

Flux switching alternators for small wind generation

P. Andrada¹ and F. Martínez²

¹ GAECE, DEE, EPSEV, UPC BarcelonaTech

Avinguda Victor Balaguer 1, 08800 Vilanova i la Geltrú, Barcelona, España
 e-mail: pere.andrada@upc.edu

² Escuela de Ingeniería Minera e Industrial, Universidad de Castilla la Mancha

Plaza Manuel Meca 1, 13400 Almadén, Ciudad Real, España
 e-mail: fernando.mgarcia@uclm.es

Abstract. This paper considers the application of flux switching alternators for small wind generation. First, after a brief presentation of the small wind energy systems, a description and the fundamentals of flux switching machines is given, then the state of art of flux switching generators is presented. Finally a critical assessment is shown, considering the main advantages and drawbacks of this type of machines as alternator for use in small wind generation systems.

Key words

Small wind power generation, alternators for wind energy, flux switching machines.

1. Introduction

Small wind turbines supply electrical power for stand-alone applications grid-tied or connected to microgrids, for residential, industrial and commercial applications in rural or even in built environments.

Although standard IEC 61400-2 defines small wind turbines as having a rotor swept area of less than 200 m², equating to a rated power of approximately 50 kW generating at a voltage below 1000 V AC or 1500 V DC, nowadays it is generally accepted that the upper limit capacity of small wind turbine is of 100 kW.

The small wind capacity installed worldwide has reached more than 755 MW as of the end of 2013. This represents a growth of more than 12% compared with 2012, when 678 MW were registered. It is also expected that, due to an increasing interest in electrification of remote areas, the major new market prospects will be in off grid applications. Based on a conservative assumption, the market may grow at a rate of 20% from 2015 to 2020, achieving a cumulative installed capacity of about 2 GW by 2020 [1].

There are different technical solutions that can be used for small wind energy conversion. These solutions can be classified according to whether or not they have gearbox and the type of electric alternator and electronic power converter used, see [2]. The election of the electric generator is an important issue in a small wind generation system. In [3] some tables list general criteria to compare generators for this kind of applications. Nowadays, there is an increasing interest in use of direct driven, without gearbox, synchronous permanent magnet machines [4]. Fig. 1 shows a scheme of a small-wind power converter system using direct drive permanent synchronous generator connected to grid. A particular case of this kind of machine is the generator with outer rotor and fractional-slot concentrated winding presented in reference [5].

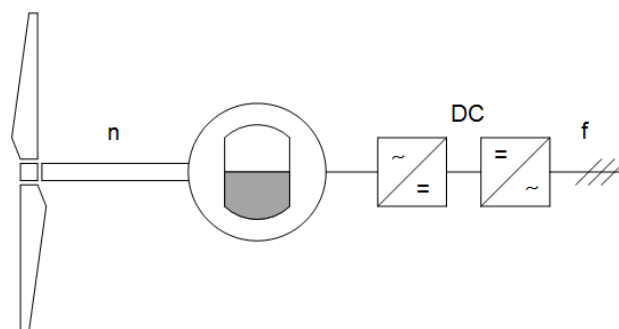


Fig. 1 Direct drive permanent magnet synchronous generator connected to grid via a DC/AC power converter

This paper is a critical assessment of flux switching alternators for small wind generation and it is organized as follows: first, in section 2, after a brief presentation of the small wind energy systems, a description and the fundamentals of flux switching machines is given. In section 3 some considerations about wind generation are introduced, following a presentation of the state of art of flux switching generators. Then some basic design outlines are given and finally the main advantages and drawbacks of this type of machines as alternator for use in

small wind generation systems are exposed. In section 4 the conclusions of the study are drawn.

2. Flux switching alternators

The flux switching alternator can be considered an evolution of the inductor generator and is known since the seminal work of Rauch and Johnson [6]. It was composed, in the simplest case, by a stator, a laminated core, with four poles where the field winding and the armature windings are disposed alternatively around the stator between the poles. The field winding can be replaced by permanent magnets giving as result the flux switching alternator shown in Fig. 2. The rotor is a two salient pole stack of lamination nailed to the shaft. As the rotor turns the flux links a path containing the field, the armature and the rotor, when the rotor has rotated 180° the flux linkage through the armature coils has been reversed in direction but maintains the same value. Flux switching has the same simplicity of the rotor of the inductor generator but adds the advantage that flux switch produces twice the flux density changes as that of the inductor generator circumstance that provides a reduction of the volume of the magnetic circuit and increasing the power/mass ratio.

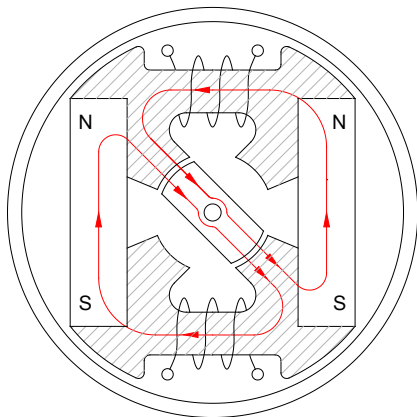


Fig. 2 Simple flux-switch alternator schematic illustrating the flux-switching principle

In the last years a novel type of flux switching machine has been developed in which the stator and rotor are composed by laminated cores with salient poles [7]. Each pole of the stator consists of a concentrated winding and a permanent magnet that is magnetized in tangential direction. The permanent magnets in adjacent poles are magnetized in opposite direction in order to get flux concentration. The rotor is free of windings, permanent magnets or cages. The topology of a flux switching machine is given by the phase number and by the ratio of the number of stator slots (Q_s) to the number of rotor poles (Q_r), Fig. 3. When the rotor moves the flux lines are alternatively guided in such a way that flux linked through the coils periodically switches and induces an alternative electromotive force in the coil, wound over the stator pole, as it is shown in Fig. 4. Then, ideally, flux-linkage, ψ , and the EMF induced in the phase windings, e , are sinusoidal functions that depend on the rotor position, Fig. 5. Hence, the machine can be considered as a particular case of

permanent magnet synchronous machine having magnets in the stator. The electrical frequency, f , is given by:

$$f = Q_r \frac{N}{60} \text{ (Hz)} \quad (1)$$

With N (rpm) angular speed

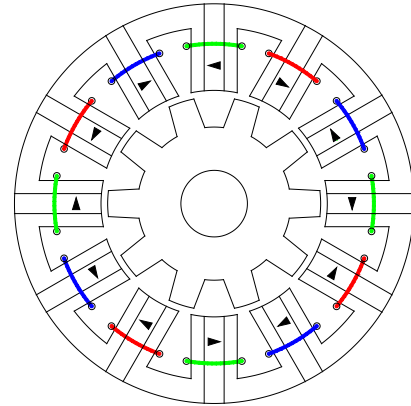


Fig. 3 Three phase 12/10 flux switching machine

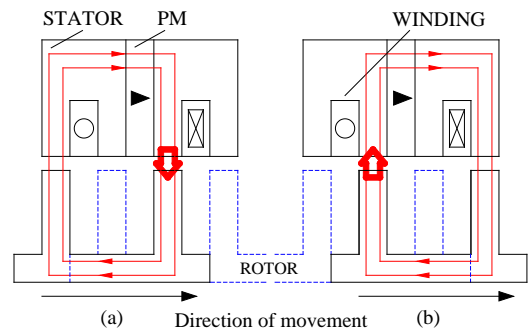


Fig. 4 Flux switching principle: (a) the rotor pole aligns with one of two stator teeth over which a coil is wound. (b) The rotor moves forward to align with the other stator tooth of the same coil. In both cases the flux linkage has the same value but the polarity is reversed.

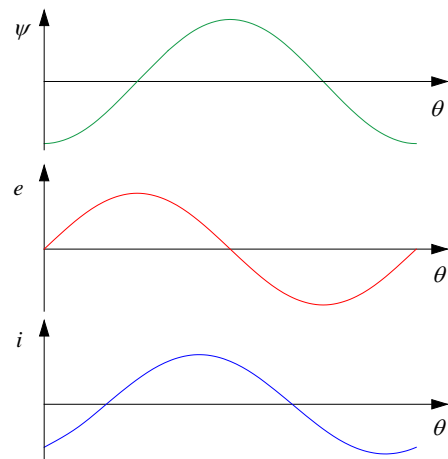


Fig. 5 Ideal phase waveforms of flux linkage, ψ ; electromotive force, e ; and current, i , vs rotor position θ .

The electromagnetic torque of a three-phase flux switching machine is determined by:

$$T = \frac{3}{2} Q_R [\psi I_q - (L_q - L_d) I_d I_q] \quad (Nm) \quad (2)$$

With:

- L_d , d axis inductance
- L_q , q axis inductance
- I_d , d axis current
- I_q , q axis current

Although permanent magnet flux switching machines have a rotor salient pole structure the values of L_d , and, L_q are very close, therefore reluctance torque is small and is usually neglected.

3. Flux switching alternators for wind generation

In this section, after a brief notes about wind energy the state of art of the flux switching alternators is presented. Then a basic outlook of the design of this type of machines is exposed. Finally, based on these arguments, the main advantages and drawbacks of flux switching alternators are presented.

A. Some considerations about wind energy

A wind generation system, for a specific site, depends on many factors as the average wind speed at the site and more specifically of the characteristics of the wind turbine mainly the cut-in velocity, v_C , the rated velocity, v_R , and the cut-off velocity, v_F .

The power curve versus velocity of a wind turbine is shown in Fig. 6 where it can distinguish four zones of operation constrained by the cut-in velocity, v_C , the rated velocity, v_R , and the cut-out velocity, v_F . In zone I, below cut-in velocity, the turbine does not provide power. In zone II the power depends on the velocity of the wind. In zone III the angular speed is maintained constant and the output power is limited by generator rated capacity. For speeds higher than cut-off speed, zone IV, the security system stops the transfer of power.

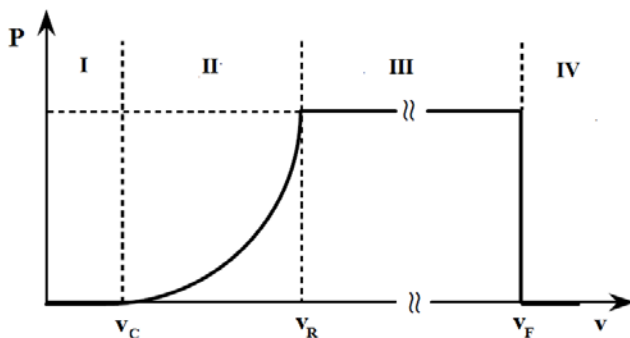


Fig. 6 Power curve of turbine showing its different zones of operation, limited by the cut-in velocity, v_C , the rated velocity, v_R , and the cut-out velocity, v_F .

The average power, P_{AV} , of a wind turbine is given by:

$$P_{AV} = \frac{1}{2} \rho S C_p v_R^3 (CF) = \frac{\pi}{8} \rho D_b^2 C_p v_R^3 (CF) \quad (W) \quad (3)$$

Where:

- ρ , air density
- S , turbine cross sectional area
- D_b , blade diameter
- C_p , power coefficient
- λ , tip ratio
- v_R , rated velocity
- (CF) , capacity factor

According reference [8] (CF) is determined by:

$$(CF) = \frac{1}{v_R^3} \int_{v_C}^{v_R} v^3 f(v) dv + \int_{v_R}^{v_F} v f(v) dv \quad (4)$$

Being $f(v)$, with v generic velocity, a Weibull probability density function given as:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (5)$$

With:

- k , Weibull shape parameter
- c , Weibull scale parameter

The power coefficient C_p depends on the type of turbine and of the tip ratio, λ , which is defined as:

$$\lambda = \frac{v_p}{v} = \frac{\omega D_b}{2v} \quad (6)$$

With ω rotational speed (rad/s)

The power coefficient versus tip ratio for several types of turbines is shown in Fig. 7.

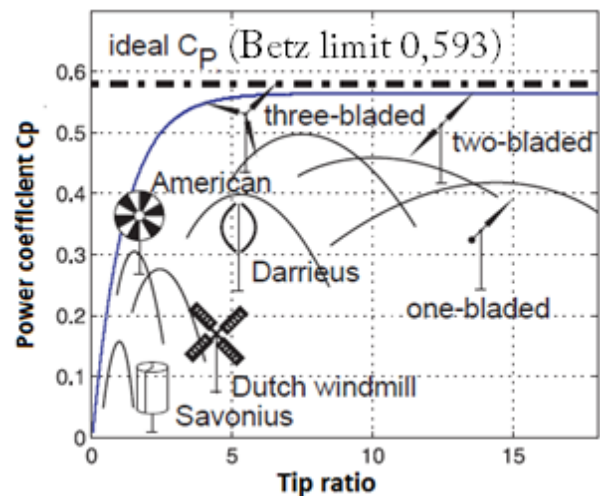


Fig. 7 Power coefficient versus tip ratio for different types of wind turbines

Therefore torque of the wind turbine can be expressed as follows:

$$T_{Turbine} = \frac{\pi}{16} \rho \left(\frac{C_p}{\lambda} \right) (CF) D_b^3 v_R^2 \quad (Nm) \quad (7)$$

B. State of art of flux switching machines for wind generation

Flux switching machines were first used as a high frequency monophasic alternator for airborne equipment. Then, they were extensively investigated for drives applications. Interest in flux switching machines has grown until the point that numerous papers have been published comparing them with surface permanent magnet synchronous machines [9] and interior permanent synchronous machines [10,11]. Recently flux switching machines have been employed as alternator for wind generation. For high power wind generation, multiphase alternatives with 9 phases 36 stator slots/34 rotor poles [12] and with 12 phases 24 stator slots/22 rotor poles have been proposed [13, 14]. A new modular flux-switching permanent-magnet drive, for large wind turbines, has been presented and measurement results have been shown from a 500-kW test rig [15]. The suitability of flux switching generators for medium speed wind generation is highlighted in [16]. In the field of small wind generation, a direct drive flux switching alternator with 120 stator slots/100 rotor poles, intended for low-wind velocity sites was developed [17]. Flux switching prototypes, with outer rotor with 6 stator slots /19 rotor poles, have also been built [18]. Finally it should be noted that, in [19], an axial field double salient structure with 12 stator slots /10 rotor poles have been presented.

C. Basic design outlines of flux switching machines [20]

According to Fig. 5 the flux linkage, the electromotive force, E_m , and the current, I_m , are sinusoidal, therefore the electromagnetic torque of the generator can be expressed as:

$$T_{Generator} = \frac{m E_m I_m}{2\omega} \quad (Nm) \quad (8)$$

Being m the number of phases

The instantaneous electromotive force is given by:

$$e = -N_f \frac{d\phi}{dt} \quad (V) \quad (9)$$

Where N_f are the winding turns per phase and ϕ is the flux, that can be expressed in function of the angular position, θ , as:

$$\phi = \hat{\phi} \cos(Q_R \theta) \quad (Wb) \quad (10)$$

With:

$$\hat{\phi} = \sigma \beta \hat{B}_\delta \frac{\pi D L}{Q_s} \quad (Wb) \quad (11)$$

Where:

σ , leakage factor
 β , ratio between stator tooth/stator pitch

\hat{B}_δ , magnetic loading, maximum value of airgap flux density
 D , armature diameter
 L , armature axial length

So:

$$e = N_f \omega Q_R \hat{\phi} \sin(Q_R \theta) = E_m \sin(Q_R \theta) \quad (V) \quad (12)$$

Therefore the maximum value of electromotive force is given by:

$$E_m = \pi N_f \left(\frac{Q_R}{Q_s} \right) \sigma \beta \hat{B}_\delta D L \omega \quad (V) \quad (13)$$

Then its RMS value is as follows:

$$E(RMS) = \frac{\pi}{2} \sqrt{2} N_f \left(\frac{Q_R}{Q_s} \right) \sigma \beta \hat{B}_\delta D L \omega \quad (V) \quad (14)$$

The maximum value of armature current is:

$$I_m = I(RMS) \sqrt{2} \quad (A) \quad (15)$$

As electric loading, A , is given by:

$$A = \frac{2m N_f I(RMS)}{\pi D} \quad (A/m) \quad (16)$$

Then:

$$I_m = \frac{\pi D A}{2m N_f} \sqrt{2} \quad (A) \quad (17)$$

Substituting equations (13) and (17) in (8) the electromagnetic torque of the generator or output equation turns into:

$$T_{Generator} = \frac{\pi^2 \sqrt{2}}{4} \left(\frac{Q_R}{Q_s} \right) \sigma \beta \hat{B}_\delta A D^2 L \quad (Nm) \quad (18)$$

As the volume of the armature, V_i , is:

$$V_i = \frac{\pi}{4} D^2 L \quad (m^3) \quad (19)$$

The torque of the generator is given by:

$$T_{Generator} = \pi \sqrt{2} \left(\frac{Q_R}{Q_s} \right) \sigma \beta \hat{B}_\delta A V_i \quad (Nm) \quad (20)$$

D. Suitability of flux switching machines for wind generation

Once it has been decided a site, set the values of cut-in, rated and cut-out velocity and selected a determined type of wind turbine, the torque of the turbine is computed. As this is a direct drive system equaling equations (7) and (20) the armature volume can be expressed by:

$$V_i = \frac{\sqrt{2} \rho \left(\frac{C_p}{\lambda} \right) (CF) D_b^3 v_R^2}{32 \left(\frac{Q_R}{Q_s} \right) \sigma \beta \hat{B}_\delta A} \quad (m^3) \quad (21)$$

Therefore the armature volume, as is shown in equation (21), and as a consequence the total volume of the machine, is strongly conditioned by the relationship between stator and rotor poles, the magnetic loading and the electric loading.

The number of rotor poles according equation (1) should be carefully chosen in order to obtain an output suitable electric frequency. The choice of the final three-phase flux switching machine structure (Q_S/Q_R) is a compromise between torque, torque ripple and stator loss.

The magnetic loading of flux switching machines is higher than in permanent magnet synchronous machines while the electric loading is similar or slightly lower, due to the disposition of permanent magnet in the stator poles, which reduces the slot area for the same output diameter.

It is important to point out that permanent magnet selection in flux switching machines plays an important role in its optimization so, if it is desirable to maximize the power mass ratio, the best choice is to use NdFeB permanent magnets however, if what is intended is to minimize the cost, the best option is to utilize ferrite permanent magnets.

The main advantages of flux switching alternators for small wind generation with low or moderate wind (8-12 m/s) velocities and medium rotational speeds (200-600 rpm) are:

- Structure simple and robust
- Permanent magnets in stator make it easier to cool
- Sinusoidal electromotive force
- Low copper losses owing to short end windings
- High power density
- Electromagnetic torque even higher than permanent magnet synchronous machines
- Fault tolerant

On the contrary the main drawback of flux switching alternator for small wind generation is its high cogging torque.

4. Conclusion

In the next years the market of small wind generation may grow at a rate of 20% from 2015 to 2020. This leads associated the need for better and cheaper wind turbines. The alternator is an important part of the power wind system that can still greatly improve. New types of alternators may be considered, between them a promising candidate is the flux switching machine. In this paper adequacy of flux switching machines as alternators for small wind generation has been proved.

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