Summary of activities undertaken in 2016 under the project
PN II–RU–TE–2014–4–1761: ***Hierarchical Intelligent Control of Grid Distributed Systems for Generating and Using Electrical Energy***

This step had, in accordance with the Project Plan, **four** objectives:

1. Obtaining the system control algorithms (with preliminary validation);
2. Achieving the wind turbine electromechanical simulator;
3. Achieving the photovoltaic system physical simulator;
4. Achieving the bidirectional converter for energy transfer to / from the battery;
5. Working / training visit.

The activities related to the four objectives are detailed in the Table below:

An		Obiective	Activități
2016	Etapă unică	Obtaining the system control algorithms (with preliminary validation)	Setting algorithms for predicting and testing random exogenous variables by numerical simulation
			Definining the multi-criteria performance indicator
			Establish hierarchical intelligent control algorithm related to the integrated system and generation of operating mode scenarios
			Preliminary validation through numerical simulation of the hierarchical intelligent control algorithm
		Achieving the wind turbine electromechanic simulator	Establishing the structure, development and testing of physical wind turbine simulator
		Achieving the photovoltaic system physical simulator	Establishing the structure, development and testing of physical PV simulator
		Achieving bidirectional converter for energy transfer to/from the battery	Determination of the structure and implementation of the bidirectional converter for energy transfer to/from the battery
		Working/training visit	Working/training visit

The objectives set in 2016 have been fully met and all activities within the framework of the implementation plan have been 100% performed. In 2016 ongoing phase the following dissemination outcome was achieved: 1 article published in ISI journal, 3 articles in ISI Conference Proceedings, 1 article in national conference and a book.

Objective I: Obtaining the system control algorithms (with preliminary validation)

1. **Setting the algorithms for predicting random exogenous variables and testing them by numerical simulation**

The objective of this chapter aims: defining the exogenous variables of the distributed system for the production and use of electricity (SDPUEE); developing programs to generate these variables under numerical simulation (ie wind power, PV power source and power consumption in the local network); developing a set of algorithms for linear and nonlinear prediction of these variables; setting the context in which it is necessary to use predictive algorithms (it is the prediction of the energy "deficit / surplus" variable).

Prediction Algorithms

Linear prediction algorithms (AR, ARMA) have been tested and the conclusions are:

1. assuming that we know the nature of the time series (eg., it is known that this is AR or ARMA type) and the filter formation order when prediction results are close to the ideal, with sigle –step prediction. In this case, the standard deviation of the residue is almost equal to that of the filter formation (= 1) and the autocorrelation function of the residue is an impulse (the residue is a white noise);
2. if prediction $M > 1$ steps is achieved, the residue is no longer a white noise and the standard deviation increases with the increase of M;

3. if we do not know the order of the formation filter (eg. real order is $n = 4$, and the predictor has the order $m = 2$ or 3), the error can be very big, even with the single-step prediction. If we adopt m higher than the actual order of the formation filter, then the residue is a white noise in the single-step prediction.
4. it resulted in the following procedure for determining the predictor order: prediction is made successively for different subtractors values of the predictor order m, starting from a higher value and we stop when the standard deviation of the residue increases sharply (autocorrelation function is no longer an impulse).

Generating exogenous variables

In the energy balance of the distributed system for the production and use of electricity (SDPUEE) the following streams of energy (power) occur:

- powes generated by renewable energy sources (wind and PV),
- load consumption powers,
- powers transferred from SDPUEE network or from SDPUEE to the network.

The last category results from the orders of the SDPUEE control system. Consequently, there will be deemed random exogenous variables the power generated by wind power, PV source and load consumption power.

In order to generate the wind power use was made of the Simulink scheme designed to obtain wind speed (including seasonal components and turbulence), given in the relevant scientific report in 2015. The wind source was considered to have 1.5 kW nominal power obtained at the rated wind speed $v_n = 11$ m/s. The source begins to charge from the turbine starting speed $v_d = 3.5$ m/s. It used a sampling period of 1 second and the time interval of one day, to found different wind speed regimes.

To study the power charged by PV in the SDPUEE under the numerical simulation, it was considered the summer mode when the PV source can generate electricity between 6.00 - 21.00. hours. The PV cells were considered to have a conversion efficiency of about 15%. For the irradiance purpose , a random variable subtracted from the electric power of the PV (only when it charges) was entered in the program generating power from PV source. The sampling period of 1 second was used.

To study the load consumption power under numerical simulation, a dwelling /house was considered.

Prediction of energy deficit / surplus in the SDPUEE

Under the control structure of SDPUEE, orders/commands are dependent on the actual values of energy deficit or surplus in the system, on their variation tendency and possibly on the prediction regarding their future development. Therefore it is more important to predict the energy deficit / surplus into the system than the prediction of the power components included in the balance equation.

The prediction of the “deficit / surplus" time series was made using the model ARMA under two distinct conditions: using a sampling step for 1 second, thus including the component of turbulence (high frequency) in the issue of prediction and using a sampling step for 1 minute, in which case no turbulence component is reproduced.

The conclusions are:

1. For the needs of the control system of SDPUEE it is not required the prediction of each time series involved (wind power, PV power source and load consumption power), but only the prediction of the "deficit / surplus" time series;

2. The main difficulty in predicting the above mentioned time series arises out of the fact that load changes can be unpredictable and, especially, they contain jumps with relatively high step amplitude compared with the average daily power;

3. An important objective pursued and achieved consisted of planning linear prediction (with AR and ARMA models) applied to the needs of SDPUEE control;

4. Generating the 3 exogenous variables (wind power, PV power source and load consumption power) is regarded as a sample from a variety of possibilities. It can be easily modified to illustrate many other situations that can be addressed in the analyses of SDPUEE control algorithms.

2. Definition of Multi-criteria Performance Indicator

Distributed system control for the production and use of electricity (SDPUEE) is ranked according to two levels:

- *Level 1,* related to SDPUEE basic subsystems: wind power, PV source and inverter/ active power filter, which performs bidirectional energy transfer, from and to the network, thus ensuring the quality performance of electricity;

- *Level 2,* which covers the entire energy system.

The performance criteria imposed on the two levels are different : at *Level 1* they are mono-criteria, and at Level 2 - where there is performance of a system with components that have different requirements - a multi-criteria indicator is contemplated.

Although the main interest is directed towards defining a multi-criteria indicator, related to *Level 2*, in the following section it is a brief reference to the performance criteria relevant to *Level 1*, given the particulars of the loow-power system addressed in this project.

At the hierarchical level 1, there were introduced the performance criteria for the control of the wind and PV subsystems and also for the control of the inverter / active power filter

For *Level 2* it is shown that the first requirement is to reduce the cost of electricity consumed by the public network. N is another important criterion to be taken into in the control of SDPUEE, that aims at increasing the battery life. The high cost of the battery and its life being dependent on the operating mode accounts for the control system requirement to ensure an as long as possible battery life. Thus, if the battery were required to operate over a charging-discharging cycle at a nominal rate, given the fact that the battery operates in SDPUEE with variable powers randomly produced by the renewable energy sources, the energy bill would be great. But if the system would be required to operate in a mode focused on minimization of the energy invoiced, then the battery may operate in a mode in which the charging- discharging switching frequency is excessive, with the consequence of a shortened battery life.

A performance criterion that would consider the two contradictory requirements, namely: reduced invoiced energy and reduced number of charging $\leftrightarrow$ discharging switching, is:

$$I = \int_0^T \left(P_{rs}(t) - P_{sr}(t) \right) dt + \gamma \cdot N_T^{\varepsilon}$$

where γ is the factor that weights the two terms of performance criterion.

Unlike *Level 1* performance criteria, which are optimized in real time by means of automatic control systems, the criterion is used off-line in the design mode for setting the control system parameters leading to the higher hierarchical level.

This feature stems from the fact that the minimization criterion is only valid for a given profile (authorized in a particular instance) of the curves of power development of renewable energy sources and load consumption power, both being ***random developments***. In another instance in which those developments differ, the parameters of the control system that would minimize the mentioned criterion would be different. In these circumstances, the parameters involved in the SDPUEE control algorithm can be established by numerical simulation analyzing the system performance in different situations related to the random exogenous variables. Choosing the "appropriate" parameters based on this analysis should take into account, in particular, the summer and winter modes under operation of renewable energy sources.

The energy component, the battery life component and the multi-criteria performance indicator habe been evaluated.

3. Establishing the hierarchical intelligent control algorithm related to the integrated system and generation of operating modes scenarios

The integrated system for production (with wind and PV sources) and use of electricity targets a multi-criteria performance indicator, like the one presented above, and raises a question of control that essentially refers to the control algorithm for conveying electricity among the system components: renewable energy sources, public grid/network, energy storage (battery) and local area network (load). The algorithm in question refers to two aspects:

a) ***the sense*** of the energy transfer, and

b) ***the level*** of energy transfer ie the transferred power.

The fact that the required load power and the powers from the renewable energy sources are random variables determines control a variety of ***control situations***, appropriate to the targets required by the multi-criteria performance indicator.

The factor that determines the variety of control situations is the random nature of the renewable energy sources and load. The presence of the battery is very important, not only in the capacity of accumulator of energy surplus (from renewable energy sources), but also that contributes to the load supply during energy shortage and also as a "sensor" of the energy situation in the system. The voltage evolution across the battery, which is directly linked to the energy gained, largely reflects the energy context of the SDPUEE. This context can be characterized by a set of "states" the integrated system can be found itself in. The "states" vectors can be defined by the current value of the accumulated electricity in the system, by the trend of variation of the accumulated energy and the predicted values of the powers of the renewable energy sources and load consumption power. Using predictions for each of the three powers is unreasonable and excessive; what matters is the prediction of the energy deficit / surplus in the system, ie the difference between the powers of renewable energy sources and load consumption power.

The control algorithm can be used in two approaches: a **"crisp"** (rough) **approach** through a simple algorithm for recognition of "control situations" preset and a **fuzzy approach where** the energy state of the system is assessed by ***linguistic values***. In this case, the principle of control shown above is maintained but all the variables involved in the system, including the control that sets the sense and level of the energy transfers are expressed by fuzzy evaluations and the control law is obtained by fuzzy inference.

Development and testing of the control system at the higher level is given by taking into account the existence of several ***scenarios of working modes***.

The analysis by simulation leads to the following conclusions:

1. The SDPUEE control algorithm established in this chapter provides commands that relate to the sense and level of the energy transfer to SDPUEE and the public network. It controls the evolution of the battery voltage, directly dependent on the energy accumulated, since this tension largely reflects the energy context of SDPUEE. Four variants of the control algorithm have been established and analyzed in scenarios that either refers to various situations on the renewable energy resources (summer / winter mode), or to the operating mode of the battery: buffer mode- regarded as the standard one- and the periodical mode, in which charge - discharge cycles occur during normal operation of SDPUEE. Variants of the control algorithm include both fuzzy algorithms, with a base of rules consistent with the rational decisions of a human operator controlling thre sense and level of the energy transfer between SDPUEE and the public network (versions 1 and 2 of the controller) or simpler algorithms (versions 3 and 4 of the controller). Analysis of these regulators was done from two points of view: 1) in terms of the voltage regulating performance and 2) in terms of the control, i.e. how the energy transfer takes place between SDPUEE and network.
2. The performance of the variants 1 and 2 of the controller as regards the adjustment of the battery voltage is excellent, but this level of performance is not necessarily required and, in addition, is obtained by a ***permanent*** circulation, in one direction or the other, of the energy in the system. In fact, a recommendation to ensure a long life battery is that the voltage be according, with an acceptable tolerance, to a field appropriate to the charged battery. Therefore, the voltage can fluctuate in this area, and the controller may have a dead zone, which dramatically reduces the energy circulation within the system. Variants 3 and 4 of the controllers are designed on this basis.

4. Preliminary validation through numerical simulation of the hierarchical intelligent control algorithm was performed for all 4 operating variants and allowed us to obtain detailed information on the energy transfer among the system components: network, renewable energy sources, load and energy storage system. This analysis was focused mainly on the influence of the control algorithm on the two components of the multi-criteria performance indicator: energy efficiency component and the component of battery operating mode. Comparative analysis of the control performance highlighted the advantage of using a controller that has a dead zone , like controller of variant 3.

Objective II: Making a wind turbine electromechanical simulator

1. Establishing the structure of the physical wind turbine simulator

It has been determined the hardware and software structure of the wind turbine electro-mechanical simulator and experiments have been conducted to validate its operation. Permanent magnet generator (PMG-GL-1500) can deliver a power of 1.5 kW, is powered by a synchronous motor of 3 kW (960 rpm) via a frequency converter Danfoss VLT5000 of 5 kW rated power. The wind turbine electromechanical simulator has a Hardware In The Loop (HIL) structure. The entire experiment was monitored in real time using a process computer and the hardware / software support of the company dSPACE (via ControlDesk package). The hardware support implies the use of the dSPACE DS 1103 board. The simulator has been tested under island operation, delivering a resistive-type load and at idle operation.

2. Making a DC / DC converter with MPPT function related to the wind source

Since the wind turbine electromechanical simulator has a synchronous generator with permanent magnets whose output voltage changes depending on the shaft angular speed, which changes, in turn, depending on the wind speed and according to the technical specifications, the generator output voltage ranging between 0 and 90V according to speed, it was considered useful a DC/DC converter whose input voltage may be higher or lower than the output voltage. Thus, to achieve MPPT function, use is made of SEPIC converter configuration due to the simplicity of the control circuit on the grid of the only static switch. The control of the operating point is achieved by generating PWM signals for the SEPIVC switches, according to MPPT algorithm integrated into the microcontroller. There were used a group of 4 SEPIC converters, connected in parallel, with interlaced operation, which makes it easier to control the static switches, releases the switching stress of the static switches, allows to increase the switching frequency and to decrease the physical dimensions of the inductances. Power transistors and diodes were chosen so as to function correctly to the set maximum current in the circuit (20A for each boost level/floor), reverse voltage of 150V, and 10 kHz switching frequency. To achieve maximum power tracking loop, use was made of two transducers, a voltage one - resistive divider and a current one - ACS758, which bring the necessary information to the analog inputs of the microcontroller. The signals from the following figures are taken directly from the microcontroller pins.

Objective III: Making the physical photovoltaic system simulator

1. Establishing the structure, development and testing of the physical PV panel simulator

The power of the physical photovoltaic system simulator was sized to 1.5 kW, comparable to the wind system. To achieve this objective, a programmable voltage source was achieved for the emulation of the power profiles of the photovoltaic panels with the following features: input voltage 230 Vac, 50 Hz, single phase, adjustable output voltage between 0 and 32 V, adjustable output current up to 46 A, communication interfaces: Ethernet, GPIB, RS-485, USB.

The source has a computer programming interface via USB / RS232, which can pass the emulated panel parameters, simulated temperature and irradiance. This programming interface is accessible from Matlab as well as classic serial port which can send real-time data and commands to the programmable source. Possible functions and keywords are shown in the user manual of the source.

The interface to specify the emulated panel parameters allows to be obtained the static characteristics, starting from the actual parameters of the panels. It is also possible to manually edit the points of the characteristic U / I.

As load, use was made of a rheostat resistance of 15.5 ohms and maximum current allowed of 10 A. The communication between the software and the hardware environment was accomplished with a serial connection. The REMOTE mode of operation was set to allow controlling the PC source. Testing the emulator has been achieved through the implementation of the three voltage-current curves corresponding to the three temperature values chosen, namely 25 ° C (red curve), 50 ° C (blue curve) and 75 ° C (green curve). Three different values of the load connected to the source were used.

2. Making a DC / DC converter with MPPT function related to the photovoltaic source

The electrochemical battery forms a voltage system of 40 ... 50 V according to the load state. The DC / DC converter should be permanently boost voltage and galvanic insulation is not required because batteries are not galvanically connect to the network. The classic structure of a boost voltage was used (boost level).

To implement the converter physically, with a maximum current circulation of about 100 A, it will be made of 4 boost levels/floors, connected in parallel, controlled by PWM interleaved signal In this way it is optimized the stress of the static switches, it is distributed the power lost across several components, it is reduced the complexity of the control circuit on the switch grid/static switches (because lower current transistors have less grid capacity which can be charged/discharged more quickly, thus reducing the switching times or increasing the switching frequency= using a lower inductance).

Also, the input and output currents of the converter contains 4 times smaller variations than if it were used a single boost level. The filling factor control is done with a digital signal processor that can generate multiple PWM signals of high resolution and frequency. Acquisition of input voltage and current is done with Hall effect current transducers and a voltage divider, respectively. It is taken into account the delay through the filters used for the attenuation of switching noise induced in the measuring wires. The numeric control circuit is based on DSPIC33FJ128GP804 circuit. It was verified the correct operation of the converter, both in terms of transistors switching and the output voltage of approx. 50V , starting from an input voltage of approx. 25V. In order to effectively introduce information into dSPACE 1103 plate, it was added a voltage amplifying and delay circuit so that the output range be within the [-10V; 10V]. For acquisition of the photovoltaic panels output current information it is necessary a transducer of a wider current range. Use ws made of the ACS758 circuit (produced by the same manufacturer and acc.to the same principles as ACS712).

Objective IV: Achieving bidirectional converter for energy transfer to / from battery

1. Determination of the structure and achieving the bidirectional converter for energy transfer from / to the battery

This converter shall enable energy transfer from the battery to the DC voltage side of the active filter (about 700V quasi-stationary voltage), and the transfer of energy to the battery, from the DC voltage side of the active filter.

It has been chosen an H- bridge circuit based with correlated control (H bridge in primary and synchronous rectifier in secondary).

It has been chosen to use one source of isolated voltage for each floating transistor and its control with an integrated circuit specialized in the no floating transistors control. Isolation of the control signal is achieved with high-speed digital optocoupler so that the dead time requirements do not increase significantly. All components have been placed on one side of the cabling so that the source can be used in the final assembly overlapped over the galvanic isolator floor and IGBT driver. In the final structure of the stand, the 4 H bridges will receive PWM signal from the control DS1103 board/plate which will set the operating point and the energy transfer by changing the PWM duty cycle/filling factor. To check the operation of the converter at this stage it was applied the supply voltage and PWM signal from a signal generator to check the control circuits operation of the power transistors across the grid.

Obiectiv V: Working/training visit

It was conducted a study visit to the Energy Technology Department, Faculty of Engineering and Science, Aalborg University, Denmark, between 10.09.2016 and 12.10.2016, by researchers Vlad Ciprian and Silviu Epure. Within this study visit the following topics were approached:

- - Conversion of wind energy and photovoltaic energy;
- - Power electronics elements related to the systems concerned and related control structures;
- - Electrical energy storage systems and technologies;
- - dSpace data acquisition systems (dSpace controller boards).

Conclusions

The objectives set in 2016 have been fully met and **100% accomplished all activities within the framework of the implementation plan.** In 2016 ongoing the set results were achieved as follows:

1. Scientific phase report;
2. Wind turbine electromechanical simulator;
3. Physical photovoltaic system simulator;
4. Bidirectional converter for energy transfer to / from the battery.

Outcome Dissemination

Indicators achieved for the outocme dissemination are:

1. 1 article published in ISI journal;
2. 2 articles in ISI conference Proceedings;
3. 1 article BDI conference (IEEE Xplore);
4. 1 article in national conference;
5. a book.