	490 kW (+ 36%)
Rated current	430 A	420 A
cos φ	0.70	0.98
Efficiency 100% load	94.8 %	95.8 %
Efficiency 55 % load	94.0 %	96.9 %
Active mass	100 %	85 %

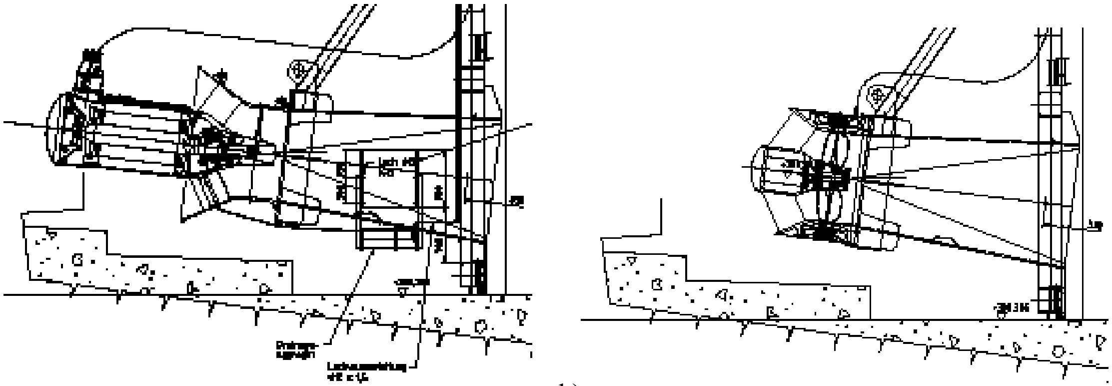
a) b)

Fig. 6: Comparison of a) bulb type induction and b) ring type PM synchronous hydro generator at *Agonitz* power plant, *Austria*. The ring type straight flow generator StrafloMatrix^{TM} (300 kW) reduces axial length by 50%, mass by 33%, as compared with bulb type machine (360 kW, *Jebel Aulia* Prototype)

From Fig. 5a it can be seen, that the generators are positioned at the flow inlet in torpedo-like bulb, like big bulb-type generators, being cooled by the water flow. A further improvement is possible, if the **straight flow turbine** concept is realized (Fig. 5b). The turbine rotor bears at its outer rim the sealed permanent magnets and the damper cylinder. The high pole count ring-like stator is arranged at the turbine runner outer circumference, thus being out of the main water flow cross section, being sealed by a non-conductive tube. No disturbance of water flow is given. The machine is operated at unity power factor by appropriate design of the permanent magnets. Similar to the data of Table IV such a ring type PM generator has been installed and is operating for already 2 years in the small hydro power plant at the river *Steyr* in *Agonitz/Austria*. The damper consists of a copper cylinder of 3 mm thickness, which is mounted on the surface mounted magnets, and is itself fixed by a non-magnetic steel cylinder of 2 mm. The mechanical air gap is in reality a "water gap" of 2 mm, as the rotor is running completely in water. The stator is sealed by a glass fibre reinforced cylinder of 3.5mm thickness, so that the magnetically active air gap is in total 10.5 mm, which is increased by the slot openings by further 0.7 mm. So a magnet height of

15 mm is necessary for sufficient air gap field, resulting at a pole coverage ratio of 85% in a total magnet mass of 72kg. Rare earth NdFeB magnets with 1.28 T remanence at 50°C are used.
The open slots of the high voltage winding cause a considerable ripple of magnetic air gap field, that induces eddy current in the damper cylinder. The rotor surface due to these additional no-load losses of 3.7 kW is cooled perfectly by the water flow. Due to the damper the sudden short circuit current amplitude of 390 A (= 7.4-times rated current) is considerably higher than it is the case of PM machines for wind mills, which are operated without damper at an inverter. But the eddy currents in the damper cylinder under short circuit conditions are shielding the magnets arranged below perfectly, so no demagnetization risk occurs.
Due to the high voltage winding the cable cross sections are reduced considerably, but the winding overhang in the stator winding increases, hence also increasing the stator copper losses. Therefore the full load efficiency is lower than of the PM machine of Table IV. But the overall length and the mass of the turbine-generator set are strongly reduced, as the comparison of the direct coupled bulb type concept and of the straight flow ring generator concept show (Fig. 6).

Table V: Straight flow turbine PM synchronous hydro ring generator for matrix turbine, 3 kV, Y, 50 Hz, 24 poles, synchronous speed: 250/min, over-speed: 560/min

	PM synchronous hydro generator
Rated power	300 kW
Rated current	52.5 A
cos φ	1.0
Efficiency 100% load	95.0 %

High speed PM generator systems for power conversion in co-generation

Co-generation of heat and electricity raises the thermal efficiency of thermal power plants from about 33% electric efficiency to about 70% thermal efficiency. So the idea exists, to integrate a “micro gas turbine” into a gas heating of bigger buildings to use the hot exhaust gas also for electric power generation. Power demand for that purpose ranges up to several hundreds of kW. Small gas turbines of 50 ... 300 kW consist of a one stage air compressor and a one stage turbine wheel (Fig. 7a). Due to its small wheel diameter and the high velocity of exhaust gases, it has to rotate at rather high speed of 30 000 ... 50 000/min. Gearless high speed PM synchronous generators have been developed for that purpose, which need a grid-side inverter to transform the high generator frequency of typically 1500 ... 2500 Hz down to 50 Hz grid frequency. Mainly 2- and 4-pole generators are used to get a small rotor diameter, which allows operation at that high speed without surpassing the circumference velocity of 200 ... 250 m/s. This is a mechanical stress limit for the with carbon fibre bandage usually fixed surface mounted magnets. Buried magnets in rotor iron sheet do not allow to operate at that high speed, as the stress limit of steel sheets is lower than for carbon fibre [10]. As power increases with cube of speed, no field weakening is necessary, so no problems exist in case of inverter failure with voltage overshoot at high speed. Fig. 7b shows a water-jacket cooled stator and the PM rotor with carbon fibre bandage and magnetic bearings, designed at our department [8], for 40 kW, 40000/min. The rather high air friction losses cause an additional heating up of the rotor and a decrease in overall efficiency. Nevertheless due to the high speed the output power per active rotor mass is 8.9 kW/kg, which is a very high power density.

As a commercial product, several manufacturers offer the complete generator-turbine set with burning stage and heat exchanger for heat co-generation. In Fig. 8 a four-pole PM synchronous generator with resin cast stator winding for better heat transfer is shown. The rotor is excited with surface mounted magnets and armed with carbon fibre sleeve for 70000/min, thus needing a stator frequency of 2300 Hz. This high stator fundamental frequency demands a special design of stator winding for reduction of eddy current losses in the conductors.

Table VI: Main data of high speed PM drive system [8]

Voltage / current (fundamental)	150 V Y / 128 A per phase
Rated torque / speed / power	9.5 Nm / 40 000/min / 40 kW
Power factor / efficiency	0.75 / 91.8 %
Stator bore / Iron stack length	d_{si} = 90 mm / l_{Fe} = 90 mm
Rotor magnet material / height	Sm_2Co_{17} / h_M = 4.5 mm
Magnet fixation / thickness	Carbon fibre / d_B = 4.8 mm
Air gap length / slot opening	δ = 3.2 mm / s_Q = 2.3 mm
Resistance 20°C / inductance	11.1 mOhm / 0.09 mH (phase)
Number of stator poles / slots	$2p = 4$ / $Q = 36$
Rated / switching frequency	f_{sN} = 1333 Hz / 4 kHz ... 6 kHz

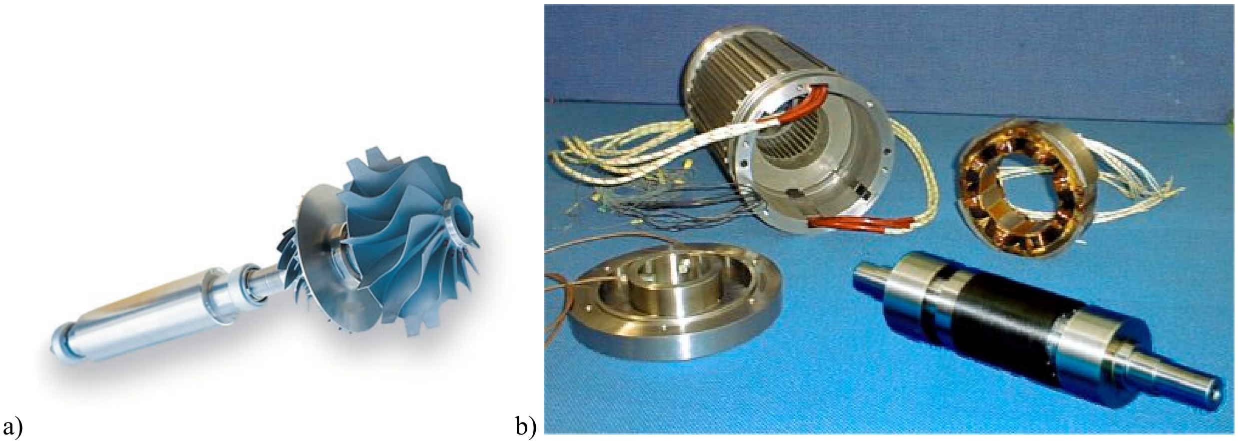

Fig. 7: a) Single stage compressor and turbine wheel 100 kW, 70000/min *(ABB, Sweden)* [4], b) 40 kW, 40000/min PM synchronous generator components: stator housing with jacket cooling, stator iron core and winding, stator end shield with distance sensor for magnetic levitation, PM rotor, magnetic bearing *(Darmstadt University of Technology)*

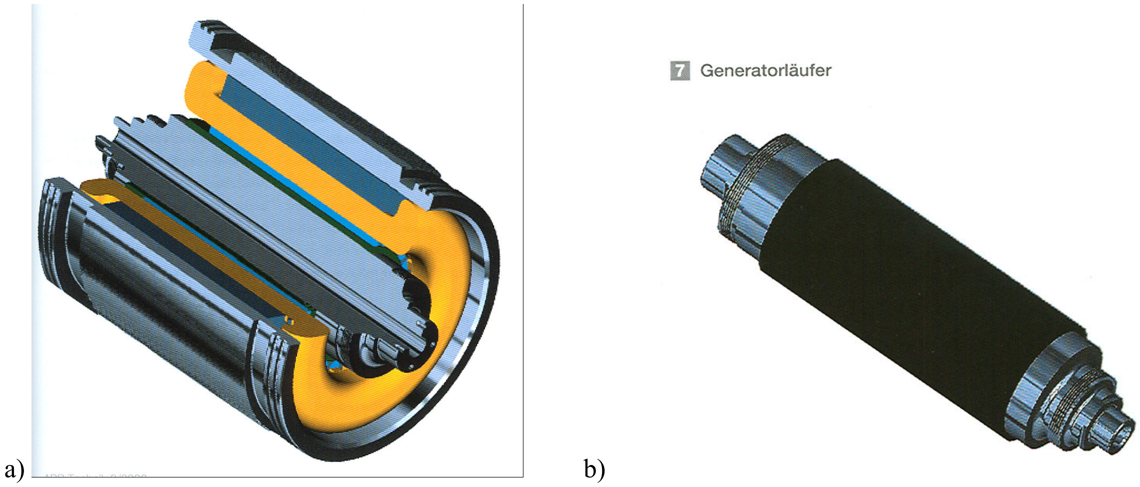

Fig. 8: a) Stator and rotor of high speed PM magnet generator for micro gas turbine, b) PM rotor with carbon fibre sleeve and special high speed mechanical bearings for a micro gas turbine 100 kW, 70000/min *(ABB, Sweden)* [4]

Rotor magnets need a rather fine segmentation to suppress eddy currents in the magnets, caused by pulsating magnetic air gap field due to inverter switching. Often inverter output filters are necessary to reduce the inverter-caused current ripple to keep rotor losses and hence rotor magnet temperature within limits. Detailed rules for design of that kind of high speed PM synchronous generators are given in [8].

Micro gas turbines with PM generator set and inverter are already introduced to the market [4], but their broad application will depend on the future development of distributed power generation, which up to now still gives problems for large scale introduction such as increased installed inverter power in the public grid, causing additional voltage harmonics, further security of switching off all these distributed units when working in the grid, etc.

Conclusion

PM synchronous generators are only used at the moment in some selected applications of regenerative power conversion, mainly wind power application and recently also small hydro power. In both cases they are a gearless alternative to geared induction generator systems, giving reduced maintenance and usually higher reliability. For thermal and electrical power co-generation they will be used in increasing numbers probably in the future as high speed small generators. Advantages are increased efficiency and compact constructive solution for gearless ultra low speed and high speed operation, but often in connection with inverters. No brushes or sliding contacts are needed. Together with gearless application this results in low maintenance solutions, which especially for the planned off-shore wind parks will be an essential advantage. Rare earth magnet materials get cheaper nowadays. Already rather low prices such as for NdFeB magnets at 10 Euro/kg are available on the market, yielding lower costs for PM machines, which will push their application in the future to larger numbers not only for applications like drive systems for ships or submarines [9], but also for regenerative energy conversion.

References

[1]. E.on Netz: Netzanschlussregeln allgemein der E.ON Netz GmbH (Nord), Stand 1.12.2001

[2]. Köhler, B.: Drehzahlvariable, getriebelose Wasserkraftanlage mit permanentmagneterregtem Synchrongenerator und Francisturbine, Ph.D. Thesis Univ. Karlsruhe, Germany, Fortschritts-Berichte VDI Nr. 256, 1998

[3]. Woditschka, P.: Fortschritte durch Permanentmagnet-Technologie im Generatoren- und Motorenbau der 1 MW-Leistungsklasse, VDE-Kongress 2004, 18-20.10.2004, Berlin, Fachtagungsberichte, Vol.1, p. 409-414

[4]. Malmquist, A.; et al.: Mikrogasturbinen als Wegbereiter der dezentralen Wärme- und Stromversorgung, ABB Technik, 3/2000, p.22-30

[5]. Schaetzer, Ch.: Ein Verfahren zur Optimierung bei elektrischen Maschinen mit Hilfe der numerischen Feldberechnung, Ph.D. Thesis, Darmstadt Univ. of Technology, Shaker, Aachen, 2002

[6]. Joeckel, S.: Calculation of Different Generator Systems for Wind Turbines with Particular Reference to Low-Speed Permanent-Magnet Machines, Ph.D. Thesis, Darmstadt Univ. of Technology, Shaker, Aachen,

[7]. N.N..: Schneller zur Serienreife – CAD für umweltfreundliche Energieerzeugung, Der Konstrukteur, 6/2003, p. 48-49

[8] . Binder, A.; Klohr, M.; Schneider, T.: Losses in High Speed Permanent Magnet Motor with magnetic levitation for 40000/min, 40 kW, Proc. Of the 16th Int. Conf. On Electrical Machines (ICEM), 5-8.9.2004, Krakow, Poland, vol.1, p.93-94, (full version 6 pages on CD-ROM)

[9]. Nerowski, G.; Kaufhold, M.: Moderne elektrische Antriebstechnik – Herausforderungen, Innovationen, Trends, VDE-Kongress 2004, 18-20.10.2004, Berlin, Fachtagungsberichte, Vol.1, p. 403-408

[10]. Binder, A.; Schneider, T.; Klohr, M.: Fixation of buried and surface mounted magnets in high-speed PM synchronous motors, Proc. IEEE-IAS Annual Meeting, Hong Kong, 2.-6.Oct. 2005 (to appear)