Performance Analysis of Permanent Magnet Synchronous Generator for Small Scale Wind Energy Applications

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Abstract: This paper presents a study of the performances of a permanent magnet synchronous generator (PMSG) used in small scale wind energy applications. The d-q model is adopted for the performance analysis of the PMSG under variable operating conditions. In addition, in order to validate the results obtained with the theoretical model, an experimental test bench based on a small PMSG equipped with a data acquisition system has been developed. The study carried out on the experimental test bench made it possible to determine both the dynamic and the steady state performances of the PMSG under variable loads and rotational speeds.

Keywords: PMSG, D-Q model, Stand-alone system, Wind energy

1. INTRODUCTION

In isolated sites where access to the electric power network is impossible or economically unprofitable, the power generation systems using renewable energy sources are frequently used [1-3].In particular, off-grid systems based on small wind turbines with an output power rating of less than 10 kW have proved to be an attractive option to meet the load demands of stand-alone sites [4].

In power generation systems using wind energy, the electromechanical conversion can be carried out through different types of electrical generators [5-8]. However, in power plants where the produced electric power are low, the permanent magnet synchronous generator (PMSG) remains the most widely used. Indeed, the main advantage of the PMSG when it is used with a wind turbine is that it does not require a gearbox (direct drive) if it has a large number of poles. In addition, this machine has good specific power and operates with good efficiency and high power factor. The PMSG stator is of the same construction as the classic synchronous machine. However, thanks to the presence of permanent magnets at the rotor, a power source for the excitation circuit is not required, which favors its use in small power plants located in isolated sites [9].

In the literature, different topologies have been proposed for supplying loads in isolated mode with the PMSG [10-12]. In addition, several papers have studied the PMSG performance in steady and dynamic states [13-15] as well as the control techniques for MPPT operation of stand-alone variable-speed wind turbine driven PMSG [16-19]. In this study, the basic tests to be carried out on a PMSG dedicated for small-scale wind energy applications are described. In addition, the models of the PMSG for steady state and dynamic conditions were established and validated experimentally on a laboratory test bench in order to evaluate the performance of the PMSG under different operating conditions.

2. DYNAMIC MODEL OF PMSG

The dynamic model of PMSG is established with the 2-phase equivalent circuit model (d-q model). Since the d-q model is very popular, the mathematical equations derivation is not detailed in this study. The electrical dynamic equation of PMSG in terms of the d-q variables in synchronous reference is as follow [20] :

$$V_q = (R_s + pL_q)I_q + wL_dI_d + w\Phi_{pm} \quad (1)$$

$$V_d = (R_s + pL_d)I_d - wL_qI_q \quad (2)$$

Where

I_d, I_q: d- and q- axis components of stator current.
V_d, V_q: d and q- axis components of stator phase voltage.
R_s: stator resistance.
p is the differential operator (p=d/dt).
L_d, L_q: d- and q- axis stator self inductances.
Φ_{pm}: peak flux linkage due to permanent magnet.
ω: angular velocity (in electrical rad/sec).

On the other hand, the produced torque (T) can be represented as:

$$T = (\frac{3}{2})(\frac{P}{2})(\Phi_{mq} I_q + (L_d - L_q) I_q I_d) \quad (3)$$

Where P is the poles pairs.

To establish the d-q model of a given PMSG, there are four parameters that are to be determined. These are the stator resistance R_s, the synchronous inductances L_q and L_d, and the flux linkage Φ_{pm}. In this study, a 1 kW PMSG with ten poles is considered. The parameters of this PMSG, which are obtained from measured data as detailed in [21] are given in Table1.

For steady state conditions, the magnitudes of voltage (V_s) and current (I_s) are [22]:

$$V_s = \sqrt{V_q^2 + V_d^2}/\sqrt{2} \quad (4)$$

$$I_s = \sqrt{I_q^2 + I_d^2}/\sqrt{2} \quad (5)$$

Table 1PMSG parameters

Parameters	Value
Phase resistance	R_s = 0.5 Ω
Synchronous inductances	L_d, L_q = 5 mH
Flux linkage	Φ_{pm} = 0.27 Wb

3. EXPERIMENTAL TEST BENCH

The synoptic diagram of the experimental test bench is depicted in Fig. 1. It consists of a three-phase induction motor (1.1 kW / 1500 rpm) powered by anATV 71 speed drive from Schneider electric, which is controlled via an M221 programmable logic controller (PLC) from Modicon. The induction motor is mechanically coupled to a PMSG which converts the incoming mechanical energy into an electrical energy.

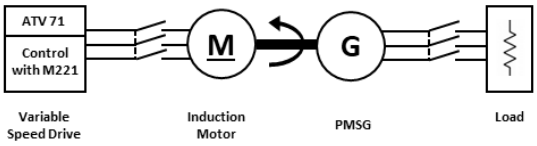
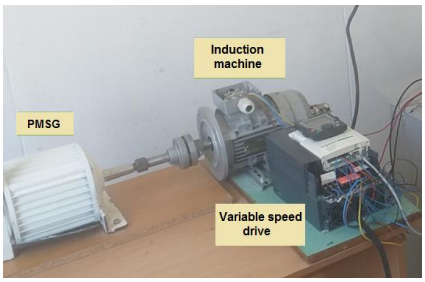


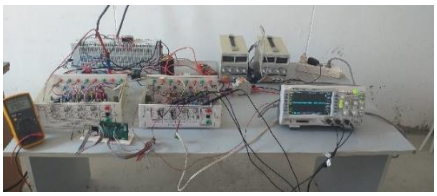
Fig.1 Synoptic diagram of the experimental test bench

Depending on the speed drive configuration, the motor can switch between speed regulation mode and operation in torque control. In this study, the test bench is used for the assessment of the PMSG performances. Hence, only the speed control mode is considered.

In the speed control mode, the speed drive is configured so that the motor operates at a reference speed. In this study, the PLC uses the RS-485 bus in order to send the reference speed to the ATV 71 speed drive as well as to exchange the measured and communication data according to the Modbus communication protocol.In addition, the data of the stator current and voltage as well as the rotor speed is acquired with an MCU control unit from STMicroelectronics. The photograph of the experimental test bench is shown in Fig. 2.



(a)



(b)

Fig. 2 Photograph of the experimental test bench: (a) Motor-generator-drive system (b) Data acquisition system

4. RESULTS AND DISCUSSION

In this section, the performances of the PMSG are evaluated by using the d-q model. Both the dynamic and the steady state operation modes are examined. The experimental validation is performed with the test bench presented in the previous section.

For all tests carried out, the speed rotation is maintained between 150 rpm and 550 rpm. This range of speed rotation variation makes it possible to have operating points close to the nominal conditions of the PMSG used in the tests.

Dynamic operation mode

For the dynamic operation mode, the induction motor drives the PMSG at variable speed but a fixed balanced three-phase resistive load of 23 Ω is supplied. For the validation of the d-q model, the recorded data experimentally for the rotor speed are used in the PMSG model simulation. The experimental and the simulation results are shown in Fig. 3. The obtained results show good agreement between the experimental and the simulation results, which confirm the consistency of the adopted d-q model for the PMSG performances evaluation.

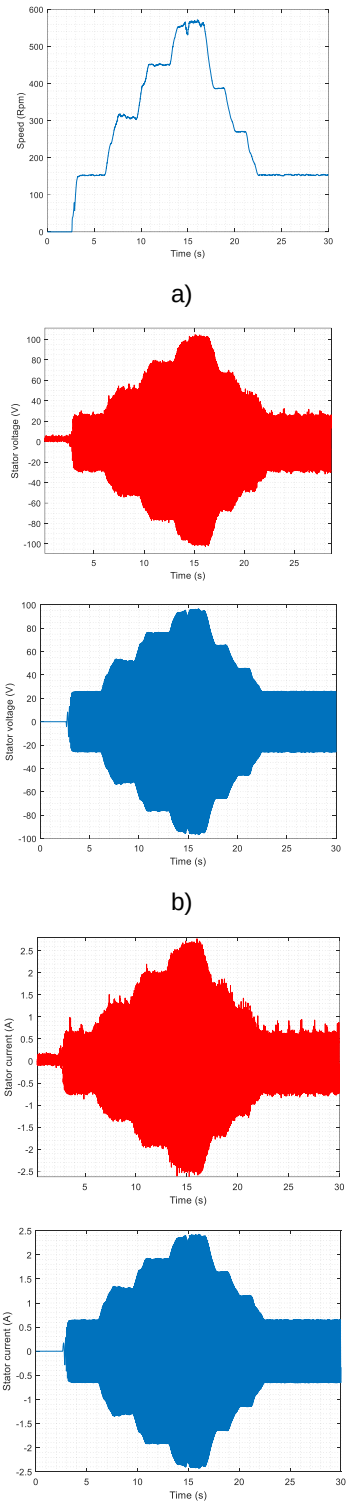


Fig.3 PMSG performances in dynamic mode: a) rotor speed b) stator voltage c) stator current. (Experimental : red color,Simulation : blue color)

Steady-state operation mode

For the steady-state operation mode, the performance analysis of the PMSG is examined for two cases: variable rotor speed and fixed rotor speed. The stator voltages and currents are measured for different values of the consumed power.

For the variable rotor speed operation mode, the three-phase balanced resistive load is maintained at 23 Ω while the rotor speed is variable. Four values of the rotor speed are considered: 150 rpm, 300 rpm, 450 rpm and 600 rpm. On the other hand, for the fixed rotor speed operation mode, the rotor speed is fixed at 500 rpm while the three-phase balanced load is variable.

The simulation and the experimental results for the PMSG stator voltage and current for variable and fixed rotor speed operation modes are shown in Fig. 4 and Fig. 5 respectively. For all examined cases, it can be noticed that the simulated results are in good agreement with the corresponding experimental results, which constitutes a second validation of the d-q model.

From Fig. 4, it can be observed that the stator voltage varies linearly with the rotor speed (variable rotor speed operation mode). However, the stator voltage decreases as the power consumption increases as shown in Fig. 5 (fixed rotor speed operation mode). This is mainly caused by the reduction in the reactive energy due to the presence of the stator reactances and the no presence of compensation capacitors in the PMSG terminals. Indeed, in this type of generator, the reactive power demand varies with the active power demand.

Furthermore, from the simulation results shown in Fig. 5(b), it can be noted that the power supplied by the PMSG reaches a point of maximum power (1160 W) above which the increase in the load causes a decrease in power and voltage (instable operation).

On the other hand, since the three-phase load is a fixed purely resistive and is directly connected to the PMSG terminals, the load current as well as the stator current increase as the power increase (see Fig. 5(a)).

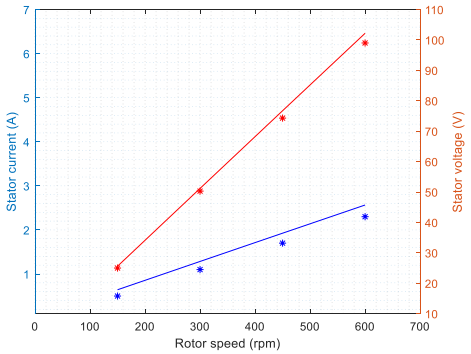
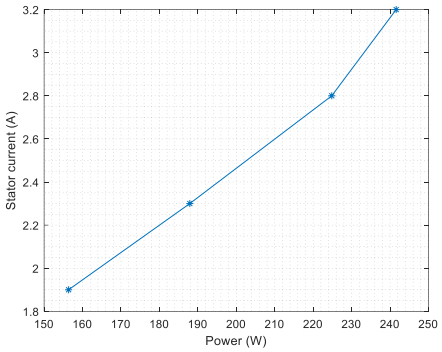
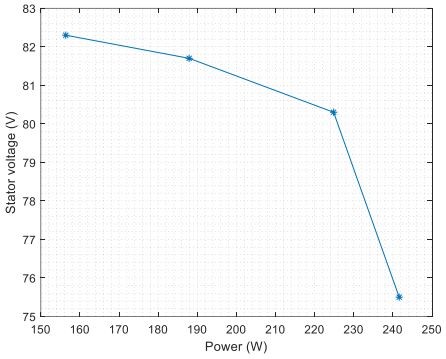


Fig.4 PMSG performances in steady-state mode with variable rotor speed

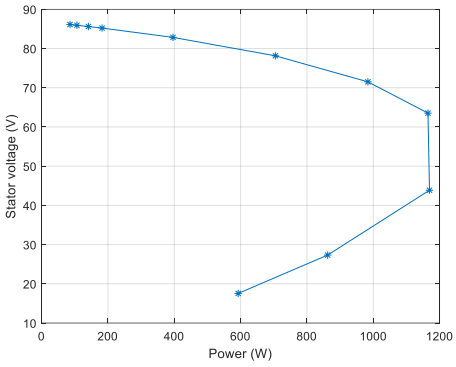


(Stator current)

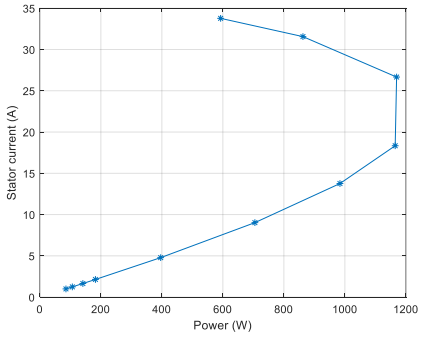


(Stator voltage)

a)



(Stator voltage)



(Stator current)

b)

Fig. 5 PMSG performances in steady-state mode with fixed rotor speed : a) Experimental results b) Simulation results

5. CONCLUSION

In this work, the performances of a small power PMSG in dynamic and steady state operation modes were examined. The theoretical results obtained from the d-q model are validated by experimental tests carried out on an appropriate test bench. The first objective through this test bench, which consists on conducting of basic tests for the assessment of the PMSG performances, has been achieved. The next objective is to improve the developed test bench in order to reproduce a small wind turbine characteristics through the emulation concept.

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