Design and Implementation of an Autonomous Wind/PV/Diesel/Battery Power System

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***Abstract*-This paper deals with the design, implementation and experimental analysis of a complex hybrid power system based on renewable energy sources. The optimal design of the Wind/PV/Diesel/Battery power system of 5kW peak power was carried out using Homer software package. The system implementation includes important contributions related to the execution and systemic integration of various components such as: pure sine-wave inverter with galvanic isolation, electronic unit for batteries charging from Diesel-electric generator, intelligent control unit that turns on/off the Diesel-electric generator depending on the battery State Of Charge (SOC), wind turbine emulator composed of a vector control induction motor drive system and a special designed PM synchronous generator, etc.**

I. INTRODUCTION

The increasing concerns of mankind regarding the long-term energy security issue opened the way for a rapid development of renewable energy harnessing technologies based on: solar energy, wind energy, tidal and wave energy, biomass etc.

Among the renewable energy sources with important potential of conversion into electricity, privileged positions are occupied by the wind and solar energy sources. The wind/solar energies conversion technologies into electricity by means of wind turbines and PhotoVoltaic (PV) panels respectively are clean, reliable and silent, with small maintenance costs and reduced ecological footprint.

In autonomous regime, a hybrid electric power system based on a combination of wind/solar energies becomes in many cases more reliable in comparison with a single energy source system (wind only or solar only) since the wind and solar energies compensate each other naturally (higher solar radiation and weaker winds during the summer months and lower solar radiation and stronger winds during the winter months) [1]-[3].

Autonomous electric power systems based exclusively on wind turbines and PV panels are not secure due to the fluctuant character of the wind/solar energy potential. To increase the electric power supply security of the local grid, these power systems are typically backed-up by Diesel-electric generators for periods without sufficient wind and solar radiation and by deep cycle batteries for energy storage [4].

Various aspects were studied lately about hybrid power systems, such as frequency stability [5], optimal sizing [6], development of simulation models [7], analysis of control strategies [8], etc.

The objectives of this paper refer to the design, implementation and experimental analysis of a Wind/PV/Diesel/Batteries hybrid power system. The principle arrangement of the studied power system is presented in Fig. 1.

The research activity at the basis of this paper is complex, with important contributions related to the execution of various system components (pure sine-wave inverter with galvanic isolation, electronic unit for batteries charging from Diesel-electric generator, intelligent control unit that turns on/off the Diesel-electric generator depending on the battery State Of Charge (SOC), wind turbine emulator composed of a vector control induction motor drive system and a special designed PM synchronous generator, etc.) and to their integration in the power system.

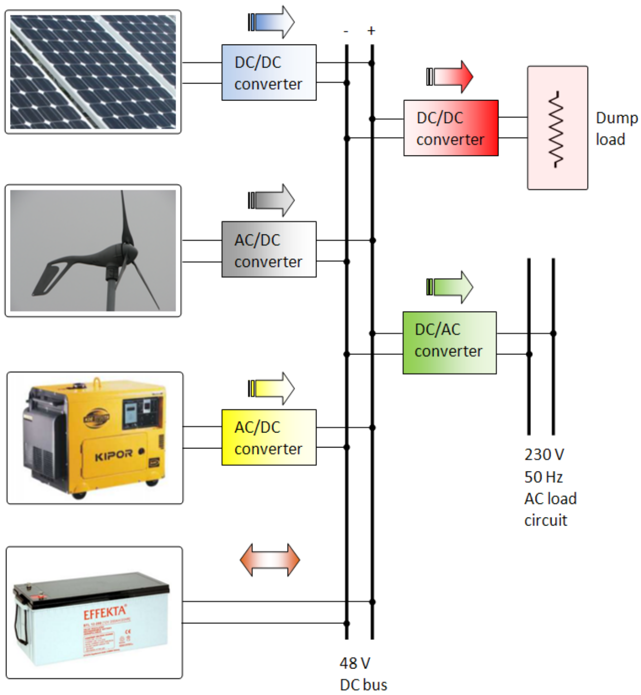


Fig. 1. Hybrid electric power system (Wind/PV/Diesel/Batteries).

The maximum power delivered by the system to the local grid is 5 kW, the system being designed for an average electricity consumption of 90 kWh per month, adequate for a small household or a holiday house equipped with energy efficient appliances.

II. Power System Design

A. *Estimation of Local Wind/Solar Potential*

The components of the power system are sized by taking into account the wind/solar potential of the installation site as provided by NASA Langley Research Atmospheric Science Data Center, Table I [9]. Ideal locations for hybrid wind/PV systems are those characterized by strong average wind speeds and high solar irradiation. In Bucharest area the daily solar radiation level can reach about 3.64 kWh/m^2 and the wind annual average speed at 70 m altitude is about 5.34 m/s.

TABLE I
WIND (70 M HUB HEIGHT) & SOLAR POTENTIAL IN BUCHAREST, ROMANIA

Month	Daily radiation	Clearness index	Wind speed
	kW/m^2		[m/s]
1	1.50	0.43	5.64
2	2.19	0.44	5.78
3	3.22	0.45	6.77
4	4.29	0.46	6.00
5	5.57	0.51	4.92
6	6.05	0.53	4.87
7	6.14	0.55	4.24
8	5.49	0.56	4.35
9	3.95	0.50	4.71
10	2.53	0.44	6.14
11	1.56	0.40	5.16
12	1.18	0.39	5.51

The hub height of the wind turbine of the power system is about 20 m and the wind speed at this altitude is not known. However this value can be estimated based on the data in Table I (that correspond to 70 m altitude), using two mathematical models presented below (logarithm and exponential types):

$$V(z) = V(z_r)(z/z_r)^{\alpha} \tag{1}$$

$$V(z) = V(z_r)\frac{\ln(z/z_0)}{\ln(z_r/z_0)} \tag{2}$$

where: z is the current height, V(z) is the wind speed at current height z, z_r is the reference height (in our case 70 m), z_0 is the terrain roughness factor, α is the speed variation exponent.

The speed variations obtained by applying the two models are presented in Fig. 2 and their profiles are very similar. Thus if at 70 m the wind speed is 5.34 m/s, at 20 m the average wind speed decreases at about 4.18 m/s (mean value obtained by the two models).

The system design will take into account therefore monthly mean wind speeds computed by averaging the values obtained by the two models proposed above as shown in Table II.

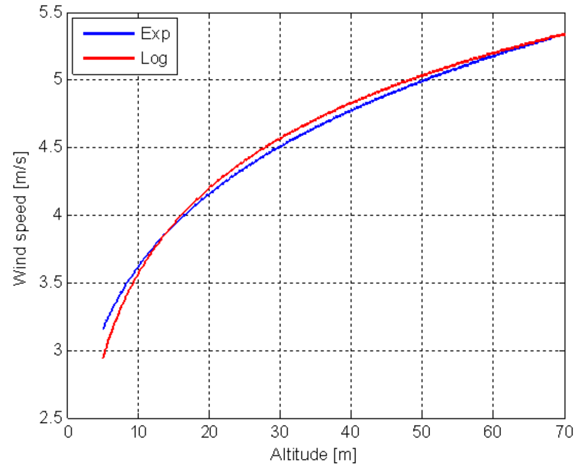


Fig. 2. Wind speed vs. hub height using logarithmic and exponential models, for z_r = 70 m, $V(z_r)$ = 5.34 m/s, z_0 = 0.2 and α = 0.2.

TABLE II
WIND POTENTIAL (20 M HUB HEIGHT) IN BUCHAREST, ROMANIA

Month	Wind speed
	[m/s]
1	4.41
2	4.52
3	5.30
4	4.69
5	3.85
6	3.81
7	3.32
8	3.40
9	3.68
10	4.80
11	4.04
12	4.31

B. *Imposed Daily Load Profiles*

The imposed daily load profiles (average monthly data) for which the power system was designed are shown in Fig. 3. The load profiles differ from a day to another by means of a randomness factor to make the data more realistic.

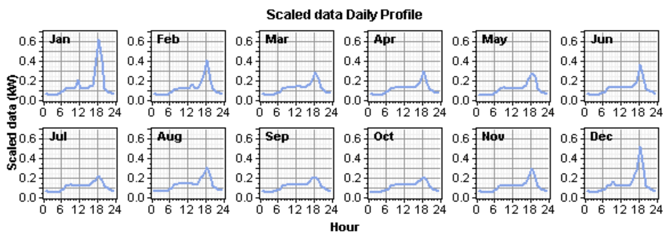


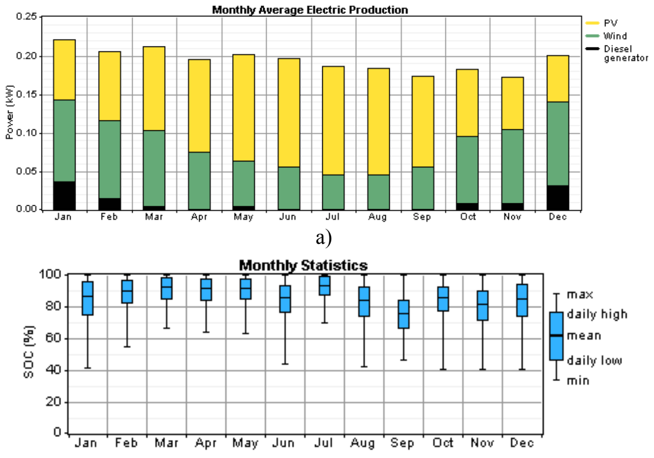
Fig. 3. Daily load profiles (average monthly data).

C. *Optimal Sizing of System Components*

The optimal sizing of the hybrid system components used the HOMER software package developed by the National Renewable Energy Laboratory (NREL) [10]. HOMER is a useful tool dedicated to the analysis and optimal sizing of power systems based on renewable sources, able to identify optimum technical and economical solutions by taking into account the renewable energy potential, the load curves, the user constraints, the replacement and maintenance costs, the fuel price etc. [11]-[12].

By a detailed numerical analysis carried out using HOMER software package, the optimum power system configuration was identified and it is composed of: 4 PV panels (175 Wp each panel) with a total peak power of 700 Wp, 2 small power wind turbines of 400 W, 4 series connected batteries of 12V and 200 Ah, a Diesel-electric generator with 5 kVA maximum output power and a 5 kVA inverter. The monthly average electric power generated by the system is shown in Fig. 4 along with the batteries SOC.

In order to ensure the electric power supply continuity during the periods without sufficient solar radiation (January - May and October - December), the hybrid system requires an estimated quantity of about 30 liters of fuel per year for the operation of the Diesel-electric generator.



a)

b)

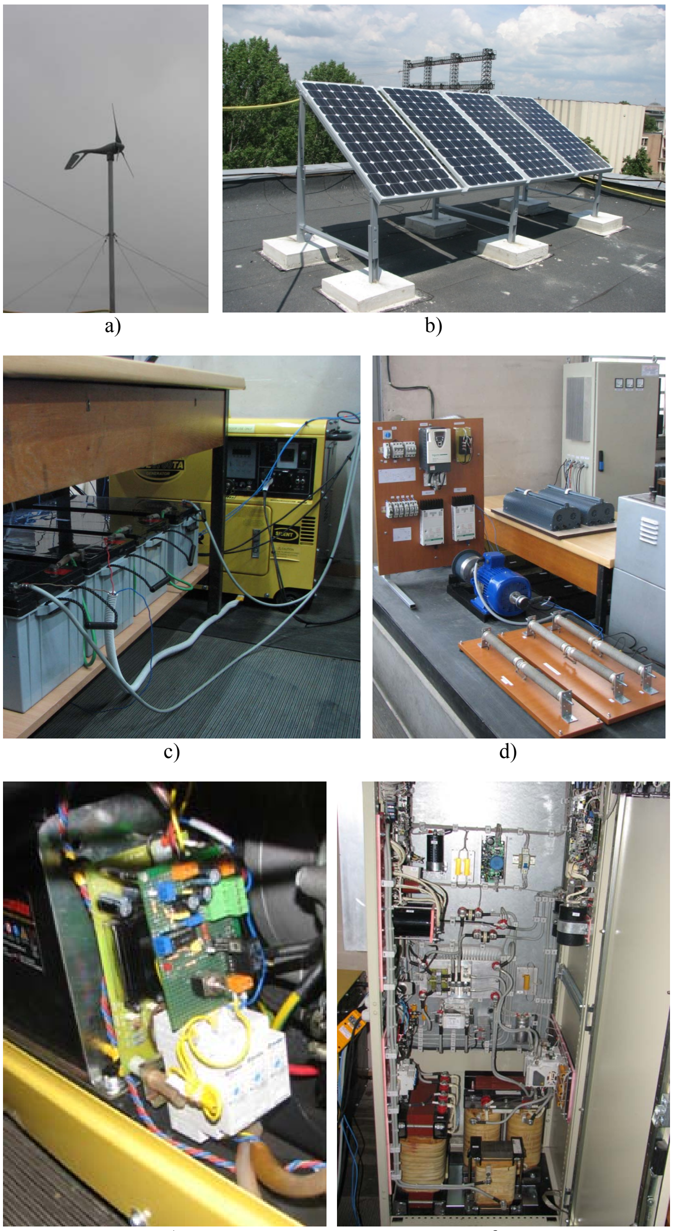
Fig. 4. Results estimated by HOMER software; a) average monthly electric power produced by the hybrid system; b) average monthly batteries SOC.

III. IMPLEMENTATION OF THE HYBRID POWER SYSTEM

Based on numerical simulations carried out using HOMER software package, the hybrid power system was implemented at the University Politehnica of Bucharest, as shown in Fig. 5. The system components are represented by:

- 4 mono-crystalline PV panels of Suntech 175S type, with rated data: 175 Wp and 24 V,
- 1 AirX 400 wind turbine with rated power 400 W [13],
- 1 wind turbine emulator composed of a vector controlled induction motor (rated power 1.5 kW and rated speed 940 rpm), supplied from an AltiVar71 inverter that drives a specially designed PM synchronous generator [14], connected to a battery charging device,
- 1 Kipor KDE 6700 TAO type Diesel-electric generator with rated power 4.5 kVA,
- 4 series connected batteries of Effekta BTL 200 type, characterized by the rated data: 200 Ah and 12 V,
- 1 pure sine wave inverter with galvanic isolation and rated output data: voltage 230 V ± 5%, frequency 50 Hz ± 1Hz, harmonic content THD ≤ 5%,
- 2 DC/DC converters of Xantrex C40 type, used for battery charging from PV panels and for dump load control,
- 1 AC/DC converter used to charge the batteries from the Diesel-electric generator and to deliver electric power to the local grid,
- intelligent control unit used to switch on/off the Diesel-electric generator depending on the batteries SOC, Fig. 6,
- dump load used when the batteries are fully charged and the wind turbines and PV panels produce more energy that is absorbed by the local grid.

The wind turbine emulator is very useful for laboratory experimental investigations during time periods without wind potential. The emulator can be used also in parallel with the wind turbine mounted on the building rooftop.



a) b) c) d) e) f)

Fig. 5. Experimental implementation of the hybrid power system; a) Wind turbine; b) PV panels; c) Diesel electric generator and batteries; d) Wind turbine emulator, dump load, control panel, inverter; e) control unit for Diesel electric generator; f) inverter and AC/DC converter used to charge batteries from Diesel electric generator.

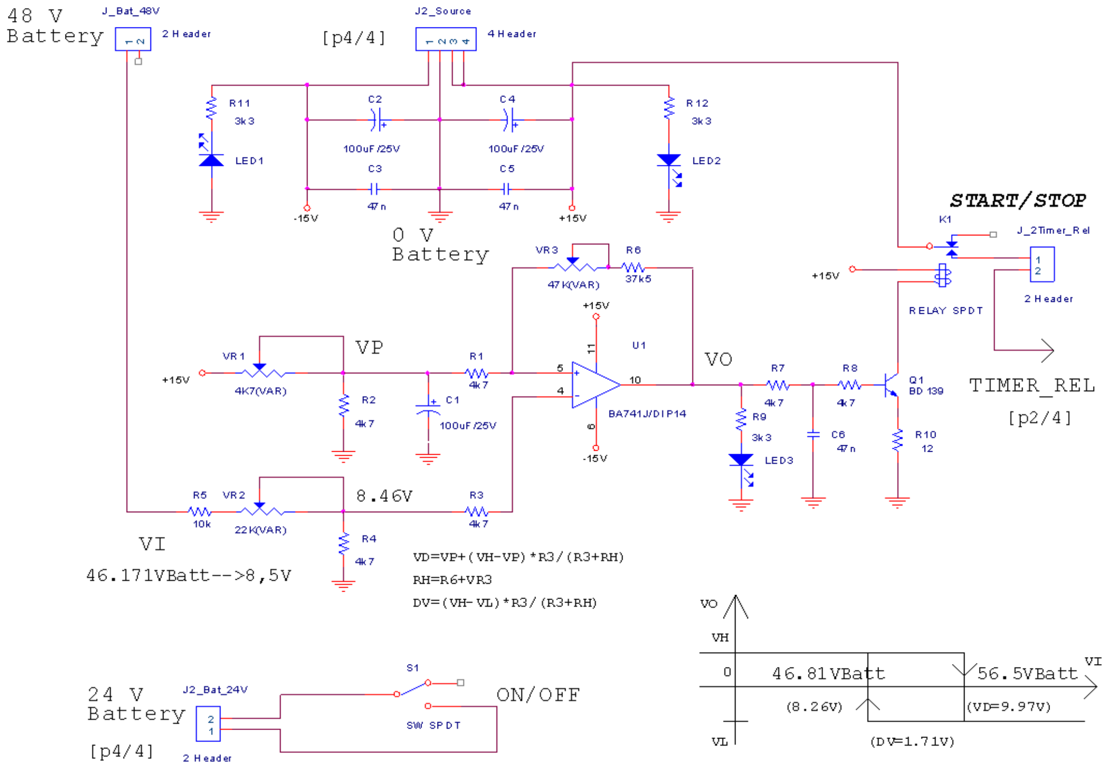


Fig. 6. Electric diagram of the developed intelligent control unit for the Diesel-electric generator.

IV. Experimental Results

The main purpose of the experimental investigation was to test the system stability in various operation conditions. For periods characterized by weak or no winds and low or no solar radiation, the system stability and autonomy is ensured mainly by the Diesel-electric generator. The fuel tank of the Diesel generator has the capacity of 16 liters and autonomy of roughly 9.5 hours at rated power, with a fuel consumption of about 275 g/kWh. For those periods, the Diesel-electric generator should be refilled with fuel to ensure the electric power supply continuity.

A special attention was focused on the calibration of the intelligent control system that turns on/off the Diesel-electric generator depending on the SOC of batteries, Fig. 6. In order to protect the Diesel engine, a special start/stop control strategy was implemented. Thus the Diesel engine is turned on without any load connected to its terminals; the load is connected to the generator terminals after an imposed time interval (≈ 3min.) that allows the engine preheating. Before turning off the Diesel engine, first is disconnected the load, the engine being turned off only after a given time period (≈ 3min.) that allows a proper engine cooling.

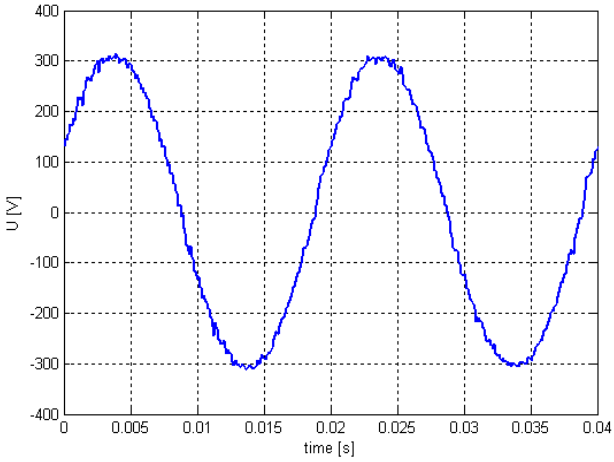
The experimental tests prove that the power quality and stability (voltage level, frequency level and harmonic content) delivered to the local grid are adequate, the frequency and voltage tolerance at the inverter output being kept within imposed limits by means of a DSP controller.

For the experimental investigations we used dedicated data acquisition systems including data acquisition boards, current and voltage transducers, conditioning systems and laptops.

In Fig. 7 are presented the inverter output voltage waveforms for no-load and for pure resistive load and in Fig. 8 are shown the batteries charging currents delivered by the various system components in different case scenarios (wind turbine, PV panels, Diesel-electric generator, wind turbine emulator).

By studying the results in Fig. 7 we can notice that the inverter output voltage waveform is very close to a pure sine-wave, both for no-load and for resistive load, the harmonic content being in both cases very reduced (THD < 5%). The voltage rms values are in both cases in the range 230 V ± 5%. The voltage and frequency values are regulated by a DSP controller and kept within the imposed limits.

The recorded results shown in Fig. 8 prove that all the system components generating electricity operate properly, injecting current into the batteries. Moreover, the wind turbine and PV panels operate properly both in stand-alone mode and in parallel connected mode. The currents injected into the batteries by the wind turbine, Fig. 7 b) and by the wind turbine emulator, Fig. 7 e) are not similar because the electric generators of the two systems and the battery charging units are not the same and moreover, the two sets of results correspond to different rotor speeds.



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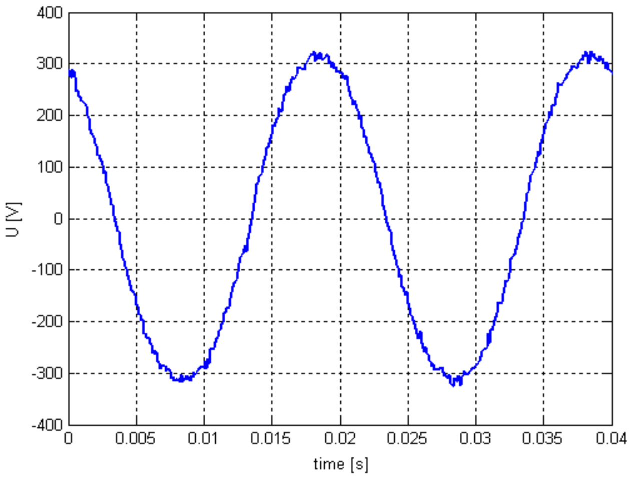

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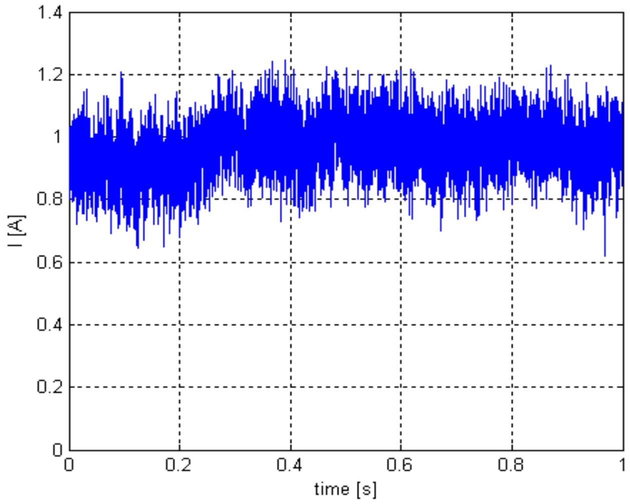
Fig. 7. Inverter output voltage waveforms; a) no-load; b) pure resistive load.



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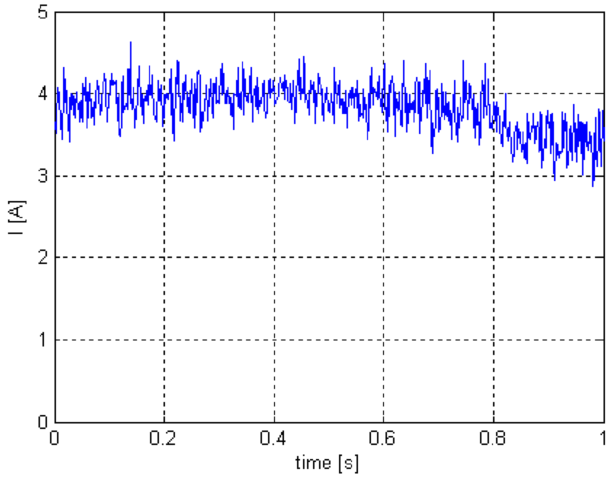

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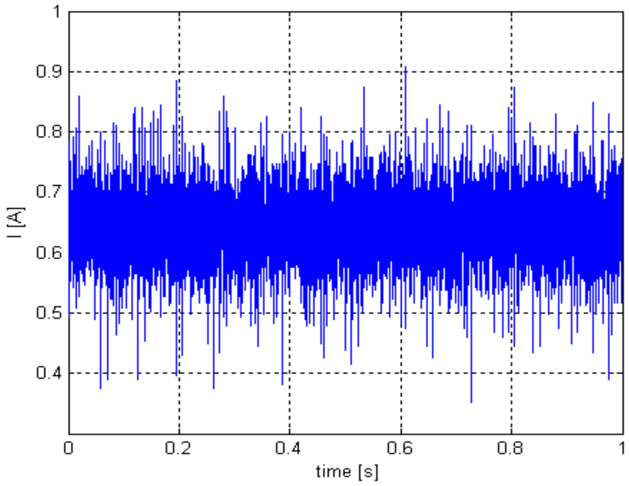

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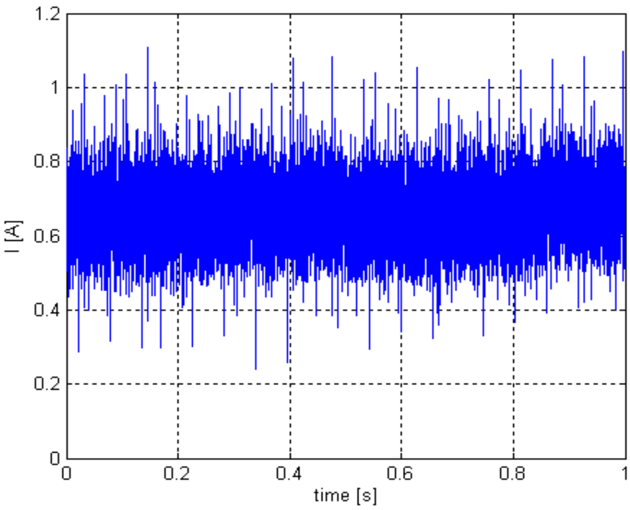
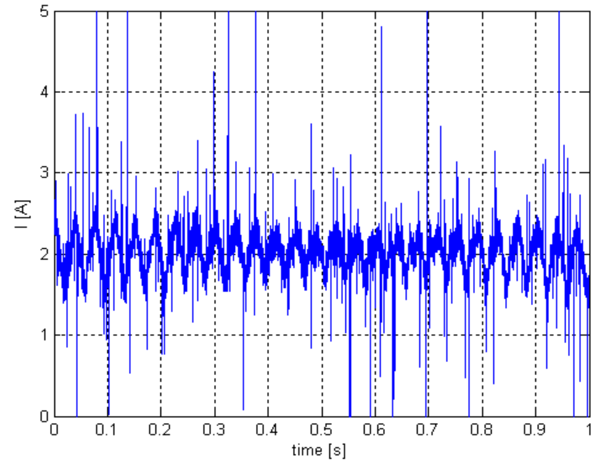


d)



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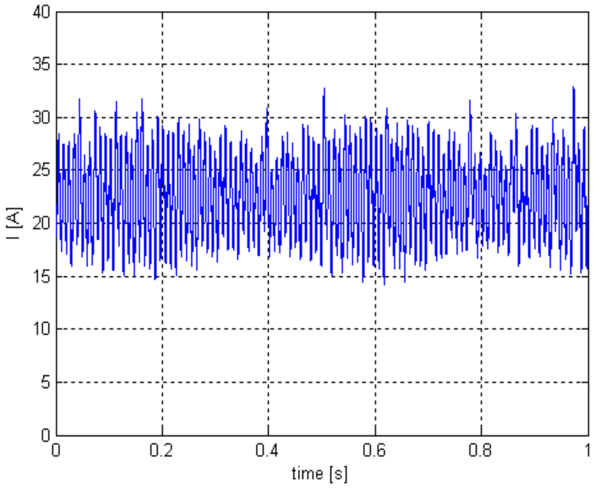

f)

Fig. 8. Battery charging currents of various system components in different operation scenarios; a) PV panels operating alone; b) Wind turbine operating alone; c) PV panels when operating in parallel with the wind turbine; d) Wind turbine operating in parallel with the PV panels; e) Wind turbine emulator operating alone; f) Diesel-electric generator operating alone.

V. Conclusions

This paper presents the design, implementation and experimental investigation of an autonomous Wind/PV/ Diesel/Batteries power system.

The system optimal design was carried out using HOMER software package based on the renewable energy potential of the installation site and taking into account imposed daily load profiles.

The power system implementation supposed the design and construction of several components (pure sine-wave inverter with galvanic isolation, electronic unit for batteries charging from Diesel-electric generator, intelligent control unit for turning on/off the Diesel-electric generator depending on the battery SOC, wind turbine emulator with special designed PM synchronous generator, etc.) and their integration in a complex system mounted at the University Politehnica of Bucharest.

The experimental investigations carried out for different operation scenarios proved the system proper operation and stability in various working conditions.

Acknowledgment

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