Summary of activities developed in 2015 under the project
PN II–RU–TE–2014–4–1761: ***Hierarchical Intelligent Control of Distributed Systems for Production and Use of Electricity***

In order to achieve the main objective of this phase, titled: *Getting integrated system structure,* four major activities have been undertaken:

1. Mathematical modeling of the exogenous variables related to the local sources and load and their numerical simulation;

2. Mathematical modeling of the wind and PV sources, including related control systems, and their numerical simulation;

3. Mathematical modeling of the network connection structure and electrical power quality control;

4. Numerical simulation of the entire integrated system.

The **distributed system of generation and use of electricity** include two electric power sources based on renewable energy conversion: a wind source and a PV source. Exogenous variables related to these sources are: wind speed, solar radiation intensity and temperature. Also non-stationary random variable is the local load.

1. Mathematical modeling of exogenous variables related to local sources and load and their numerical simulation

1.1. Wind speed modeling

Modeling the wind speed as a random process can be made in relation with two objectives:

1. preliminary assessment of the energy potential based on the first order moment of the wind speed. The methodology for determining electricity from the wind power includes the following stages: determining, from experimental data, the wind speed distribution function in the site concerned; determining the average density of the wind power; calculation of optimal value and the most probable value of the wind speed; calculation of the average power from the wind turbine;

2. preliminary assessment of the energy potential based on the second order momentum of the wind speed. This assessment relates to determining the properties of the wind speed as **time series.** Within this project it is considered that the energy potential deducted from the first order momentum of the wind speed is known and substantiates the use of the wind source to produce electricity. Of particular interest in the project are the properties of the random process reflecting the **time evolution of the wind speed**. This evolution determines the change of the the operating mode of the proposed system of production and use of electricity, which includes: renewable sources (wind and PV), the mains and a battery.

The project considered that the wind speed is an unsteady random variable, which may be in the form of:

$$v(t) = \overline{v}(t) + v_t(t) \tag{1}$$

where $\overline{v}(t)$ is the long- and medium term component, and $v_t(t)$ is the turbulence component.The long- and medium term component was modeled using a general spectral model derived from the Van der Hoven spectrum and the turbulence on the turbine blade was modeled so as to be obtained in two steps: 1) the fixed point turbulence (anemometer) is determined, corresponding to the position in which the wind source is placed and 2) the turbulence on blade turbine is calculated, passing the previous variable through a spatial filter and a rotational sampling filter.

The properties of turbulence depend on the average wind speed value by means of two parameters: *the intensity of turbulence, and the length of the turbulence.* These parameters depend on the average wind speed, roughness of the soil and the height from the ground. They are calculated in accordance with various standards (eg., IEC Standard, DS 472 Danish Standard etc).

1.2. Modeling the solar radiation and temperature

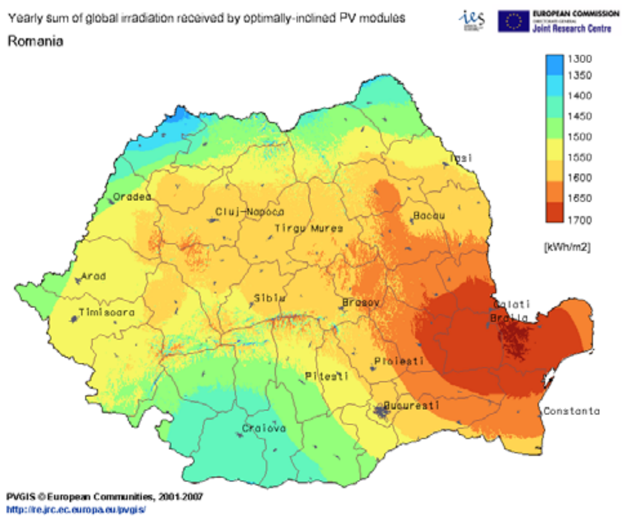
Solar radiation is the solar radiant flux received by a unit area. Global solar radiation consists of direct radiation and diffuse radiation (due to atmosphere air and clouds). On a blue sky, direct radiation is the maximum and the diffuse one is minimum and on a cloudy sky, vice versa. Global solar radiation is different depending on the time of day, and the direct solar radiation is different according to the receiving surface orientation. Modeling and measuring the terrestrial solar radiation are important for assessment and implementation of solar renewable energy systems. Solar radiation is one source of renewable energy with predictable evolution, both in the short and long term. Predictability comes from the fact that the diurnal and annual variation of the solar radiation caused by Earth's rotation around its axis and around the Sun can be accurately described mathematically.

At ground level, the amount of incident solar radiation of a solar panel is not constant, but varies due to the multitude of disturbances, such as:

- atmospheric disturbances (clouds and fog local conditions) - that makes solar radiation of the photovoltaic panels to reduce considerably,
- air temperature and the degree of air pollution in the area - which, for high values lead to lower efficiency of the solar cells,
- geographical coordinates (latitude and longitude),
- season and time of day.

Given the existence of numerous online databases able to provide *real time* information on solar radiation intensity and temperature, both data important in the operation of a photovoltaic system, in the preliminary validation of the distributed system operation for production and use of electricity, use will be made of an evolution of the solar radiation and temperature in the area of Galati, also available online.

The spatial distribution of the total radiation incident at ground level for Romania is shown in the Figure below.



1.3. Modeling the local load

In order to validate the operation of the distributed system of producing and using electricity two types of consumers were analyzed: a domestic one-phase consumer fed from a three-phase system of the National Power System (and the load curve obtained by measurement will be used for predicting the load for a long period of time); and more consumers typically encountered in a consumer household (modeled and simulated in cyberspace Matlab, to highlight aspects of power quality and validation of the active power filter operation). From the analysis presented the following conclusion can be drawn: all electrical equipment being analyzed have shown a nonlinear structure of the power supply by the significant content of odd harmonics of the current generated in the network.

2. Mathematical modeling of wind and PV sources, including the related control systems and their numerical simulation

2.1. Mathematical modeling and simulation of wind energy conversion system

From the characteristic of the wind turbine power output depending on wind speed four regions of operation can be identified:

- region 1, corresponding to lower wind speeds than the starting speed of the turbine. In this area the wind turbine does not produce energy;

- region 2, in which the wind speed is within the start speed of the turbine and the nominal speed. This area is also known as the *partial load area* and the power delivered is proportional to the cubed wind speed;

- region 3, known as the *maximum load area* corresponds to wind speeds between nominal speed and maximum working speed. In this area developed the wind turbine power is maintained equal to the nominal power;

- region 4, where the wind speed exceeds the maximum permissible speed of the wind turbine and to protect mechanical part and to avoid destruction it is turned off.

The general solutions addressed use two separate controllers for partial load and full load working regime. The schematic diagram illustrating the structure of the adjustment loops considered that the adjustment design has the following attributes:

- Control of the optimization loop is based on the shaft rotational speed (not according to wind speed);
- Controlling the power to the nominal value is achieved by moving the operating point, in the plan of the the optimum regime characteristics;
- Calculation of the reference power of the optimization loop is achieved through a relationship deduced by polynomial regression.

At the same time, it has been shown that to avoid system unstable behavior and for a smooth transition of state variables when switching between part load and full load regions, the proposed solution considered an intermediate zone in partial load regime. In this intermediate zone, the angular speed is held constant at a reference saturation limit of the power controller. Partial load regime will consist of two areas: area 2a - here the system is maintained on ORC (Optimal Regime Characteristics) and the area denoted 2b of constant shaft rotational speed, while full load regime will be assigned area 3.

The validation of these strategies of automatic control was achieved using Matlab Simulink and SimPowerSystems computing environments.

2.2. Modeling and simulation of the photovoltaic system

Since the operation point of maximum power depends on the incident radiation and temperature, the panel operation at maximum efficiency can be achieved only by means of an electronic circuit able to find and track this operation point.

Getting the maximum amount of energy from solar panels involves:

- Use of a mobile positioning system so that sunlight fall always perpendicular to the solar panels;
- Use of an electronic interface circuit between the panel and energy storage / use elements so that the panels operate with maximum efficiency at any time.

The first requirement is not cost-effective for low power photovoltaic systems. The second requirement can be applied anywhere, as there are electrical converters of high efficiency (> 95%) that allow tracing the operating point of maximum power (MPPT). The literature lists numerous simulation environments for photovoltaic systems. It presents classical control structures for achieving MPPT function and relies either on disrupting the current point of operation or on the mathematical estimate depending on technical parameters of the solar panel, temperature and solar radiation. To implement the MPPT function, two classical algorithms "*perturb & observe*" and "*incremental conductance*" were tested and which were further improved.

2.3. Modeling and simulation of two-way DC / DC converter for connecting batteries to the active power filter

The proposed platform accumulates electrical power from renewable sources (sun, wind) into a group of 200Ah and 48V batteries. The use of energy in batteries to power feed the appliances connected to the three-phase voltage mains involves:

- voltage increasing circuit with 48V input and at least 300V output;
- galvanic isolation between input and output, as the platform works with network connection;
- distribution of energy from batteries in one, two or three phases of the consumers network according to the their connection arrangement in each phase.

Since the active three- phase filter is connected in parallel with consumers and the control algorithm of the filter allows energy transfer from / to any direction between network, consumers and DC capacitor of the active power filter, the APF will be used to transfer the energy from batteries to consumers or network. Immediate benefits are:

- when functioning as active filter, the additional energy coming from batteries will automatically be distributed to consumers irrespective of their location on the three phases of the network;

- when functioning as as voltage inverter, the filter is already connected in parallel with the consumers of the three phases and the hardware structure allows the available energy in the DC condenser to be fed to the consumers.

Of particular interest is the ability to charge the batteries with energy from the mains, when renewables are not available. Using an autonomous battery charging circuit connected to the mains is possible but adds complexity in the management of charging and discharging cycles of the battery.

3. Mathematical modeling of the grid connection structure and power quality control in the Matlab/Simulink/SimPowerSystems software environment

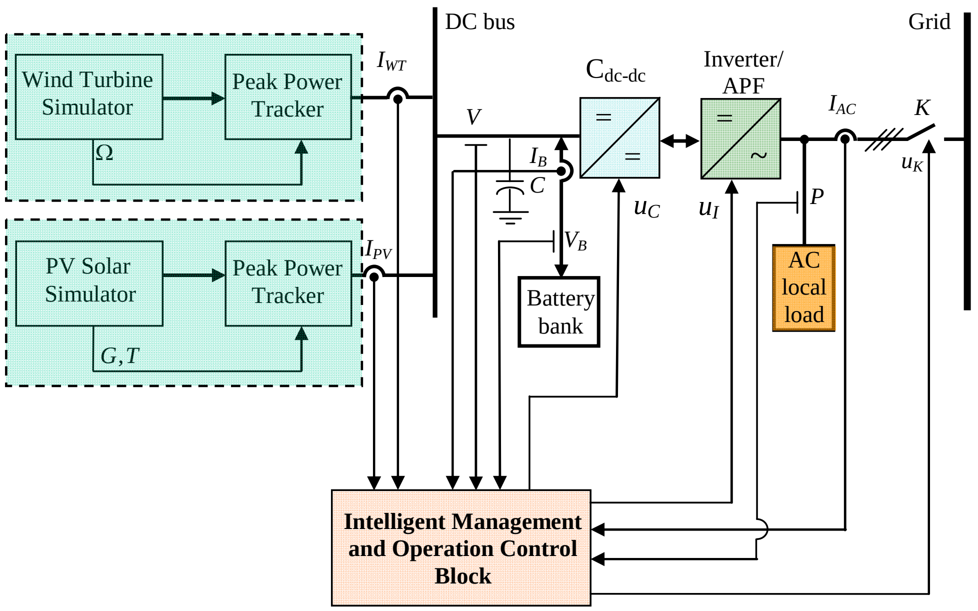


Fig 1. Simplified block diagram of the proposed system

The main objective of the project is the design, preliminary test under simulation and then experimental validation through physical achievement of a distributed low-power (up to 5 kW) system of producing (with wind and PV) and using electricity. The schematic diagram of the system is shown in Figure 1.

Inverter Block / APF, in this case, is defined as an electrical equipment having two roles in the proposed structure:

1. Active power filter (APF);
2. Inverter.

APF - ensure the level of the quality indicators of electricity passing through the point of common connection (PCC), and can achieve bidirectional energy transfer to and from the national grid.

Inverter - is designed to provide power to local consumers based on available battery power and renewables, when the national grid is not connected (or not available / functional).

Since most domestic consumers of electricity are of single-phase type (powered between phase and neutral) even in a household connected to the three-phase mains, it appears that in the connection point the set of all consumers is a three-phase unbalanced one with different amplitudes and harmonic distortions for the currents per each phase. This implicitly leads to the existence of a significant current through the neutral conductor, loaded with all the harmonics generated by nonlinear single-phase consumers.

To reduce the harmonic distortion factor (THD) of the mains currents, to reflect consumption and to cancel the current through the neutral conductor it is needed a three-phase active 4-arm filter. From the analysis of the implementation solution, there is a possibility that the 4th arm to be passive, made by splitting the DC capacitor in the filter into two equal parts or of an active type, made with static switches like the other three active arms. The capacitive divider can be used if the electrical load compensated from the active filter consists of symmetric three-phase equipment (electric machines, transformers, three-phase rectifiers etc).

The particular feature of the consumer in the grid/network considered under the project requires the use of active 4-arm filter because the consumer asymmetry would unbalance fast the voltages across the terminals of the two capacitors in series in the passive arm, which would lead at least to the malfunction of the active filter.

4. Numerical simulation of the entire integrated system

To simulate the entire integrated system, they were connected at the same Simulink model the blocks tested in previous activities. Since the mathematical calculations necessary for the simulation of the entire system for a sufficient period of time (minutes / hours / days) exceed the computing capacity available in the project, it was chosen to preserve only the essential elements of each functional block, removing any nonessential component The sampling step time has also been increased 10 times therfore the waveforms corresponding to fast variable signals contain bigger errors.

5. Conclusions

The results from the simulation in the computing environment Matlab / Simulink, of the components of the distributed system for electricity generation and use analyzed in this project are conclusive to design solution for the automatic control and physical achievement, related to the next stage of the implementation plan.

It was validated, by numerical simulation, the operation of the conversion of the renewable energy sources (wind and PV) into electricity, including related control systems, DC / DC bi-directional converter, which provides the energy transfer to / from the filter or battery. It was validated, by numerical simulation, the active power filter operation governed by the strategy of indirect control. The results show that this ensures rejection of interference and compliance with the power quality requirements.

At the same time, it was also analyzed the functioning of the system in autonomous mode, in which case the Inverter / AFP block serves as a voltage inverter.