Generator Solutions For Stand Alone Pico-Electric Power Plants

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***Abstract*- This paper presents several solutions for stand alone pico-electric power plants, which are used for electric energy production from water power. Up to now, the induction and permanent magnet synchronous generators were studied and presented as best variants for small power generation. Another topology is proposed here: a hybrid excited synchronous generator, based on two different types of excitation field: permanent magnets and auxiliary winding. By means of simulations and tests this paper depicts a comparative study for the most suited pico-generator for stand alone hydro-plants.**

***Key words*- hydro-generators, pico-electric power plants, hybrid excited synchronous generator.**

I. INTRODUCTION

The exploitation of renewable energy sources to increase power generation or to suite the conventional exhausting ones, as a matter of necessity is an established procedure witch comes extremely important in our days. Among the sources which can be exploited small hydro, wind, and biomass are proving to be in the forefront of power generation. Feeding such generated power to utility interconnected grids has often become invisible and it is not always of convenient efficiency. Therefore, a stand alone autonomous unit to feed local consumers using such renewable energy sources is a very good and quite efficient option (even if it is situated in a site where the grid is available).

There are a lot of researches undergoing in the field of the pico-electric (1÷10 kVA) power plant, which must be simple, rugged economically and user-friendly [1]-[7]. Considering the very large number of existing rivers (in Europe, in this case) it means that a tremendous power amount can be produced at very low cost and with a small initial investment only by using these hydro potential sites. For the pico-hydro power plant until now mainly only two variants of generators were considered [1]:

- the induction one (with the squirrel cage, IG, or doubly fed, DFIG), and
- the permanent magnet synchronous generator (PMSG)

The present work proposes a new solution in this field: a hybrid excited synchronous generator (HESG) having double excitation source: permanent magnets (PMs) and an auxiliary winding place on the rotor core. By means of simulations and tests the authors will present a comparative work on the main suited solutions for pico-generators in order to emphasize their advantages and drawbacks.

II. GENERATORS UNDER STUDY

Several solutions suited for generator applications in general, and for hydro-generator in particular, were studied. The global layout for such a system is given in Figure 1a (here, the block "G" can be seen as any kind of the studied generator). Also, the electric circuit added for each specific configuration is presented in Figure 1b-d.

From the electrical machine's point of view, the cheapest and simplest variant is the IG, having the excitation assured via a capacity bank (Figure 1b), which is linked to the three phase stator winding. It is well known that the disadvantage of such a topology is due to is poor efficiency and to its limited propeller speed.

The second variant under study is based on a DFIG. The rotor's three phase winding is supplied via a 3-phase converter. The main drawback of this topology is its poor efficiency and relatively high cost. But it can assure the desired induced voltage since the speed can be easily varied.

The third studied topology is a PMSG, which is linked into the circuit via two converters, as it is shown in Figure 1c. In this case the converters are placed just between the generators. The efficiency is better, but the PMs price and the limited speed variation capability are the major drawbacks.

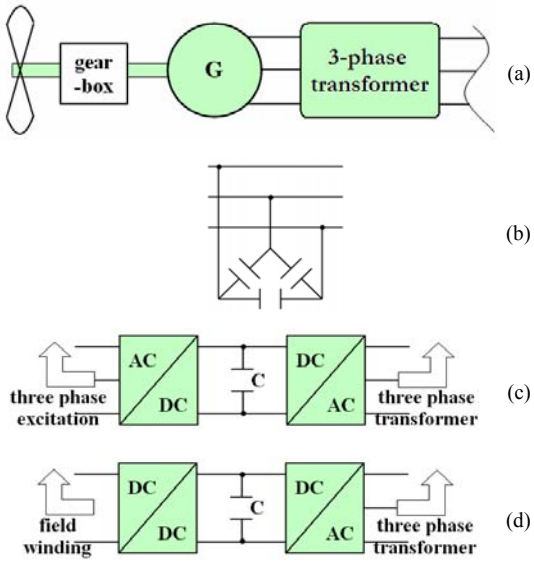


Figure 1 The hydrogenation: (a) basic layout; (b) capacitors bank for IG; (c) power converter unit for DFIG (or adapted, for PMSG); (d) power converter unit for HESG.

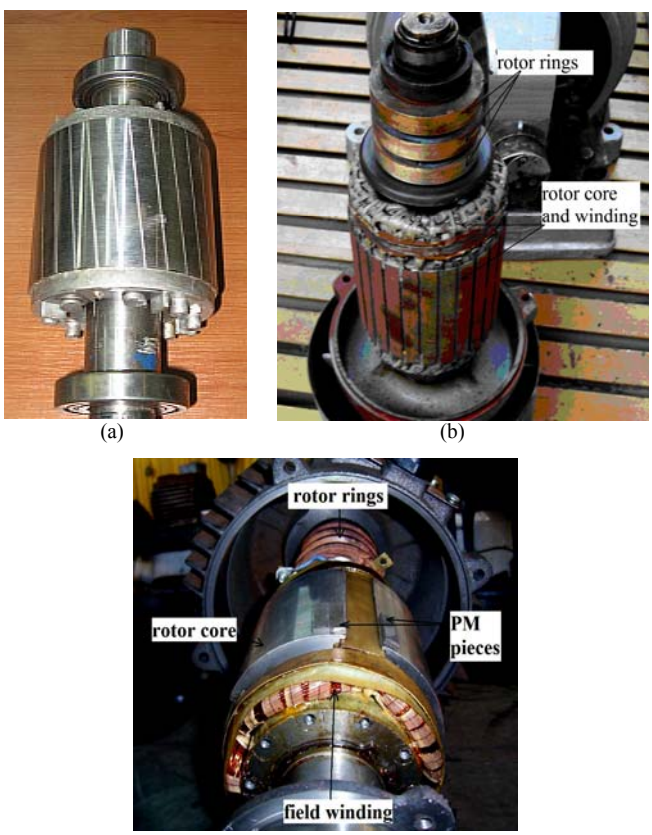
Finally, a HESG was studied for power generation (Figure 1d). The main excitation field component is generated by high quality PMs (of NeFeB type). A second auxiliary electromagnetic field winding, supplied in dc, is placed on the rotor core. The electric circuit associated to this variant is given in Figure 1d. Even if it is not the cheapest solution, it can be stated that even for speed values below or above rated one, the necessary induced voltage can be assured by supplying the auxiliary windings in the way of producing an auxiliary field:

- in opposition with the main field given by the PMs (field wakening) - if the speed and the induced electromotive force (emf) are grater than the rated values
- in the same direction with the magnets field (field strenthening) - if the speed or the voltage levels are below the rated values.

Of course, the voltage level can be controlled via specific power converters (generally if the induced voltage is higher than the rated one), but for speeds below the rated one, the necessary amount of electric power is no longer sufficient. In the case of HESG the investment made for the electronic device and control technique can be reduced, while the desired electric power can be also maintained.

III. The Studied Generators

The rotors of the studied generators are presented in Figure 2a-b-c: for IG, DFIG and HYSG, respectively.



(a) (b) (c)

Figure 2 The rotors of the studied generators: (a) IG, (b) DFIG, (c) HESG.

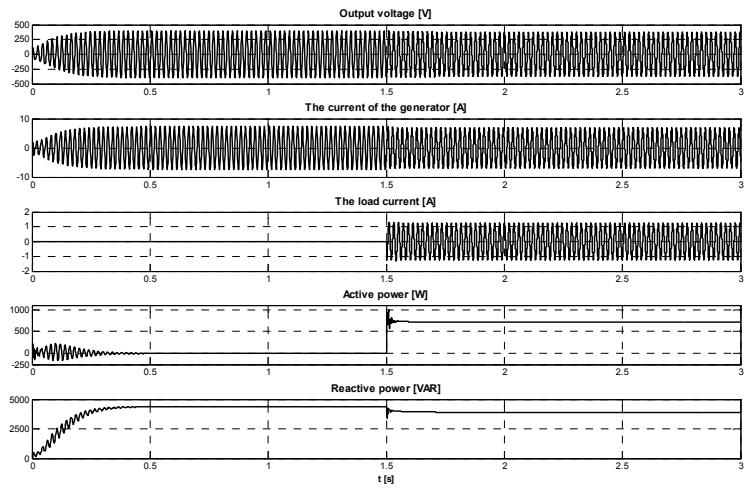
As the first two variants are well-known in the technical literature, the last one will be presented in detail [8]. As it can be seen from Figure 2c the PMs are placed on the rotor poles (made of steel sheets in order to reduce iron losses). In addition an auxiliary concentrated winding is placed around each rotor pole. This field winding is fed with dc current and is placed just under the PMs polar pieces in order to act directly on the main field.

IV. Results

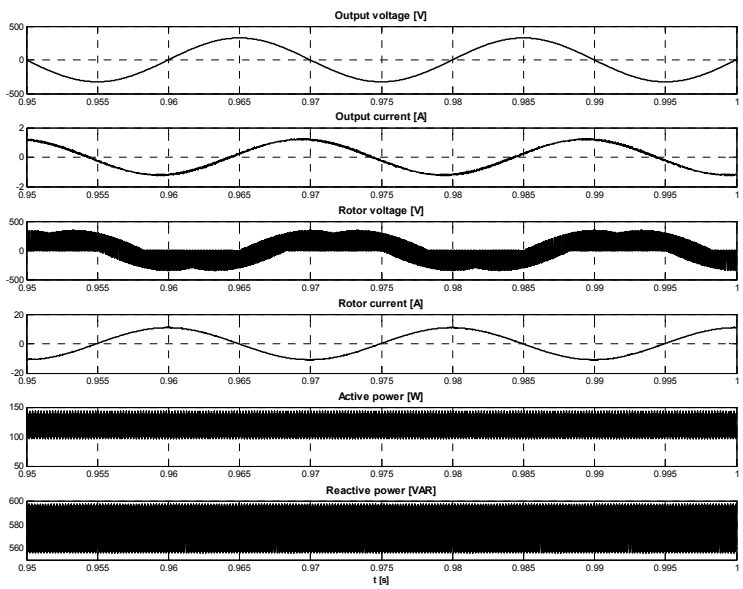
A. IG and DFIG results

Next results of the simulations will be presented.

The IG was rotated with its rated speed, 1500 rpm. The generator is started at no-load, only after 1.5 s the load is coupled to the generator. The main results of this simulation are given in Figure 3a.



(a)



(b)

Figure 3 Simulation results: (a) IG; (b) DFIG.

Studying Figure 3a it can be clearly seen the effect of coupling the load at 1.5 s: the load current appears, the active power produced by the induction generator is also increased. The reactive power, the terminal voltage and the current through the generator are a little bit decreased.

Studying the results for the DFIG given in Figure 3b both the stator and rotor currents have a sinusoidal waveform. The rotor voltage waveform is chopped due to the inverter. In the simulated conditions the doubly fed induction machine was delivering to the grid in steady-state regime the following active, respectively reactive power: $P = 132$ W, respectively $Q = 568$ VAR.

Laboratory tests were performed using the IG.

The squirrel cage induction machine in study has the following main data:

i.) Type: AST 1129284
ii.) Rated power: 3 kW
iii.) Rated voltage: 220/380 V (Δ/Y)
iv.) Rated current: 11.4/6.61 A (Δ/Y)
v.) Rated speed: 1430 rpm.

The laboratory setup is given in Figure 4. The induction generator under study was rotated by a dc motor connected to its shaft.

The electrical circuit of the test bench is given in Figure 5.

Next, in order to validate the simulations of the IG. The results presented in Figure 6 are for the steady state regime when the IG was speeded up to its rated speed and in both cases the same load is coupled to its terminals. As it can be seen the two sets of results are closed.

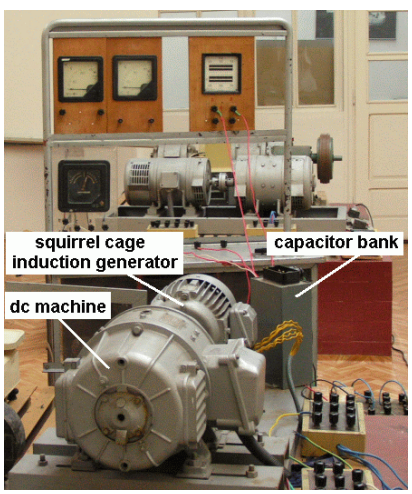


Figure 4 . The laboratory setup used for testing the squirrel cage IG

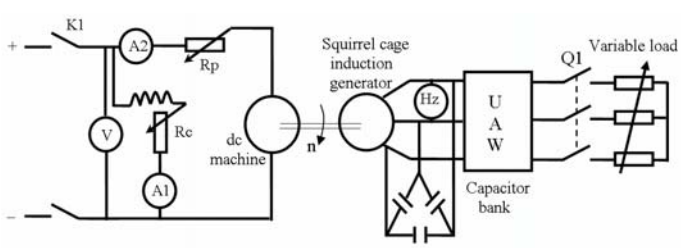
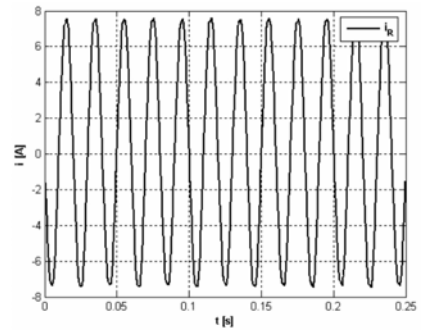
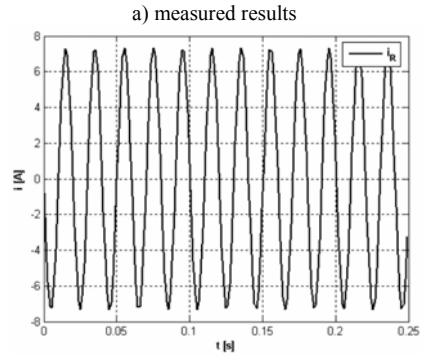


Figure 5. The electrical scheme of the test bench



a) measured results



b) results obtained by simulations

Figure 6. Comparison of the results

B. HESM results

The machine under study is of 5 kW, 1500 rpm and 380 V ac line voltage. The auxiliary winding is supplied on dc. For the HESM, the main results, simulated and tested, are given in Figure 7-Figure 10.

In the case of a real application, for a small farm for example, where all the electric equipments are connected to the same grid, the voltage has to be maintained constant. A specific converter can assure a smooth level of voltage (even for values below or beyond the rated voltage), but the electric power will not be the same. Here comes the advantage of the proposed HESM. By supplying the auxiliary winding with dc current, it is possible to maintain the voltage, and also the power at desired levels.

In order to evaluate the HESM performances working in generator regime and the influence of auxiliary winding supplied with a dc current, it has been employed a numerical analysis via finite element method (FEM).

For several levels or rotor speed it has been computed the induced emf when no-load has been considered, Figure 7. Thus, one can see the induced voltage increasing/decreasing while the speed is increased/decreased. This means that the generated voltage (and finally electric power) varies correctly with the rotor speed.

The speed variation was controlled in this way, see Figure 7:

- 1st stage (0..0.15 sec): from zero to 1500 rpm, the HESM induced emf increases up to the rated voltage
- 2nd stage (0.15..0.325 sec): the propeller was accelerated up to 1800 rpm. The induced voltage surpasses the rated one. No converter controlled was used for the decrease of the induced emf, and only the auxiliary winding was

supplied in order to obtain again the desired rated voltage (the PMs flux was decreased this time, due to the current which flows into the rotor turns)

- 3rd stage: the speed was decreased to a value below the rated one, 1300 rpm. This time, the applied auxiliary voltage is negative, so the induced emf is assured via a negative current which flows into the auxiliary winding (the flux is increased in this stage).

The same kind of study has been employed for the HESM for load operating, Figure 8. The same levels of speed have been considered and the desired induced emf has been maintained constant (except the speed transient zones, off course) by supplying the auxiliary winding with '±auxiliary_voltage', while the auxiliary current flowing through the rotor coils assures the needed electric current (and finally, the electric power) – see the 3-phase load current in Figure 8.

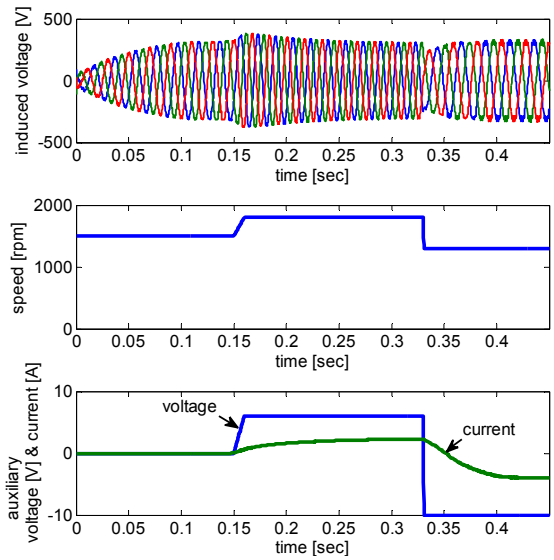


Figure 7 HESM: induced EMF for several speed values (FEM analysis).

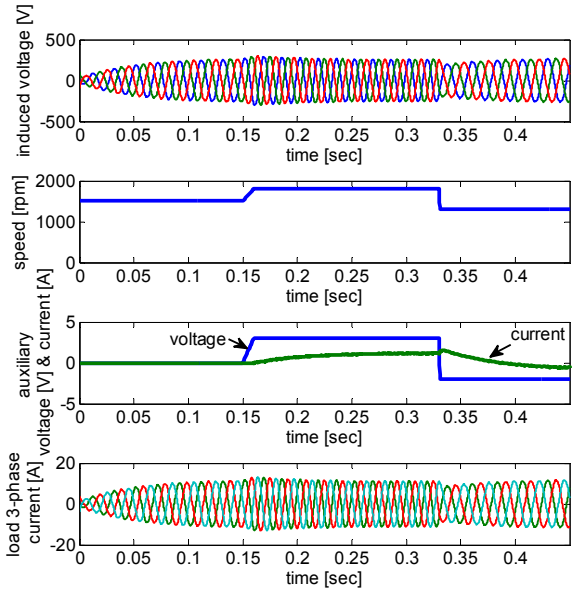


Figure 8 HESM: generator-load operating regime (FEM analysis).

Two remarks should be made concerning the obtained results. The 1st one is related to the fact that the auxiliary winding is supplied with less voltage for the load operating: this is due to the fact that the induced voltage is less that the one studied in the no-load case. The 2nd remark regards the fact that the frequency varies with the rotor speed (see the emf and load current wave-forms): this should be corrected with a specific static converter (case not discussed here) which can be employed to assure the desired frequency; anyway, the clear advantage of the HESM is given by the fact the output power can be controlled at rated values (for important variations of the speed, beyond and below rated values) while for a common generator system, the static converter controls only the levels of frequency and voltage amplitude for example.

So, the HESM under study is connected to a virtual propeller and analyzed in generator regime. By numerical analysis or measurements the authors have evaluated the influence of the dc auxiliary current (called excitation current, I_{ex}) on the emf level. By supplying the excitation coil with a $\pm I_{ex}$, two operating zones can be distinguished: one zone where the main flux is weakened, called the flux weakening zone, and another zone where the flux is strengthened, also called flux strengthening zone, Figure 9.

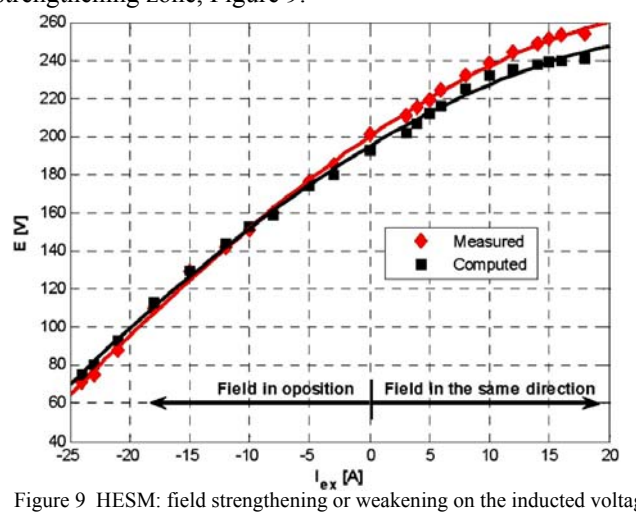


Figure 9 HESM: field strengthening or weakening on the inducted voltage characteristic.

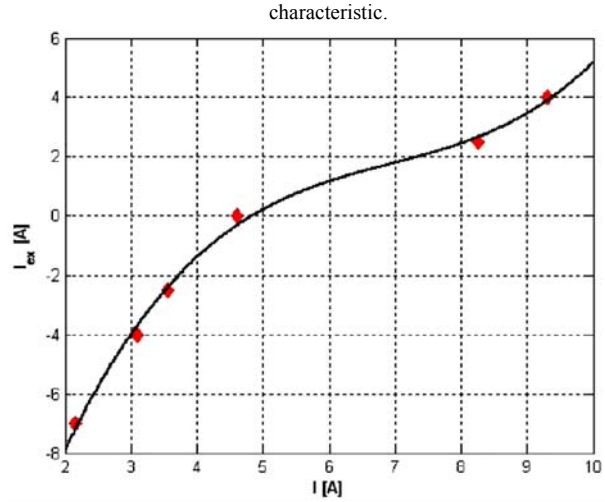


Figure 10 HESM: excitation vs load currend for 190 V induced voltage.

In Figure 9 are presented the two zones of HESM operation in generator regime. It was obtained, in safe conditions, a 3 times decrease of the induced emf. Also, in flux strengthening, from a given value of the excitation current, one can see the iron saturation phenomenon, when the supplied dc current is no more useful in the delivered electric power.

(The "safe conditions" refers to the fact that the thermal stability limit of the PMs is not surpassed, and the risk of irreversible demagnetization limits is maintained above the risk point [9], [10].)

Another important advantage of the HESM is presented in Figure 10; this time in load operating. It can be seen that at a very large variation of the load the output voltage can be maintained constant by varying the auxiliary field winding. This case cannot be tested on ordinary synchronous machines (excited through PMs or electromagnet). This is a very important issue regarding the generating operation of the HESM, and it should be very carefully considered.

V. Conclusions

This paper presents a comparative study on the generator solutions for stand-alone pico-electric power plants. From the electrical machine point of view, the most common generator solutions are: the induction generators (squirrel cage, IG, or doubly fed, DFIG) and the permanent magnet synchronous generator (PMSG). Here, a novel solution is proposed: the hybrid excited synchronous generator (HESG).

Simulations and measurements were employed for the IG, DFIG and HESM, thus proving their operability. Having in mind their performances, it can be concluded with the following:

- for the IG: it is the cheapest solution, the voltage regulation can be easily employed, but a capacitor bank is needed in order to have the generated electric power. From the power electronics point of view, the IG solution is the simplest variant. The capacitor bank increases the system price and also reduces the lifetime of system operation (due to the number of operation cycles). Another disadvantage is related to the speed variation limitation: the electric power is obtained only when the synchronous speed is surpassed. Also, the efficiency of the system is quite reduced.
- for DFIG: the supplementary power electronic equipments needed for rotor winding supply increases slightly the system costs, but a large amount of speed variation can be considered for electric power generation. The most important disadvantage for DFIG is its poor efficiency and the fact that the generated power exists only if the rotor winding is supplied (there is also a sliding contact to remind as a drawback).
- for HESM: the electrical machine's price is two times bigger than the classical squirrel cage topology, due to the permanent magnets (PMs) price. It can be seen also as a drawback the auxiliary source as well as the sliding contacts, while the dc rotor winding is supplied. On the other hand, the electric power is generated in any conditions (even for low speeds and auxiliary winding not supplied), due to the PMs induced electromotive force. Also, this power can be maintained constant even below and beyond the rated speed since the rotor winding can be supplied in order to produce a flux in opposition (if speed exceeds the rated value) or in the same direction (if speed is below the rated value) with the PMs field. Moreover, the HESM is working very well in load conditions, since the necessary amount of power can be guaranteed while the rotor coil is supplied, with no irreversible demagnetization risk.

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