MEASUREMENTS AND DATA COMMUNICATION FOR A SMALL HYDROPOWER PLANT CONNECTED TO THE NATIONAL GRID

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An advanced measurement system for a group of small and medium Hydropower Plants is presented and analyzed. The system is synchronized by the time code obtained from Global Positioning System (GPS) and is based on embedded Phasor Measurement Units (PMU) and emulated ones developed on National Instruments CompactRIO Real Time Controller. Based on these measurements a series of power line parameters can be estimated, including the loads. This data can also be used for line differential protection.

Keywords: hydroelectricity, electrical energy, hydropower plants

1. Introduction

Hydroelectricity is a well-established technology, which has been producing power reliably and at competitive prices for 125 years [1]. It has the advantage over the other renewable of being more predictable and controllable. Moreover, it is the only economical solution for storing electrical energy by pumping overnight water from a lower reservoir to an upper reservoir and generating it back when there is a demand in the system.

These features can be observed in *Fig. 1* which represents a graph of production and load in the Romanian national grid. On the 03.12.2012 at the 4:59:31, one nuclear group of 700 MW suddenly switched off due to the effect of a snow storm. Consequently, this drop shall be covered from other sources. As Romania was connected to a European Grid, the plant got up to 1300 MW during 10 minutes in order to stabilize the system. Also, Romania exported 200 MW in natural in first 20 minutes. Generally, the hydropower plants reach 1900 MW in 20 minutes. Therefore, the import of the energy was no longer necessary and the system came back to the initial situation to export 200 MW. All this operations took place in 20 minutes.

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When these procedures are finished, the natural load increased and was also compensated by hydro energy power (blue) and slowly by the plant working on coal (black). So the energy necessary was cover.

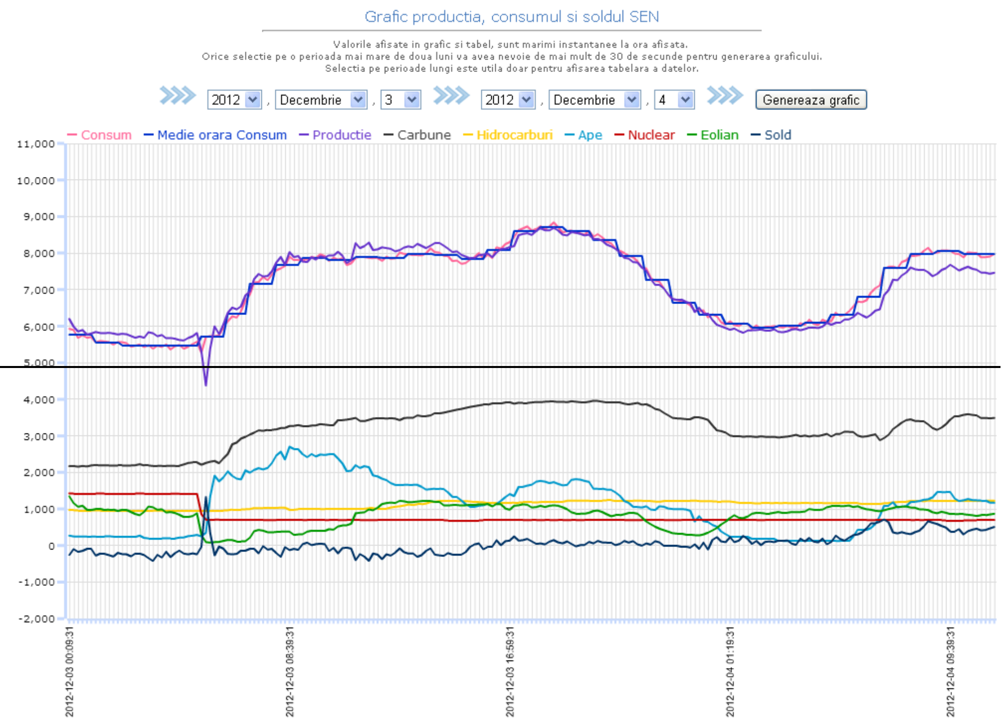


Fig.1 The graph of production and load in the Romanian national grid [2]

In conclusion, this example demonstrates the advantages of operating in more powerful systems than those from Romania and of having access to lower power sources that can react very quickly [2].

Hydroelectricity is still the biggest available renewable source. For instance, although in the United States the hydropower was accounted only for 7.8% of the power provided in 2011; this energy is equivalent to about 83% of what the renewable provide. [3]

Globally, the new hydroelectric capacity improvements have generated more power than all other renewable sources combined have provided since 2005. China's Three Gorges Dam, the largest hydroelectric facility in the world at 22 500 MW capacity and about 80 TWh annual output, came online during that period [9]. 92% of Africa's and 80% of Asia's hydroelectric technical potential remained untapped until now. In North America, this number is lowered to 61% and in Europe, it is 47% [2].

Although small run-of-the-river plants are certainly possible in many of the developing countries, a real and efficient capacity is obtained from large projects that have a significant impact on the environment. Recently the China Society for Hydropower Engineering announced that a 38-Gigawatt hydropower plant is under consideration in Tibet [8]. In these conditions the International Energy Agency (IEA) considers that the worlds can double the hydroelectric output over the next 40 years [9].

In Romania, as presented in the Fig. 2 [4], the total install power in hydro energy is about 7 GW, covering about 33% of total electrical energy produced. Small hydropower plants represent 9% of this total install power, e.g. about 3% of total produced energy. [4]

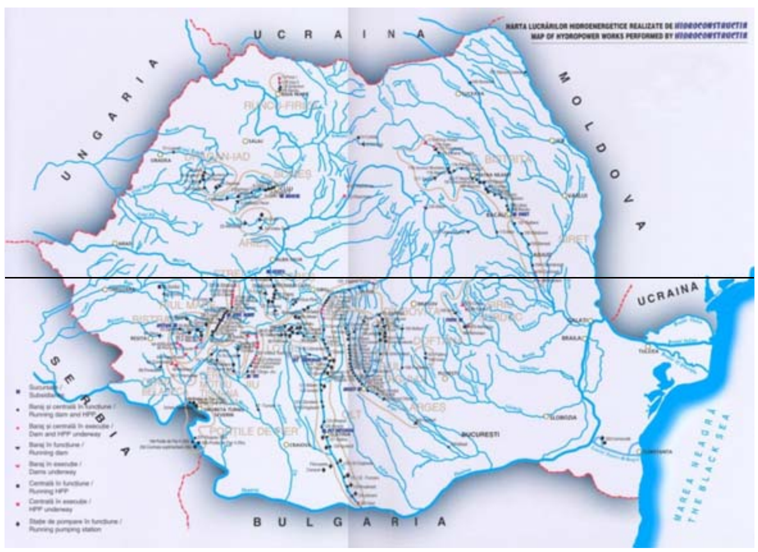


Fig.2. Romanian Hydro potential with the most important small and medium hydropower plants [4]

2. The physical system

The European system in charge with transporting and distributing the electrical energy represents the world most sophisticated, complex and costly manmade single technical achievement. It can be seen as an advanced system representing a combination of physical elements coordinated by computers through communication networks.

It was interesting to present our work in a particular case, the physical system covering the area of Hydropower Plants placed on river Argeş (Fig.3). [13]

In this case, the main physical element is the water coming from upstream storage lakes or directly run on the river. The conversion of hydro energy into mechanical energy is done by different type of hydro turbines which are chosen on the available head H and the discharge Q, Fig.3. [13]

The power P produced by any of these turbines can be calculated as

$$P = 10 x \eta x Q x H \quad (1)$$

where η represents its efficiency, function of water discharge Q and head H [5], [6]

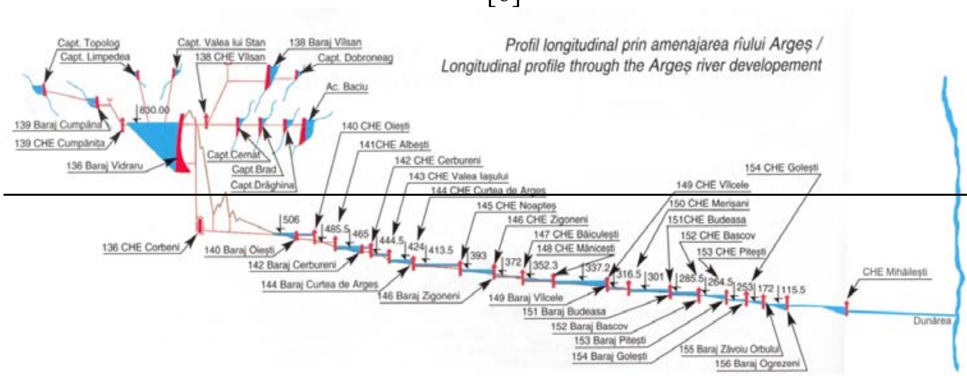


Fig.3. River Argeş with major, medium and small hydropower plants [13]

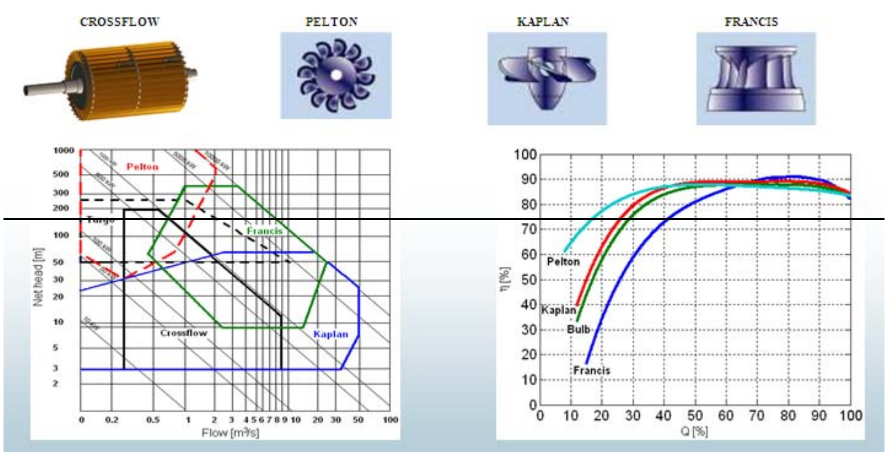


Fig.4. Types of turbines and their domains of utilization [13]

For a hydro turbine, it is recommended to operate in its optimal domain, in order to function within its maximum possible efficiency. Although the water turbines are designed for a given flow Q, head H and a speed n, at which their efficiency is maxim, in reality these parameters vary, even when they are supplied from reservoirs with high dams. In order to improve the efficiency of hydro mechanical convertors for all possible domain of operation, Q, H, n, the turbines have to present variable geometry through controlled stator director and seldom the pitch angles of the rotor.

The Francis turbines Fig. 4 [13] have a guide vane which controls the discharge and consequently influences its efficiency. The Kaplan Fig. 4 [13] turbines are optimally adjusted by the way of control of α, by the direction angle of the guide vane and by ф the angle of the runner blades, the efficiency being dependent on the combination of these two angles. [13]

3. Mathematical Model

For a system to be controlled, simulated and protected we should be aware of all the states of the system and where these conditions (e.g. currents) cannot be measured due to various reasons, they shall be "seen" in real time using the Kalman "observatories". Unknown parameters that can change depending on the network load shorting should also be identified in real time. Therefore, we present the mathematical model for analysis and synthesis of power systems.

A power system can be described as having a number m matrix entry (references generators) - u (t), n states - x (t) (currents in different nodes), r - interference (load or events on transmission lines and distribution) - v (t) and p outputs (final tensions to users) - y (t) [5], [6]:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{E}\mathbf{v}(t)$$

$$\mathbf{y}(t) = \mathbf{C}\,\mathbf{x}(t) + \mathbf{D}\,\mathbf{u}(t) \tag{2}$$

Where the matrix: A has dimension $n \times n$, B - $n \times m$,C - $n \times m$, D - $n \times r$, E - $p \times n$ and it is function to the physics system achievement.

$\mathbf{x} \in \Re^{n}$, $\mathbf{u} \in \Re^{m}$, $\mathbf{v} \in \Re^{r}$, $\mathbf{y} \in \Re^{p}$, $\mathbf{A} \in \Re^{n\times n}$, $\mathbf{B} \in \Re^{n\times m}$, $\mathbf{C} \in \Re^{p\times n}$, $\mathbf{D} \in \Re^{p\times m}$, $\mathbf{E} \in \Re^{n\times r}$

Form discrete system can be described by the following equations [5], [6].

$$\mathbf{x}(k+1) = \mathbf{A}_d\,\mathbf{x}(k) + \mathbf{B}_d\,\mathbf{u}(k)$$

$$\mathbf{y}(k+1) = \mathbf{C}_d\,\mathbf{x}(k+1) + \mathbf{D}_d\,\mathbf{u}(k+1) \tag{3}$$

where, obviously:

$$\mathbf{C}_d = \mathbf{C} \text{ and } \mathbf{D}_d = \mathbf{D} \tag{4}$$

For system with only one input and only one output, we can write:

$$\boldsymbol{x}(k+1) = \mathbf{A}_{\mathrm{d}}\,\boldsymbol{x}(k) + \mathbf{b}_{\mathrm{d}}\,\boldsymbol{u}(k)$$

$$\boldsymbol{y}(k+1)=\mathbf{c}_{\mathrm{d}}^{\mathrm{T}}\,\boldsymbol{x}(k+1)+\mathbf{d}_{\mathrm{d}}\,\boldsymbol{u}(k+1) \quad (5)$$

where: $\mathbf{c}_{\mathrm{d}}^{\mathrm{T}}=\mathbf{c}^{\mathrm{T}}$ and $\mathbf{d}_{\mathrm{d}}=\mathbf{d}$ [5], [6].

Observation

In most cases the number of states is greater than the number of system outputs. $(\mathbf{x}\in\Re^{n},\ \mathbf{y}\in\Re^{r},\ r\leq n)$

As we will see, performance tuning knows all these states, or at least most of them. As these conditions are not often directly measured (e.g. currents in a cage induction motor rotor) it requires that these conditions to be even estimated based on input and output quantities and assumed model of the system.

This operation is possible only for observable system. About a system is said to be observable if based on measuring inputs and outputs on a finite time interval the initial state of the system can be determined.

The transposed matrix of observation which shall have the rank "n" in order the system to be observable $\mathbf{O}_N$ is:

$$\mathbf{O}_N^T=\left[\mathbf{C}_d\ \vdots\,\mathbf{A}_d^T\mathbf{C}_d\ \vdots\left(\mathbf{A}_d^T\right)^2\mathbf{C}_{\mathrm{d}}\ \vdots\ \ldots\ \vdots\left(\mathbf{A}_d^T\right)^{n-1}\mathbf{C}_{\mathrm{d}}\right] \quad (6)$$

4. Measuring system

Each of the mentioned Hydropower Plants produces AC electrical energy at 6kV which through local step-up transformers it is raised to 20 kV, thus covering the local demand of energy. The rest is supplied through an aerial line to a utility substation where the voltage is stepped-up again to 110kV. Similarly, the substation is connected through an 110kV line to a 110/400kV substation, part of the National Grid, Fig. 5. [13]

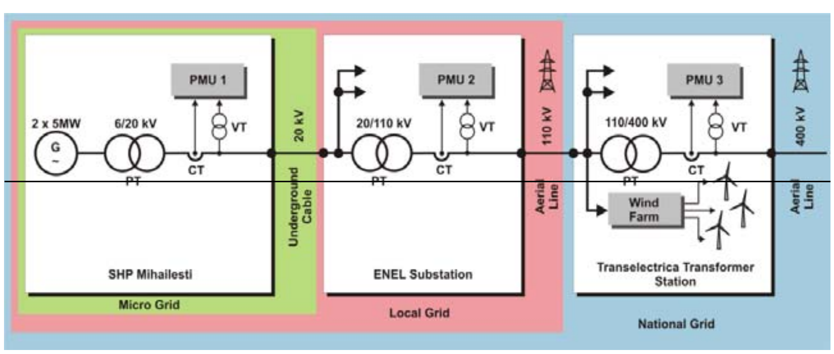


Fig. 5. The way from low-medium to high voltage national grid [13]

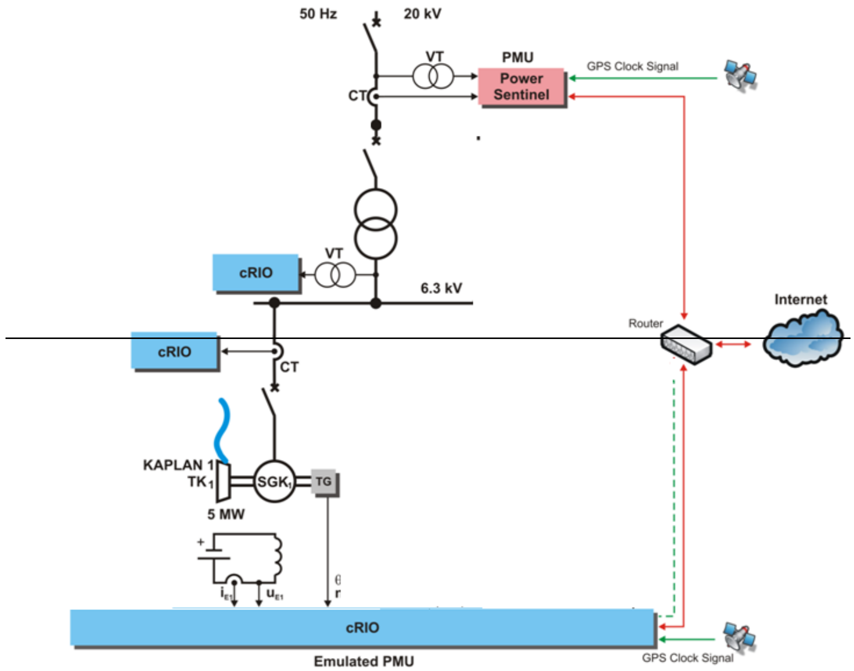


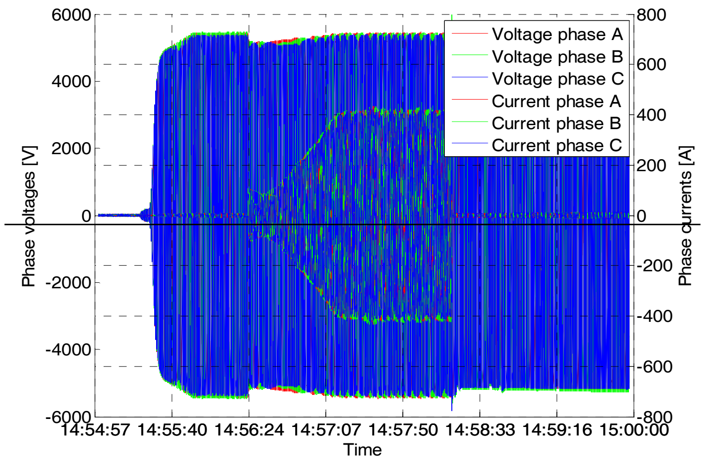
Fig. 6. Typical measuring system for a SHP [13]

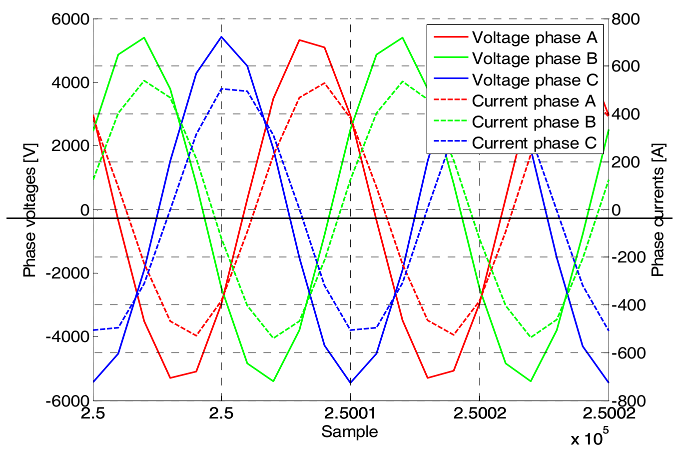
In order to control such a system it is necessary to measure all the state variables, or at least part of them and observing the rest. In principle, most of parameters are known, but there is incertitude to the loads which by their nature are variable. In this case parameter estimation techniques shall be used.

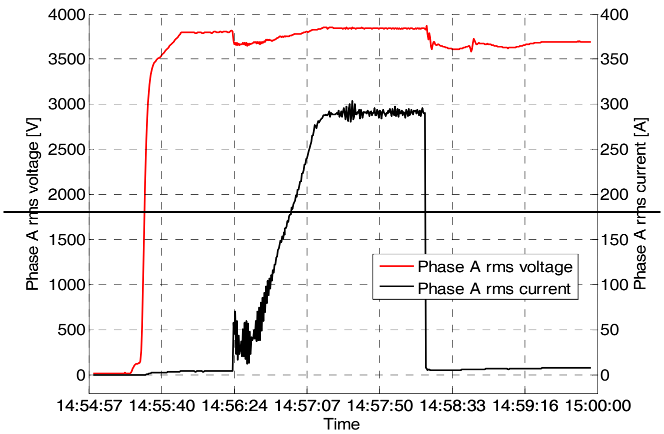
The basic measurements start with those from the power plant, Fig. 6. [13] The developed measurement system is based on Phasor Measuring Units (PMU) placed in the grid nodes and a National Instruments CompactRIO programmable automation controller placed in every Hydro Power Plant and substation. The NI Compact RIO is a reconfigurable control and acquisition system which contains also a Field. [12]

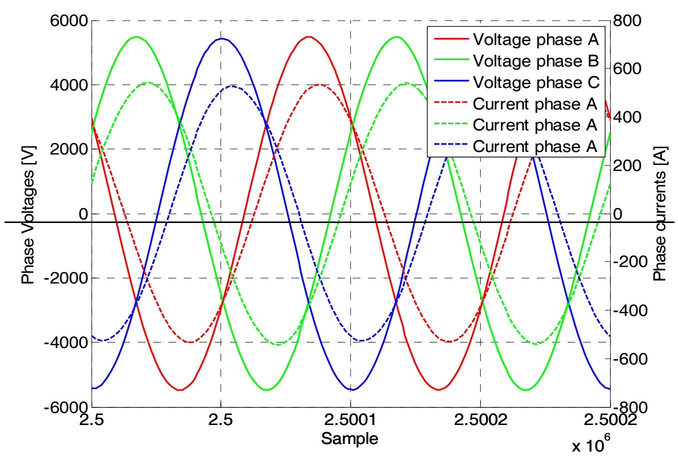
The CompactRIO system can also be used for Real-Time Simulations and Hardware-in-the-Loop, (HIL) control. For time synchronization, both equipment use a time stamp obtained from Global Positioning System (GPS).

In Fig.7 [13] it is presented the transient operation of a hydropower plant starting to steady state with the 75% of rated load and rejection of the load. Initially the hydro system is stationary and it is brought to synchronous speed by the speed regulator. The voltage regulator controls the output voltage through the current of excitation. The no load voltage is brought equal with that of the grid and the process of synchronization takes place. The loading of the generator is controlled by the speed and voltage regulators.


6000
4000
2000
0
-2000
-4000
-6000
800
600
400
200
0
-200
-400
-600
-800
Phase voltages [V]
Phase currents [A]
14:54:57 14:55:40 14:56:24 14:57:07 14:57:50 14:58:33 14:59:16 15:00:00
Time
Voltage phase A
Voltage phase B
Voltage phase C
Current phase A
Current phase B
Current phase C


6000
4000
2000
0
-2000
-4000
-6000
800
600
400
200
0
-200
-400
-600
-800
Phase voltages [V]
Phase currents [A]
2.5 2.5 2.5001 2.5002 2.5002
Sample
x 10^5
Voltage phase A
Voltage phase B
Voltage phase C
Current phase A
Current phase B
Current phase C


Phase A rms voltage [V]
Phase A rms current [A]
Time
Phase A rms voltage
Phase A rms current
14:54:57 14:55:40 14:56:24 14:57:07 14:57:50 14:58:33 14:59:16 15:00:00


Phase Voltages [V]
Phase currents [A]
Sample
x 10^6
Voltage phase A
Voltage phase B
Voltage phase C
Current phase A
Current phase A
Current phase A

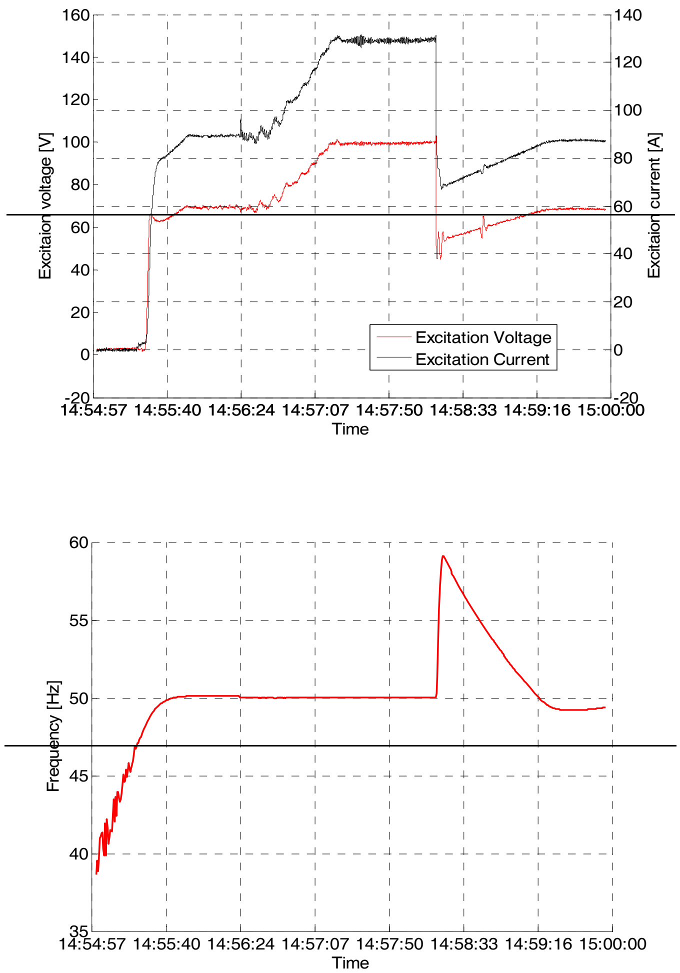


Fig. 7. Records of transient process during a start-up, steady state and load rejection [13]

When the load rejection takes place, the generator is cut off from the line and its speed increases to about 20% the rated value. The speed regulator cuts the water supply of the turbine and the speed is brought back to the nominal value [13].

5. Conclusions

For optimal management of Hydropower Plants either automatically or by a human dispatcher, it is necessary to know at any time, in real time, various electrical and hydraulic sizes that need to be synchronized, the synchronization performed on the basis of GPS satellites, allowing not only knowledge of ground coordinates, and universal time, accurate in our case ± 400 ns. These measurements are made using equipment developed by various manufacturers either European or U.S., and that information was acquired and transmitted by various SCADA protocols. Measurements were made in Hydropower Plants placed on Arges River, in two low power Hydropower Plants respectively Mihăileşti and Vâlsan, the lake Mihăileşti being at the highest altitude (957 m).

In both cases we used specialized equipment type CRIO and Carlo Gavazzi and data transmission have used various methods using either optical fiber links all converging server machines as in the laboratory of the Department of Materials and Drives Faculty of Electrical Engineering, Polytechnic University of Bucharest. Such physical connections have been used on the fiber cable, the copper cable connection using ADSL technology and radio communication through the RADIOCOM [11], [12].

In this paper, the part that authors consider to be their original contributions can be resumed as follows:

1) Implementation of system equipment type PMU (phasor measurement unit) for nodes in transmission lines that allow for synchronous measurement (via GPS) of the instantaneous current and voltage, active power, reactive, harmonics etc. and their inclusion in a European Academic involving Germany, the Netherlands, Slovenia and Romania and five UK Universities.

2) For measurements of power equipment more than 11 MW we developed measurement applications on CRIO system using a specific CRIO module system based on FPGA (flexible programmable gate arise) for acquisition and processing data which also allow processing in real-time of actual values of current and voltage, active and reactive power, frequency, THD, etc.

3) We used advanced equipment but lower price. For example in Mihăileşti, although purchases are made at 10 kHz, the outputs are effective values of current and voltage, active and reactive powers, etc. and sent out to 100 ms sampling time. All these devices have a web address (IP) so readable or on request by the dispatcher.

Acknowledgment

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