Autonomous Three-Phase Induction Generator Supplying Unbalanced Loads

Cătălin Petrea ION, Corneliu MARINESCU
Transilvania University of Brasov, 500036, Romania
catalin.ion@unitbv.ro

***Abstract*—This paper presents a control method for a stand-alone micro hydro with induction generator (IG) supplying unbalanced three-phase loads. Besides voltage and frequency regulation, the phase balancing is ensured for this particular operating regime. The proposed control topology relies on a combination between a voltage source inverter (VSI) and a dump load (DL). The VSI imposes the system frequency and performs the unbalances compensation, while the DL deals with the voltage regulation. Experiments have yielded the reliability of this configuration during generator loading and unbalanced loads supply.**

***Index Terms*—micro hydro power plant, induction generator, phase balancing, three-phase, unbalances.**

I. INTRODUCTION

Electricity production from renewable energy sources (RES) is a must for the actual energetic sector, due to environmental concerns, fossil fuels depletion and increasing energy demand. At European level, the so-called 20-20-20 strategy imposes to each EU country to sustain at least 20% of its electricity consumption from renewable sources by 2020. The corresponding research area covers a wide range, from hundreds of MW like in the case of large wind farms to several kW units, suitable mainly for isolated consumers [1].

Romania has a hydro-graphic network that still offers a significant unexploited potential for micro and small plants. The national energetic strategy for 2007-2020 states that “micro hydro power plants (MHPPs) represent a good alternative for supplying rural areas that are still not connected to the national utility grid”.

For low power generation units based on micro hydro power plants, the induction generator (IG) is more suitable than the synchronous one, based on advantages like price, robustness, simpler starting and synchronization. Moreover, for the low power range of few kW, induction machines are not manufactured specially for the generator regime; thus, series induction motors are employed as generators [2]. Based on this aspect, any improvement in motor manufacturing [3], motor modelling [4] or control [5] can have a positive impact on the machine behaviour in generator regime.

The three-phase IG autonomous operation represents a very dynamic research filed. The studies have focused on a very wide range of load types, such as passive, dynamic, non-linear and even unbalanced loads [6]. In terms of unbalanced load supply, the available literature can be divided into two major categories. The first (and more extensive) category is the one in which the three-phase generator supplies single-phase loads, connected usually between two of the three-phases [7]. The second one deals with unbalanced three-phase loads, yielding aspects such as equivalent circuit development [8] or steady state performances investigation [9].

In this paper an unbalances compensation algorithm is implemented for a three-phase induction generation supplying unbalanced loads. Experimental investigations confirm the effectiveness of the proposed approach. The paper is organized as follows. Section II presents the system configuration and control, while in Section III the experimental test-bench is detailed. Section IV shows the obtained results, while conclusions are provided in Section V.

II. SYSTEM CONFIGURATION AND CONTROL

The block diagram of the considered system is presented in Fig.1. It contains the three-phase induction generator, a capacitor bank, the unbalanced loads and the control part. The control system is a combination between a Voltage Source Inverter (VSI) and a Dump Load (DL) circuit. By operating at constant synchronous frequency (excepting the start-up process), the VSI imposes the IG frequency. The dump load connected to the VSI DC side controls the voltage across the DC capacitor, maintaining the system voltage in a standard variation range by dissipating the exceeding active power. A more detailed presentation of the control system capabilities in terms of voltage and frequency regulation can be found on a previous author’s research [10]. It shows good results when feeding balanced three-phase loads.

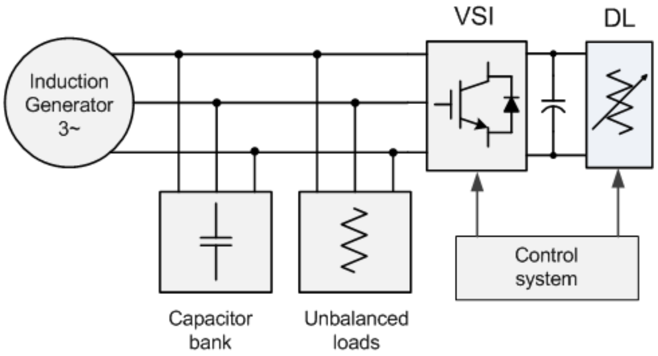

Figure 1. Block diagram of the analyzed system

The unbalances compensation technique, which is included in the VSI control loop, is based on the use of two

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Proportional-Resonant (PR) controllers. The balancing algorithm is presented in Fig. 2 and has been successfully tested by the authors in previous research papers [11, 12], which involved the three-phase induction generator supplying single-phase loads. In this work, the same principle has been applied to the case when the generator is feeding three-phase unbalanced loads. The transfer function of a PR controller is defined as [13, 14]:

$$G_{PR}(s) = K_P + K_I \cdot \frac{s}{s^2 + \omega_0^{\;2}} \tag{1}$$

where: K_P and K_I are the controller parameters and ω_0 is the resonant frequency. The K_P and K_I parameters give the dynamic behavior of the controller, but also they influence the controller bandwidth.

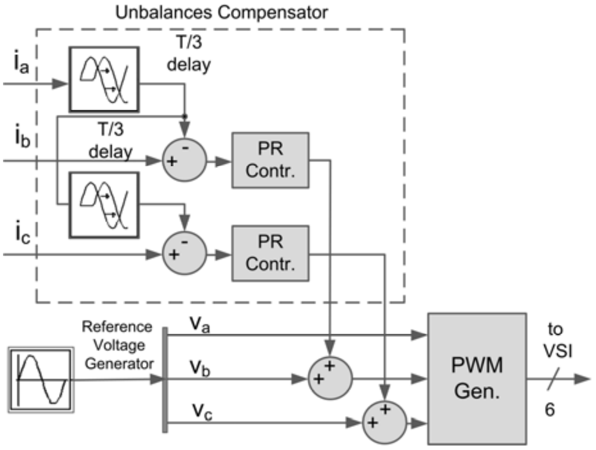


Figure 2. The unbalances compensation block (detailed)

The basic characteristic of a PR controller is that by introducing an infinite gain at the selected resonant frequency ω_0 it eliminates the steady state error at that frequency [15]. The block diagram of the PR controller is given in Fig. 3. It contains also an anti-windup function that has the role of limiting the controller output at the desired maximum value. This function is expressed as [14]:

$$a\omega = \begin{cases} y_{\max} - y, & y > y_{\max} \\ -y_{\max} - y, & y < -y_{\max} \end{cases} \tag{2}$$

The use of the PR controller instead of the classical PI has several advantages. The main one is the PR portability to the natural (abc) frame, which leads to a simpler transfer function then in the case of the PI controller [16]. As the considered topology has no neutral conductor, only two PR controllers are necessary [17]. Other advantages of the PR controller over the PI are the capability of eliminating the steady state error when regulating sinusoidal signals, along with high dynamic characteristics (see Ref. 18 and 19).

In order to test in laboratory conditions the proposed topology a hydro turbine emulator is required, as results from Fig. 4. The hydro turbine emulator operation relies on a control loop in which the input parameter is the induction motor electromagnetic torque, which is estimated by the frequency converter, while the output parameter is the motor imposed rotational speed. The other input parameter, which is directly controlled by the user, is the turbine gate opening. A complete description of the hydro turbine emulator can be found in a previous author's research [20].

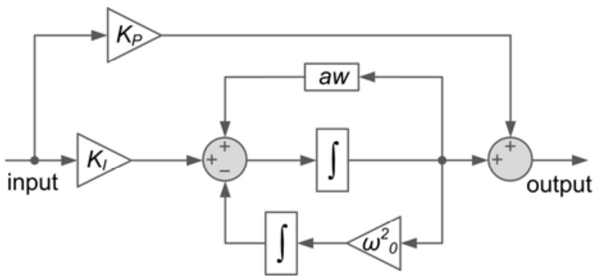


Figure 3. The PR controller block diagram

III. EXPERIMENTAL SET-UP DESCRIPTION

The system electro-mechanical part is based on a motor-generator group containing two three-phase induction machines (see Fig. 4). The left side machine, along with its frequency converter (FC), forms the hydro turbine emulator. The induction motor is a 7.5kW/1500 rpm series motor, while the frequency converter is a Danfoss FC302 7.5kW. For an accurate mechanical power measurement, the test bench is fitted with speed and torque transducers. Due to the torque transducer presence on the common shaft, three elastic couplings are required. As generator, a 4kW/1500rpm series induction motor is employed. Its nameplate power is the mechanical shaft power, thus, in generator regime, the machine will deliver a maximum of 3.3kW (assuming 0.82 efficiency). The parameters of the two electrical machines are provided in Appendix A.

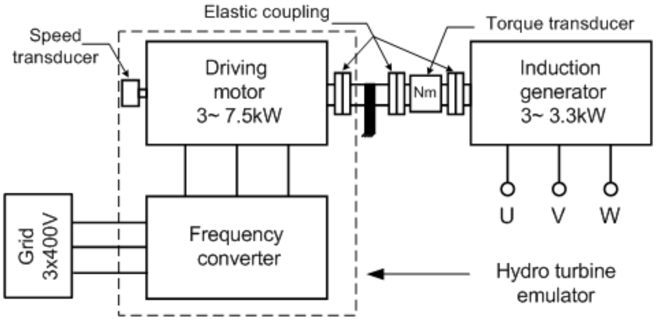


Figure 4. Driving system structure

The control side topology is presented in Fig.5. It relies on a 5.5kW FC302 Danfoss frequency converter. The converter structure involves an uncontrolled rectifier, a DC bus and an IGBT based three-phase inverter. The inverter part, along with a special interface to allow external control, constitutes the voltage source inverter (VSI). The VSI connection to the generator leads is made through an LC filter, with L=3.1mH and C=10uF.

Two aspects should be detailed with respect to the control system physical structure. First, for the system start-up a DC voltage source able to deliver between 100 and 150V is required. But the special interface that enables the VSI Real-Time control requires a minimum voltage of 240V. Thus, by connecting in series five Manson SDP 2405 DC voltage sources, each capable of delivering 40V/5A, along with another Weir 413D 60V source, the interface opening voltage was obtained. The sources unique output was connected on two of the three inputs of the frequency converter. The second aspect is related to the VSI DC bus capability. The frequency converter standard structure hosts two 560uF/450V series connected capacitors on the DC side, thus a total capacitance of 280uF. But for the system stability during transients, a higher capacitance value is required. Thus, a high value 2350uF/450 capacitor was added in parallel with the main one. The dump load (DL) topology is also based on the frequency converter facilities. It consists in the converter braking chopper and a 2200W braking resistor.

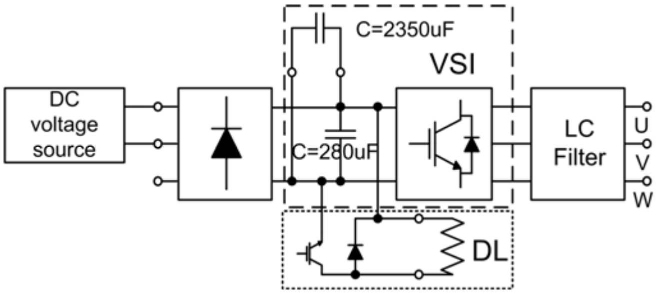


Figure 5. Control system structure

A picture is provided in Fig. 6 with the control part. On the top side, from left to right are present the driving motor frequency converter, the additional capacitors, the VSI and the LC filter. In the middle the dSPACE DS1003 expansion box with the IN/OUT cables is present, while the bottom side shows the user interface and the DC voltage sources. Another picture (Fig. 7) shows the mechanical part with the two induction machines, the torque transducer and the three elastic couplings.

Signals processing and control is ensured by a dSPACE DS1103 board. The control algorithm is built in Matlab/Simulink and implemented in dSPACE through a Real Time Interface. The ControlDesk program realizes the interface between the dSPACE system and the user. Data acquisition is made on both electrical and mechanical side. The values of the driving motor torque and speed give the mechanical power value. The line voltage and currents are measured on the VSI side; the DC voltage value is provided by a high voltage measurement block. Three current sensors placed at the generator leads give the three currents through the machine. The torque estimated by the driving motor frequency converter is also an input signal; the control system gives the motor speed corresponding to a certain loading degree. As for the control PWM signals, six of them go towards the inverter bridge and one to the braking chopper.

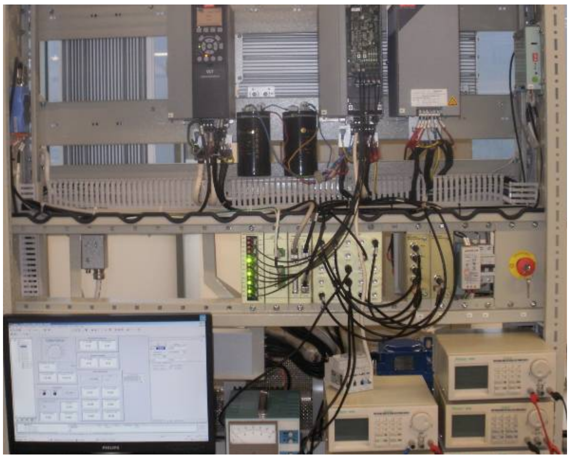


Figure 6. Experimental test-bench (control side)

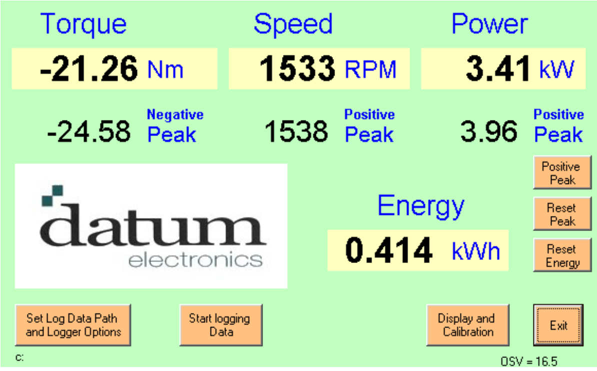
Figure 7. Experimental test-bench (mechanical side)

IV. RESULTS AND DISCUSSIONS

The experiments focused on two main directions: the induction generator loading and the system behaviour when supplying unbalanced loads. Due to the fact that the induction generator operates in parallel with the compensating voltage source inverter (VSI) at any moment they should be synchronized. The VSI is connected from the beginning at the IG leads, enhancing the start-up process.

A. Generator loading

After the start-up, the machine delivers around 600W, which represents slightly less then 20% from its capability in generator regime. The generator is then slowly loaded by increasing the mechanical power delivered by the turbine emulating motor, process that mimics the admission vane opening in the case of the real operation. It lasts for about 8 seconds, and the delivered mechanical power reaches 3.41kW, which represents 85% from the nominal one (see Fig.8).



Torque -21.26 Nm
Speed 1533 RPM
Power 3.41 kW
-24.58 Negative Peak
1538 Positive Peak
3.96 Positive Peak
Energy 0.414 kWh

Figure 8. Mechanical side measurements

On the generator side, due to the fact that there is no consumer connected, the entire active power circulates through the VSI and is consumed by the DL. At 85% mechanical loading, the generator delivers almost 2.85kW (see top of Fig. 9) which means that efficiency value in generator regime is 0.82 (the efficiency for motor operation is 0.85). Further tests were conducted as the machine was loaded up to its nominal mechanical power (3.96 kW); the available resulting active power was 3.3kW, confirming the 0.82 efficiency value.

In the mean time, after the loading process was over, the VSI delivered 200var, while initially absorbing 400var; this is due to the fact that the generator magnetisation requirements increase with loading (See bottom of Fig. 9). Due to generator loading, the VSI phase current increases from 1.2 to 4.6A (see top of Fig. 10).

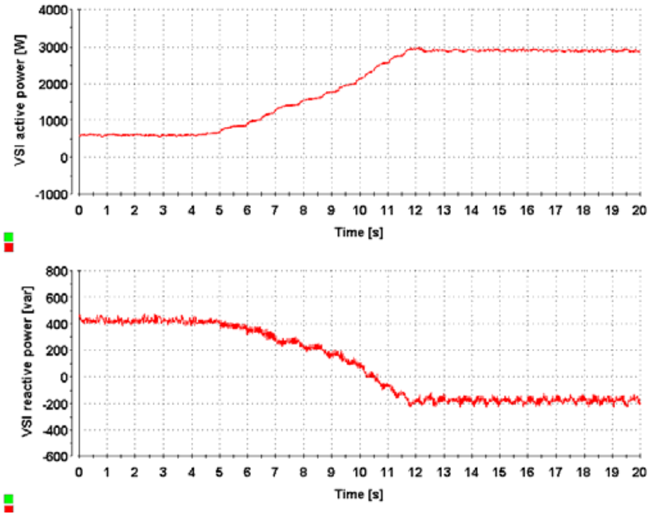


Figure 9. The active and reactive power circulation though the VSI

On the mechanical side, any increase in the power delivered by the prime mover induces a speed variation. Thus, the generator speed increases from 1508 to 1524 rpm as results from Fig. 10 (bottom).

During the loading process, the main system parameters (voltage and frequency) variation is insignificant, as it is depicted in Fig. 11.

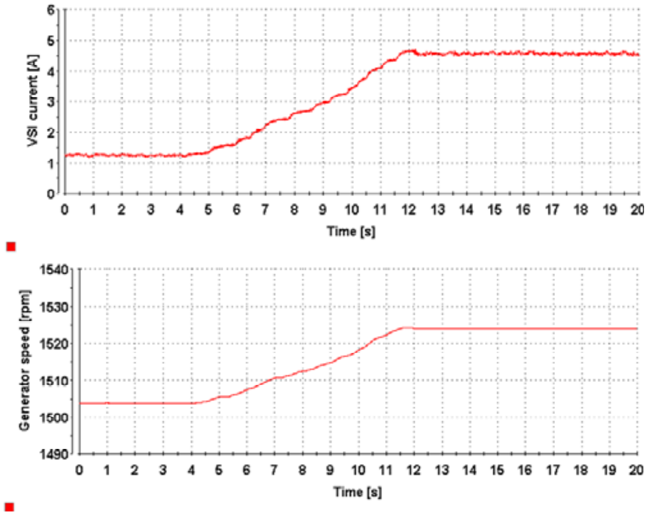


Figure 10. The VSI current and the generator speed variations

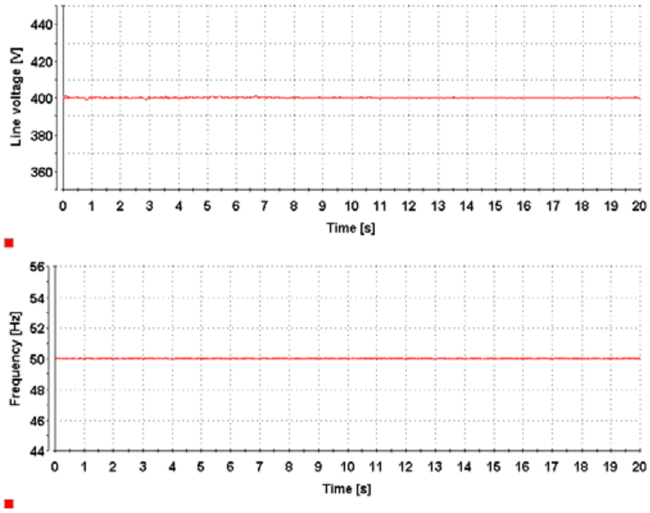


Figure 11. The line voltage and frequency variations during the generator loading

B. Unbalanced load connection

In order to investigate the system response to unbalanced load, the generator is loaded up to 2/3 of its nominal power (i.e. 2.2kW). Then, a three-phase unbalanced load with a total power of 70% from the available one is connected at t=6s and then disconnected after 8 seconds. The electrical parameters are monitored and the results analyzed.

In terms of voltage variations, they are in the range of 8V when the load is connected and 6V at its disconnection; the voltage regulator reacts promptly and the nominal value is reached after only 1 second (see top of Fig. 12). As for the frequency, its variations are insignificant as results from Fig. 12 (bottom). The VSI active power decreases from 2.2kW to 0.55kW, while the DC voltage hardly varies around the 640V value, as depicted in Fig. 13.

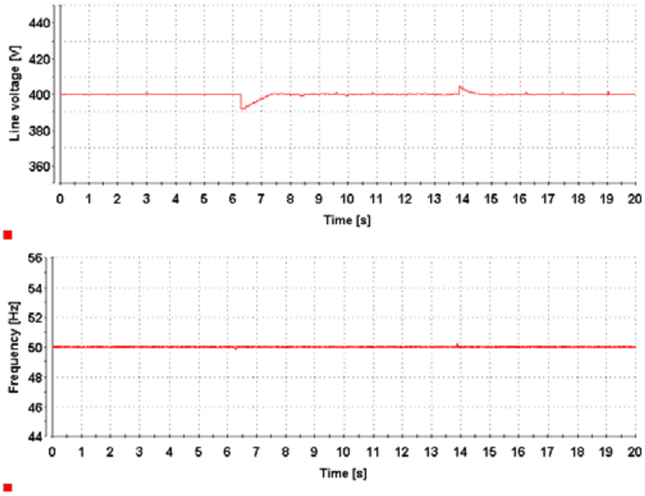


Figure 12. The line voltage and frequency variations during the transitory regime

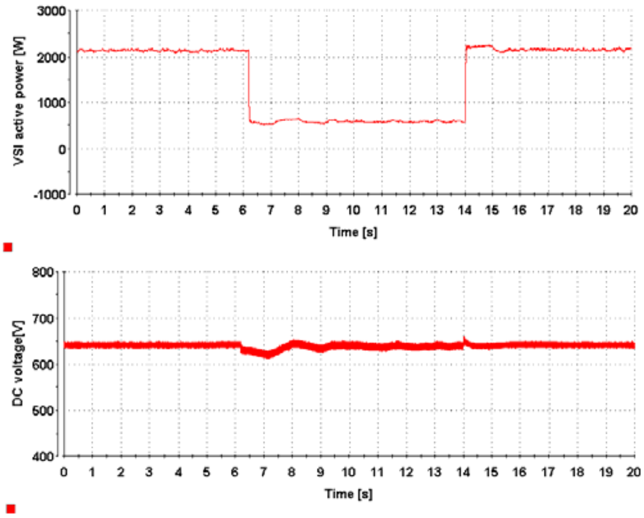


Figure 13. The VSI active power and DC voltage variations during the transitory regime

For the present situation, the currents through the machine and VSI are depicted in Fig. 14. For a more accurate analysis, the generator currents are measured using a 324A WaveJet type Le Croy Oscilloscope. The measurement yielded RMS values of 5.84A, 6.70A and 7.67A respectively (see Fig. 15).

If the unbalances compensator is activated the currents through the generator remain balanced (see top of Fig. 16), around the value of 7A. The compensation algorithm actually redistributes the currents through the VSI (see bottom of Fig. 16), in order to keep the generator currents balanced and avoid all problems associated with an unbalanced operation. A current capture using the oscilloscope when the unbalances compensator is active is depicted in Fig. 17.

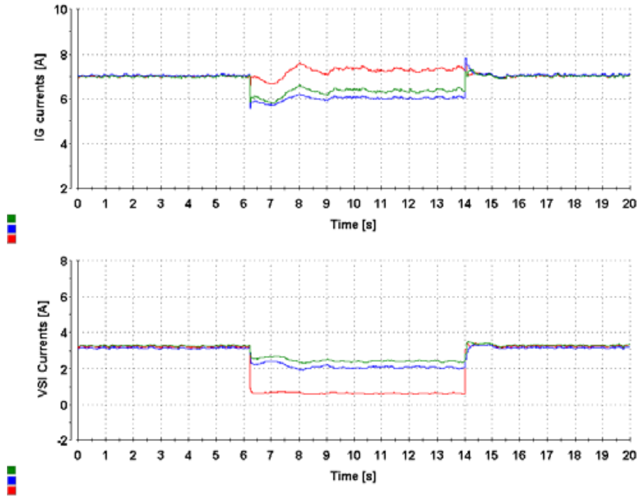


Figure 14. The IG and VSI RMS currents without the unbalances compensator

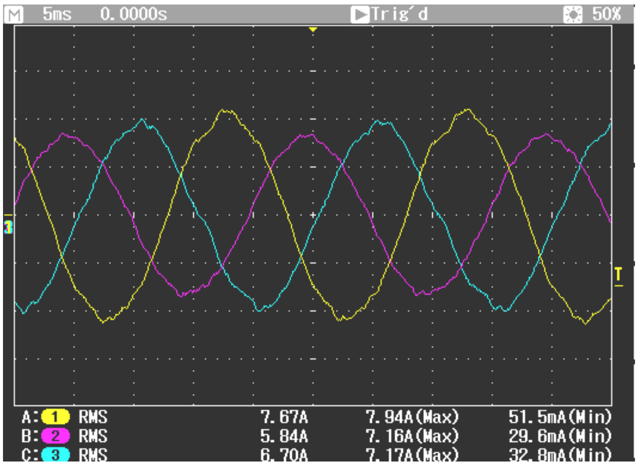


Figure 15. The IG currents waveforms without the unbalances compensator

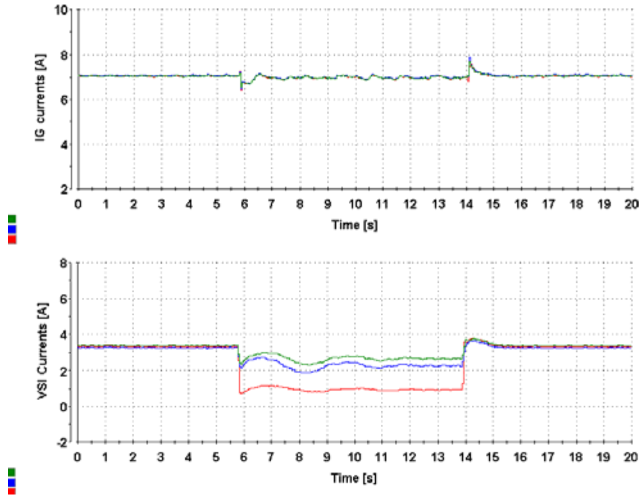


Figure 16. The IG and VSI RMS currents with the unbalances compensator activated

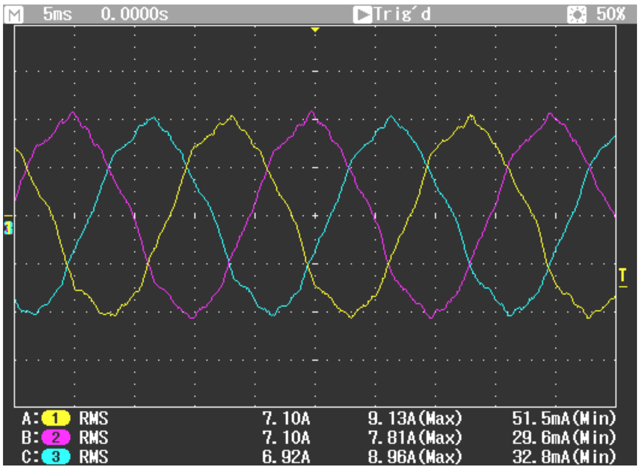


Figure 17. The IG currents waveforms with the unbalances compensator

V. CONCLUSIONS

This paper focuses on the experimental validation of a control topology for a stand-alone micro hydro power plant equipped with a three phase induction generator supplying unbalanced three phase consumers. The control topology relies on a combination between a voltage source inverter (VSI) and a dump load (DL) and ensures basically the voltage and frequency regulation.

The main contribution of this paper is that, by adding an unbalances compensation block based on Proportional-Resonant (PR) controllers to the VSI control loop, phase balancing is ensured when unbalanced three-phase loads are supplied. Using the proposed technology even single phase networks can be optimally supplied by a three phase generator. Experimental results obtained with the help of a laboratory test bench have yielded the following:

- the control system ensures a smooth loading for the generator; it reacts promptly and brings the main parameters (voltage and frequency) to their nominal values in case of transitory regimes;
- by using the VSI, DL and PR controllers, unbalanced three phase loads are converted into balanced ones, ensuring a stable operation and high performance for the three-phase IG.

APPENDIX A

The induction generator parameters (from the nameplate)
Mechanical power: 4kW;
Nominal power: 3.3kW;
Connection type: Delta;
Nominal voltage: 400V;
Nominal frequency: 50Hz;
Nominal current: 8.64A;
Power factor: 0.8.

The driving motor parameters (from the nameplate)
Nominal (mechanical) power: 7.5kW;
Connection type: Delta;
Nominal voltage: 400V;
Nominal frequency: 50Hz;
Nominal current: 15.3A;
Power factor: 0.81.

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