

HRES Power Generation: the Power Injection Control and the Grid Synchronization Cases

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Abstract- This work shows a Hybrid Renewable Energy System (HRES) and the management technique of power injection into the grid or into a load. A three-phase system is used to connect the HRES with the grid and the consumer. This case takes the two principal modes of the HRES operation into account: The off-grid and the grid connected modes. They require different systems of power management and control of the three-phase inverter. The objective of the three-phase inverter is to exchange the power between the outside part of the HRES, as the consumer and the grid, and the inside part as the systems of photovoltaic (PV) production and the storage. This paper shows the multipurpose techniques of control of the voltage in the off-grid mode, and the control of the current in the mode of grid connection with the synchronization with the grid voltage, and the practical verification.

Keywords Hybrid renewable energy system, Power injection, Off-grid mode, Grid connected mode, Grid synchronization, Voltage control, Current control.

1. Introduction

Access to electricity in flexible, reliable, and sustainable forms brings a range of social and economic benefits. It is one of primary goals for humanity. But for many years, the society has been obligated to use renewable energy more efficiently because of the increase of greenhouse gases, exhaustion of fossil fuels, and the growth of energies demand and prices [1], [2]. For this purpose the Hybrid Renewable Energy Systems (HRES) is one of the most suitable solutions to achieve stable energy supply for unstable grid systems, isolated islands and small remote zones [3], [4]. HRES includes the renewable production system (PV plant, wind farms, etc.), storage energy system (batteries, supercapacitors, etc.) and the control system. As the production of renewable sources is variable, the system of energy storage assists to solve the problems of irregular production and helps to increase the system ratio of self-

consumption. The stable supply for the consumer is the principal goal of the HRES, despite the absent or perturbed main grid. This supply is provided by the renewable energy, stored in the storage system or produced by the PV or wind farms.

In order to improve the stability of the power supply of the consumer, the HRES may help to unstable grids feeding the consumer, and fully supply the consumer in the event of failure of the main grid. For these goals, two common operation modes of the HRES are required: the grid connected [5] and the off-grid modes [6]. In this paper these modes are described, their current and voltage control systems, the systems of refining, normalization and synchronization.

2. Hybrid Renewable Energy System

2.1. General review of a HRES

The components, measurements and control system of the HRES is shown in “Fig.1”.

In the normal case, the consumer is connected to the grid directly through the three-phase DC-AC converter, or inverter, of the HRES (grid connected mode) [7]. In the moment of a grid failure, the consumer is automatically disconnected from the grid and supplied by the inverter of the HRES with the stored or produced renewable energy (off-grid mode).

The use of a grid connected filter helps to align the output of the inverter to sinusoid form [8]. This filter can be a simple inductive filter or a more sophisticated filter, as the

Fig. 1. Hybrid Renewable Energy System (HRES).

inductive-capacitive-inductive (LCL) filter, and is very important in the off-grid case, since the HRES must supply the consumer with the required power quality in the off-grid mode.

When the grid is present and stable, it is connected to the inverter of the HRES. The grid keeps the voltage level in the three-phase inverter of the HRES and the HRES control system injects the necessary current into the three-phase inverter of the HRES for supplying the consumer. In this case, the synchronization system is needed to synchronise the output of the HRES inverter with the grid.

When the main grid fails or is unstable, the HRES disconnects itself automatically from the grid and continues supplying the consumer with the required power quality. This off-grid mode requires a voltage control system and does not need a synchronization system.

“Equation (1)” shows the power balance of the DC part of the HRES. In order to achieve “a balance” between the produced, stored, consumed and exchanged energy, the PV production P_{pv} is equal to:

$$P_{pv} = P_{Cbus} + P_{3phs} + P_{bat} + P_{loss} \quad (1)$$

where P_{Cbus} is the power exchanged with the DC bus capacitor C_{bus} , P_{3phs} is the power exchanged with the inverter of the HRES and the grid (in the grid connected case), P_{bat} is the power stored into the battery storage system, and P_{loss} is the losses power due the filters, semiconductors, etc.

The dotted lines in “Fig. 1” show the measurement nodes, necessities for the control systems and for checking the grid presence and its reliability.

2.2. Off-grid mode of the HRES

In the case of the off-grid operation, the HRES must keep the voltage level in the three-phase inverter of the HRES, isolated from the grid. For this goal the control system of the HRES needs to have the measurement normalization system and the voltage control, but it does not require the system of the grid synchronization (due to absence of the grid). The full control circuit is shown in “Fig.2”.

This sequence of the systems of the voltage control of the HRES starts from the subsystem of voltage normalization.

At the beginning, the voltage is measured for each phase. These measurements are the main input of the control system of the HRES. In the measured signal are presented numerous imperfections, such as the unbalanced three-phase system, the measurement noise, the harmonics, etc. In order to not pollute the control loop and have more accurate control system is necessary to apply some normalization and extraction methods. There exist numerous methods that employ the Fixed Reference Frame (FRF) [9] and the Synchronous Reference Frame (SRF) [10] with Phase-Locked Loops (PLL) [11], or adaptive filters to estimate the frequency in Frequency Locked Loops (FLL) [12] However, this paper will use the open-loop method implemented in the Rotating Reference Frame (RRF) explained in [13], which employs robust notch harmonic filters [14].

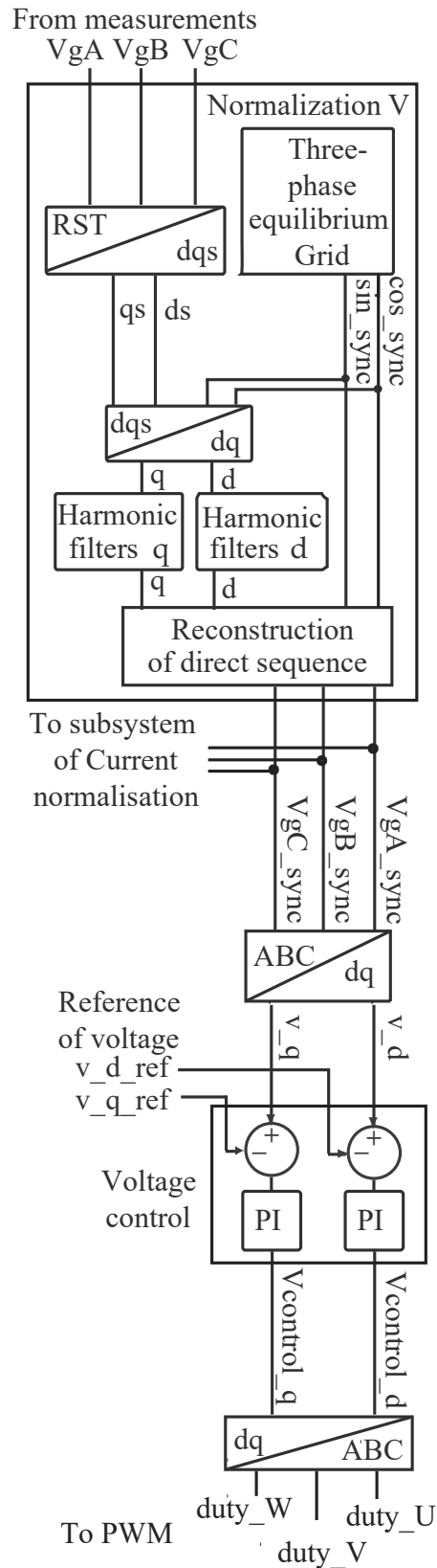


Fig. 2. Off-grid voltage mode of the three-phase inverter control of the HRES.

In order to reject the possible harmonics, perturbations, measuring noise, etc. due the unbalanced three-phase grid, the measurement signal of the voltage in the RRF

transformation is synchronized with a virtual balanced three-phase grid. This helps to balance the three-phase measured signal in the unbalanced case.

The next step is the treatment of d and q components of the measured signal. Because the first harmonic ω_1 in three-phase systems is equal to the frequency of the grid (50 Hz), enough simple to determinate all harmonic frequencies. Moreover in the RRF, in the case of a completely balanced three-phase systems, the 5th and 7th, 11th and 13th harmonics in d and q reference frame transform into the 6th and 12th respectively [15], and so on. Nevertheless, in the case of an unbalanced grid, the 5th and 7th harmonics in d and q reference frame transform them respectively into the 4th, 6th, and 10th and 12th harmonics, etc. For completely rejecting the harmonics in both cases, the notch harmonic filters will be adjusted to the $h = 0, 2, 4, 6, 8, \dots, 26$ harmonics with $\omega h = h\omega_1$, and connected in series for the d and q components of voltage measurements. The importance of this step is that it rejects almost all measurement noise, perturbation and harmonics from measured signal, but the array of filters increases the time delay due the signal transport through the filters.

To solve this problem, during the operation of reconstruction of the direct sequence, the transformed three-phase measured signal is again synchronized with the balanced three-phase, which allows to obtain by means of the "Normalization V" system the three-phase reconstructed signal with the same phase and frequency as in the measurement point.

After that, this three-phase signal is driven to the voltage control system and used in the current control system in the case of the current regulation mode of HRES ("Fig. 3").

The most suitable voltage control solution for the three-phase systems is to use two PI regulators in the RRF for d and q components, respectively [16], [17], instead of using the regulation directly in sinusoidal three-phase signals. This method is very robust and easy to implement. After the voltage control step, signals pass through the inverse RRF transformation and are driven to the Pulse-Width Modulation (PWM) process of the inverter to close the control loop.

2.3. Operation of the HRES connected to the grid.

All the participants connected to the grid are obligated to follow the grid European IEC standards (IEEE 929, IEEE 1547 and IEC 61727) and restrictions about harmonic limits, besides the consumer power restrictions. In order to follow the above mentioned restrictions for the injected power into the grid, the HRES needs to have a system of power synchronization with the grid [18].

"Fig. 3" shows the flowchart of the control mode of HRES connected to the Grid. It consists of the system of current measurement normalization "Normalization I", the system of current control and the system of synchronization.

level in the three-phase system, and the control system of the HRES regulates the current flow.

The measurements of three-phase system currents are the inputs of the system of the current normalization. Here, during the direct RRF transformation, the current is synchronized with the clean balanced voltage measurements from the system of voltage normalization. This helps to reject disturbances due to the unbalanced grid and to reach the unity power factor (UPF) [19], [20].

Furthermore, the measured current signals in d and q frames are the inputs of the system of the current control. Here, they are compared with the references of the current flow from the energy management system and proceed to the PI regulation step.

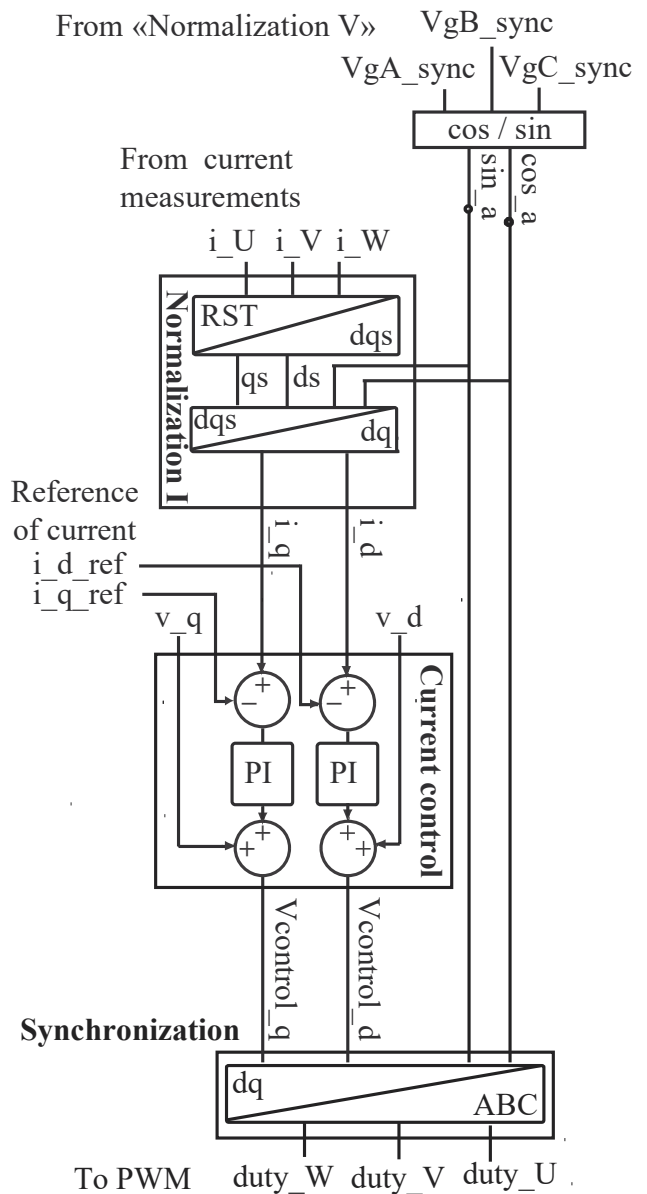


Fig. 3. Grid-connected current mode of the three-phase inverter control of the HRES.

According to [21], for the aim of i_d and i_q control, the transfer functions of the PI controllers for d and q

components, are respectively represented in “Eq. (2)” and “Eq. (3)”.

$$W_d(s) = \frac{K_i (i_d(s) - I_d^{ref}(s))}{s} - K_{pi} * i_d \tag{2}$$

$$W_q(s) = \frac{K_i (i_q(s) - I_q^{ref}(s))}{s} - K_{pi} * i_q \tag{3}$$

where K_i and K_{pi} are the integral and the proportional coefficients of the PI controller, I_d^{ref} and I_q^{ref} are the current reference for d and q components respectively.

The PWM process has been using the sinusoidal voltage signal as reference. Therefore, it is necessary to transform the d and q components of the current reference into the voltage reference frame. For this purpose, the voltage reference from the voltage control of the off-grid mode of the HRES is added to the current reference after the PI control to get the voltage reference of the injected power [22], [23].

The final step of the grid-connected control mode of the HRES before the PWM operation is the synchronization with the grid. During the inverse RRF transformation, the reference of the voltage signal is synchronized with the measured phase and frequency of three-phase system of the HRES. In the grid-connected case, there are the phase and the frequency of the grid. It is one of the paramount aspect to follow the grid codes [24], and to inject the power into the grid.

This solution accords with the injected power in the three-phase system and let to connect/disconnect the HRES from the grid without perturbations. In addition, the multipurpose of the developed methods is that they allow the stable operation of the HRES and the change between modes almost instantly. These methods are easily applicable and universal. This is a good advantage compared to similar methods of only current control [25], [26] or voltage control [27].

3. Practical Validation

To validate the two proposed methods of the HRES control, the case of the connection of the HRES to the grid was chosen. Before the connection, the HRES works in the off-grid mode and the vottage control system. During the connection time, the operation mode of the HRES changes to the grid-connected with synchronization and the current control system. The two tests will be provided. Firstly with the HRES connection without power injection to validate the synchronization alorythm. The second test will be similar to the first one, but with power injection into the three-phase system of the HRES with instant consumer supply.

The test system is described below. The three-phase inverter of testing HRES is shown in “Fig.4”. It is the three-phase inverter IGBT SEMIKRON SKS 22F B6U + E1CIF + B6CI 13 V12 (the rated current is 22 A, while, the maximum voltage is 1200V, the advise maximum switching frequency is 6 kHz).

Instead of the PV production, the programmable DC supply AMREL SPS800X6-K12D (maximum voltage rating is 800V, maximum current rating is 6A, maximum output power is 1200W) was used, which represented all the DC bus part of the HRES. The three resistances of 470 Ω represent the consumer. To create the control sheme Matlab/SIMULINK software was used. To operate the equipment according the control sheme, the dSPACE1103 real-time platform and dSpace interface software were used, as shown in “Fig. 5”.

As the connection instant is very fast (a few milliseconds), to seize this moment and to study the transfer process, the Yokogawa DL850 ScopeCorder was used (recordind speed up to 100 MS/s, recording resolution is up to 16-bit). It is shown in “Fig. 6”. This modular waveform oscilloscope is able to record voltages, currents, accelerations, etc.

The results obtained for the first and the second tests are shown in “Fig.7” and “Fig.8”, respectively. In both cases, at the beginning, the HRES works in the voltage control off-grid mode. In the moment of time M. 1, the grid connection appears. At this time, the HRES detects the grid and changes the control mode to the current control grid-connected mode with synchronization. The time between moments M. 1 and M. 2 is the transfer time.

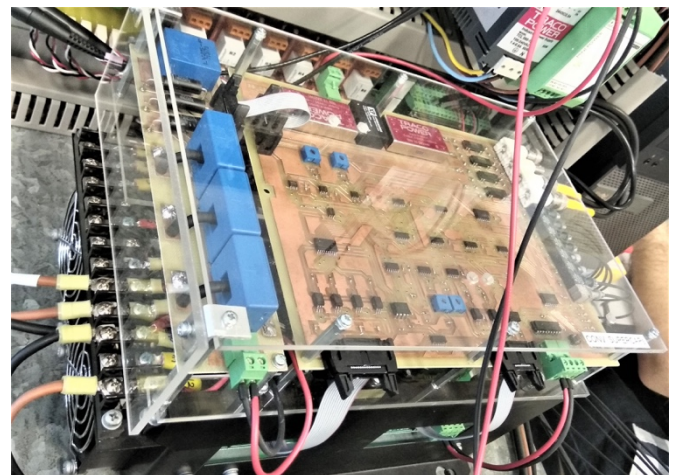


Fig. 4. Three-phase inverter of the tested HRES.



Fig. 5. AMREL SPS800X6-K12D DC source in the top-left and dSpace1103 real time platform in the centre.



Fig. 6. Yokogawa DL850 ScopeCorder waveform recording tool.

In the moment M. 2 the transfer process of the grid-connected mode of the HRES appliance is finished, and the HRES grid connected mode is applied completely.

“Fig.7 a)” and “Fig.8 a)” represent the grid voltage. Owing to the synchronization system of the HREs, in the moment of the connection of the grid to the three-phase system of the HRES, the system remains stable and this operation does not perturb the grid.

“Fig.7 b)” and “Fig.8 b)” show the voltage of the three-phase system of HRES. Before the moment M. 1, the system works in the voltage control mode and the HRES controls the voltage level in the three-phase system of the HRES. Using the PWM algorithm for voltage modulation, the shape of voltage signal is a little noisy, but correct in the voltage level, phase and frequency. It is sufficient for supplying the consumer with restricted power quality. At the moment M. 1 the grid is connected and start to maintain the voltage level in the three-phase system of the HRES. The voltage plot shape starts to be the same that in the grid system (the same that plot a) of “Fig.7” and “Fig.8”).

“Fig.7 c)” and “Fig.8 c)” represent the current



Fig. 7. First test chart: a) the voltage in the grid, b) the voltage in the three-phase system, c) the current injected into three-phase system from the HRES.

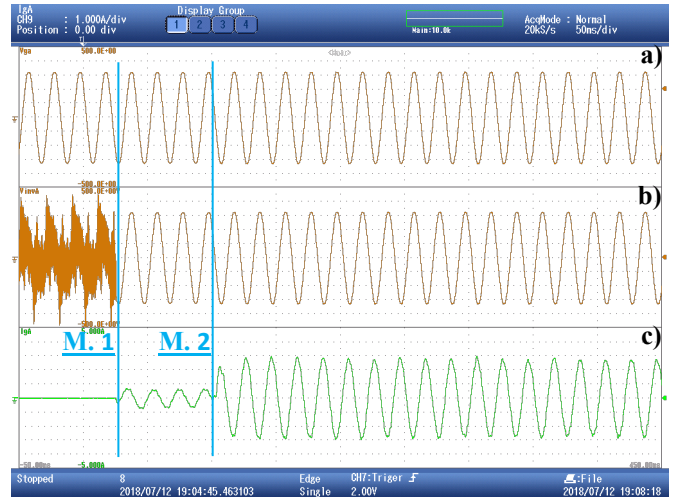


Fig. 8. Second test chart: a) the voltage in the grid, b) the voltage in the three-phase system, c) the current injected into three-phase system from HRES.

change of mode transfer process. Between instants M. 1 and M. 2, a small current flow appears. At first, it is due to the not full beginning of current control of the HRES mode operation. Secondly, it is due to the necessary time for the first control input to close the control loop and to create the control output. However, after the end of this transfer process, the current flow stops, and for the first test the system stabilizes, see “Fig.7”, or the HRES starts to full injection of the required current in the three-phase system of the HRES to fully supply the consumer required power.

The synchronization solution is in accordance with the injected power into the three-phase system and let to connect/disconnect the HRES from the grid without perturbations.

4. Conclusion

In this work the common aspects of the HRES system was shown, its components and its two main operation states are depicted: the grid connected mode and the off-grid mode. In the case of unreliable or failed grid, the HRES needs to detect the failed grid and immediately isolate itself from the grid. When operating in isolated mode, the HRES uses the voltage control mode to supply the consumer. In the case of appearance of reliable grid with allowable parameters, the HRES automatically detects this fact and connect its three-phase inverter to this grid. In this case, the grid keeps the voltage level in the three-phase system of the HRES and the HRES operates in the current control mode to inject the required current for supplying the consumer.

The practical tests in this paper shows the good operation of developed multipurpose control system in the island case (off-grid mode) and in the grid connected case. Owing to the developed system of grid synchronization the HRES may connects and disconnect to/from the grid without any perturbations and with plenty fast transfer time (about 70-80 milliseconds). Techniques of control of the voltage in the off-grid mode, and control of the current in the mode of grid connection with synchronization of voltage, explained in

this work, show good performance and their easy and practical implementation.

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