Fractional-slot permanent magnet synchronous generator for low voltage applications

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Abstract. This paper considers the implementation and application of a small direct drive fractional-slot permanent magnet synchronous generator for low voltages applications in distributed generation. Finite element analysis of the generator is performed and the results are compared with those obtained by test.

Key words

Synchronous generator, permanent magnet, outer rotor, fractional- slot concentrated windings, direct drive.

1. Introduction

Distributed generation is related to the use of small generating units installed at strategic points of the electric power systems or locations of load centers. Distributed generation can be used in isolated way, supplying the consumer's local demand, or integrated into the grid supplying energy to the remainder of the electric power system [1]. They can run on renewable energy resources, fossil fuels or waste heat. Equipment ranges in size from less than one kilowatt to tens of megawatts. The design of appropriate generators is a key issue in distributed generation. Up to now many different designs has been proposed [2-5]. This paper deals with the implementation of a small direct-drive permanent magnet synchronous generator, suitable for low voltage applications in distributed generation that employs fractional slot concentrated windings. Direct drives means that there is no gearbox between the prime mover, a low speed wind turbine, and the generator avoiding losses and reducing maintenance. The generator includes a diode rectifier with filter and a voltage regulator DC-DC converter, Fig. 1.

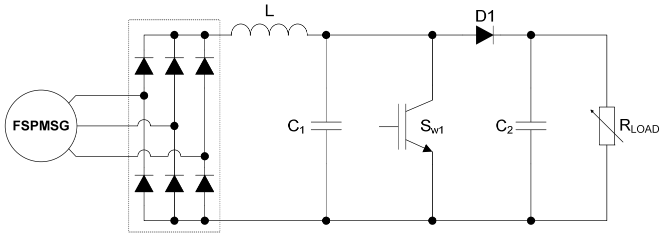

Fig. 1 Fractional slot permanent magnet synchronous generator (FSPMSG) with voltage source diode rectifier and voltage regulator

2. Description of the generator

The generator under study is a variable speed with outer rotor for better integration with the wind turbine. The rotor is constituted for a series of permanent magnet segments hooked to a solid back iron. The stator is a slotted laminated pack; using low loss magnetic steel in order to obtain a good efficiency. Fractional slot concentrated winding is used due to the advantages of this type of winding including: high winding factor, high power density, high efficiency, short end turns, low cogging factor, fault tolerant capability and in the case of use segmented stator structures high fill factor [6-8]. The generator is designed with terminal voltage at maximum speed to allow for a small boost in DC-DC power converter.

3 Generator design

The objective is to design a three phase generator, with a rated DC voltage of 30 V that can deliver a power of 2.5 kW in a speed range between 200 to 500 rpm.

Some initial design choices have been taken as:

- Rotor outer diameter 305 mm, conditioned by the application.
- Use of NdFeB magnets (Br = 1,2 T)
- Use of double-layer fractional-slot concentrated windings.

In this paper fractional-slot concentrated windings are referred to those windings with concentrated non-overlapping coils with a number of slots per pole and phase, n_{pf}, between 0.25 and 0.5. These windings can be classified according to the number of layers in; single-layer windings with coils wound only on alternate teeth and double-layer windings in which all teeth have a coil. In this paper only double layer windings will be considered, although they have lower winding factor and slot fill they have a more sinusoidal back-emf, lower content of mmf and shorter end-windings. Once selected the type of layers an important issue is to determine the number of poles (2p) and the number of slots (Ns). The frequency gives a range of pole numbers and a good first approach is to consider $N_s \approx 2p$. Then the number of slots is chosen in combination of the pole numbers according to the feasibility of the winding, the value of winding factor, the magnetic asymmetries, the cogging torque and other considerations, in accordance with the following rules.

Feasibility of the winding. The winding is feasible when the ratio $\frac{N_s}{m\,GCD(N_s,p)}$ is an integer.

Winding factor k_w. High winding factor is desirable in order to maximize torque. The winding factor for the fundamental can be calculated using equation (1):

$$\boldsymbol{k_w} = \frac{\left|\sum_{i=1}^{n_l\frac{N_s}{3}} \vec{\boldsymbol{E}}_i\right|}{n_l\frac{N_s}{3}} \quad (1)$$

where:

n_l , is the number of layers

$\vec{\boldsymbol{E}}_i$, back-emf of phasor i

Cogging torque. Low cogging torque can be achieved if the least common multiple between the number of poles and the number of slots, *LCM (Ns, 2p),* is as larger as possible.

Magnetic unbalance. In order to avoid magnetic unbalanced magnetic pull, great common divisor between number of slots and number of pole pairs should be higher than unit, *GCD (Ns, p) > 1.*

According to this rules a combination of 40 poles and 36 slots has been chosen. The double layer winding has a number of slots per pole and phase n_{pf} = 0.3 and a winding factor k_w = 0.945. The winding layout is:

…/C´A/A´A´/AA/A´B/B´B´/BB/B´C/C´C´/CC/….

Each phase has four groups of three coils connected in parallel.

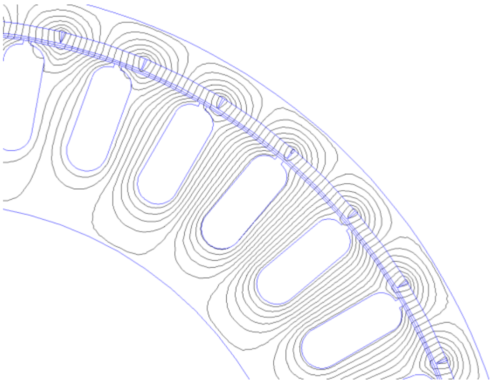

Fig. 2 FEA analysis of proposed generator, field lines due to permanent magnets

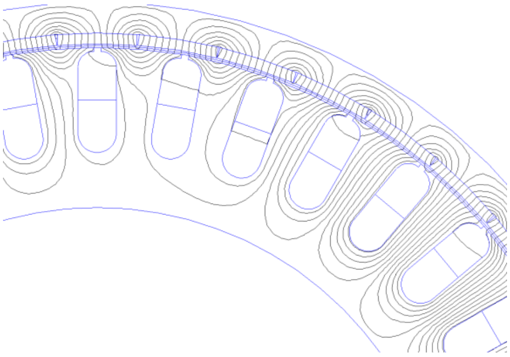

Fig. 3 FEA analysis of proposed generator, field lines at load (I_{max} = 75 A)

A first sketch of generator main dimensions has been determined using well-known formulas [10, 11] then a finite analysis has been carried out in order to verify its performance. In Fig. 2 shows field lines in the generator due to the only action of permanent magnets obtained by FE analysis while in Fig. 3 the field lines at load resulting of the combination of stator currents and the permanent magnet effects are shown. The main dimensions and parameters of the generator are listed in Table 1.

TABLE I. – Generator parameters

PARAMETER	SYMBOL	VALUES
Number of phases	m	3
Number of poles	2p	40
Number of slots	k	36
Rated Power	P	2.5 kW
Rated voltage DC	V_{DC}	30V
Rotor outer diameter	D_{out}	305 mm
Stator diameter	D	281.1 mm
Stack length	L	35 mm
Speed range	N	200-500 rpm

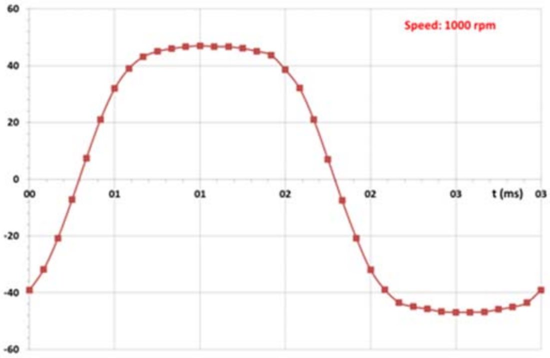

Fig. 4 Computed back-emf waveform at 1000 rpm (FEA)

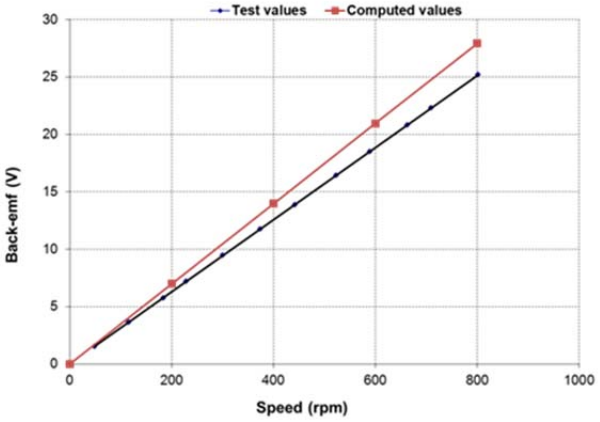

Fig. 5 Back-emf versus speed computed values (red) and test values (blue)

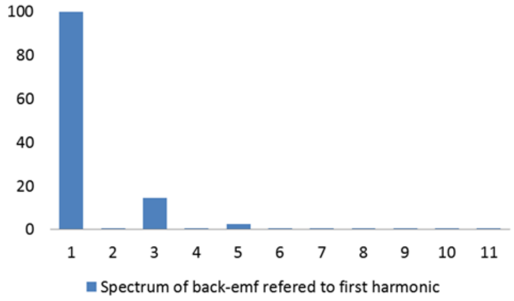

Fig. 6 Spectrum of back-emf referred to first harmonic

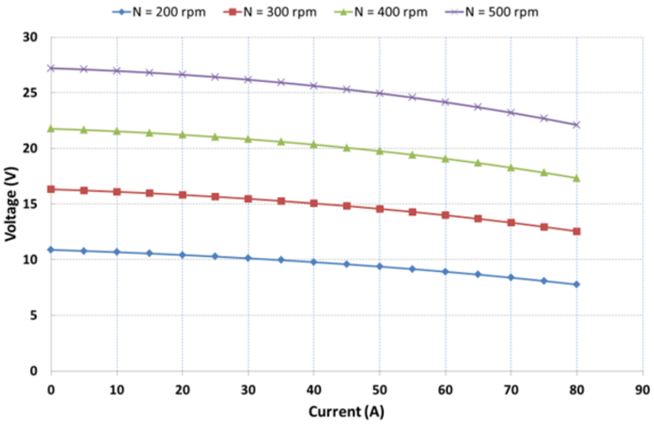

Fig. 7 AC voltage (RMS line voltage) vs AC current (RMS) for different speeds

Table II. Generator main parameters (obtained by test)

PARAMETERS	SYMBOL	VALUES
Resistance (20º)	R	11 mΩ
Inductance	L	0.09 mH
Phase voltage/speed	V_f (RMS)/N	0.0314 V/rpm

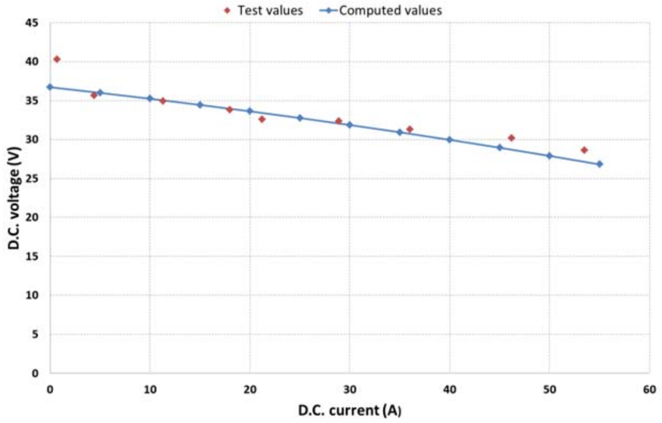

Fig. 7 D.C. voltage vs D.C. current at 500 rpm. Computed values (blue) Test values (red)

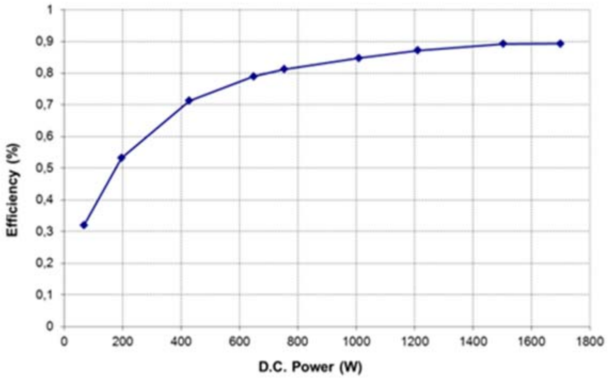

Fig. 8 Efficiency versus D.C. power at 500 rpm

4 Results

Fig. 4 shows the FE computed back-emf waveform of the generator at 1000 rpm while in Fig. 5 the computed back-emf (RMS value) against speed is plotted and compared with the obtained by test. The spectrum of back-emf is shown in Fig. 6 where can be seen that the third (14.4%) and fifth harmonics (2.5%) are the most relevant. The main parameters of the generator experimentally determined are listed in Table II.

In Fig. 6 calculated values of line voltage versus current for different speeds are shown. In Fig. 7 DC voltage, without DC-DC power converter, versus current for a speed of 500 rpm are compared with experimental results. The efficiency of the generator against D.C. output power is plotted in Fig. 8. In Fig. 9 waveforms of line voltage and line current, for a specific load, can be seen while in Fig. 10 DC voltage and DC current for this load are shown.

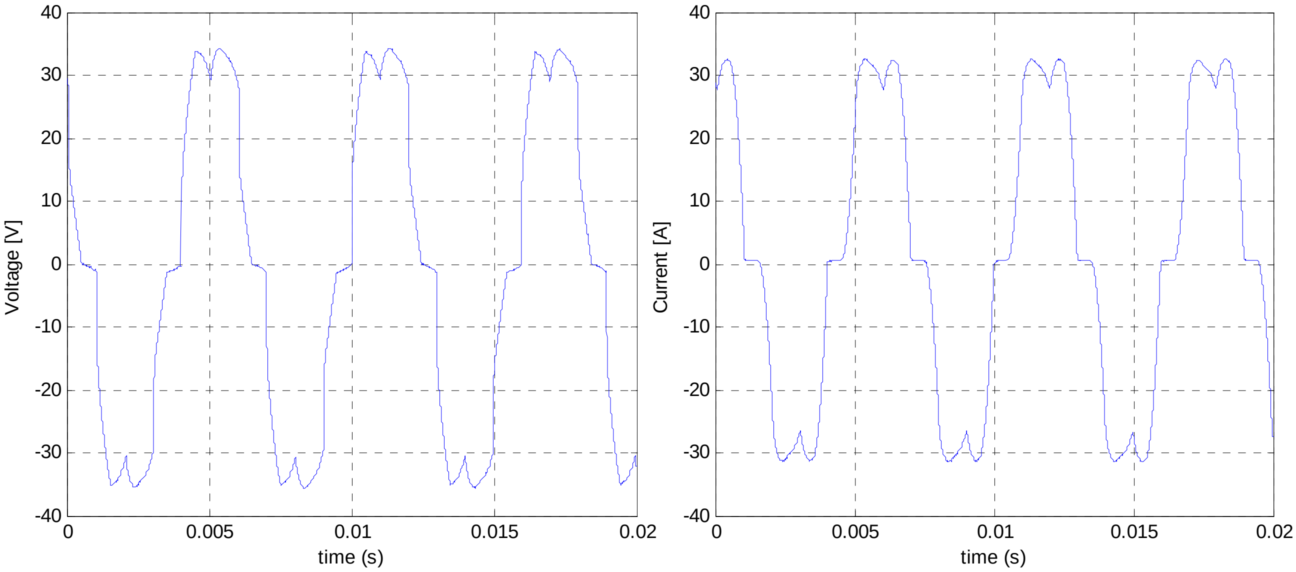

Fig. 9 Waveforms of A.C. side: Line voltage (left) and current (right)

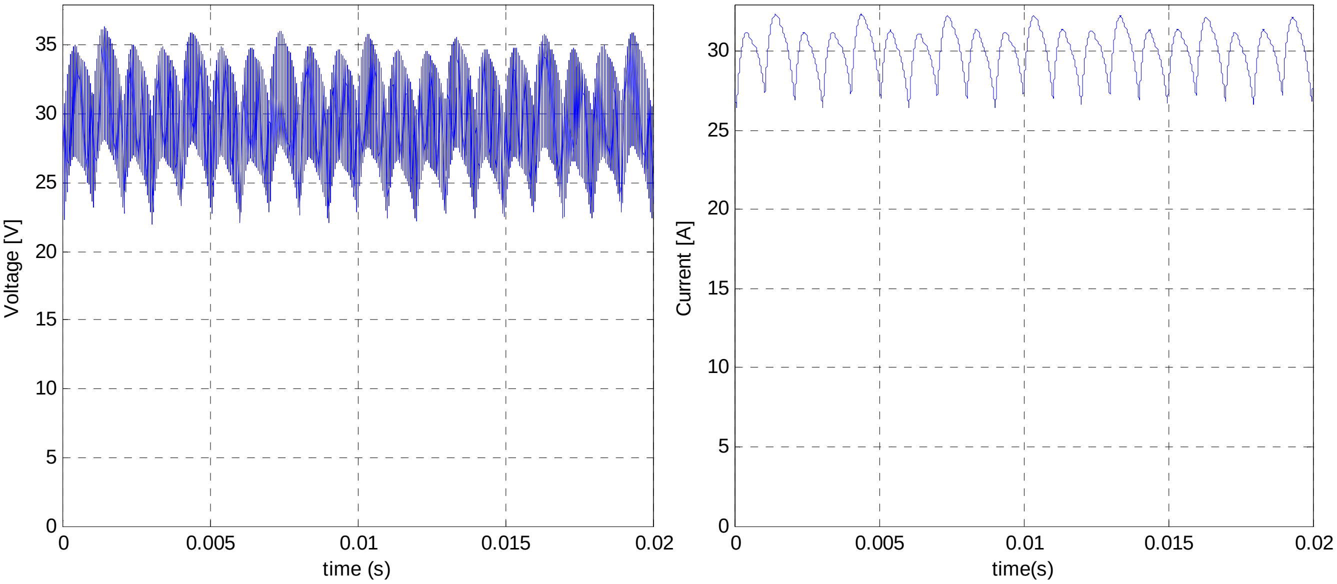

Fig. 10 Waveforms of D.C. side: Voltage (left) and current (right)

5 Conclusion

In this paper a small direct drive variable speed generator that employs fractional-slot concentrated windings has been implemented and used in applications requiring low voltage in distributed generation. Fractional-slot concentrated winding is selected in accordance with a set of well-established rules. The generator is designed based on a well-known formulas and finite element analysis. The performance of the proposed generator has been evaluated and confirmed by experimental results.

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