Coexisting of islanded and parallel operation mode in 2 MW SHPP plant to supply electricity to rural villages: problems and optimization of the design

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Introduction

The supply of electricity to rural villages in developing countries is challenging from - at least - a technical, economic, environmental and social point of view. In most of the case, rural villages don't have an existing distribution grid so both production and distribution has to be designed together giving the chance to optimize the entire system.

In the paper, the main technical features connected with the management of a distribution grid in the remote Tanzania areas (Ludewa Discrit) fed in two different ways - directly by the 2 MW Lugarawa/Madope SHPPs working in islanded mode and in parallel with the national grid have been described.

The operation of a small hydropower plant under those two very different conditions (islanded operation and parallel operation) implies a high technical effort, especially for the management of the transient phenomena occurring when the hydropower plant must shift from islanded operation to grid operation and *vice versa*.

Despite of those problems the double operation mode is revealed itself a very effective solution for the electrification by means of hydropower plant as it allows for (i) exploiting completely the natural hydropower potential without any limitation due to the consumption diagram of the islanded grid and (ii) getting a very high reliability of the energy supply because the connection with the national grid gives also the chance to supply the rural grid taking the electricity from the national grid, if the SHPPs are out of service.

1 Background (Project description)

The project is implemented by ACRA CCS with Studio Frosio as technical partner. The whole project will consist in (i) refurbish the Old Lugarawa SHPP, (ii) built a new SHPP with a capacity that will be able to supply the energy demand of the area involved in the project, (iii) creation of a reliable distribution grid to bring electricity in more than 20 villages in the surrounding area of Ludewa.

1.1 Localization

Ludewa District is one of the four districts of the Njombe Region and it is located approximately 150 km south of Njombe Town. Ludewa district is a rural area with a huge number of natural resources that could offer great development potentialities: agriculture, forestry, water. On the other side, it is very isolated and the villages are not reached by the national grid and large scale agriculture. At present, only 4% of the population has access to electric energy coming from different source privately owned and managed. Among them the Old Lugarawa SHPP supply energy for the Saint John Hospital and surrounding families, solar panels supply energy for 544 families. Internal lighting generally has done by kerosene lamps while diesel engines are generally used only for milling and welding machines.

The Old Lugarawa HPP, owned and managed by the hospital, was built more than 30 years ago. The original power output of the plant was about 150 kW but at the present, the turbine can provide only half of the original power about 75 kW which is not enough to run the Hospital and the village together. Especially in the dry season, during the day only the hospital is connected to the power station while private has energy only for 2-3 hours during night. Because of its poor efficiency, of water shortages and of Lugarawa village development, the existing SHPP is inadequate and far below the required capacity. Interruptions of the electric supply is quite common and it becomes a problem for the hospital. It also must be added that, during the night and the rainy season part of the energy produced must be wasted because it is an off-grid system. While during the dry season, even if the turbine is repaired, the interruption in the supply of energy will not be completely solved due to the insufficient flow of the water.

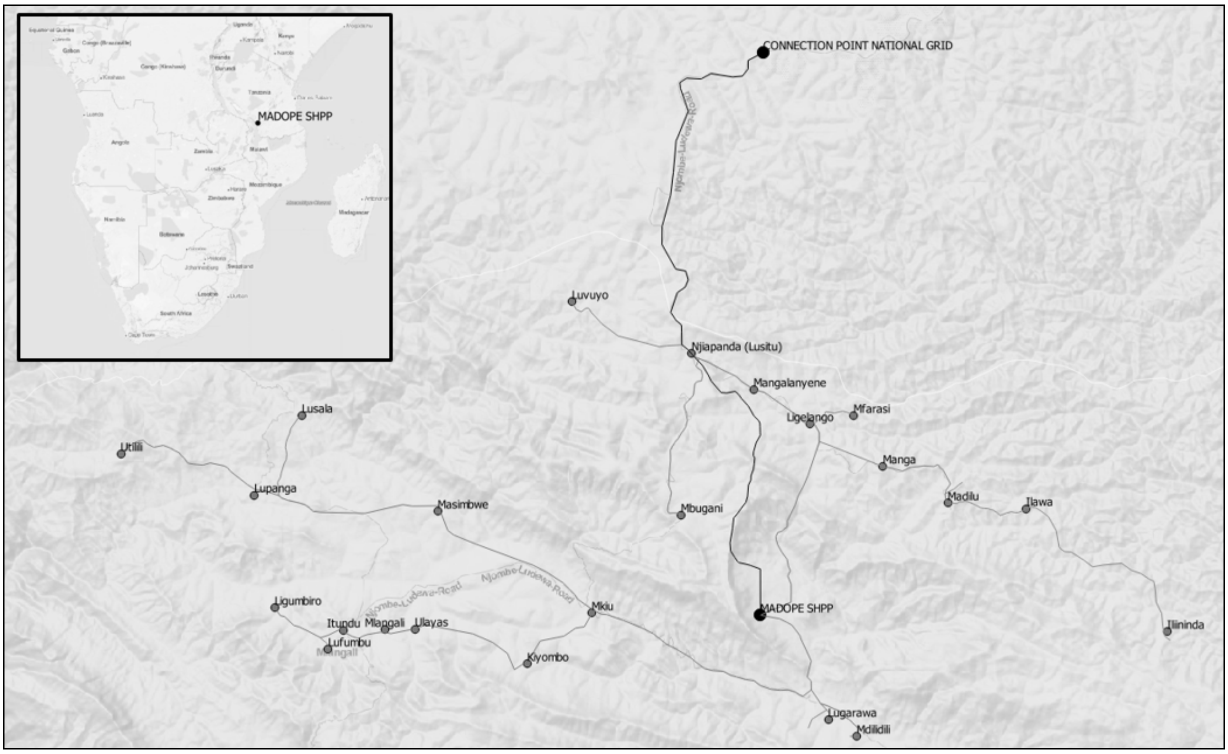

Figure 1 – Project localization and new distribution rural grid

1.2 Project layout

The waterfall exploited by the new SHPP is not natural but "manmade". The diversion was done in the year 1999-2000, with the authorization of Water Basin Nyasa Authority, to increase the water supply for the old Lugarawa power station; it was designed for diverting the river water (run-of-river diversion) and not for a power station. The head works consist of weir wall, gates and intake combined, a 543 m long concrete culvert and a channel around 200 m long. These head works convey water through a cliff of some 200-m fall and it continues with steep slopes for another 250 m, until it joins a stream flowing to Lugarawa power station about 5 km downstream. Under all this effort the waterfall is not utilized to develop any power: the water, instead, is running downstream to provide a few more kilowatts at Old Lugarawa power station.

The new SHPP will use some of the existing civil works, with the necessary improvements; for instance, the right wall of the weir will have to be raised to protect the intake structures from the flood, while the intake will have to be equipped with new flushing gates and a trash rake. Moreover, no desilting bay is operated and the existing structures, as they were designed, don't allow for any storage. The headrace culvert will be maintained as it is, except for a small portion at the beginning, converted into a desilting basin with flushing canal, and the last part, where a forebay and a small storage basin will be set up.

A penstock will lead water from the forebay to the powerhouse: its length will be around 1.320 m and it will lose a little more than 5% of the total (gross) head, so the net head will be approximately 400 m. The powerhouse will be a small building in which a Pelton turbine - designed for a maximum flow of 500 l/s, directly coupled with the generator, without a gearbox - of an installed capacity of about 1700 kW will be installed; the powerhouse will also host all the electrical equipment and protection to manage the new rural distribution grid. A short tailrace will take the turbined water back into the river.

2 Energy option analysis

The alternatives taken into consideration to achieve the project goals are:

1. to built a distribution grid in the remote areas and to connect it to the national grid;
2. to built a distribution grid and to supply electricity to it by SHPs in standalone way;
3. to built a distribution grid and to supply electricity to it by SHPs connected to the national grid.

Theoretically also the option to produce energy by means of many gen sets could be considered, but it was preliminarily rejected for the following reasons:

- cost of the fuel, at present and in future (probably it will grow up);
- cost of the transport of the fuel into remote areas;

- environmental impact both of the fuel use and of the fuel transport;
- no economic fall down of the fuel costs on the local economy, as the construction of the grid and of SHPs gives instead.

Moreover, the PV technology was taken into consideration, for its environmental attractiveness, but it did not pass the preliminary check because of:

- high specific cost per unit of energy produced;
- storage needed, which are affected by a short technical life and significant managing problems;
- not attractive for private investors, as they aren't suitable to supply the great amount of energy needed by the industrial activities, even small, such as mills, sawmills, forgeries and so on.

2.1 Benchmark

The choice among the three options above mentioned has been done on the basis of benchmarks, taking into account the economic, ecologic and social point of views.

a) *Technical benchmark*: reliability of the energy supply;
b) *Economic benchmark*: cost of the kWh for the families in the rural areas;
c) *Ecologic benchmark*: CO_2 emission (produced or avoided);
d) *Social benefit for the local communities*: Possible investments in social services (health, school, electric grid extension and so on).

For the energy option analysis an overall capacity request for the area of 3,992,560 kWh/y has been considered (2013). The option (3), as we will see, is clearly the best choice, because it has the best performance for all the indicators: Technical, Economic, Ecologic, and Social, as it is showed in the resuming table of the benchmarks (*Table 1*).

2.1.1 Reliability of the energy supply

The reliability of the electricity supply is a crucial point for the Lugarawa Saint John Hospital.

For the option (1) it has been considered an availability factor of 95% for the energy supplied by the national grid, taking into account the fact that the reliability of the energy supply is poor, due to the long lines without any decentralized generating points.

For the option (2), the reliability of the energy supply is not again very high, because there are two generation facilities but only one with a suitable capacity (the New Madope SHPP). Taking into consideration that there will be two SHPP available in this option, we can assume an availability factor of 97%, which means about 10 days of outages each year.

The reliability of the scheme proposed in the option (3) is very high because there are two options to supply the electricity to the rural grid by the SHPPs but also the option to supply energy by the national grid, in the future. We can assume an availability factor of 99 %.

2.1.2 Cost of the kWh for families

For the option (1) the estimation of the cost of the kWh for families has been computed as sum of Metering, Capacity and Energy cost. Metering unit cost considered was 4.27 €/each, capacity unit cost 4.33 €/kVA while the energy unit cost was 0.1226 €/kWh [1]. Those costs are not considered if the energy is produced independently by the SHPPs.

In every option it is considered also fixed and maintenance costs. Fixed cost has been estimated in 20,000 €/y, while the proportional costs has been calculated as the sum of 1 % of the new rural grid erection cost and 1.5 % of the SHPPs cost.

The depreciation is considered as a fixed rate of 5%, which means 20 years of the technical life of the installation.

Basically, in option (3), the sold energy covers every cost and, moreover, generates a positive cash flow. In this situation, we can use as tariff the price per kWh suggested by REA (Rural Energy Agency) for the rural areas (0.0425 €kWh).

2.1.3 CO_2 saved

The options needs an evaluation of the CO_2 production associated with the average amount of CO_2 of the generation set of the energy company in Tanzania.

From IEA statistic publications, [2] 1.6 kg of CO_2 is produced for every kWh in the grid. As the ecological benchmark if the CO_2 is saved (by consuming energy by SHPPs), the benchmark is kept positive, while if the energy consumed derive from the national network the benchmark is kept negative.

2.1.4 Social benefits for the population

The social benefits of an electrification project of rural areas are many and the same for the three options we are discussing. What is different in the three options is the money available for social investments, mainly in the health field and for a future extension of the grid to other remote villages to assure they can enjoy the benefits of the electricity facilities.

We underline that the participation of the Lugarawa Saint John Hospital in the project is a great chance to address social investments to the health field in a very direct and efficient way in favor of the local people.
The available resource for social investments is what remains of the income collected by means of the REA suggested tariff (0.0405 €/kWh) minus the O&M and the technical depreciation costs.

Benchmarks	Option 1	Option 2	Option 3
Technical	95	97	99
Economic	0,1856	0,0860	0,0425
Ecologic	-6.388	6.388	14.40
Social	0	0	170.706

Table 1 – Benchmark value for the different energy option considered

3 Electric layout

The new rural grid will be able to supply energy at 20 villages and 53,380 people. There will be access to the hydroelectric energy to 10.508 families, 32 primary and secondary schools, 19 health centers, more than 500 shops, more than 100 milling machines and 38 mechanical and carpentry laboratories.
The new rural grid will be composed by 150 km of medium voltage line (33 kV) subdivided in four different electric lines. i) *line 1*, about 17 km long, connecting the SHPPs to the national grid (Point of Supply), no loads are connected on this line. The line will reach the national electric line in the Luponde area, to sell the energy surplus to the National Authority ii) *line 2* and *line 3*, on which the loads are connected. Those lines will be the new distribution grid connecting several rural villages. The line 2 links northbound the villages of Madope and Madilu ward. Line 3 will reach Lugarawa and then, going from Shaurimoyo village, will end in the villages of Ngongobaky ward iii) *line 4* connecting the Lugarawa Old SHPP with the Madope SHPP.
The old line connecting the old Lugarawa SHPP to the hospital will be manteined.
In the designed rural grid it is possible to recognize three different generation points which are: i) the new HPP of Madope. ii) the existing SHPP of Lugarawa Old (1 generator of about 150 kVA) iii) the existing national grid.
All the main switches of the different lines are located in the new Madope SHPP powerhouse in order to have the direct control on the different components.

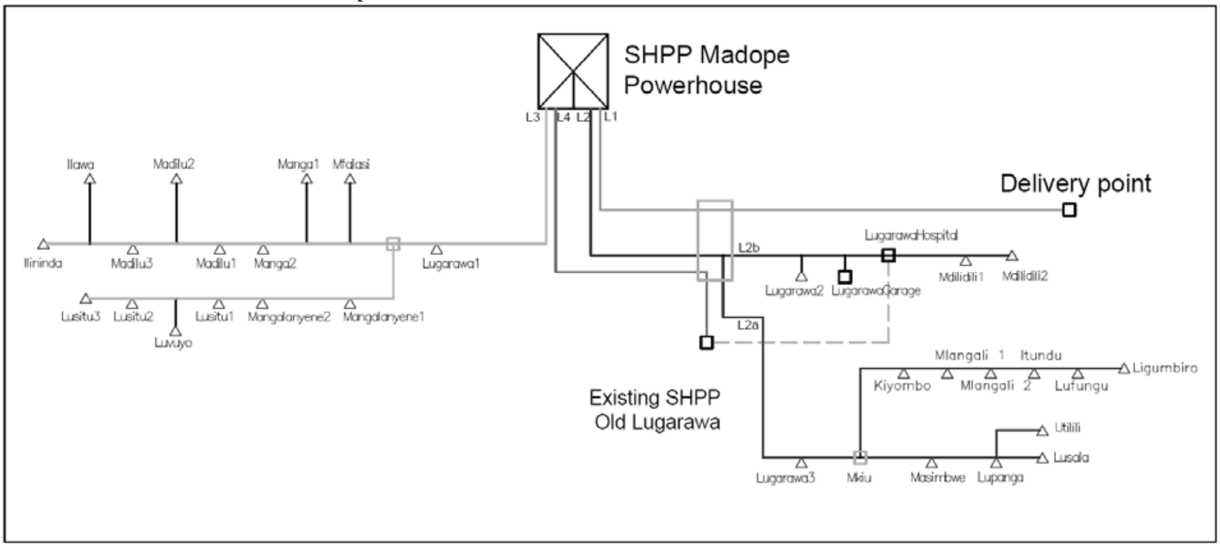

Figure 2 – Conceptual scheme of the designed rural distribution grid

3.1 Operation mode

The system is planned to work in different conditions:

i) *The national grid is operating*: Madope SHPP works in parallel mode with the National Grid. The balance of the loads (positive and negative) is basically ensured by the national grid. Madope SHPP can produce energy without limitation according the hydrological potential. If the energy production is higher than the grid demand, the surplus will be sent to the national grid, on the other hand, if the produced energy is not enough to meet the energy demand of the new grid, the required energy will be purchased by the national grid.

ii) *The national grid is down*: Madope SHPP operates in islanded mode. If the energy production is higher than the requested one by the load connected to the new grid, the surplus will be lost, on the other hand if the produced energy is not enough to meet the energy demand, and a deficit occurs, the system will provide an hour of autonomy to balance the situation, after that it will be necessary to disconnect some load in a hierarchic way.

In the system, the Old Lugarawa SHPP will work in parallel mode with the Madope SHPP in both the cases (National grid on/off). Furthermore, in case of the Madope SHPP is out of service, it can continue to work in islanded mode suppling energy to the Hospital directly using the old connection line.

3.2 Transients Management

The most important goal to achieve in the electrical design is the stability of the network and of the turbine parameters during transient from one mode of operation to the other.

To keep voltage and frequency as much as possible stable during the transient between one operation mode to the other, the hydroelectric generation unit of Madope HPP is equipped with a fly-wheel.

In addition, the small pond at the intake ensures, in the dry season (most unfavourable conditions), about 75 min of turbine operation at the maximum discharge (computation is clarified in §. 4.3). This means that the pond can be operated, if kept full during normal operation, as an additional energy storage for about 1,000 kWh.

To obtain quite stable transients the regulation of the turbine must be as fast as possible. On the other hand, fast regulation can easily generate water hammer that can damage the penstock and the other plant elements. To avoid that it has been imposed to regulate flow on the turbines blade by means of deflectors first, instead to use the needle valves. This option allows to have a sudden effect on the turbine runner and at the same time to maintain constant conditions in the penstock upstream. Once the turbine is sudden stabilized by the deflectors it is possible to control also the needle valves more slowly to avoid water hammer effects.

Another important aspect for handling transients is the knowledge in any moment of the power delivered by the hydroelectric group of the Madope HPP and of the power exchanged with the existing network as well as of the energy available in the reservoir (function of water level in). Based on these values it is possible to set promptly the hydroelectric unit to a power output very close to the one needed to balance the loads in the grid without waiting for the operation of the various regulators.

In addition, load separations can be handled appropriately in relation to the energy available in the pond.

4 Simulation

4.1 Plant Simulator

A simulator using MATLAB® and Simulink® software was made for Lugarawa power plant in order to be able to analyze, estimate and improve the performances of plant. The modelization includes reservoir, penstock, turbine and the controller. As a first instance, the main components of the power plant and their mathematical model was studied. The main aim of this work was to create a Simulink® model able to simulate the entire power plant giving the possibilities to have an overview of the system performances before the physical installation. An overview of the simulator is shown in *Figure 3*. Every section corresponds to a block in the Simulink® diagram. Globally the system is formed by the cascade of blocks representing speed governor (primary and secondary regulation), actuators system, pipeline, real turbine efficiency and characteristic curve, mechanical and electrical losses, and finally the turbine itself. The speed governor block implements the real control scheme used in Lugarawa project by Zeco, the turbine manufacturer, and not a generic PID controller, in order to check the availability and stability of it for this particular case.

The simulation starts from the calculation of the difference between the rotational speed set-point and the actual turbine speed, that value is elaborated by the governor that gives as output in the range [0; 1] representing the requested position to the servo-mechanism.

This signal is used as input for the actuators block where is simulated the dynamic response of the actuation system.

It gives the actual opening of the needles. The opening determines, through an equation that is implemented into the Penstock block, the hydraulic power. This last block was designed to give us also data about pressure, flow rate and head losses in the pipeline.

Hydraulic power is computed in the efficiency block, which signal is fed into the turbine simulator; in this way the input power, opportunely decreased by mechanical and electrical losses, determines, by simulating the rotational masses, the turbine velocity.

The turbine block also integrates the simulation of power demand from the distribution network.

The Forebay block allows, by knowing the input and output flow rate, to get the water level inside the reservoir.

4.2 Model from real components

One of the main focus of this work was to create a simulator as scalable as possible and "block oriented" in order to allow the end user to simulate a wide variety of working conditions of the power plant, simply by changing

parameters of blocks. Most of the equations that are describing the system are implemented by blocks instead of using a single transfer function: such strategy allows to access to intermediate control variables that may be unobservable in a real plant.
Unlike other simulation software, this tool allows you to describe by parametric blocks the components really used by the manufacturer in its installation. This allows you to understand in advance the operating variations in relation to changes in physical parameters of objects used as dimensions, pressures, or temperatures.
As an example, and for synthesis reasons, it is possible to focus on the way it was modeled the actuation system of the jets and the proportional valve that controls the oil flow to the actuators.
The model is based on the real component and it introduces dependence to oil pressure, non-linearity by current-position converter and some limit imposed by the motion law in the actuators.
Let consider a commercial electrical proportional directional valve (Model 4WRE produced by Bosch-Rexroth).
In datasheet is available a graph that correlates the command value (in %), flow rate in GPM (Gallons Per Minute) or l/min and the valve pressure. An extract of datasheet is visible in *Figure 4*.
It is of course possible to consider other types of components simply by entering the relevant data in tabular form.

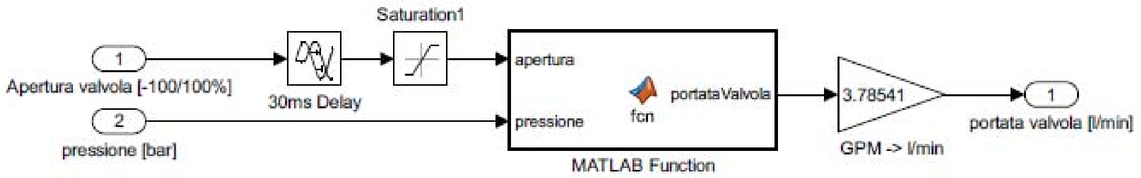

Figure 3 – Simulator block scheme

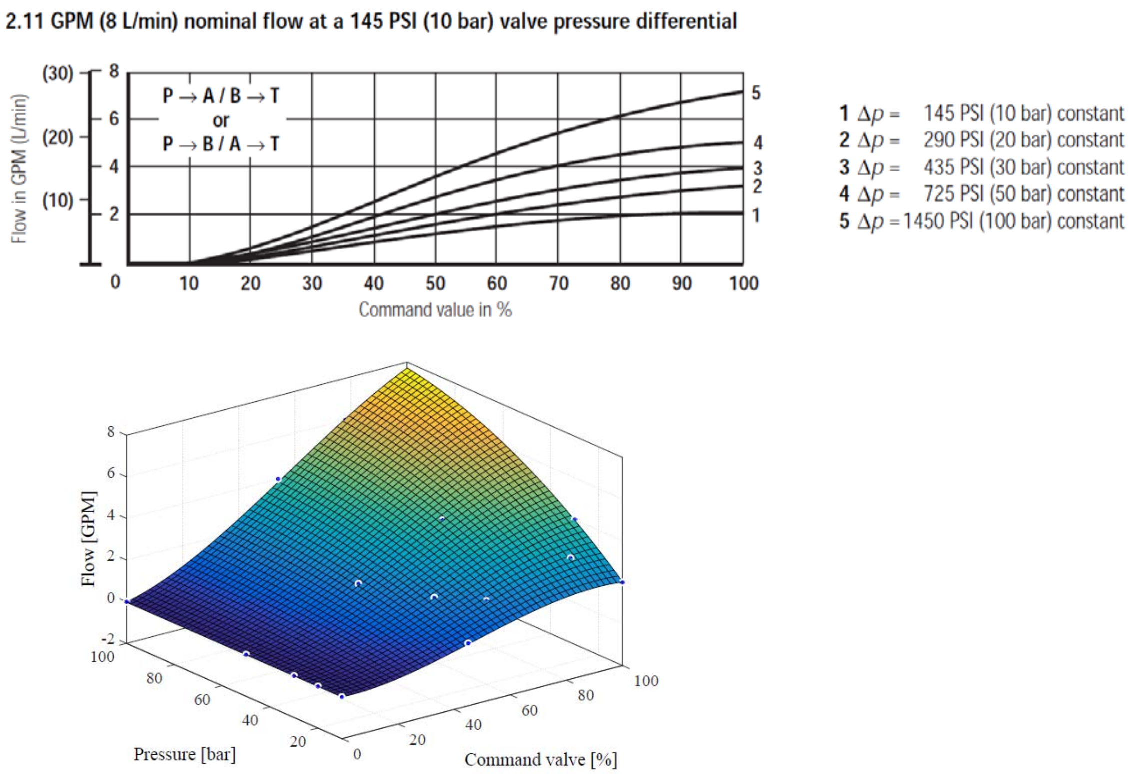

Figure 4 – Commercial electrical proportional directional valve chart correlating command value (%), flow rate and valve pressure

A further step is to consider a real servomechanism to take into account the dependencies from the oleo-dynamic system pressure, oil leakage, head losses and direction of actuation. In general, the time required during a "opening" sequence is not the same of a "closing" sequence of the needles.
In addition, for large transients, the response of the entire system is limited by the actuator which are limited in speed. This restriction combined with the delay in responses and insensitivities will cause different effect on the regulator.

4.3 Intake pound simulation

The Lugarawa power plant is supplied by a pond that collect water from the Madope River. Its volume based on the plan view data is 1546.2 m^3. The inlet flow rate in the pond given by the Madope river is the one reported in *Table 2.*

Month	*Q [m^3/s]*		*Month*	*Q [m^3/s]*
Jan.	0.500		July	0.152
Feb.	0.500		Aug	0.146
Mar.	0.500		Sept.	0.165
Apr.	0.500		Oct.	0.222
May	0.374		Nov.	0.340
June	0.159		Dic.	0.500

Table 2 - monthly discharge of Madope River

It is necessary to investigate the trend of the level in the pond area in order to analyze and prevent emergency stops due to dearth of water. During the normal operation, since the plant is connected to the distribution network, the loads are shared between various generating units. Anyway, the Lugarawa plant is designed to be able to work in islanded mode. In this condition, it must cope with the loss of the other generating units and bear the whole loads. This entails a big demand for water. The simulation is performed to analyze the reservoir's emptying time, considering the worst case for the inlet flow rate (i.e. 0.146 m^3/s) and under the hypothesis that the turbine is always at the maximum load.
It is supposed to start from the full pond condition.
From the simulation results it is clear that in case of disconnection from the distribution network, the plant must operate in islanded mode, it is able to ensure the supply of electricity to the maximum of 75 minutes before completely emptying the reservoir and then running into an emergency stop.
The simulation code has been inserted into the plant controller software resident in the PLC, so it will then be able to estimate the residual running time of the plant during live operation of the plant, starting from a disconnection from the national distribution network according to the current water level at the intake pond and input water flow. This will ensure an early notice of the need to lighten non-essential loads connected to the isolated network at the moment.

3.3.4 Lugarawa HPP simulation

First, all the data needed for the simulation were collected, that is, all the numeric values needed as inputs for the simulator operation. Then, the lengths, the diameters and the materials of each stretch of penstock were collected as well, so that the calculation of the friction factor of each section can be calculated, then it was possible to estimate the fundamental parameters for getting the penstock model that are (i) pipeline starting time and (ii) head-loss coefficient.
Transfer function of the penstock and relative function block was updated with Lugarawa data.
After that, all the characteristic data of the generator, turbine and speed governor was collected, in particular the initially planned inertia, the parameters and data of the components of the hydraulic control unit, the dimensions of the actuators, the turbine efficiency curves. Also, correspondent functions blocks were updated.
As a result, a Lugarawa plant simulator was available. This fact led to a significant result, in fact thanks to the simulator it was possible to drive subsequent simulations to fine-tune the operating parameters of the Zeco speed controller, in order to optimize the speed regulation and to confirm or improve the mechanical design choices in terms of rotating masses and sizing of the actuation system of jets and deflector system.
The simulator was primarily used to understand whether the turbine and the head pond could provide electric power to the user by ensuring the expected load curve and an acceptable network frequency value for the loads connected.
This has been verified with day-time simulations.

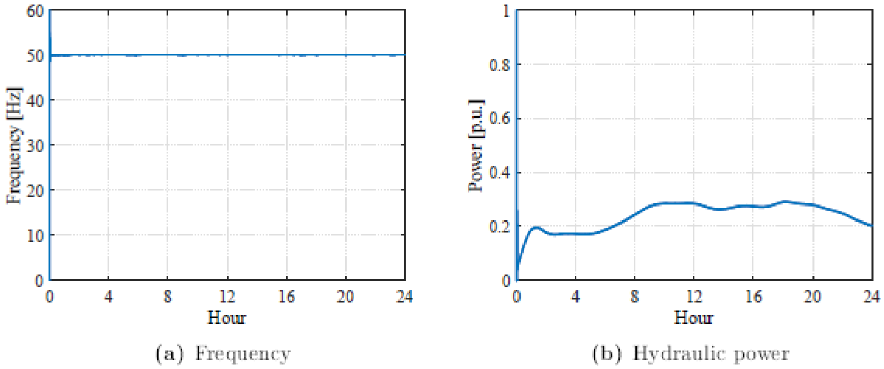

Figure 5 – Day time simulations, frequency and power

The most significant simulations are those relating to the step load insertion and rejection, with the aim to track the speed of the turbine-alternator group during those transient events and consequently of the frequency delivered to the isolated electric grid. For example, a step load insertion and rejection of 500 kW is shown in *Figure 6*.

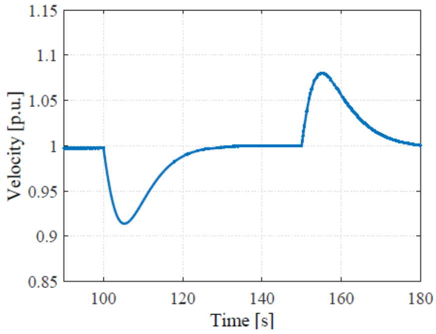

Figure 6 – Simulation results: turbine velocity behaviour according an insertion and rejection of 500 kW load

The plant, in islanded configuration, has been simulated also working in critical situations, even quite far from reality, like on a time span of 1 hour (i.e. 3600s) considering a casual change in power demand every 3 minutes (i.e. 180 s) as shown below (*Figure 7*), so with very wide step variation of load.

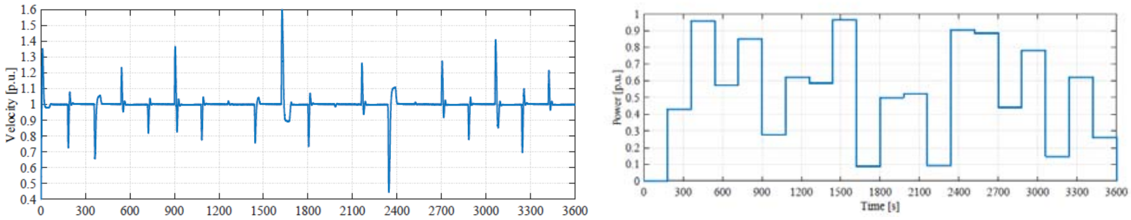

Figure 7 – Simulation in islanded mode of operation, input load (right) and turbine velocity response (left)

5 Conclusion

The results of the analysis show very clearly that the hydroelectric exploitation of the Madope site is the only real and concrete chance to supply electric energy to many small villages in the Ludewa district area

This unique chance happens thanks to two favourable situations:

a) the existing water fall of 420 m of head allows to build a significant hydroelectric scheme (2.300 kVA of installed capacity) in a simple and cheap way;

b) the opportunity to sell a part of the plant energy takes away any limitation to the energy production due to the energy consumptions, mostly in the first years of the project, and it assures a significant budget to develop the rural grid and the connections to the most disadvantaged areas of the district.

From the *economic*, *social*, and *environmental* point of view, the indicators are also very good.

- Economic: the excellent performances of the hydroelectric scheme and the low implementation costs, thanks to the favourable morphology of the site, ensure a relevant income, suitable to finance the maintenance of the project, which is the most important factor for its durability in the future. Moreover, the project profitability can self-finance the rural grid extension, following the increasing needs connected with the natural growing of the population and of the energy consumption.

- Social: the hydroelectric scheme of Ludewa looks like the only chance to boost the economic development of the remote villages in the Ludewa district, supplying electric energy at affordable prices.
- Environmental: the hydroelectric scheme exploits the already existing intake structures at Madope and the old Lugarawa hydro plant, completely rehabilitated and updated, so that the environmental impacts are minimised as much as possible. Taking into account the significant amount of avoided CO_2 emissions and the ecological flow realised from the intake structures, the total environmental impacts of the project look like very positive.

4.1 State of progress of the project

Figure 8 – Works in progress at the pond and the powerhouse

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