ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1216388

FEASIBILITY STUDY OF THE ELECTRIC POWER GENERATION UNIT START-UP USING THE THREE-PHASE SYNCHRONOUS GENERATOR WITH THE AC EXCITER

Szymon Racewicz, Arkadiusz Olejnik

University of Warmia and Mazury in Olsztyn
Department of Mechatronics and Technical-Computer Sciences Education
Oczapowskiego Street 11, 10-719 Olsztyn, Poland
tel.: +48 895245487, fax: +48 895245150
e-mail: szymon.racewicz@uwm.edu.pl

Abstract

The article presents the feasibility study of using the three-phase synchronous generator with the AC exciter as a starter for the Fiat 0.9 TwinAir CNG 80 HP internal combustion engine. The investigated power generation unit consists of the above mentioned internal combustion engine which can be powered by a biogas and the three-phase electric power generator MeccAlte 16 kW with the AC exciter. The use of an electric generator for starting a combustion engine is an innovative approach, which eliminates the need for additional components like starter reducing the mass and the failure frequency of the device. Similar approaches have been already investigated by the aircraft manufacturers for starting the jet engines of the airliners and are widely used in the hybrid engines for vehicles. The field winding of the three-phase synchronous generator described in the paper is connected to the AC exciter via a rotating rectifier bridge. This solution eliminates the necessity of using slip rings and facilitates a voltage regulation of the generator. The authors of the paper analyse the technical and practical possibilities of using such a synchronous generator with the exciter as a starting motor by measuring its output power and starting torque. The economic aspects of such a solution for unit and mass production have been also considered.

Keywords: *brushless synchronous generator, starter-generator machine, CHP system*

1. Introduction

Synchronous generators are still one of the most used machines for energy generation. As asynchronous induction motor is usually used to convert electrical energy into mechanical, synchronous machine is the principal mean of converting mechanical energy into electrical [7]. Due to their mature technology and relevant widespread technical knowledge gathered over the years synchronous machines are commonly installed as the main generating units in the power plants but also in the Autonomous Electrical Power Systems (AEPS) [4].

Stationary AEPS are usually Combined Heat and Power systems (CHP) which means that they are producing useful energy in terms of heat and electricity. Thanks to the decentralised production of heat and electricity, we avoid high losses related to the long distance transfer from a power plant to the final customer as it happens in the centralised CHP production. It results in the fact that the AEPS become a fast growing part of general electricity production.

Generators used in the AEPS systems are usually self-excited brushless synchronous machines (BSG) with or without sub exciter, so-called three-stage or two-stage machine respectively [8, 9]. Such a construction with rotating rectifier bridge eliminates the necessity of using slip rings so the whole device requires much less maintenance and is more reliable. Fig. 1 and Fig. 2 present respectively the two-stage and three-stage structure of the modern BSG. The three-stage machines are widely used in the Aircraft Electrical Power Systems (AEPS) as the small excitation current of the AC exciter in comparison to the nominal current of the main generator enables to use much smaller and lighter Generator Control Unit (GCU) [5]. The GCU controls the main generator voltage by changing the excitation current of the exciter. Above mentioned weight, volume and also reliability criteria in the aircraft industry has led over the years to significant advance in the AEPS and by extension in the BSG construction and design [3, 6].

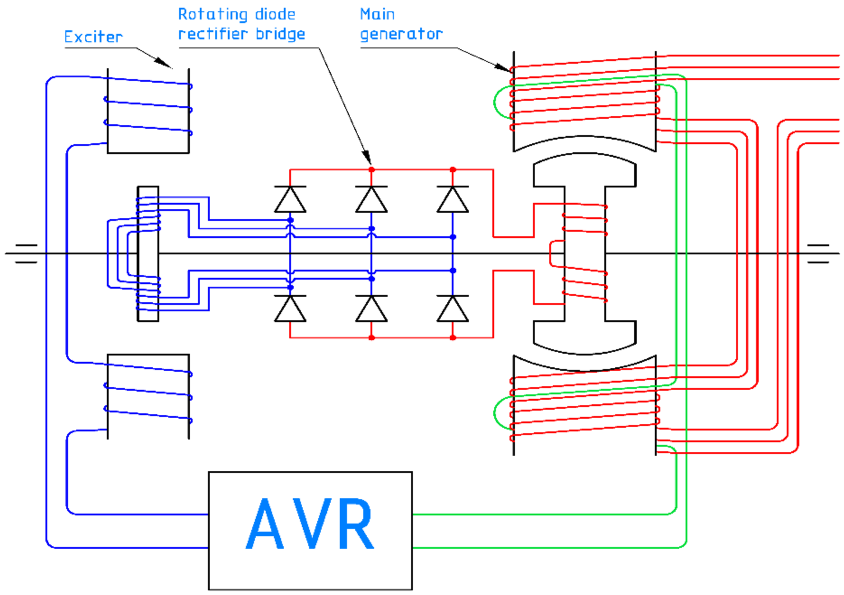

Fig. 1. Two-stage structure of the modern brushless synchronous generator

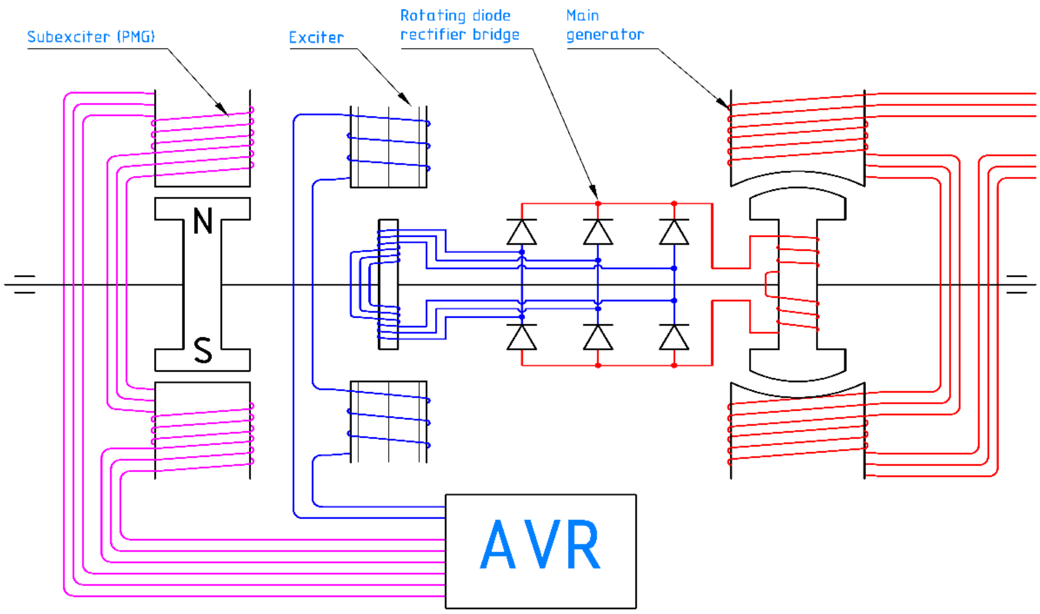

Fig. 2. Three-stage structure of the modern brushless synchronous generator

Mechanical energy delivered to the synchronous generator can be provided by water flow, high-pressure steam, wind or by some external torque source like a jet or a combustion engine, which need to be started up. Therefore, recent research on BSGs has focused on possible utilisation of the BSG as the starting device [2, 10]. This increasing demand for the integrated starter/generator (ISG) systems is especially seen in the More Electrical Aircraft (MEA) projects where aircraft become more and more dependent upon electrically powered services replacing hydraulic and pneumatic systems.

In the stationary AEPS which is used as the CHP system the synchronous generator is usually coupled with a combustion engine powered by petrol, diesel, compressed natural gas (CNG) or more and more often by a biogas. In the traditional power generation unit the combustion engine is started by a dedicated starter, usually small DC motor. Therefore, two electric machines and two standards of supply voltage are required. In order to avoid this disadvantage the BSG has to be used as the integrated starter/generator system (ISG). In the further parts of the article, the possibility of the electric power generation unit start-up using the three-phase brushless synchronous generator with an AC exciter has been investigated.

2. Two-stage synchronous machine start-up

In conventional synchronous machine, the main field winding is excited by a direct current throughout the brushes and the slip rings. In the BSG construction, these elements have been eliminated by adding to the machine shaft an AC exciter with the diode bridge rectifier. This AC exciter is in fact a reversed synchronous machine with a stationary DC field winding and a rotating armature. In this way, when the machine rotates the field winding of the main generator is excited by the rectified voltage coming from the AC exciter. Therefore, the control of the main generator excitation current is obtained by adjusting the DC field current of the AC exciter. This adjustment is usually realised by the Automatic Voltage Regulator (AVR), which can be powered in one of three ways:

- directly from the machine terminals via voltage transformer,
- by additional winding placed on the armature of the main generator (Fig. 1),
- by additional Permanent Magnet Generator (PMG) mounted on a common shaft (Fig. 2).

The first two methods require existence of residual magnetism or adding small pieces of permanent magnets to the exciter (i.e. PMI – Permanent Magnet Insertion) for initial voltage building.

Basically, there are two types of synchronous machine start-up – synchronous and asynchronous one.

For asynchronous start-up rotor of the machine has to be equipped with a “squirrel cage” induction winding with specific number of bars, which allows to generate an electromagnetic torque and to accelerate the machines rotor near to the synchronous speed. Then, the field winding is excited and the rotor pulls into synchronization. This kind of start-up is not appropriate for the brushless synchronous generators because the main field winding cannot be shorted by a resistance (lack of the slip rings) and the induced high voltage would damage the rectifier diode bridge.

To overcome the problems with the induced voltage one has proposed the synchronous start-up with the use of a variable frequency drive (VFD). This approach requires main field winding to be exited during standstill. This can be done by supplying the field of the AC exciter with an alternative current as the AC exciter operates in standstill conditions as an air core transformer under the condition that the exciter stator core is laminated (Fig. 3).

Fig. 3. Laminated stator core of the brushless synchronous generator exciter

3. Laboratory stand

The studied power generation unit consists of the internal combustion engine Fiat 0.9 TwinAir CNG 80 HP that can be powered by a biogas and the three-phase brushless synchronous generator MeccAlte 16 kW with an AC exciter. Electrical and mechanical characteristics of the generator can be found in Tab. 1.

Tab. 1 Electrical and mechanical characteristics of the MeccAlte ECP 3-2/2L brushless synchronous generator

Parameter	Value
Frequency	50 Hz
Voltage (series star)	400 V
Rated power class H	20 kVA / 16 kW
Regulation with	DSR (±1% with any power factor and speed variations between -5% and +30%
Insulation class	H
Execution	brushless
Stator winding	12 ends
1,93Rotor	with damping cage
Reactances	X_d=193% / X_q=101%
Rated impedance	Z_n=7.967 Ω
Excitation at no load	0.35 A
Excitation at full load	1.27 A
Overload (long-term)	1 hour in a 6 hours period 110% rated load
Overload (per 20 sec.)	300%
Stator Winding Resistance (20°C)	0.221 Ω
Rotor Winding Resistance (20°C)	9.627 Ω
Exciter Resistance (20 °C)	rotor 1.453 Ω / stator 15.71 Ω
Protection	IP 23
Weight of wound stator assembly	27 kg
Weight of wound rotor assembly	14 kg
Weight of complete generator	88 kg
Maximum overspeed	4 500 rpm
Noise level at 1m/7m	85 / 70 dB(A)

Combustion engine is coupled with the generator by a shaft with Cardan joints. No transmission is used. The whole equipment is embedded on the steel construction with rubber wheels. Fig. 4 presents the visualisation of the future look of the designed power generation unit.

Figure 5 presents measurement setup used to investigate electrical characteristics of the AC exciter. It consists of the Agilent oscilloscope with two voltage probes and several digital multimeters. As the voltage source for the field winding excitation of the exciter, a one-phase 230 V autotransformer has been used. Therefore, the frequency of the exciter excitation has been fixed on 50 Hz. One has to take into account that during acceleration of the machine the induced excitation current of the main field winding will be variating from minimum when the exciter rotor is in q axis position to the maximum when the exciter rotor is in d axis position. This undesired feature is problematic especially during start-up from standstill, as we do not know what the actual position of the rotor shaft is. The studied BSG is equipped with the AC exciter with three pairs of excitation poles, which means that the neuralgic rotor speed is about 1000 rpm.

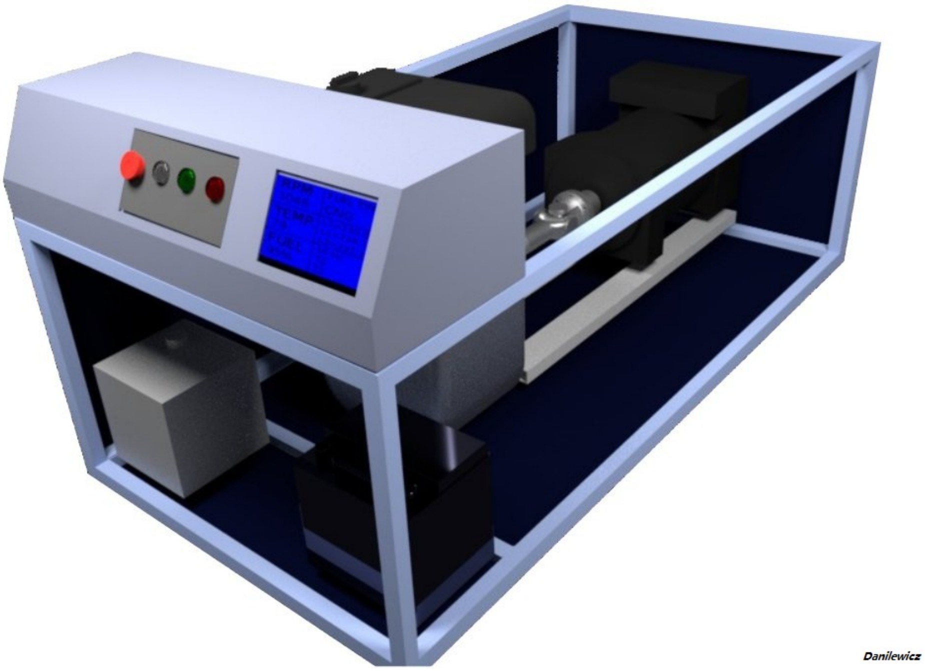

Fig. 4. Visualization of the designed power generation unit

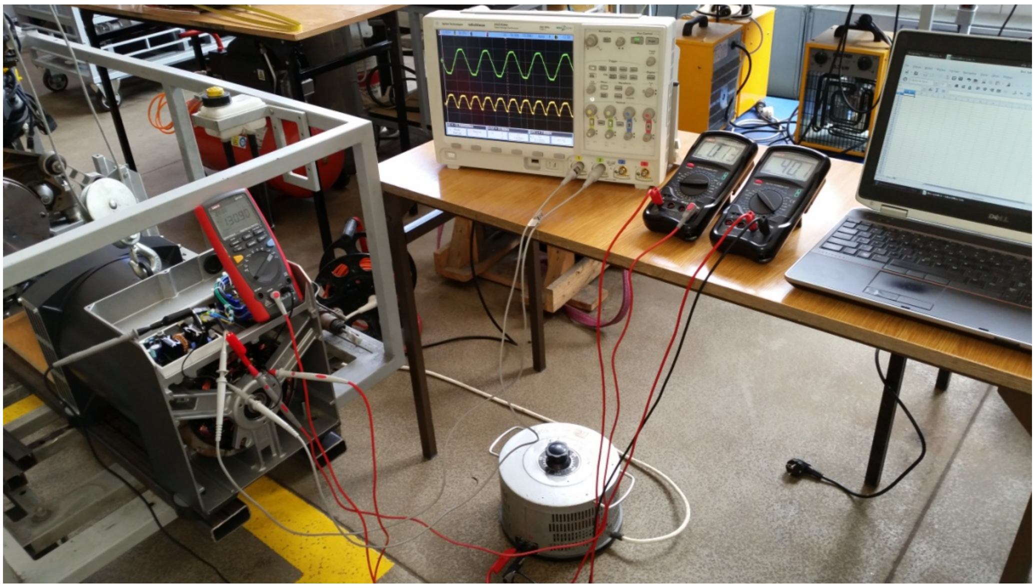

Fig. 5. Measurement setup for the AC exciter characteristics study

4. Experimental results

Value of the BSG torque needed to start-up the spark ignition combustion engine can be evaluated using approximate empirical relation (1):

$$M_e = 30 \cdot V_e, \tag{1}$$

where:
M_e – braking torque [Nm],
V_e – volume of the engine [dm^3].

For the Fiat 0.9 TwinAir CNG 80 HP engine this value is about 27 Nm. In order to start-up the spark ignition engine, it has to be accelerated to the speed of about 50 rpm. Using formula (2) one can estimate the approximate power of an adequate starting device, which should be about 140 W.

$$P_s = \frac{M_e \cdot n}{9550}, \tag{2}$$

where:
P_s – starter power [kW],
n – shaft speed [rpm].

Torque generated by the studied BSG can be calculated using the formula (3) and the approximated relation for induced voltage in synchronous machine motor mode (4):

$$M_s = 9.55 \cdot \frac{m}{n} \cdot \left(\frac{U \cdot E_f}{X_d} \cdot \sin \vartheta + \frac{U^2}{2} \cdot \frac{X_d - X_q}{X_d \cdot X_q} \cdot \sin 2\vartheta \right), \tag{3}$$

$$E_f = 0.95 \cdot U, \tag{4}$$

where:
m – number of phases,
U – phase voltage [V],
E_f – induced voltage [V],
X_d – direct-axis reactance [Ω],
X_q – quadrature-axis reactance [Ω],
ϑ – power angle [rad],

The maximum torque is obtained for the power angle equal to 90°. Its value for the synchronous speed is then equal to about 31 Nm, which is sufficient for spark ignition combustion engine start-up.

In order to excite the main field winding via the rectifier diode bridge the exciter field winding has been supplied with alternative voltage variating from 0 to 100 V. It resulted in the main field excitation current variating from 0 to 0.6 A. Fig. 6 presents the exciter armature to field current relation when the exciter rotor is in d axis position.

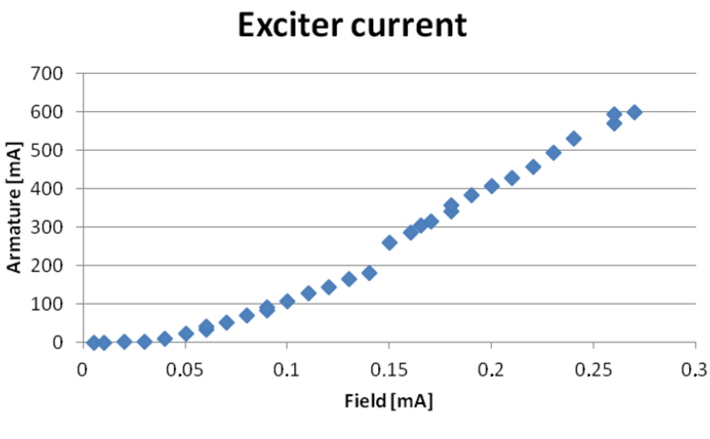

Fig. 6. Exciter armature to field current relation in d axis

5. Conclusions

The article presented the feasibility study of using the three-phase brushless synchronous generator with the AC exciter as a starter for the spark ignition internal combustion engine. Obtained results showed that the MeccAlte 16 kW BSG is able to start-up the Fiat 0.9 TwinAir CNG 80 HP engine. Further studies will focus on the realisation of the start-up control using programmable logic controller (PLC). Moreover, the output power of the generation unit powered by the biogas will be investigated [1]. Presented setup will be used as the stationary Autonomous Electrical Power Systems (AEPS). In the scope of further studies, the Combined Heat and Power (CHP) generation is also included.

Acknowledgement

We would like to thank Tomasz Danilewicz for his useful help with laboratory stand construction and measurement setup preparation.

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