Analysis and Testing of the IPB Pico-hydro Emulation Platform with Grid Connection

Gabriela Moreira Ribeiro

Dissertation presented to the School of Technology and Management of Polytechnic Institute of Bragança to the fulfillment of the requirements for the Master of Science Degree in Industrial Engineering (Electrical Engineering branch), in the scope of double degree with Federal Center of Technological Education Celso Suckow da Fonseca - Rio de Janeiro

Supervised by:
Professor Ph.D. Américo Vicente Teixeira Leite
Professor Ph.D. Aline Gesualdi Manhães
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Dedication

I dedicate this piece of dissertation to the Brazilian education system, in particular the Federal Center of Technological Education where I studied for many years of my life and which currently suffers severe attacks and attempts to dismantle it.

Acknowledgments

I would like to thank my parents Carla Ribeiro and Marco Ribeiro, who concern about my physical and mental health. Also, for their daily efforts to provide all that they could not have during their childhood and youth.

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I am very grateful to all workers that contribute to the basic services at CEFET/RJ and IPB.

Special thanks to my mentors for the guidance, supervision and opportunities.

Epigraph

Não há ensino sem pesquisa e pesquisa sem ensino. Esses que-fazeres se encontram um no corpo do outro. Enquanto ensino continuo buscando, reprocurando. Ensino porque busco, porque indaguei, porque indago e me indago. Pesquiso para constatar, constatando, intervenho, intervindo educo e me educo. Pesquiso para conhecer o que ainda não conheço e comunicar ou anunciar a novidade.

Paulo Freire, *Pedagogia da Autonomia*, 1996.

There is no such thing as teaching without research and research without teaching. One inhabits the body of the other. As I teach, I continue to search and re-search. I teach because I search, because I question, and because I submit myself to questioning. I research because I notice things, take cognizance of them. And in so doing, I intervene. And intervening, I educate and educate myself. I do research so as to know what I do not yet know and to communicate and proclaim what I discover.

Paulo Freire, Pedagogy of Freedom, 1996.

Abstract

The global context in which there is a need to reduce environmental impacts intensifies the search for new technologies for renewable sources. In addition to environmental issues, access to basic rights and social inclusion are also motivation for electricity generation, in a context including distributed generation (DG). Currently, the pico hydro power plant is an attractive application because of its resource availability; also, it is an interesting solution for a microgrid (on-grid or off-grid). On the other hand, usually, the conversion system is not "plug and play". This project presents the tests of convertion system for a "plug and play" solution, using different turbines and water wheel, permanent magnet synchronous generators (PMSG) and photovoltaic (PV) inverters. In this approach, generators can work at variable speed, having an overvoltage protection circuit. The prerequisites for device integration must be considered: power compatibility, minimum and maximum limit voltage, and the maximum current of PV inverter. The tests were done in the pico-hydro emulation platform, in the Superior School of Technology and Management (ESTiG). The low head propeller, Turgo, and Pelton turbines are tested in the emulation platform; as well as the vertical axis water wheel. The turbines were connected to the grid using SOLAX inverters (up to 1650 W) and OMNIK (up to 2300 W), presenting satisfactory results in both. The water wheel tests used five microinverters (up to 300 W), showing grid connection with three: BEON, GWL, and INVOLAR.

Keywords: Renewable energies; microgrid; pico-hydro systems; photovoltaic inverters.

Resumo

O contexto global em que há necessidade de redução dos impactos ambientais intensifica a busca por novas tecnologias para fontes renováveis. Além das questões ambientais, o acesso a direitos básicos e inclusão social também são estímulos à geração de energia elétrica em áreas remotas, incluindo o contexto de geração distribuída (GD). Atualmente, as plantas pico-hídricas têm sua aplicação interessante pela disponibilidade do recurso primário; e interessante solução para microrredes (*on-grid* ou *off-grid*). Por outro ponto de vista, geralmente o sistema de conversão não é "*plug and play*". Este projeto apresenta o teste dos sistemas de conversão com uma solução "*plug and play*", uttilizando diferentes turbinas, geradores síncronos de ímã permanente (GSIP) e inversores fotovoltaicos. Utilizou-se a abordagem em que os geradores podem trabalhar em velocidade variável, tendo um circuito de proteção contra sobre-tensão. Devem ser considerados os pré-requisitos para integração dos componentes: compatibilidade de potência, tensões limites e corrente máxima do inversor fotovoltaico. Os testes foram feitos na plataforma de emulação de sistemas pico-hídricos na Escola Superior de Tecnologia e Gestão (ESTiG). Testaram-se turbinas para baixa queda do tipo hélice, Turgo e Pelton; e também a roda d'água de eixo vertical. A conexão das turbinas com a rede foi feita com os inversores SOLAX (até 1650 W) e OMNIK (até 2300 W), apresentando resultados satisfatórios em ambos. Com a roda d'água foram testados cinco microinversores (até 300 W), apresentando conexão com três: BEON, GWL e INVOLAR.

Palavras-chave: Energias Renováveis; microrrede; sistemas pico-hídricos; inversores fotovoltaicos.

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Acronyms

ABNT	Associação Brasileira de Normas Técnicas
AC	Alternate current
CV	Constant Voltage
DC	Direct current
DG	Distributed generation
ESTiG	School of Technology and Management of Bragança
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INC	Incremental Conductance
IPB	Polytechnic Institute of Bragança
LH	Low head
LSE	Electromechatronic Systems Laboratory
MPP	Maximum power point
MPPT	Maximum power point tracking
NBR	Normas Brasileiras
PID	Proportional-Integral-Derivative Control
PM	Permanent magnet
PMSG	Permanent magnet synchronous generator
PV	photovoltaic
SG	Synchronous generator

List of Symbols

	Description	Unit if applicable
E	Electromotive force	Volt (V)
g	Acceleration of gravity	meter per second squared (m/s^2)
h	Head	meter (m)
I	Electrical current	Ampere (A)
j	Imaginary unit	–
p	Number of poles	–
P	Active power	Watt (W)
Q	Fluid flow	cubic meter per second (m^3/s)
R	Resistance	Ohm (Ω)
V	Voltage	Volt (V)
X	Reactance	Ohm (Ω)
Z	Impedance	Ohm (Ω)
f	Frequency	Hertz (Hz)
N_c	Number of coils	–
n_s	Shaft synchronous speed	rotation per minute (rpm)
t	Time	second (s)
η	Efficiency	–
ρ	Fluid density	kilogram per cubic meter (kg/m^3)
Φ_B	Magnetic flux	Weber (Wb)

Chapter 1

Introduction

Chapter 1 is dedicated to describe the current state of renewable energy, focusing on hydropower, and its motivations for use. The objectives and methodology give the project an authentic context; it also includes materials needed and used.

1.1 Motivations

The incentive to explore renewable energies driven by the environmental importance to reduce fossil fuel consumption, as well as the need to end energy crisis. The World Energy Council shows fossil fuel as primary energy source in the world and that it has had a minor decrease in consumption from 86% in 1970 to 81% in 2014 [1]; but also addresses the development of technologies related to renewable energy and promotes the change in the use of primary energy. The document [2] and the Figure 1.1 show global primary energy consumption increasing in the use of fossil fuels, which in 2017 exceeded 133 PWh.

In addition, through a political intermediary, there is the possibility of social inclusion of marginalized communities and access to basic needs. According to [3], one of the most empowering inputs to a community is electrical energy, as it can develop society and improve outlook; therefore, its access might be seen as a basic right for all population. Electrical energy restriction leads to social inequality. Investments in electricity generation projects and infrastructure offer comfort and socioeconomic benefits to the community, as well as access to citizenship.

Third of the population has its health and productivity affected by the dependence on fuels and traditional technologies, children and women who suffered the most damaged. Also, current energy production methods and their use are major contributors to the environmental problems faced [3].

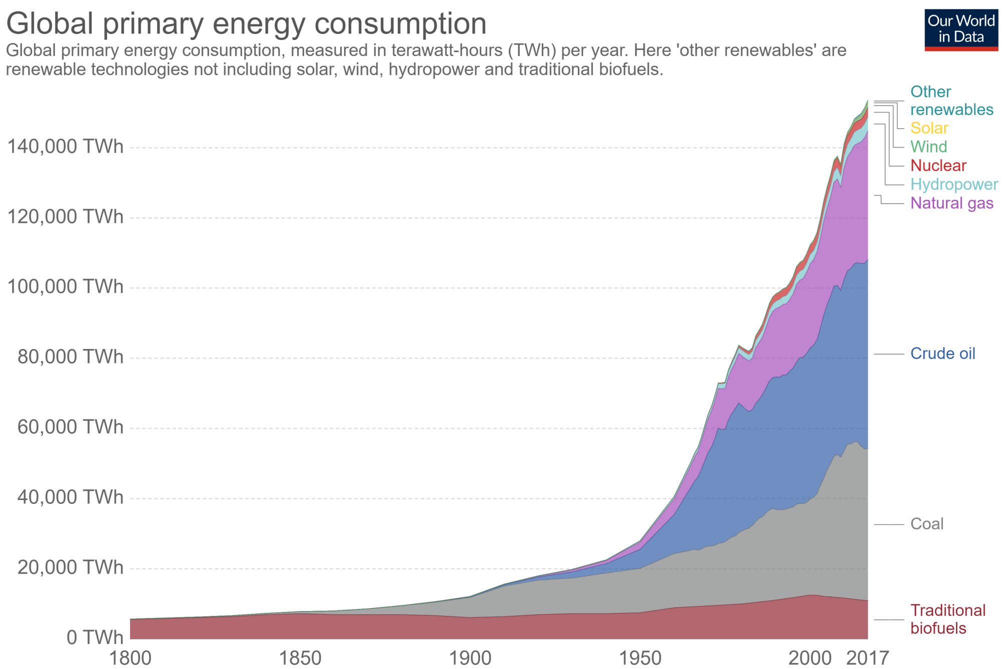


Figure 1.1: Global primary energy consumption [4].

The construction model in which the electrical energy production is located in the vicinity of its final consumer is known as distributed generation (DG). Until the first half of the twentieth century, this model was the most widely used.

However, the centralized generation, wherein the high power production plants are far from users, has been utilized by the nations for decades. This paradigm shift, since the 40s, has been the result of technological advances in energy transmission, and also large plants starting to have a reduced cost per mega Watt produced [5].

The increase of the investment of centralized production meant that distributed generation was discredited for a long time. With current studies of technological and environmental factors providing the impetus there has been an increasing use of distributed generation and other significant changes, in order to reduce dependence on nonrenewable resources. Some of the advantages for this techno-scientific stimulus are related to the reduction of electrical transmission losses, improvement of concessionaire services and consumer autonomy.

Currently, riverside communities can be found with no or restricted supply of electrical power by the concessionaire. These sites are characterized by low population density, few connections to the conventional power grid, and consequently low power consumption. However, the geographic capacity for autonomous systems of electrical generation is visualized in riverside communities has been foreseen by researchers, especially using hydropower, as can be seen at [6]–[9].

1.2 Background

Since 2016 the Eletromecatronic Systems Laboratory (*Laboratório de Sistemas Mecatrónicos, LSE*) has been investing in pico-hydro studies using permanent magnetic synchronous generator (PMSG) as a way to use the available energy of riverside communities. Both on-grid and off-grid for a distributed energy production [10]–[12].

In 2017, the laboratory presented a project to SilkHouse, in Bragança, based on renewable resource plants integration [13].

In 2018, the laboratory published calculations and construction design for the water wheel installed in IPB pico-hydro platform and there are also plans to be established at SilkHouse [14]. In the same year, it made generator characterization and grid connection testes using low head turbine and impulse turbines, the same turbine showed in this document [15].

In 2019, solar voltaic panels were installed and pico-hydro system are being implemented, creating a smart microgrid in SilkHouse [16]. Also, there is a research about power interface for pico-hydro system connected to the grid using a photovoltaic (PV) inverters [17].

1.3 Objectives

This thesis proposes to validate the experiment platform of the Geotechnical Laboratory of the IPB, which works with educational and scientific methodologies to research renewable energies. Also, the purpose of the project is to test the conversion approach for pico-hydro power system. It has a practical application and discusses widely exposed technologies in the market, based on [11], [15].

The research involves characterization of the elements, as well as suggestions for changes and improvements in its structure resulting from the tests done with the turbine-generator sets. Furthermore, it includes the use of photovoltaic inverters which are to connect to the power grid of the institution.

1.4 Methodology

The methodology applied to the presented study was distributed in order to integrate the multiple subareas of Engineering, especially mechanical and electrical. Hence, the following operations occurred:

- Familiarization with the existing platform in the IPB's geotechnical laboratory.
- Understanding and analytical characterization of the equipment belonging to the systems contained in the platform.
- Analysis of the electrical diagram for the application and connection of the system to the local grid.
- Setting Frequency inverter parameters.
- Operation and commissioning of the arranged systems.
- Analysis of obtained responses and experimental characterization of the models, considering the limits and compatibilities of the systems.

1.5 Thesis outline

This work has its theoretical and practical aspects, and one is foundational to the other. Hence, theory acts as a basis for tests on the platform. The following proposed topics discuss this work.

The chapter 2 presents a brief review going through the theories of hydroelectric generation (especially pico-hydro power), distribution generation (DG), turbines , permanent magnet synchronous generator (PMSG), and photovoltaic (PV) inverters, and an approach to connect a PMSG working in variable speed to the grid.

The chapter 3 presents the contextualization of the emulation platform, dividing generation systems. It is dedicated to showing the technical equipment needed for hydro power generation and a proposal for on-grid layout using PV inverters. The chapter also shows the tests, results, and discussion of hydro generation by using water wheel, low head, Turgo and Pelton turbines.

The chapter 4 shows possible technical mechanic and electric proposals that can be implemented in the pico-hydro platform.

The chapter 5 is a conclusion and suggest further work for platform changing and testes for pico-hydro plant with grid connection.

1.5.1 Extra material delivered from this thesis

- **Symposium DD2019**: Analysis and Test of the Experimental IPB Pico-Hydro Platform with Grid Connection; abstract and presentation for Second Double Diploma Summer School & Symposium DD2019, in IPB (Appendix A).
- **ICSC-Cities**: Over-Voltage Protection for Pico-Hydro Generation Using PV Microinverters; paper presented and published in Ibero-American Congress of Smart Cities, in Soria (Appendix B). The document was accepted to be included into the special volume of Communications in Computer and Information Science (CCIS), Springer. Moreover, the paper was selected to submit an extended version to Revista

Facultad de Ingeniería, in Colombia.

- **IECON**: Grid Connection Approach for Very Small-Scale Pico-Hydro Systems Using PV Microinverters; paper presented and published in IEEE 45th Annual Conference of Industrial Electronics Society, in Lisbon (Appendix C).

Chapter 2

Theoretical Background for Pico-Hydro Power Plants

Chapter 2 is a state of the art of power electric generation using small-scale hydro power plants for distributed generation. It has the purpose of showing the applications of the pico-hydro system field, its restrictions and investigations made until now. Moreover, it presents the technical equipment needed for pico-hydro power generation and a proposal for on-grid layout using photovoltaic inverts and over-voltage protection.

2.1 Distributed Generation

In the conventional system, which has been in use for more than 100 years, from the generating plants, electricity is first passed by transformers that raise the voltage to avoid excessive losses of energy. Then, it follows a long route through the transmission lines to reach the substations where transformers lower the voltage to begin the distribution system. Although this voltage is low, the electricity still needs to go through another step-down transformer voltage that is present on the poles in front of the buildings, or appropriate power stations where such distribution is made by the underground in some sites. Figure 2.1 illustrates the path that electricity travels until it reaches the final consumer for this case. The grid control, monitoring system, and maintenance are done by the local energy concessionaires of each region.

The ordinary and current model of energy generation, transmission, and distribution do not offer as many facilities for companies and end users as distributed generation; besides corroborating with failures in the long term of operation. This situation is aggravated by the growing demand for electricity and the variety of energy matrices.

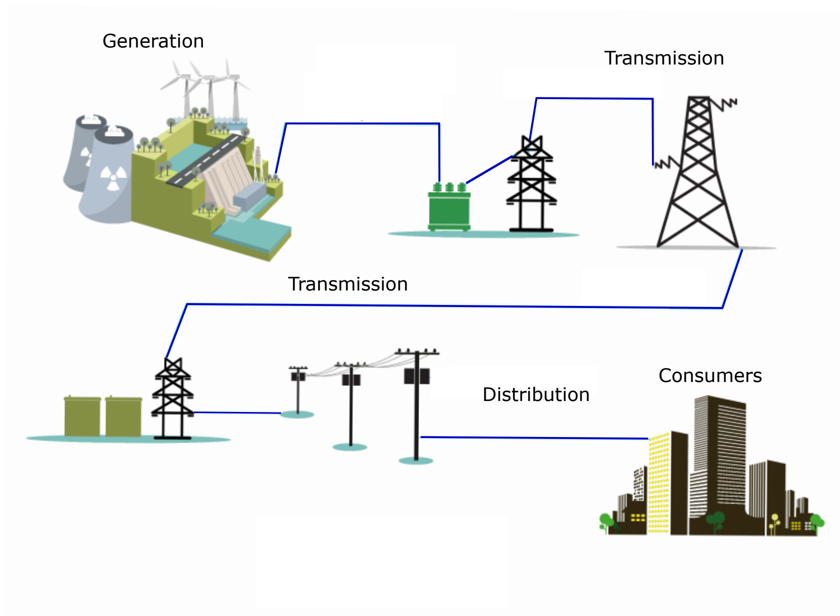


Figure 2.1: Centralised generation, adapted from [18].

Energy engineering is deal with a distinct scenario in which distributed generators and energy storage equipment are incorporated together into the grid. Distributed generation has different approaches and definitions in the literature. It is currently being discussed in the electricity industry and has several terms, such as: ’embedded generation’ for Anglo-American countries; ’dispersed generation’ for North American countries; and ’decentralized generation’ in some Asia countries and Europe [19].

Government regulations also affect the distributed power definitions and rates. The broad variations in literature make necessary some specifications: locations, purpose, technology, environmental impact, rating of distributed production, operations mode, among others. [20] shows there is no consensus about distributed generation definition. In general it is seen as small-scale production and relatively close to the place of consumption.

IEEE characterize DG as being enough smaller comparing to local central generation plant which includes interconnection technology. For CIGRE (*Conselho Internacional das Grandes Redes Elétricas*), DG has a maximum capacity of 50 to 100 MW, and it is often connected to the distribution grid, and it does not discourse about grid connection. IEA despite addressing site and grid connection definition, does not attribute value to power capacity [20].

About power rating of distributed generations, disregarding technology type, [19] suggest the following categories:

- $\approx$ 1 W $<$ micro $\leq$ 5 kW
- 5 kW $<$ small $\leq$ 5 MW
- 5 MW $<$ medium $\leq$ 50 MW
- 50 MW $<$ large $\leq \approx$ 300 MW

It means, a distributed generation up to 5 kW also may be called as microgeneration, according to [19].

The possible motivations for the application of distributed generation and microgrid are the safety of the electrical system and the variety in the implementation of renewable energy sources, such as photovoltaic panels and wind generators with pre-existing plants. Thus, with the different generating zones, there is a reduction of grid load.

The need for energy access to locations far from urban centers and increasing energy demand in developed regions make sustainable energy production a continuous effort. Distributed production has been considered a feasible application solution in order to reduce environmental impact and have lower economic expenses [21], [22], applying when the power production is closer to the consumers.

Renewable energy plants have been an ally of small-scale production and a good solution for microgrid creation. Within this field, low power hydroelectric plants, covered in section 2.2, have their potential located in rural properties and riverside populations [23]. For instance, in Bangladesh [23], Brazil, India [24] and Portugal [12] exist examples of standardized technologies applied by small consumers.

In Portugal, Law Decree 162/2019 promotes the energy transition of companies and citizens interested in investing in renewable and distributed energy resources. The goal of the country is to achieve 47% of energy from renewable sources in final consumption in 2030. As an example, Article 3 (Exercise Conditions) states that production for self-consumption with installed power up to 350 W (microgrid) is not subject to prior control; and installed power between 350 W and 30 kW (micro or small-grid) is only required prior communication [25].

In many cases, microgrids form isolated systems of the conventional grid, called off-grid, to supply small consumers or villages. In these conditions, there is a need for voltage and frequency regulation to suit the electrical supply of the conventional equipment. On the other hand, there are circumstances where the microgrid is connected to the utility grid, called an on-grid. However, the direct connection of generators to the grid must have one more concern: the synchronization with the grid; which means voltage, frequency and phase regulation. There are four possible configurations for microgrids [26]:

- **On-grid with batteries**: consumers can sell back electricity. Also this scheme has backup during energy interruption.
- **On-grid without batteries**: consumers still can sell back electricity, but they do not have a backup system.
- **Off-grid with batteries**: the charging source applies energy into battery bank, at the same time the load is on.
- **Off-grid without batteries**: this scheme there is no back up and is often used for generation higher than 2 kW.

Small-scale hydro systems can be applied disconnected to the grid, but also linked with. This second option permits consumers to "sell back" electricity or to use as a credit.

2.2 Small-Scale Hydro Power Plant

The hydraulic power engineering deals with the conversion of potential and kinetic energy from water into electrical energy by the usage of technology. However, previously in history, it was used for mechanical movements, strength and irrigation. Hydroelectric generation is currently the main renewable source in the world. In 2015, it accounted for approximately 70% of the electricity supply with production from renewable resources. Despite the increase in its use, it is estimated that the undeveloped potential worldwide is around 10,000 TWh per year [27].

Hydroelectric generation is directly dependent on the flow of water and its column. The power available has the following mathematical representation [28]:

$$dP = \rho.h.g.dQ \tag{2.1}$$

where P is mechanical power [W], ρ is fluid density [kg/m^3], h is head [m], g is acceleration due to gravity [m/s^2] and Q is fluid flow [m^3/s].

The paper [29] proposed a simplified electric analog circuit for the hydraulic plant. In figure 2.2 volumetric flow, water head, surge tank, tubes and turbine are corresponded to current, voltage source, capacitor, inductors and variable conductance (G), respectively.

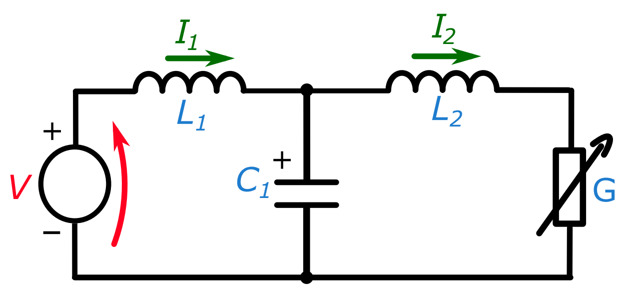


Figure 2.2: Electric analogous circuit for hydro system.

When considering the load losses in the piping, turbine, generator, converter device, transformer, and mechanical transmission, the final power (P_f) will be:

$$P_f = P \prod_{i=1}^{n} \eta_i \tag{2.2}$$

in which P is the generated power and η_i is the efficiency of each component or stage of the process.

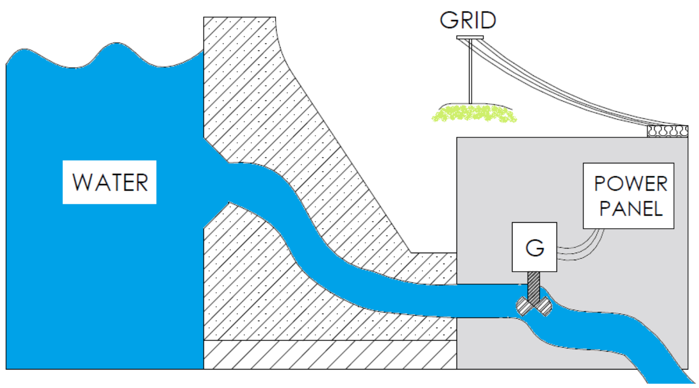


Figure 2.3: Hydroelectric power plant.

In order for the kinetic energy to be used, an adduction system must be applied as the water reaches the turbine (upstream), according to Figure 2.3. It is the rotary movement of the turbine coupled to the generator that performs the energy transformation. In other words, speed and torque are converted to voltage and current. The fluid coming out of the turbine (downstream) returns to the riverbed. In the case of large plants, constructions of dams that intersect the natural river path can be used so that water can be stored [30].

There are two ways to connect a hydro power plant to the grid:

- **Fixed speed generation**: it uses induction generator and does not have converters. It needs a governor to control the turbine speed. This type of control are frequently malfunctioning and require regular maintenance.
- **Variable speed generation**: it used synchronous generator and needs converter to set grid's voltage and frequency, as shown in Figure 2.4. Also, The system may promote greater energy capture according to the energy variation coming from the source.

According to [31] the types of developments are:

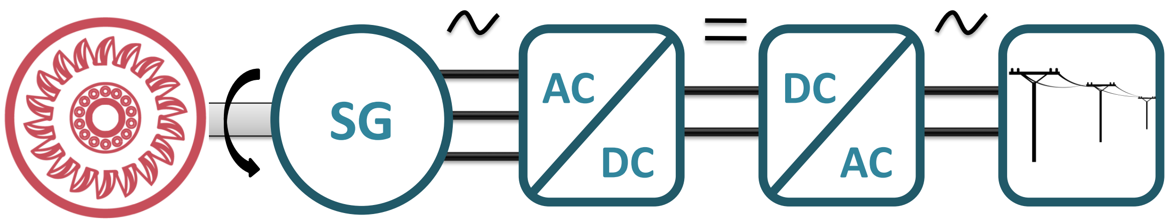


Figure 2.4: Block diagram to connect a SG to the single-phase grid.

- **Run-of-river**: it uses natural water flow, or with little adjustments, of the channel directly to the turbines.
- **Diversion and canal**: it rechanneled from natural path to a canal, for a noticeable distance.
- **Storage regulation**: it allows flow river modifications by storing water, depending on the period needed.
- **Pumped/storage**: the fluid can be pumped from a lower reservoir to a higher one, during low demand.
- **Tidal power**: it harnesses water movements, and the difference in elevation, as a consequence of tidal actions.

Furthermore, the hydroelectric plants are categorized from their productive capacity [32]. They are:

- 0 kW $<$ pico $\leq$ 5 kW
- 5 kW $<$ micro $\leq$ 100 kW
- 100 kW $<$ mini $\leq$ 1 MW
- 1 MW $<$ small $\leq$ 10 MW
- Large $>$ 10 MW

Between 1940 and 1970, small-scale hydro units (small, mini, micro and pico) had their generation affected and they were forced out of the market, hence large-scale hydro power plants and large steam power plants had low cost and fossil fuel as an attractive source [31]. The [33] examines the global context and how oil prices made small-scale hydro power plants became strategical and economically important again. [31] shows a comparison of energy sources in the United States of America from 1940 to 2000. Above all, nowadays the governments and population are more aware of climate changing.

The usage of small-scale hydro plants may be considered again, once large-scale plants' extensive damage has been publicised. Some impacts to be considered about large hydropower plants:

- **Financial**: this is one of the first impacts and occurs at the beginning of plant construction, when there is local economy changing with due to a sharp increase in inflation [34].
- **Historical and social**: archeological material can be lost in flooded areas. Also, relocation of families promotes the loss of local culture. An example is the impact on indigenous people in Brazil [35].
- **Hydrological**: for construction and use of hydro power plant there are changing of the water flow, the widening of the river bed, the depth and the groundwater table level [36];
- **Climate**: local temperature, humidity, precipitation, and evaporation also pass through changing because of flooding [36].
- **Fauna and flora**: there is loss of biodiversity. There are migration or deaths of species,the former; for the latter, there are increases of organic matter and consequently, the levels of oxygen decreases [36].

According to [37], hydroelectric plants are considered as a renewable resource when generating up to 1 MW; since above this value, their capacity reduces over the years.

Pico-hydroelectric plants have their primary energy source from rivers, streams, small water reservoirs, water channels of low depth and despite relatively small diminished flow, and it is capable of generating up to 5 kW [32].

The usage of small-scale hydro power plants and their potential has been shown to have low environmental impact, operational costs and financial investment in literature such as [7], [23], [32], [37]–[39] as low environmental effect, operational cost and financial investment. Moreover its capability to produce energy during all day shows it is an important alternative for integration into microgrids. The engineering challenge for these plants is design a quality device and scheme, which is financially feasible and harmonius with the ecosystem.

In Portugal, the Decree-Law No. 49/2015 establishes the adaptation of the infrastructure to the production of electricity from hydro source [40]. The Article 1, translated freely, says:

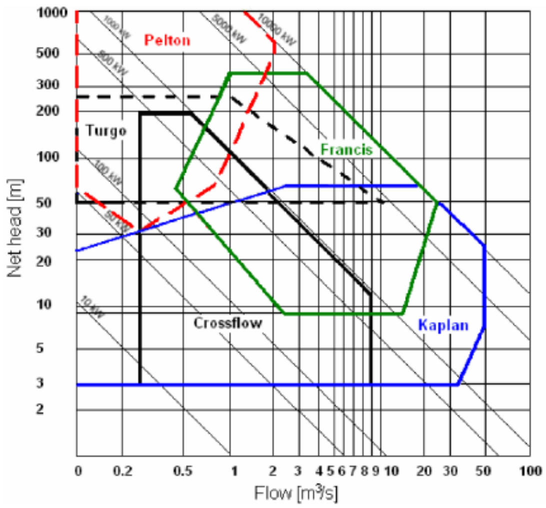
> "This Decree-Law establishes the special regime applicable to the adaptation of mills, water mills or other equivalent hydraulic infrastructures for the production of hydroelectric power, including the terms and conditions of the granting of the respective title of use of water resources for the purposes of electricity generation and its articulation with the regime of access to the electricity generation activity that is subject to the prior notification or prior registration regimes for the production for self-consumption, in accordance with the applicable legislation." (Decree-Law No. 49/2015 of April 10 [40])

2.2.1 Turbines

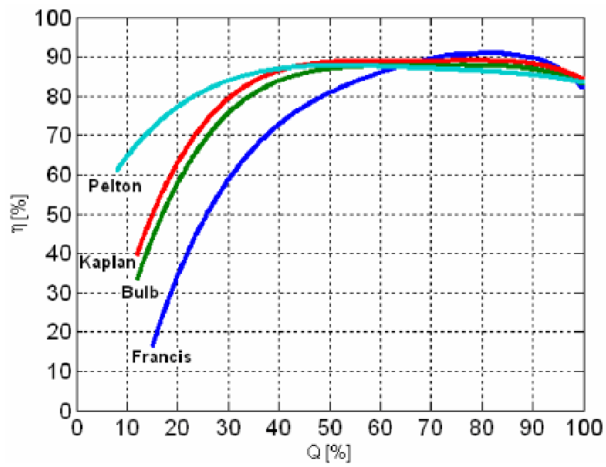
There are three common turbines used for hydro power generation: impulse turbine, also known as Pelton and Turgo; reaction turbine, or Francis; and propeller turbine, also called Kaplan. A fourth modern turbine is Deriaz, which incorporates reaction and propeller designs [30]. Additionally, there is water wheel, one of the older prime movers in history, used for many purposes such as irrigation and navigation.

The topology of each area and elevation (head) of the stored water, or channel, set the most suitable type of turbine. Figure 2.5a introduces the connection between flow and head for each turbine, and expected power. Furthermore, Figure 2.5b presents the turbine efficiency according to the water flow; in which higher is the flow, higher is the efficiency.

A way to regulate turbine rotation velocity, consequently voltage and frequency, for power generation in hydraulic systems is to control the governator position for speed



(a) Turbine application according to flow and head.



(b) Turbine efficiency.

Figure 2.5: Turbine application according to flow and head [41] and turbine efficiency [41].

reference. Also, There are hydraulic and electronic control devices. A commum example for impulsive turbines is water flow adjustment by needle nozzle [30].

For an isolated system, an example of electronic control applied on turbine shaft is Figure 2.6. The turbine speed is related to a reference speed, or position, and its error is treated to calculated mechanical torque. Afterward, it is compared to the current load. For interconnected systems, the speed is measured according to predominating load [30]. Nevertheless, this type of control uses complex technic and high-inertia mechanism adapting the flow to fit fluctuations in power demand [42].

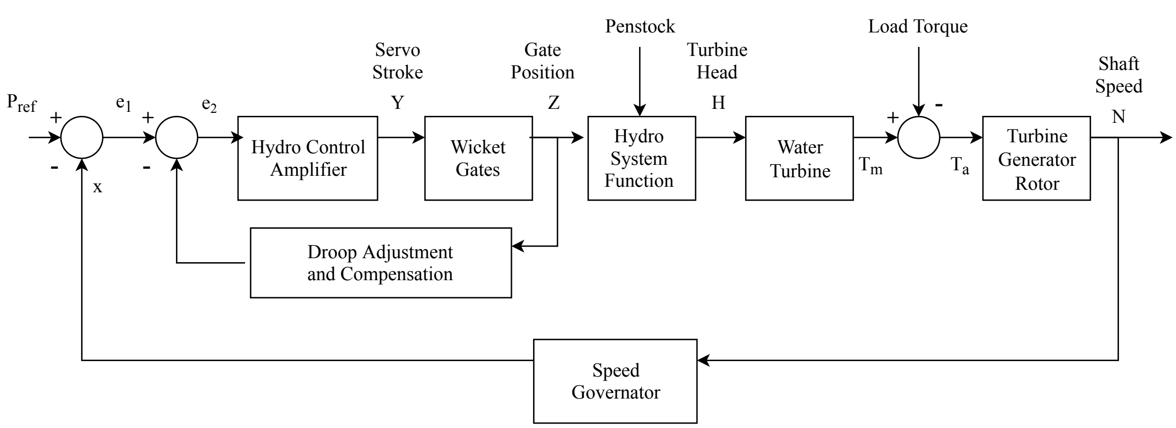


Figure 2.6: Block diagram of a hydro turbine speed control system, adapted from [30].

This document does not cover specifically the Deriaz turbine since it is not part of the platform created in ESTiG.

2.2.1.1 Water Wheel

A water wheel is an old design machine built from metal or wood. It has buckets or paddles (blades) arranged symmetrically around its shaft, forming a driving surface [43]. Some models are:

- **Vertical axis**: it has a horizontal wheel, has low efficiency and needs a waterfall (head).
- **Stream**: it has a vertical wheel, horizontal shaft and does not need a head.
- **Backshot**: it also has a vertical wheel and horizontal axis, but it needs a water head. Comparing to others, it has great efficiency. Similarly, there is the overshot water wheel, which has opposite direction rotation.

The vertical water wheel was implemented in IPB platform, according to [14], and approached in section 3.2.

2.2.1.2 Impulsive Turbine

Usually this type of turbine has horizontal axis and generator applied beside. A possible design has two turbines, with a generator in the middle, sharing same shaft, called "double-overhung". The Pelton and Turgo, two models of impulsive turbines, use the high momentum of the fluid, when the water from nozzles goes against paddles to run the shaft.

Turgo turbines have been in apply since beginning of 20th century [38], and Pelton was created in the end of 19th century [44]. The most meaningful difference between these model is Pelton may handle considerably lower water flow comparing to Turgo.

In IPB platform there are a Turgo and a Pelton turbines for heads up to 30 and 130m, respectively.

2.2.1.3 Propeller Turbine

This model of turbine uses pressure and velocity to move the blades, therefore it is also known as a type of reaction turbine, but with a higher and extent range of water speed [30]. They are:

- **Fixed blade**: it is efficient for fixed head and constant flow and works at high speed.
- **Adjustable blade**: it works over wide range of head. It has adjustment of blade angle and also wicket gate setting, allowing optimization of turbine efficiency.
- **Kaplan**: it is applied at sites elevation of 15m to 150m. Comparing to reaction turbines, it operates at higher speed and flow for a given head.

The propeller turbine with fixed blade, for low head, was implemented in IPB platform.

2.2.2 Permanent Magnet Synchronous Generator

Aspects such as output power, nominal speed, range of voltage and current, on or off-grid connection, with or without battery need to be considered to select a generator. Main generators are [45]:

- **DC brushed machine**: request brushes or slip rings for commutation.
- **Asynchronous (or induction) AC generators**: based on the induction principle, stator field induces rotor magnetic field. Electric and mechanical frequency are slightly different.
- **Synchronous AC machine**: rotor magnetic field based on permanent magnets or DC currents (electromagnets). Electric frequency is proportional to mechanical shaft.

Due to the necessity of frequent maintenance with the changing of the slip rings and brushes, the use of DC generator is often discarded for small-scale operation. Furthermore, induction generators require capacitor banks when they are used in off-grid operation to provide the reactive power [45].

According to [45], PMSG is an agreeable choice for small-scale pico-hydro systems, once it has advantages in performance and cost. For a PMSG, the rotor (shaft assembly) produces a rotating magnet field, while the stator (armature winding), where the main voltage is induced, is connected to the load. It is named "synchronous" due to the fact that rotation velocity is synchronized with induced voltage frequency. Also, the frequency is proportional to rotatory axis speed and its poles number. The speed versus frequency behavior of synchronous machines is given by [46]:

$$f_e = \frac{n_s p}{120} \tag{2.3}$$

where f_e is electrical frequency [Hz], n_s is the shaft synchronous speed [rpm], and p is the number of poles.

The armature windings are the part where AC voltage is induced as result of magnetic flux variation by shaft rotation. In synchronous machine, the armature is located in stator, while field winding is on the rotor and has the following equivalent circuit [47].

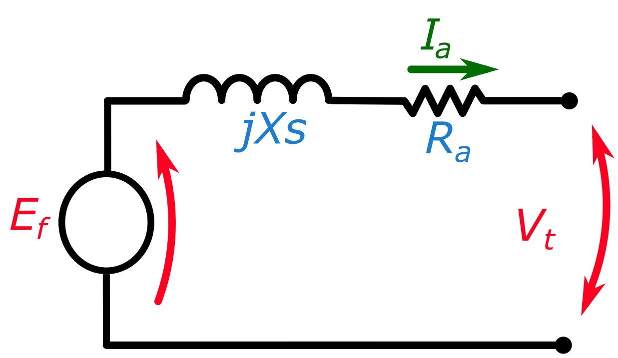


Figure 2.7: Equivalent circuit of rotor of a synchronous generator.

The voltage V_t is obtained considering there is a voltage drop on stator impedance, given by:

$$Z_s = R_a + jX_s \tag{2.4}$$

$$V_t = E_f - I_a Z_s \tag{2.5}$$

The magnetic poles has two types of construction: salient or nonsalient. The first one is a magnetic pole applied out from rotor; while the second configuration has its magnetic pole aligned to the rotor. Nonsalient pole is commonly used for generator with 4 poles or more [46].

A DC current supplies the field circuit since machine is working, and it is called the exciter. There are two possible ways: external source, using brushes and slip ring; or a DC power source on the generator shaft. The voltage induced in stator phase is:

$$e(t) = -N_c \frac{\mathrm{d}\Phi_B}{\mathrm{d}t} \tag{2.6}$$

where e is voltage [V], N_c is the number of coils, and Φ_B is magnetic flux [Wb].

Equation 2.6 indicate that voltage is proportional to magnetic flux variation. And equation 2.3 shows the frequency being directly proportional to the rotation speed. So, a way to regulate voltage produced by synchronous generator is regulating frequency, or shaft rotation speed.

There are cases in which microgrids are an isolated system (off-grid). They often supply a small demand, such as villages. For off-grid system there is a need of voltage and frequency regulation. On the other hand, when the microgrid is a on-grid system it needs to synchronize to the conventional grid (frequency, voltage and phase regulation). The generator is connected to the grid as Figure 2.4 and the inverter device needs to follow some requirements (Subsection 2.3.3).

2.3 Integration Between Synchronous Generator and Grid

As approached in section 2.1, there are on and off-grid applications for distributed generation. Both of then need voltage and frequency regulation, to supply conventional devices. For on-grid systems, there is one more consideration: phase synchronization with conventional grid.

The conventional hydro power plants commonly operate at a constant speed, by mechanical or hydraulic control. In favor of widespread small-scale hydro system and make it cheaper, there is integration using PV or wind converters.

Specific power converters for hydro power plants were not found in the market. The uniqueness related to the topography is a barrier for the design, development and widespread of this type of converter.

The method of applying PV inverter after the rectifier circuit is presented in Figure 2.8.

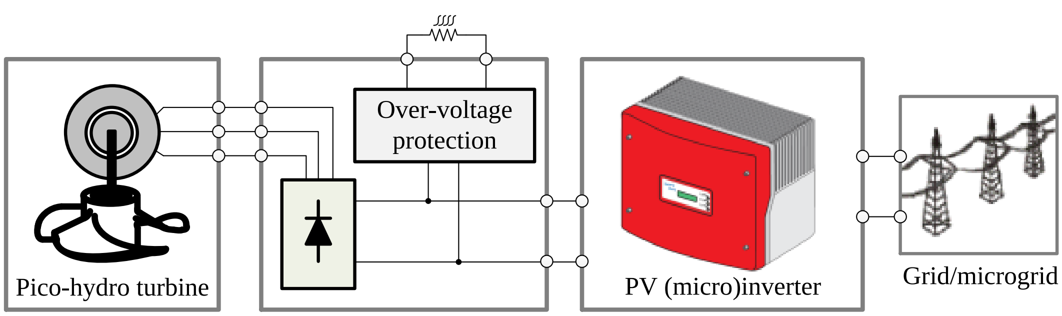


Figure 2.8: Practical approach for grid-connected pico-hydro systems [11].

The scheme applied in Figure 2.8 allows the PMSG to work at variable speed, once the inverter produces a constant voltage and frequency for a voltage range applied to the input. PV inverters are extensively accessible on the market and does not require parameterization, being a fordable option for consumers who want design an on-grid system with pico-hydro plant. Also, an over-voltage protection may be applied to prevent damage to the devices.

There are prerequisites to integrate PMSG with grid. The integration is based on the PV inverter and PMSG characteristic curve overlapping. The prerequisite to integrate were proposed in [11]:

- The DC power of PMSG may be between 0.4 P_{DCmax} and 1.0 P_{DCmax} of PV inverter.
- maximum output DC voltage of PMSG should be up to input DC voltage of PV inverter.
- No-load DC voltage of PMSG for initial work must be higher than $V_{PV start}$.
- Maximum DC voltage permited by protection circuit must be up to V_{DCmax} of PV inverter.
- DC current of generator may be up to I_{DCmax} of PV inverter.

Moreover, it is important the MPPT algorithm has to have its dynamic compliant to the system.

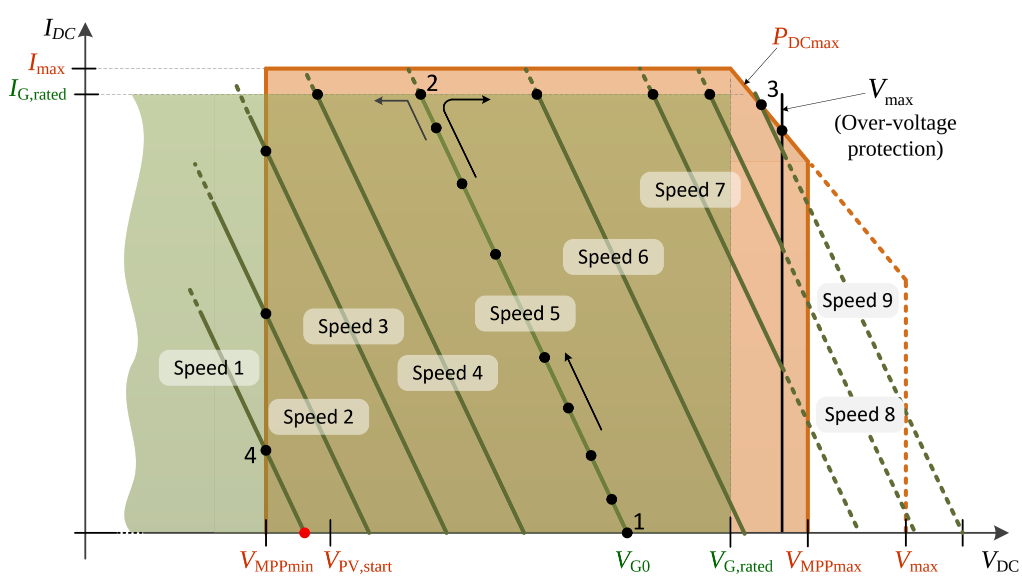


Figure 2.9: Overlapping of the operating areas of PV inverter and generator [11].

Figure 2.9 shows possible paths of PMSG operation by MPPT algorithm setting, considering the prerequisites for integration were succeeded. Point 1 corresponds initial operations from "speed 5" or higher, as an example. The current is increased until the maximum value, point 2, while the voltage is slightly reduced. From point 2, if PMGS has its power decreased, the operation position will be the point 4, where the voltage and current are lower. On the other hand, if it increases, the operation position will be the point 3. The over-voltage protection circuit needs work regulating voltage, limiting to a maximum value and dissipating power [11].

2.3.1 Photovoltaic Inverter

Inverters are power electronic equipment that operate transforming DC source into AC output. They have classes depending on function, nominal power and voltage, control algorithm, among others.

The photovoltaic inverter is one of the possible inverter functions, and it also has its proposal on the grid synchronizations and connection onwards DC power by PV power plants. PV inverters are categorized as [26]:

- **Module integrated inverters**: ordinarily between 50 and 400 W range.
- **String inverters**: commonly between 0.4 and 2.0 kW range.
- **Multistring inverters**: commonly between 1.5 and 6.0 kW range.
- **Mini central inverters**: commonly higher than 6.0kW, including three-phase topology.
- **Central inverters**: commonly between 100 and 1000 kW, including three-phase topology.

Some topologies applied are [26]:

- **Basic full-bridge inverter**: it has the classical H-bridge topology, as Figure 2.10.
- **H5 inverter**: it was patented by SMA in 2005. It has an extra switch in the positive bus on a classical H-bridge topology. It has an advantage of isolating PV modules from conventional grid during no voltage state.

- **Highly efficient and reliable inverter concept (HERIC)**: it was patented by SMA in 2006. It disconnects the grid from PV module when there is no voltage.

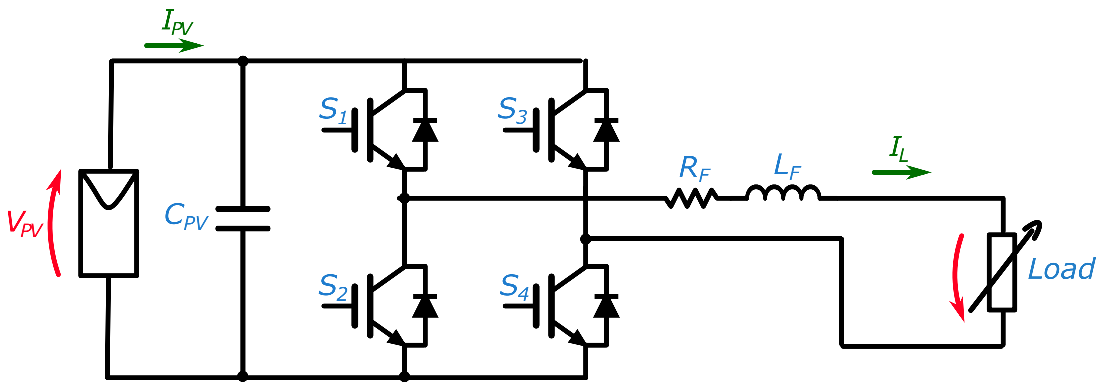


Figure 2.10: Basic full-bridge inverter.

Comparing to conventional motor drive inverter, PV inverters have their hardware and software control more complex. Some of PV inverters requirements are: grid connection filter, disconnection relay, maximum power point tracking (MPPT).

2.3.2 Maximum Power Point Tracking for Photovoltaic Systems

The goal of MPPT algorithm is to obtain the highest power from a PV plant, working in optimum point, according to the weather conditions, such as temperature and solar irradiation or even angle of incidence. The manufactures have been improving the MPPT constantly. There are a variety of MPP trackers implemented, and they usually depend on environmental circumstances and inverter topologies where they are utilized. Some common algorithms are known as [48] :

- **Perturb and Observe (P&O)**: also called "hill-climbing" MPPT method and often used, the advantage of this algorithm is to have low programming demand, consequently it is also easy to be implemented. It is useful for most of the system and does not have requirements or special information about the PV array. On the other hand, it is a generic algorithm with oscillations problems and poor tracking under rapidly-changing irradiation.

- **Incremental Conductance (INC)**: it is similar to P&O (it also has a "hill-climbing" algorithm), but INC has a better performance. Both, INC and P&O, make power tracking wrongly during low inertia of the system [49].
- **Constant Voltage (CV)**: comparing to the other methods, this algorithm is the least efficient. On the other hand, when the irradiance is lower, it has its performance better than the INC or the P&O. So, in a way to use the best of those algorithms, CV is often programmed in a combination with one of the algorithms previously said.

2.3.3 Grid Connection Requirements

Commercial converters need to be accorded to the standards established by IEC and IEEE to connect to the conventional grid. In 2013, the Brazilian Association of Technical Standards (ABNT) published ABNT NBR Std. 16149 based on IEC 61727, which implement requirements for interface between PV inverter and public low-voltage grid. The standards are:

1. **IEC 61727:2004**, "Photovoltaic (PV) systems - Characteristics of the utility interface" [50].
2. **ABNT NBR 16149:2013**, "Photovoltaic (PV) systems – Characteristics of the utility interface". In portuguese it is found as "*Sistemas fotovoltaicos (FV) – Características da interface de conexão com a rede elétrica de distribuição*" [51].
3. **IEEE 1547:2018**, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces" [52].

The document [53] shows as abstract a comparison of these three standards. It corrilates the following characteristics: odd and even harmonics; disconnection time for voltage and frequency variations and limitations for DC current injection.

2.4 Over-Voltage Protection Circuit

A protection circuit is elementary to assure the appropriate working of the inverter and integrity, preventing from damage during no-load working. It can happen when there are:

1. Low power demand.
2. High power produced by PMSG.
3. Grid failure.
4. high time required by the inverter for synchronization with the grid.

In cases 1 and 2, the generators operate at overpowering. With generator unloaded operation, in cases 3 and 4, the voltage at the generator output is high.

The over-voltage protection circuit restricts the PMSG to a maximum speed in order to limit the output DC voltage. This restriction is made by heat dissipation on the power resistor. If the power exceeded is higher than the dissipator can handle, the generator has its winding short-circuited.

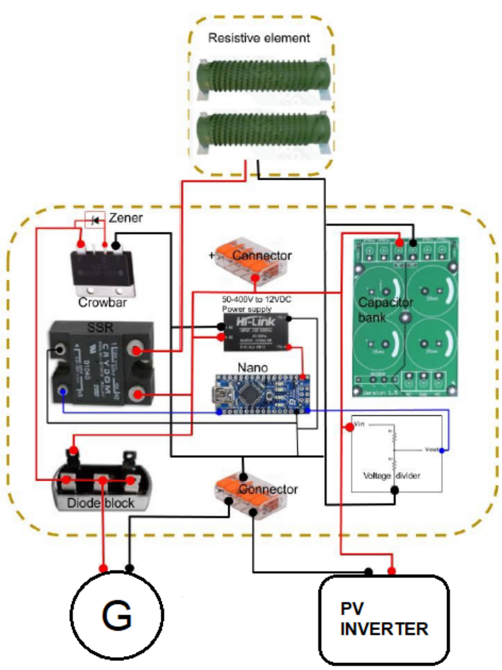


Figure 2.11: One-phase AC input over-voltage circuit designed by PowerSpout, adapted from [54].

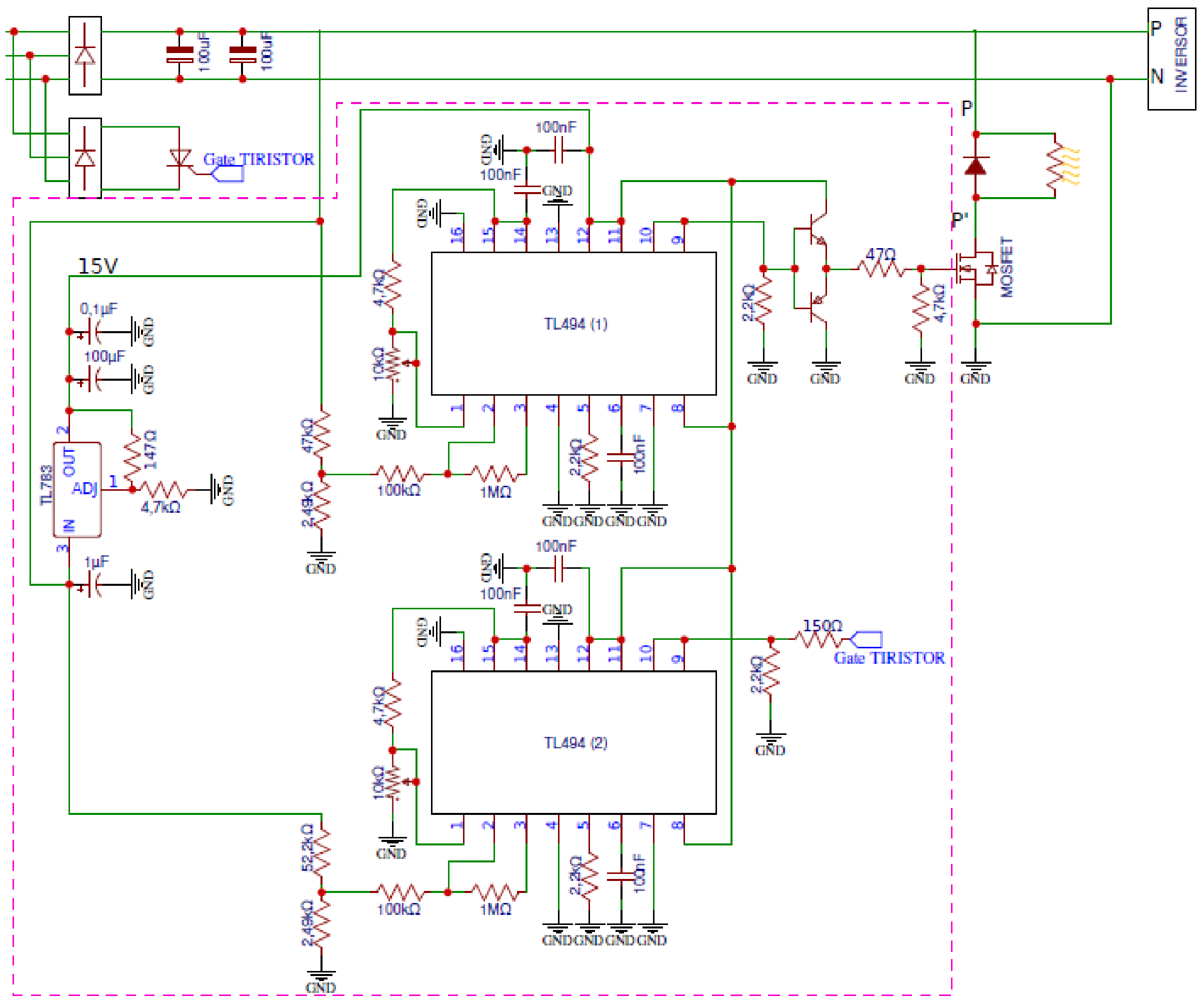


Figure 2.12: Over-voltage protection circuit schematic for PMSG up to 300 W [55].

Models with AC or DC inputs can be found in the market. Figure 2.11 presents a model available by PowerSpout. Moreover, some tests were done using PC AC4 350/400 from PowerSpout, as is shown in Chapters 3. In the case of equipment on the market, the voltage is previously determined and cannot be changed. The consumer must choose a voltage below the maximum allowed by the PV inverter.

The IPB laboratory designed and tested a protection circuit presented in [11], which had hardware modification and updated to Figure 2.12 and Appendix A. This circuit has its working voltage adjustable by a potentiometer. Also, in cases of high power, the generator phases can be short-circuited by the thyristor drive.

Chapter 3

Pico-Hydro Platform: Tests, Results and Discussion

Chapter 3 is dedicated to showing the construction of the emulation platform as an overview of all devices in the structure, how it is built, linkage between devices and their main data. Also, the structure is presented as four schemes split by turbine and generator system: water wheel, low head, Turgo and Pelton turbines.

3.1 Platform overview

In order to measure energy production, whether for the Silk House, Castrelos Aquaculture Centre or any other plant with compatible carachteristic, the pico-hydro generation emulation platform was built in the geotechnical laboratory of ESTiG.

This platform has 3 turbines and a water wheel which are generating electricity. Their specificities are in accordance with table 3.1. As can be seen, both the water wheel and propeller turbine are for low water column designs. In contrast, Pelton and Turgo turbines require considerably higher water heads. Figure 3.1 shows how all hydro systems are connected, and Figure 3.2 is a photo of the pico-hydro platform located in ESTiG.

Figure 3.1 shows the propeller turbine and Water wheel systems sharing the same motor pump machines and tubes. It happens because both do not need high pressure for the system, they emulate low head plants, and need a higher water flow. On the other hand, figure 3.1 also shows the other group of motor-pump machine, conventional inverter, tubes, and sensors shared by Turgo and Pelton turbines. These 2 turbines need higher pressure and lower flow, comparing to water wheel and low head schema.

To test the required turbine or water wheel, in which the same motor-pump is shared, it is necessary to open its valve and close the others. The same happens to turgo and pelton turbines.

Table 3.1: Turbines information [56].

Turbine	Model	Head [m]	Pressure [bar]	Flow [l/s]
Pelton	PLT350 HP	3-130	0.29-12.75	≤10
Turgo	TRG350 HP	2-30	0.2-2.94	8-16
Propeller	LH400	1-5	0.1-0.49	25-55
Water Wheel	Made at IPB	3.5	0.29	≤40

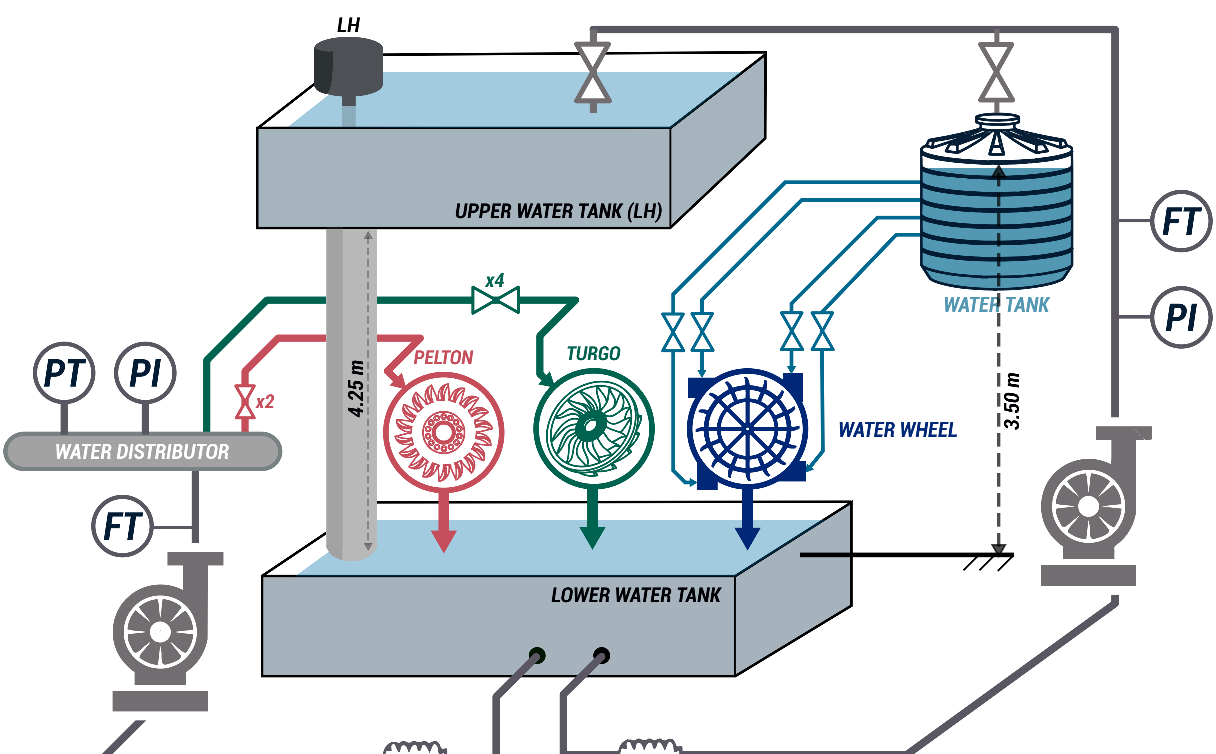


Figure 3.1: Platform overview (designed by Matheus Montanini).

Wherein PT is pressure transmitter, PI is pressure indicator and FT is flow transmitter. The FT is not discussed in this chapter, hence it was not activated during the tests because of mechanical structure vibration.

In Figure 3.2, pelton, turgo and water wheel are behind the whiteboard. Secondary tank (part of water wheel system) is in the top right side. The low head turbine and its channel is on top of the metal structure.

Figure 3.2: Platform overview located in ESTiG.

To simplify the understanding of the platform was split into four systems, which are covered in subchapters 3.2, 3.3, 3.4 and 3.5.

3.2 Horizontal water wheel system

3.2.1 Configuration

The horizontal water wheel was done for pedagogic propose and also as a prototype to be applied in the SilkHouse. For this system, there are:

- A conventional frequency converter ACS355-03E-12A5-4+J404 [57].
- A motor-pump group CronoBloc-BL 125/185-5,5/4 of 5.5 kW [58].
- A secondary water tank, located up to water wheel.
- A water wheel made ate IPB [14], Figure 3.3.
- A mechanical transmission (1:5) made with one timing belt and two toothed wheels.
- An electrical generator, Table 3.2.
- A over-voltage protection circuit.
- A rheostat.
- A photovoltaic microinverters, Table 3.3.

Figure 3.3: Top view of Water wheel.

The pumping water to the tank located 3.5 meters above water wheel is made by a motor-pump of 5.5 kW. The pump can operate up to 250.0 m^3/h (69.4 l/s), and has it available barometric head up to 6.0 m, Figure 3.4. Its motor has its frequency set by the frequency converter ACS355 using the macro Standard ABB. Consequently, the flow water is regulated too. Nonetheless, the flow is mainly controlled by the 4 valves located at the tank outlet.

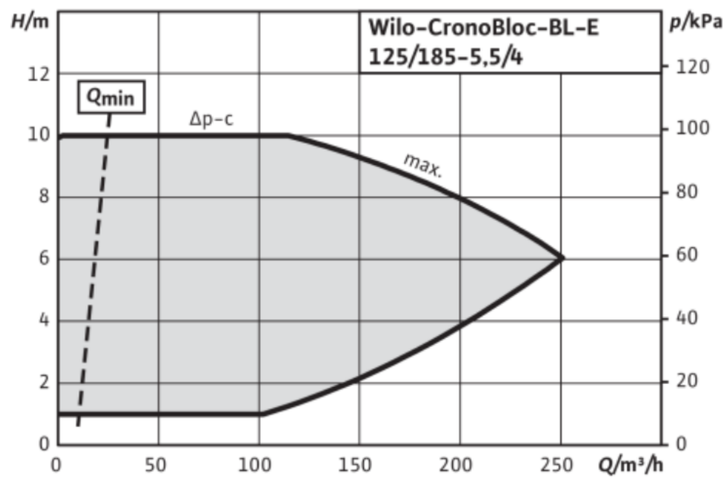


Figure 3.4: Head vs flow, CronoBloc-BL 125/185 - 5,5/4 pump [58].

For the all fully open valves, it is indicated the electric motor operating around 46.6 Hz. In this way, the water level is kept stable in the upper tank.

The water wheel system is composed of an electric generator, a mechanical transmission (timing belts) and the water wheel itself, as shown in figure 3.3. The water wheel is 1.2m in diameter with 32 paddles, its dimensions was specified considering SilkHouse layout. There are 4 water jets, each one has 50 mm in diameter, spaced 90 degrees apart close to paddles tip [14]. Its mechanical structure was built to stabilize the vertical shaft, two toothed wheels for movement transmission, and generator.

The tests made in this system used all microinverters in Table 3.3. They were also used connected with PV models to validate if they can operate suitable. It was observed all of them could turn on and synchronize to the grid properly.

Table 3.2: Water wheel PMSG technical data

Gen.	**Speed** (rpm)	V_{DCo} (V)	V_{DC} (V)	I_{DC} (A)	P_{DC} (W)
	300	45	28	10.7	300

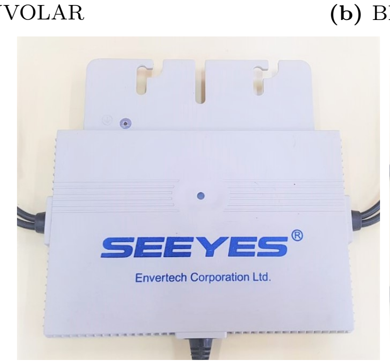
Table 3.3: Microinverter information

Parameters	**Unit**	**Microinverter**				
		INVOLAR	**BEON**	**APS**	**SEEYES**	**GWL**
Maximum input power	W	280	300	310	2x300	300
Operating range	V	22-48	20-50	22-45	18-54	18-54
Peak power tracking range	V	28-40	24-40	26-45	24-42	20-40
Maximum input DC voltage	V	50	55	55	54	50
Maximum input current	A	10	11.5	10.5	2x9.5	9.5
Rated output power	W	245	250	250	500	235
Nominal voltage	V	200-240	230	230	230	230
Nominal output current	A	1.06	1.08	1.08	2.17	1.02
Nominal Frequency	Hz	50/60	50	50	50/60	50

(a) INVOLAR

(b) BEON

(c) APS



(d) SEEYES

(e) GWL

Figure 3.5: PV microinverters

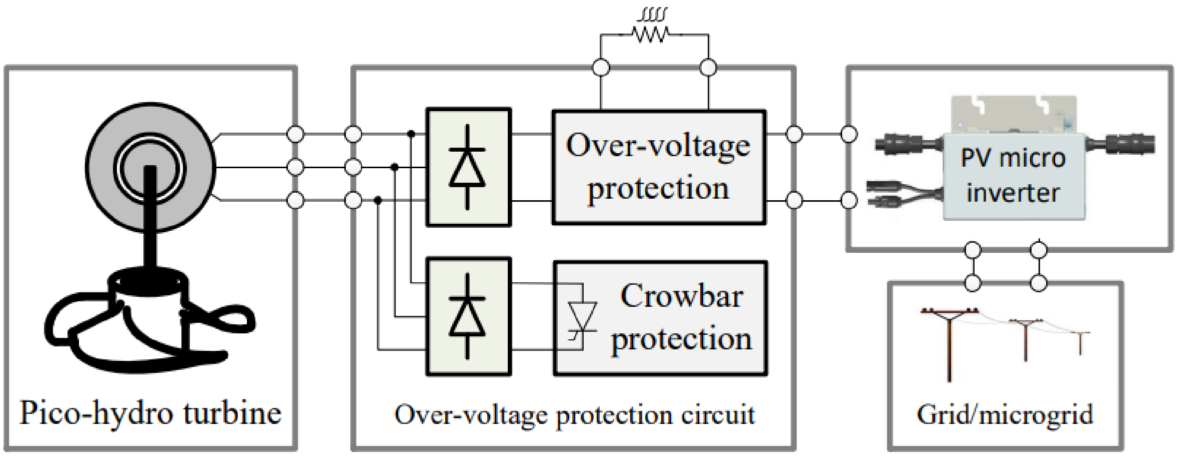


Figure 3.6: Design topology for grid-connected water wheel system with microinverter and protection circuit [55]

The approach to connect the devices is similar to the Figure 2.8. In this case, the protection circuit was built in laboratory [55]. The figure 3.6 shows how they are connected.

3.2.2 Results and Discussion

First of all, the water wheel system was tested with no load to check the maximum DC voltage. The head set was 3.5 meters. The water flow rate was increased until all valves were completely open, while the DC voltage was observed. The maximum value achieved was approximately 57.5 V_{DC}. It is above the maximum input DC voltage permitted by all inverters. Thus, there is a need of over-voltage protection circuit.

When the system is used with no protection circuit, the valves cannot be fully opened at the beginning of the operation. They must be closed enough, it means the water needs to be low enough, to the rectified voltage value does not exceed the maximum input voltage value to the rectifier. After the same grid synchronization, the valves can be fully opened. However, this operation is risky, hence the inverter can disconnect, and a sudden increase in voltage may occur and could damage the devices.

The second investigation was how much power the water wheel could supply to a passive load. It means no connection to PV microinverter, and consequently no synchronism. According to Table 3.4, the average of samples was 100.4 W_{DC}, and the maximum value

Table 3.4: Water Wheel grid connection results with generator, different microinverters and a passive load.

	Microinverter			
	BEON	**GWL**	**INVOLAR**	**Passive Load**
V_{DC}(V)	40.2	29.9	39.5	18.7
I_{DC}(A)	1.4	2.8	1.4	5.4
P_{DC}(W)	57.0	82.9	56.8	100.4
V_{AC}(V)	233.7	234	233.7	-
I_{AC}(A)	0.24	0.33	0.23	-
P_{AC}(W)	55	77.1	53.7	-
$\eta_{\mathrm{inv}}(-)$	0.96	0.93	0.95	-

was approximately 120 W_{DC}. For the passive load, there was no need of over-voltage protection circuit. The rheostat selected was in accordance with input current, and its resistance (Ω) was adjusted until find the maximum power possible.

The BEON, GWL and INVOLAR devices had 57.0 W_{DC}, 82.9 W_{DC} and 56.8 W_{DC}, respectively; and syncronized with grid suppling 55.0 W_{AC}, 77.1 W_{AC} and 53.7 W_{AC}, respectively. All values were obtained during the generator steady state.

Figure 3.7 shows graphically the proportion among the devices. The GWL device showed the best use of the generation potential, demanding approximately 83% of the available power. BEON and INVOLAR had a demand of approximately 57%.

During the water wheel operation, APS and SEEYES microinverters did not synchronize to the grid, so the circuit was open. It made the generator works in a high velocity and voltage. It is important to remember that the dynamics of a hydraulic system are different from a photovoltaic. Also, the MPPT algorithm was designed for a solar dynamic.

3.2.2.1 Extra test: Synchronization

The tests shown in this section and the next (subsection 3.2.2.2) are related to the master thesis [55], by Isabella Scotta. Some tests in the pico-hydro power plant were done together and also generated the article in Appendix B.

The placement of the works served to validate both the over-voltage protection circuit

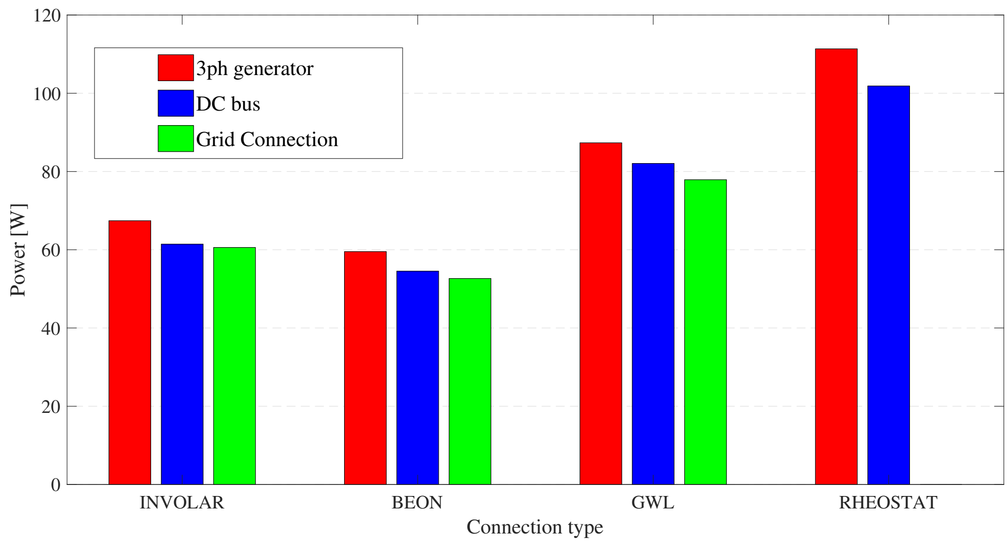


Figure 3.7: Water wheel generation results

and the pico-hydro emulation platform. The circuit used is shown in Figure 2.12, with the following prototype (Figure 3.8) was made by Isabella Scotta and Wellington Maidana.

The tests in Figure 3.9 represent the behavior of the microinverter when connecting to the grid. The channel 1 represents the rectified voltage at the microinverter input. The channel 2 shows the operation of the PWM. When PWM was set to actuate at 45.0 V_{DC}, and it means that there is current passing through a rheostat and there is power dissipated as heat. The DC bus voltage was limited to 47.0 V_{DC}.

The BEON and GWL microinverters required the circuit and protection at the time of connection. There were three connection attempts to BEON (Figure 3.9a); while only one was needed for GWL (Figure 3.9b). The PWM started to work as set, when the generator reached around 45 V_{DC}; and had its limit at 47.2 V_{DC} in bouth cases.

The INVOLAR microinverter was connected to the grid on the first attempt, as shown in Figure 3.9c.

3.2.2.2 Extra test: Grid Failure

The PV inverters may be disconnected from the grid in case of a power failure and the voltage or frequency parameters are not according to the established. For this case, to

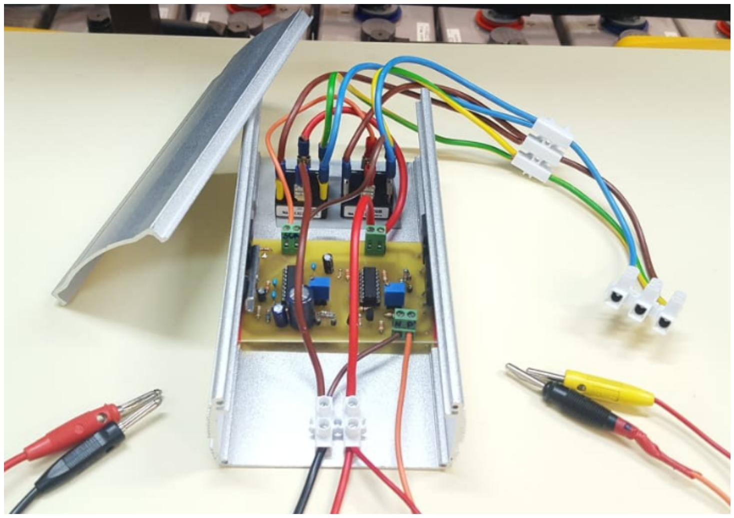
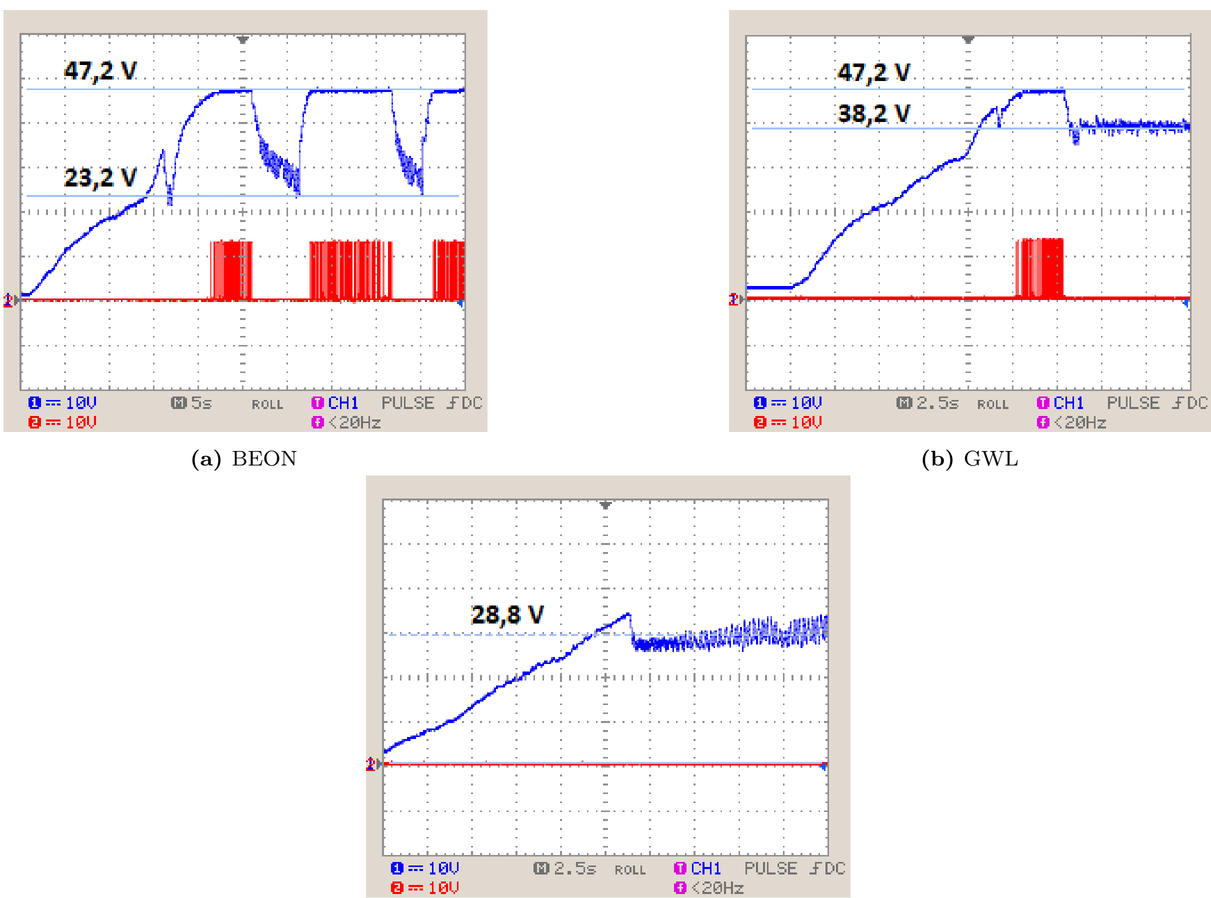


Figure 3.8: Over-voltage protection circuit prototype, adapted from [55]



(a) BEON

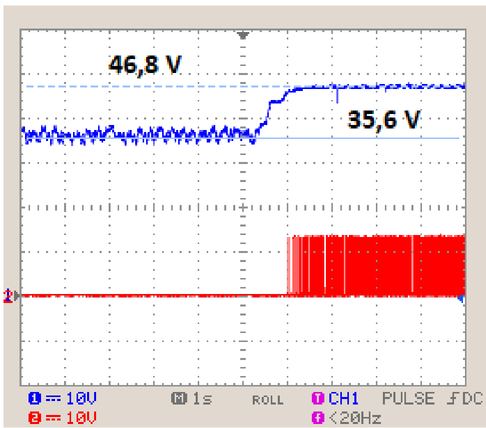
(b) GWL

(c) INVOLAR

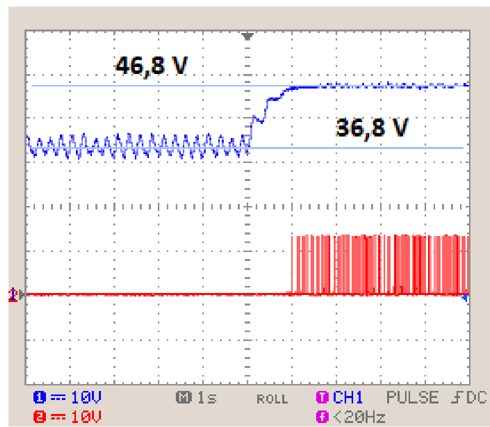
Figure 3.9: Synchronization test results [55]

simulate a grid failure, the generator was working in steady-state when the microinverter was unplugged. The over-voltage protection circuit had the same setpoint.

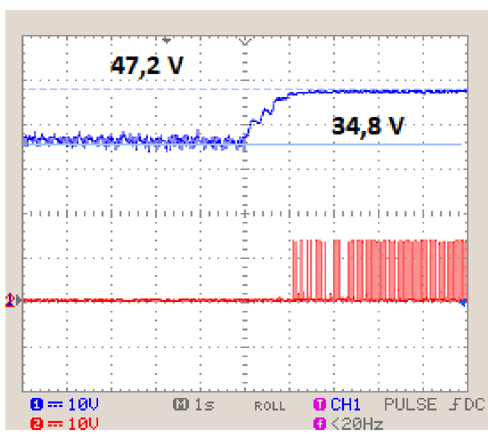
The generator was working around 35.5 V_{DC}. When it was unplugged, the PWM starts to work and the voltage increased to the limit, around 47.0 V_{DC}. Also, the exceed power was delivered to the rheostat.



(a) BEON



(b) GWL



(c) INVOLAR

Figure 3.10: Grid failure test results [55]

3.3 Low Head system

3.3.1 Configuration

The low head turbine was bought also for pedagogic propose and to emulate the hydropower generation designed for SilkHouse Project. It has 4.25 m head and high flow, up to 55 l/s. For this system, there are:

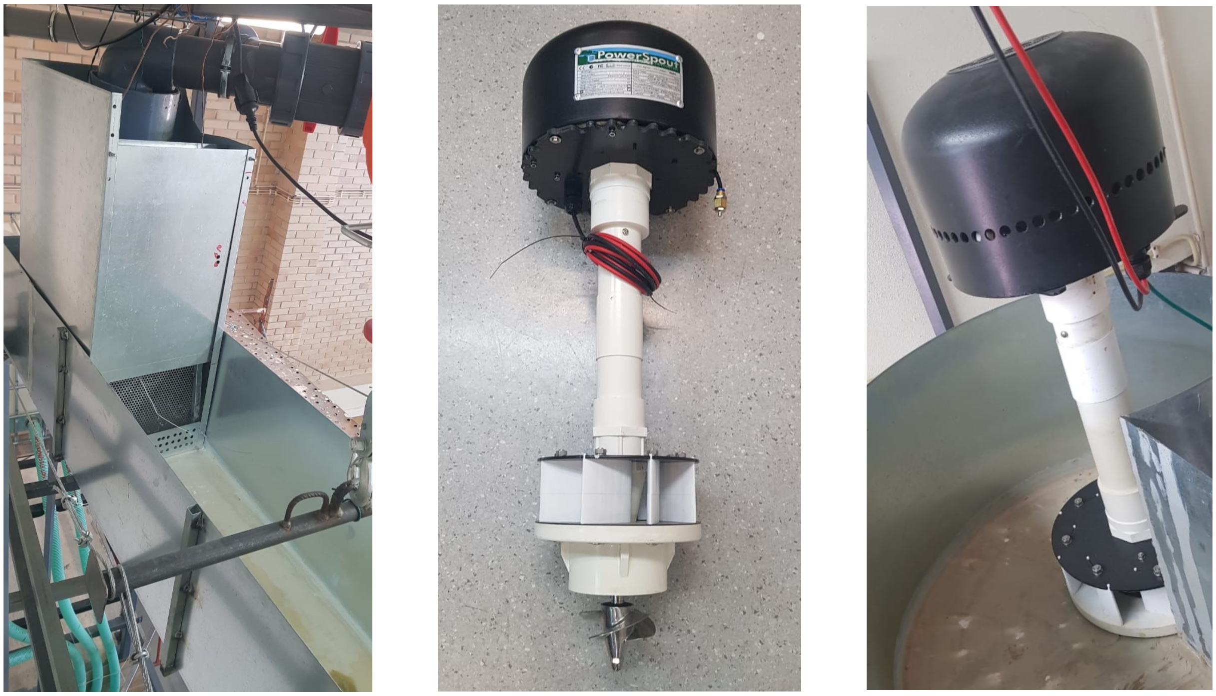
- A conventional frequency converter ACS355-03E-12A5-4+J404 [57].
- A motor-pump group CronoBloc-BL 125/185-5,5/4 of 5.5 kW [58].
- A low head turbine, Figures 3.11b and 3.11c.
- A water channel, Figure 3.11a.
- An electrical generator 60R110-4S3P-S-HP, Table 3.5, Figures 3.11b and 3.11c.
- An over-voltage protection circuit.
- A photovoltaic inverters, Table 3.6, Figure 3.12.

The electrical connection is approached in Figure 2.8.

The previous work with platform shows test results made with 60R110-4S3P-S-HP generator [15]. Moreover, Figure 3.13 shows the rectifier circuit for this generator. The circuit is located close to generator.

To set the water flow it was used the conventional frequency converter [57] to regulate the motor-pump speed by the frequency, working with the Macro Standard ABB. The same used for water wheel system. The pumping water flow for 4 meters of head is up to 200 m^3/h (55.56 l/s) is a bit higher than the maximum water flow for the low head turbine, Which makes the pump suitable for use, as showed in Figure 3.4 and Table 3.1.

It is important to notice that the mechanical structure where the flow meter is located has a high vibration, impairing laminar water flow. Wherein it was decided on the measures to be made concerning the frequency of pumping instead of the flow.



(a) Water output and channel **(b)** Front view of LH **(c)** LH applied at platform

Figure 3.11: Low head turbine system

(a) Omnik **(b)** Solax

Figure 3.12: Photovoltaic inverters

Table 3.5: LH PMSG technical data.

Gen.	**Speed** (rpm)	V_{DCo} (V)	V_{DC} (V)	$Imax_{\text{DC}}$ (A)	P_{DC} (W)
	1500	487	275	10	1600

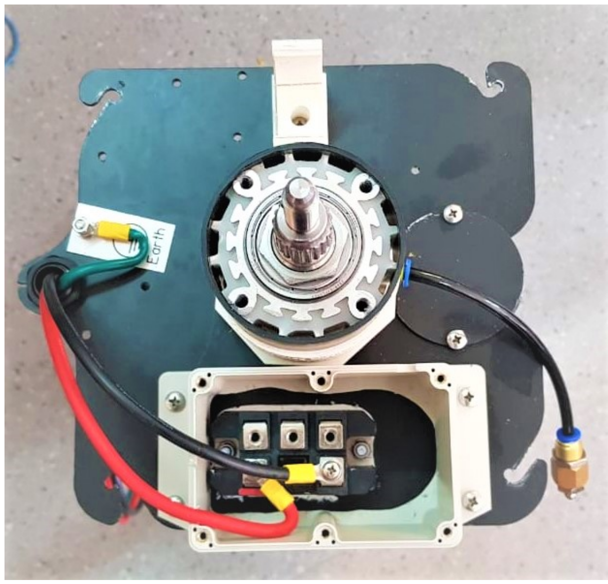


Figure 3.13: Rectifier circuit of low head system.

Table 3.6: Photovoltaic inverter information.

Parameters	**Unit**	**Inverter**	
		SOLAX	**OMNIK**
Maximum input power	W	1650	2300
Peak power tracking range	V	70-380	120-450
Maximum input DC voltage	V	400	500
Maximum input current	A	10	16.5
Max. DC short circuit current	A	12	18
Rated output power	VA	1500	2200
Nominal voltage	V	220/230/240	230
Maximum output current	A	7.5	8.5
Nominal Frequency	Hz	50/60	50/60

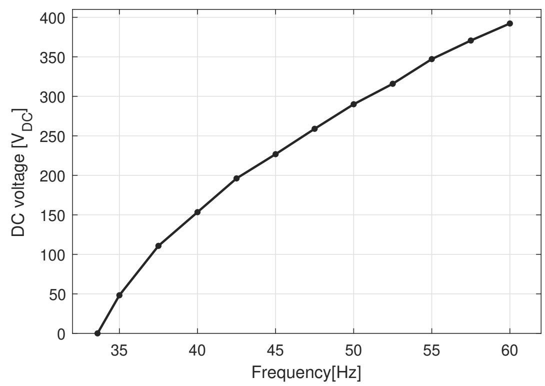


Figure 3.14: LH turbine with no load, V_{DC} of electrical generator vs. motor-pump frequency.

3.3.2 Results and Discussion

As subsection 3.2.2, the open-circuit test was made to check the DC voltage of generator 60R110-4S3P-S-HP. For the maximum frequency applied on motor pump, 60 Hz, the average DC voltage was approximately 392.2 V_{DC}, as shown in Figure 3.14. This value exceeds the maximum allowed by the SOLAX device. For values bellow 35 Hz, the DC voltage was senseless.

The Figure 3.15 shows the magnitudes of generation, according to the frequency of motor-pump 60 Hz was applied to the motor pump and was subtracted 2.5 Hz until it is no longer possible to connect the inverter to the grid. For OMNIK, bellow 37.5 Hz, there was no power delivered to the grid; while for SOLAX it was bellowed 35 Hz.

OMNIK and SOLAX inverters had similar power required from the generator and delivered to the grid during steady state. The main difference is the operation (the voltage and current required), which is defined by the MPPT algorithm.

OMNIK and SOLAX have diferent MPPT voltage range. In Figures 3.16 and 3.17 is possible to check OMNIK working close to the minimum MPP voltage, 120 V, from its maximum to minimum power generated during the test. On the other hand, SOLAX had had a higher voltage variation. When SOLAX had its power lower than 400 W, the voltage is quickly reduced. Additionally, at very low power, the voltage is below minimum MPPT voltage.

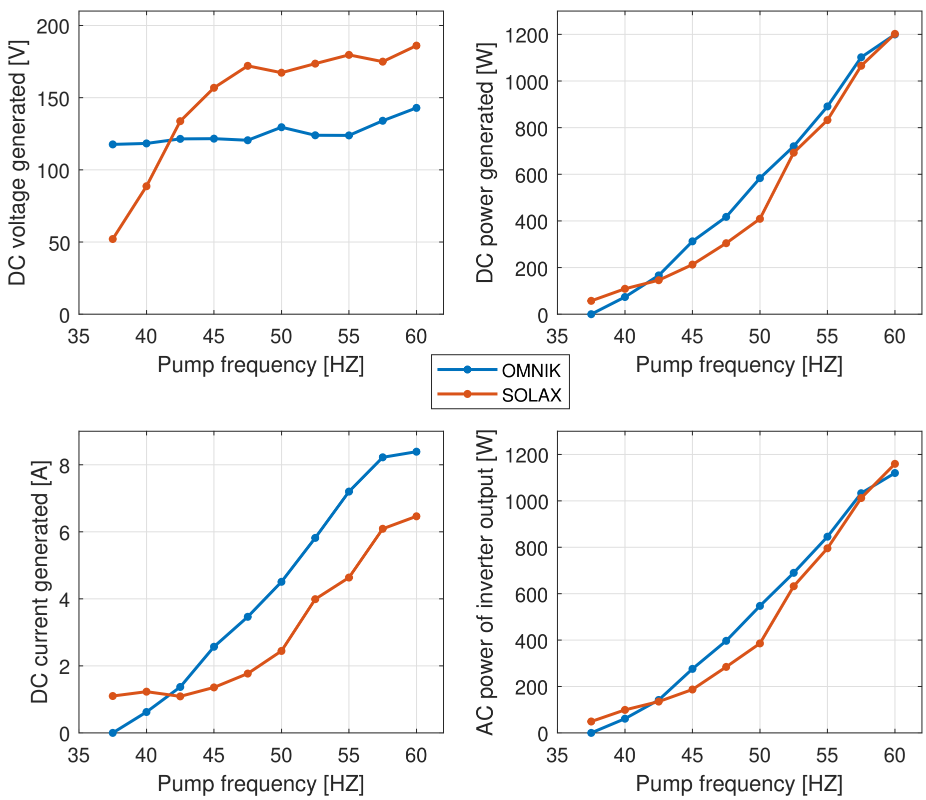


Figure 3.15: PMSG production according to motor-pump frequency (water flow).

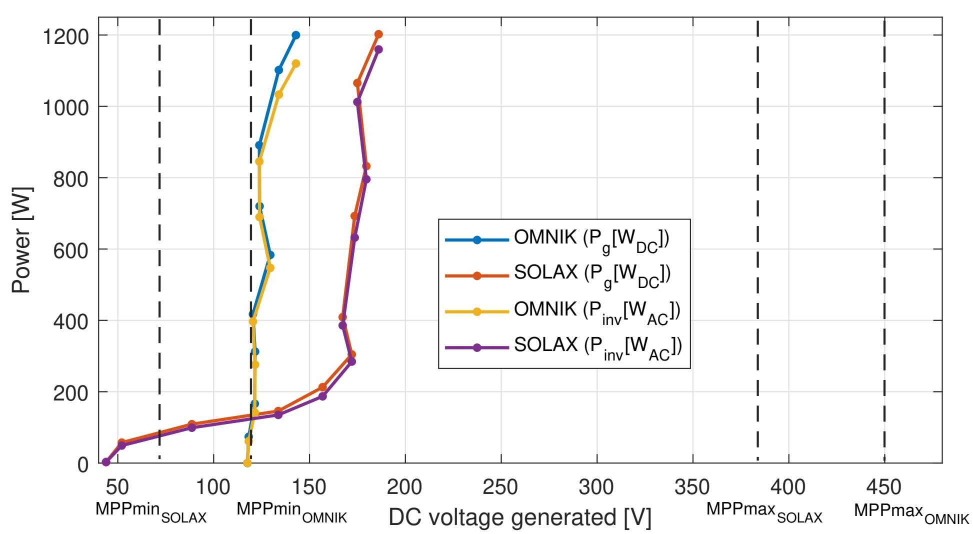


Figure 3.16: Power on the DC bus and on the grid vs. DC voltage

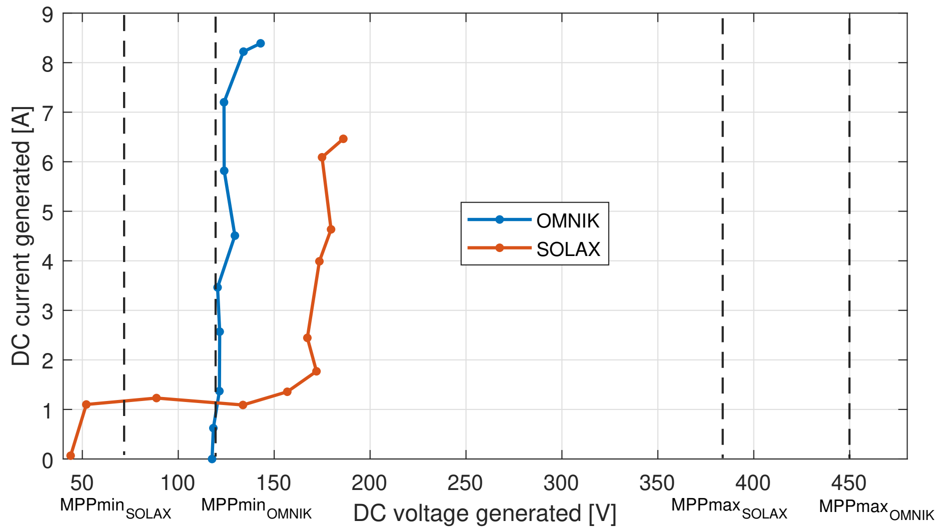


Figure 3.17: DC current vs. DC voltage

3.4 Turgo System

3.4.1 Configuration

This model of Turgo turbine has to be applied for an head between 2 and 30 meters. So, there is a water pumping system for pipe pressurization to emulate this head. For this system, there are:

- A conventional frequency converter ACS355-03E-31A0-4+J400 [57].
- A motor-pump group of 11.0 kW [59].
- A pressure transmitter XMLG016D21, pressure sensor range of 0 to 16 bar, analogue output function from 4 to 20 mA [60].
- A pressure gauge.
- A Turgo turbine TRG350 HP, Figures 3.18 and 3.23.
- An over-voltage protection circuit, Figure 3.19
- An electrical generator PMSG 60R90-6S2P-S-HP.
- A photovoltaic inverters, as can be seen at Table 3.6, Figure 3.12.

The pressure conversion is:

$$1[bar] \approx 10.20[mH_2O] \tag{3.1}$$

It means that the minimum and maximum turbine operating values are 0.20 and 2.94 bar, respectively.

The head emulation is done by a motor-pump of 11 kW, using a pressure transmitter with PID Macro Control from frequency converter ABB ACS355. The water pressure inside the pipe simulates a column of water located above the turbine. The flow transmitter is not used for frequency converter control.

The Turgo turbine applied in platform has 4 jets equally spaced around its diameter.

PowerSpout informs that a standard Pelton turbine can generate up to 1200 W, and 1600 W as maximum output power.

Figure 3.18: Turgo turbine

The generator 60R90-6S2P-S-HP has star connection and has a short circuit DC current of 9.8 A. In an open-circuit (unload), the relation between DC voltage and speed is 0,259 V/rpm [15]. Also the thesis presents the generator characterization.

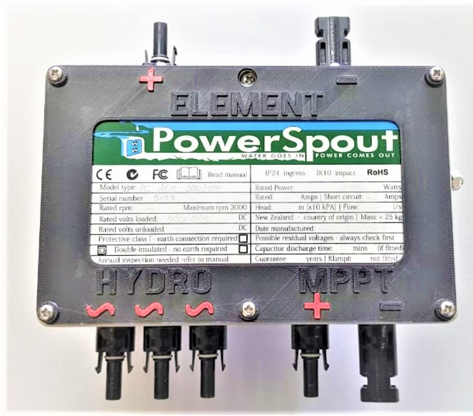


Figure 3.19: PowerSpout over-voltage protection circuit.

The over-voltage used for this test is PC AC4 350/400, made by PowerSpout. It has included a rectifier circuit in which can supply up to 400 V_{DC}. The device limits the output voltage and protects the circuit dissipating the power by heating in a power resistor. Moreover, it can short-circuit the engine's wire.

The approach used for this experiment was shown in Figure 2.8.

3.4.2 Results and Discussion

For the tests in this subsection, the pressure was increased up to 3 bar until the system works in steady state. From this point, the results were taken decreasing 0.5 bar until it had no power produced. The Values seen in the graphs are the average of at least 4 samples.

The Figure 3.20 shows the variable voltage, power and current according to the pressure in the tubes, with OMNIK and SOLAX PV inverter. So, it is the PMGS 60R90-6S2P-S-HP generation according to the water head as well. In the same figure, comparing the pressure with power, SOLAX could extract the same power or higher comparing to OMNIK.

The Figure 3.21 shows both inverters working most of the times inside MPP voltage range. Also, SOLAX achieve its maximum input power of 1545.0 W_{DC}; while OMNIK had it maximum input power of 1187.6 W_{DC}. It means SOLAX could working closest to maximum power available during steady state.

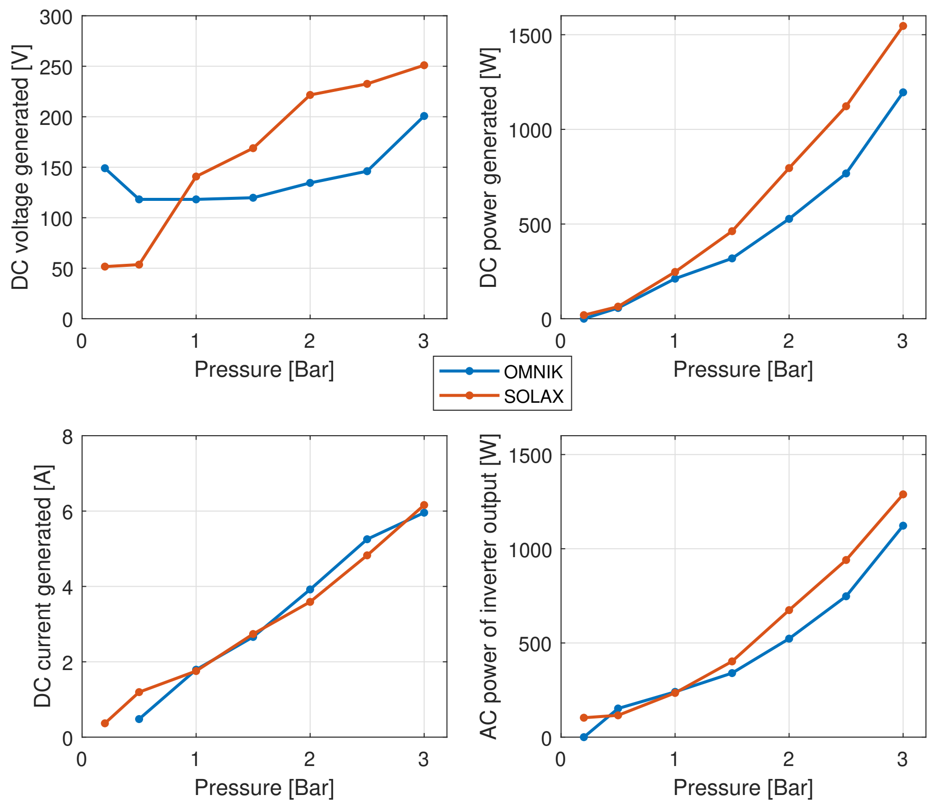


Figure 3.20: Turgo system, PMSG production according to pump pressure.

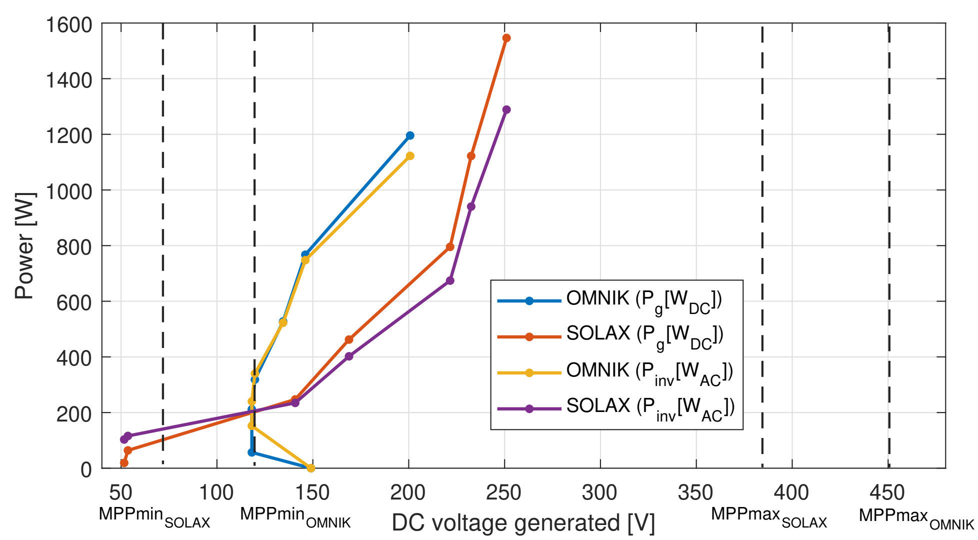


Figure 3.21: Turgo system, power on the DC bus and on the grid vs. DC voltage.

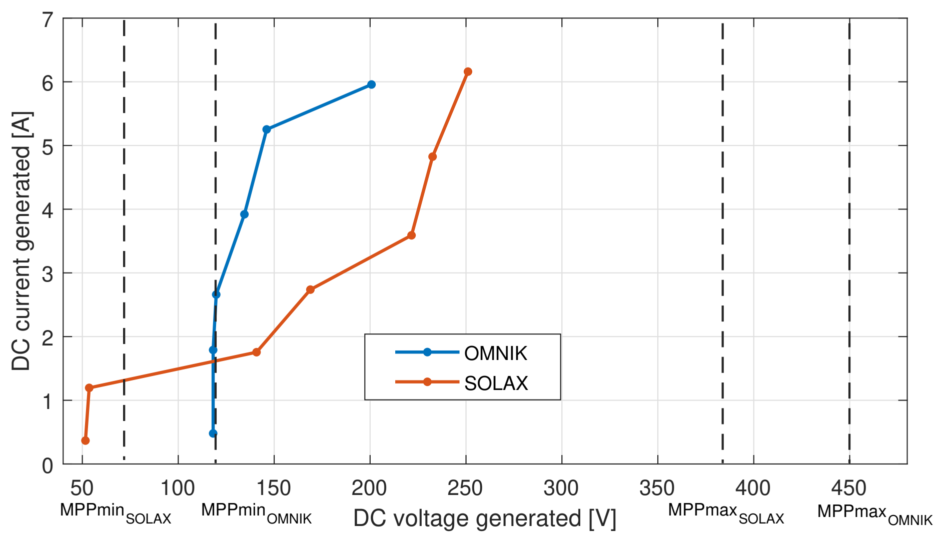


Figure 3.22: Turgo system, DC current vs. DC voltage

3.5 Pelton system Configuration

The Pelton turbine shares the same water pumping system to emulate an head between 3 and 130 meter. For this system, there are:

- A conventional frequency converter ACS355-03E-31A0-4+J400[57].
- A motor-pump group of 11.0 kW [59].
- A pressure transmitter XMLG016D21, pressure sensor range of 0 to 16 bar, analogue output function from 4 to 20 mA [60].
- A pressure gauge.
- A Pelton turbine PLT350 HP, Figure 3.23.
- An electrical generator 60R120-6S2P-S-HP.
- A photovoltaic inverters, as can be seen at Table 3.6, Figure 3.12.

Similar to subsection 3.4, PowerSpout informs that a standard Turgo turbine is able to generate up to 1200 W, and 1600W as maximum output power. 60R120-6S2P-S-HP has star connection and has a short circuit DC current of 7.3 A. In an open-circuit (unload), the relation between DC voltage and speed is 0,345 V/rpm.

The [15] performs PLT350 HP connected with SUNNY BOY 1.5, SUNNY BOY 2100TL and OMNIKSOL-2K-TL2. There are results considering DC current and DC power vcs. DC voltage, up to turbine power limit.

Figure 3.23: Turgo and Pelton turbines

During the tests made in laboratory, the pipe which goes to turgo turbine presented water leakage from 4.5 bar. Also, turgo system had leakage in its connection between steel clamp and the tube. Due to these facts it was considered to stop doing its grid connection test.

Chapter 4

Pico-Hydro Platform: Technical Proposals

This chapter presents an approach to possible improvements for the pico-hydro emulation platform, considering improvements in data collection, prevention wearing of parts or devices and increasing equipment useful life

4.1 Vibration Reduction

Vibration is a common characteristic in the work of rotating machines: turbines, pumps, and fans. The vibration may have several causes such as hydraulic disturbance, cavitation, presence of solid particles in the liquid, unbalance of the rotating parts of the system and operation of the machine. The latter can cause resonance in the system [61]. These problems may affect decreasing the useful life of the material for wear, heat, and crack growth.

It was observed problems with vibrations in the metal structure and pipes during experiments. One of the most striking factors is the impediment to proper data collection from the flow sensor. In the following are some observations made during the study that can be considered in order to improve the platform.

Figure 4.1: Current centrifugal water pump fundation.

Figure 4.2: Current tube and flexible joint.

- The Current foundation of centrifugal water pump, shown in Figure 4.1, should be improved in order to absorb more vibrations from the water pumps.
- Improvement in the alignment and balancing of rotating parts.
- Use of check valves (non-retun valves).
- Use of filter between water tank and water pump, 4.2, section 4.2.

4.2 Water Filter

In rivers and canals, it is difficult to maintain water cleanliness. Particles and residues are always present and they often pass through the turbine and can affect the power output and also the component wear.

The laboratory water tank is exposed to the residues present. It also happens in real cases. Nevertheless, it is important for the proper functioning of water pumps, and for them to have a longer useful life, that water has fewer residues. For this reason, a water filter in the input of both pump can be an interesting improvement for this system.

It is important to know what needs to be filtered to select the filter to be implemented. There are hard solids, soft solids and living organisms of different sizes. Some types of filters are [62]:

- **Simple basket strainer**: it is fit upstream the pump. It is a very economical option, but inefficient.
- **Cut-away of Y-strainer**: it is fit in the system as part of hydraulic pipe design. It usually has its apertures greater than 1 mm.
- **Cartridge filter**: It is an economical option for fluids with few particles. It is often fit upstream the equipment to be protected. It usually has its apertures between 5 and 500 µm.

4.3 Leakage

The Poly Vinyl Chloride (PVC) hose used in the pico-hydro platform is made of soft plastic and reinforced with rigid helix material, with 50 mm of diameter. Considering the system at 30 °C, its working pressure is 4.5 kg/cm^2 (4.4 bar) and bursting pressure is 18 kg/cm^2 (17.6 bar).

In the Pelton system there are adjustable clamps to fix the hose to the pipe union connector (Figure 3.23). During the performed tests, the Pelton system presented some leakage (Figure 4.3). The manufacturer of the turbine suggests the use of a retaining cap, jet sleeve and camlock set [63].

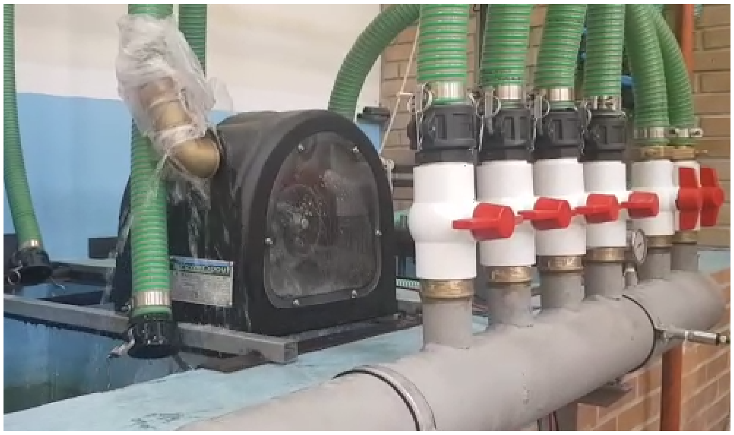


Figure 4.3: Leakage on Pelton system.

Figure 4.4: Water wheel and its oxidation.

4.4 Water Wheel

The water wheel on which the tests were performed showed rapid oxidation, as shown in Figure 4.4. Materials working in contact with water must receive anti-corrosive treatment and maintenance. Another option is to use stainless steel (iron, carbon, and nickel alloy).

The water wheel for the SilkHouse Project is in Figure 4.5 and still needs to be tested in the platform.

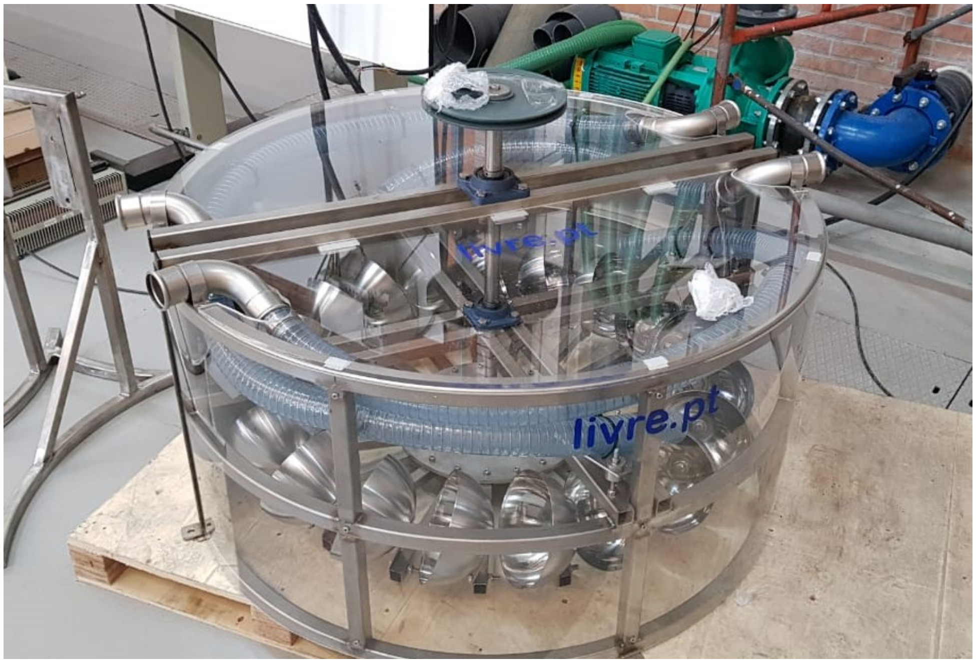


Figure 4.5: New Water wheel for SilkHouse application.

4.5 Application of Flow Sensors

For good sensor measurement, it is important that the sensor model and its installation are done in the best way. Swirl flow inside the pipe affects the measurement accuracy of the device.

Swirl flow means that the fluid is moving through piping paths and curves in different planes. Usually a swirl flow occurs when there are a poorly mounted flange gasket or a valve partially opened. These types of obstruction close to the flowmeter or uptream can lead to errors beyond 50 % [64].

The flow sensor in platform is VFI 12-240 DN100. Its specification is found in [65], as well as its instructions to be applied and flow behaviour according to the pressure.

This flow meter measures the differential pressure across the flow element inside the tube. So, the flow value is a function of pressure drop. It is important for this type of sensor to have a fluid profile that allows a predictable pressure drop. In other words, it requires a laminar flow.

Electromagnetic flow meters is applicable with conductive liquids, such as water. It uses induction Faraday's law to measure the flow. Consequently, it is independent of density, viscosity, temperature or pressure [66]. Electromagnetic flow meter can be an alternative for flow sensor.

4.6 Grounding

The importance of electrical grounding systems is related to personal safety, equipment protection and reduction of electrical noise. Many power quality issues are related to improper electrical contact and poor quality grounding.

Not only do electromechanical equipment require grounding, but also structures, junk boxes, and piping. In general, conductive materials require grounding. The materials present on the platform require improved grounding.

According to [67], grounding must be done by the protective conductor, and it is included in all pipes and connected to the general ground circuit. The ground conductors shall always be green/yellow. It also informs that all the metallic structures constitutive of the building, such as pipes and beams, must be equipotencialização with the ground circuit.

Chapter 5

Conclusions and Futher Work

This chapter presents the main conclusion about the reseach performed and possible future test and improvements of the pico-hydro system emulation platform.

5.1 Conclusions

This work explores the concept of pico hydro power plants under the concept of DG, which, associated to the microgrid trend, present an enormous potential under the actual scenario of climate changes and growing of energy demand.

Hydro energy conversion systems using a water wheel, low head, Turgo and Pelton turbines were analysed and tested considering educational and research purposes. From the turbines explored, the water wheel and low head turbines analyses are of special reference, taking into consideration the ongoing projects in the SilkHouse, Bragança.

Besides the turbines experimental tests, the integration of these systems in the grid were also explored. The turbines, PMSG and inverter data were correlated to check the possibility to integrate them in the same system.

The water wheel system presented the possibility to be connected with 3 of 5 microinverters. The best case (using GWL inverter), in pico-hydro platform, presented 17% of its DC power lower than when connected to a passive load. The other two cases (using BEON and INVOLAR) had 43% less than DC power, comparing to passive load.

For low head system, OMNIK and SOLAX inverters had similar behaviour and the input DC power in both inverters were approximately 1200 W.

During the tests made with Turgo turbine, SOLAX inverter can extract more power compared to OMNIK: 1545.0 W and 1187.6 W, respectively.

5.2 Further Work

The future work, should continuously more improve the pico-hydro platform, mainly to minimize vibration. Considering this improvement, the new results can have not only water pressure data, but also the water flow to compare with power generation.

Some proposed improvements for pico-hydro emulation platform can be tested. Also, the low head system with closed loop control based in flow data is a possible further investigation.

Moreover, a new water wheel needs to be tested to be implemented in SilkHouse, as well its connection to the grid using the microinverters [16]. Other types of turbines can be implemented to be tested, such as Francis and Kaplan.

Considering the LSE researches made during 2018 and 2019 years, this project can be integrated with the projects [17] and [55].

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Appendix A

Abstract: Analysis and Test of the Experimental IPB Pico-Hydro Platform with Grid Connection

ANALYSES OF AN EXPERIMENTAL PLATFORM FOR GRID-CONNECTED PICO-HYDRO PLANT

(✉) **G. Ribeiro[1,2], A. Vicente[3], Â. Ferreira[3]**

[1]Mestrado Eng. Industrial - Eletrotecnia, ESTiG,Instituto Politécnico de Bragança, Portugal,
[2]Departamento de Engenharia Eletrônica, CEFET/RJ, Brasil,
gribeiro.eletronica@gmail.com
[3]Departamento de Eletrotecnia, ESTiG, InstitutoPolitécnico de Bragança, Portugal,
avtl@ipb.pt e apf@ipb.pt

Abstract

Investment increase on centralized production caused distributed generation to be left aside for a long time. With current studies highlighting its technological and environmental benefits, distributed generation is being further explored and incurs significant changes, helping reduce dependence on non-renewable resources.

Riverside communities have a restricted or no electric power supply. These sites are characterized by low population density, few connections to the conventional power grid, and consequently low power consumption. The geographic features in these sites allow extensive usage of small-scale systems of electric generation and this potential has been studied in literature, for example pico-hydropower plants, as exemplified in [1-2].

This project proposes to validate the experimental platform located in the Geotechnical Laboratory of the IPB, that has educational purposes to enable applied research on renewable energies. This project focuses on practical applications and discussion of converter technologies widely available in the market for pico-hydro plant employment.

It is part of theresearch aiming the characterization of the elements, as well as suggestions for changes and improvements in its structure from the tests done with the turbine-generator sets. Furthermore, the use of photovoltaic inverters to synchronize and connect to the power grid of the institution.

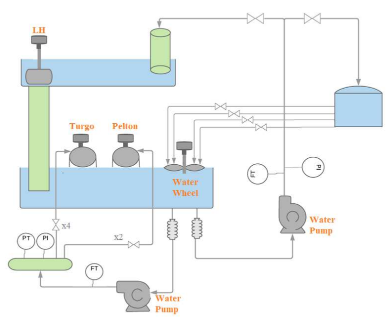

Fig 1. Pico-hydro emulation plant diagram

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Appendix B

Paper: Over-Voltage Protection for Pico-Hydro Generation Using PV Microinverters

Over-Voltage Protection for Pico-Hydro Generation Using PV Microinverters

Isabella Cristina Scotta[1,3][0000−0002−7401−0979], Gabriela Moreira Ribeiro[1,4][0000−0003−3434−578X], Wellington Maidana[1,2][0000−0002−5361−3850], and Vicente Leite[1,2][0000−0002−8790−519X]

[1] Instituto Politécnico de Bragança, Bragança, Campus Santa Apolónia, Portugal
[2] Research Centre in Digitalization and Intelligent Robotics (CeDRI)
[3] Universidade Tecnológica Federal do Paraná, Campus Toledo, Paraná, Brazil
[4] CEFET/RJ, Campus Maracanã, Rio de Janeiro, Brazil
isahcs9@gmail.com; gribeiro.eletronica@gmail.com; maidana@ipb.pt; avtl@ipb.pt

Abstract. Innovative, low-cost, environmentally friendly and renewable resource-based solutions are emerging to meet growing global energy demand. Hydroelectric technology is quite old and mature. Despite its importance, it is associated with large plants, with environmental impact. On contrary, small-scale systems, called pico-hydro systems (up to 5 kW) are not yet explored. Anyway, the exploration of pico-hydro systems has been increasing consistently, from the first off-grid applications in remote places to distributed generation, with the injection of the generated energy in the main grid or microgrids. Very recently, there have been advances in grid connection of these small-scale systems, using off-the-shelf components. Indeed, pico-hydro systems can be connected to the grid using off-the-shelf components, namely photovoltaic inverters. Thus, grid-connected pico-hydro systems have gained an enormous potential in distributed production. However, in situations of over-power, or whenever the generator is under no load, there is a need for effective over-voltage protection, unlike photovoltaic systems. The goal of this paper is to propose an over-voltage protection circuit, designed to ensure the integration of low-power pico-hydro systems connected to the grid using conventional photovoltaic microinverters. Extensive tests were performed on an experimental platform using three microinverters easily found on the market and a low power generator (300 W) developed for small wind turbines. The experimental results, demonstrated the performance of the proposed over-voltage protection circuit in four different situations, presented in this work, thus avoiding irreversible damages of generators and microinverters, in the context of the above described grid connection approach.

Keywords: Microgrids · Distributed Generation · Photovoltaic Microinverters.

1 Introduction

The growing need for energy from renewable resources is undeniable today as a consequence of the increase in energy consumption, besides environmental commitments made by many countries to reduce greenhouse gases [3]. The new technologies to be developed for micro-generation based on green energy allow the creation of solutions that currently facilitate the electrification in developing countries [16], as well as promoting self-sustaining, growing systems in developed countries [5, 11]. Distributed generation (DG), through different renewable resource plants, despite the low power, may contribute significantly to the increase in sustainability at the local and global levels [8, 14].

According to [6], small hydropower plants can be considered one of the best methods for producing renewable energy, as long they are based on cheap, reliable, mature technologies and do not cause significant environmental changes where installed. Pico-hydro systems generate up to 5 kW [1] and have potential in meeting growing energy demand, once they allow widespread exploitation of small rivers, shallow water reservoirs, and wastewater [6, 13].

Recent studies have shown the integration of low power wind generators with pico-hydro applications, in which they are connected to the grid through the use of photovoltaic (PV) inverters [9]. PV inverters are mature technologies widely available on the market. Its combination with a permanent magnet synchronous generator (PMSG) is an alternative for energy generation. Although PV inverters have been created to operate with PV modules, a PMSG and a bridge rectifier can be used as DC source, instead of those modules [9, 10].

As is the case with large hydropower plants, in order to provide a stable voltage output, mechanical devices are generally used for water flow adjustments. Afterwards, the rotation of the turbine is controlled so as to reduce voltage and frequency deviation [15]. Hydraulic dynamics, with the seasonal variations of water flow, influence these parameters in a generation. The energy production efficiency is improved with turbines or water wheels performing at variable speed. Therefore, the characteristics of the generators and inverters require that they be integrated. Furthermore, to prevent damage to the electrical system, a protective circuit is required. Indeed, an over-voltage protection circuit is necessary to ensure that, during grid synchronization or disconnection and overpower generation, the generator does not damage the inverter [10].

This paper proposes a simple and low-cost over-voltage protection circuit that limits the rectified DC voltage of the generator by dissipating the energy in a power resistor or by short-circuiting the generator if over-power generation is detected. The reliability of the designed circuit is demonstrated with numerous tests carried out on a laboratory workbench and an experimental platform. The connection of low power PMSGs to the electrical grid through PV microinverters is also demonstrated.

2 Over-Voltage Protection

2.1 Integration Between Generator and PV Inverter

PV inverters, up to 5 kW, are widely diffused, have a competitive cost and are very widespread. There is also a significant set of manufacturers that provide a wide offer of generators, for that power range, namely for small wind turbines. Although the compatibility between PMSGs and PV inverters is not always guaranteed, their integration is possible by combining the safe operating areas of both, shown in Fig. 1.

Three parameters that establish the operating limits in which the inverter can operate, V_{DCmax}, I_{DCmax} and P_{DCmax} which are voltage, current and maximum power, respectively. In Fig. 2, the green lines represent the voltage and current characteristics of a generator after rectifying on the DC side, when it operates with constant speed. The brown area marks the safe operating area of the PV inverter [9].

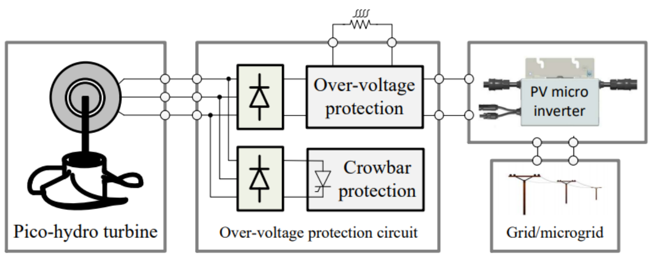


Fig. 1. Design topology for grid-connected pico-hydro systems.

To ensure the generator will work in the safe operating area of the inverter, certain conditions must be guaranteed. First, the no-load DC voltage of the generator, or the one imposed by the protection circuit, must be greater than the voltage $V_{PV_{start}}$ which enables the inverter to start operating. Also, the nominal power of the generator should be in the range of 0.4 P_{DCmax} to 1.0 P_{DCmax} of the inverter and the output DC voltage of the generator must be within the input voltage range of the inverter, thus less than V_{DCmax}. Finally, the rated current of the generator must be equal to or less than I_{DCmax}. Moreover, a current greater than P_{DCmax}/V_{DCmax} is recommended to ensure that the inverter will be able to process the available power without overloading the generator [10].

An over-voltage protection circuit is required to ensure the operation within the limits V_{DCmax} and P_{DCmax} allowed at the PV inverter input. Another important feature in PV inverters is their internal maximum power point tracking MPPT algorithm, which is the selection of a point of operation where the current and voltage pair allows the process of maximum power available from the connected power source. Unlike PV modules, generators have their maximum power point when their current approaches their rated value $I_{G_{DCrated}}$ [10].

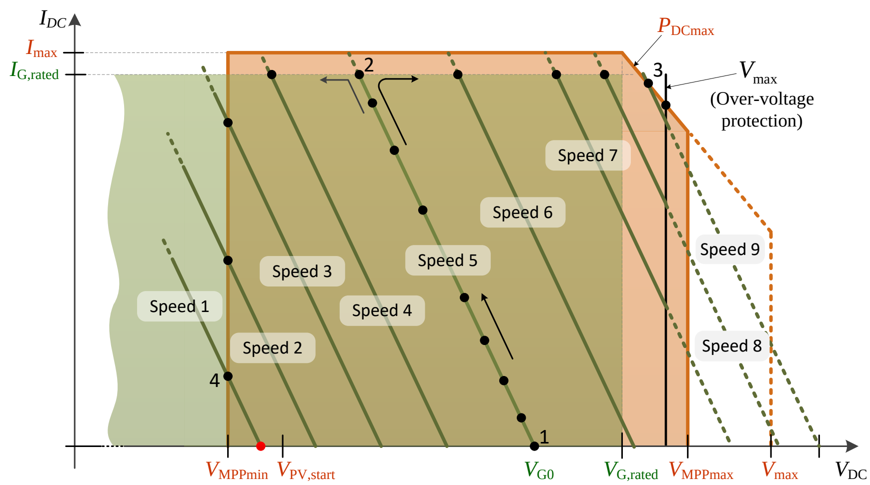


Fig. 2. Overlapping of the operating areas of PV inverter and generator.

Taking into account all of the conditions above and also the MPPT algorithm, the green lines in the graph show the behaviour of the inverter for different speeds of a generator. At "Speed 5", for example, the point at which the generator is operating guarantees that the inverter will turn on, that the MPPT will start at point 1 and it will increase to the maximum current at point 2. If the speed and, consequently, the power increase to "Speed 9", the operating point is defined by point 3 and does not exceed this value, because at that point the protection comes into action and the excess energy is dissipated in the auxiliary resistor. In contrast, if the power and speed decrease to "Speed 1", the inverter operates at point 4, where there is the minimum voltage for which it can operate [10].

2.2 Over-Voltage Protection Circuit

This section presents an over-voltage protection circuit to limit the speed and, consequently, the output DC voltage of the generator. This is done by dissipating the energy in a power resistor or by short-circuiting the generator if the power is too high. The protection circuit is fundamental to ensure that the inverter will not be damaged and whenever the generator runs at no load. This can occur due to:

- Low power demand or high power delivered by the generator;
- Grid failure (e.g. due to frequency or voltage outside the limits) that turns off the inverter;
- The time required by the inverter for synchronization with the grid.

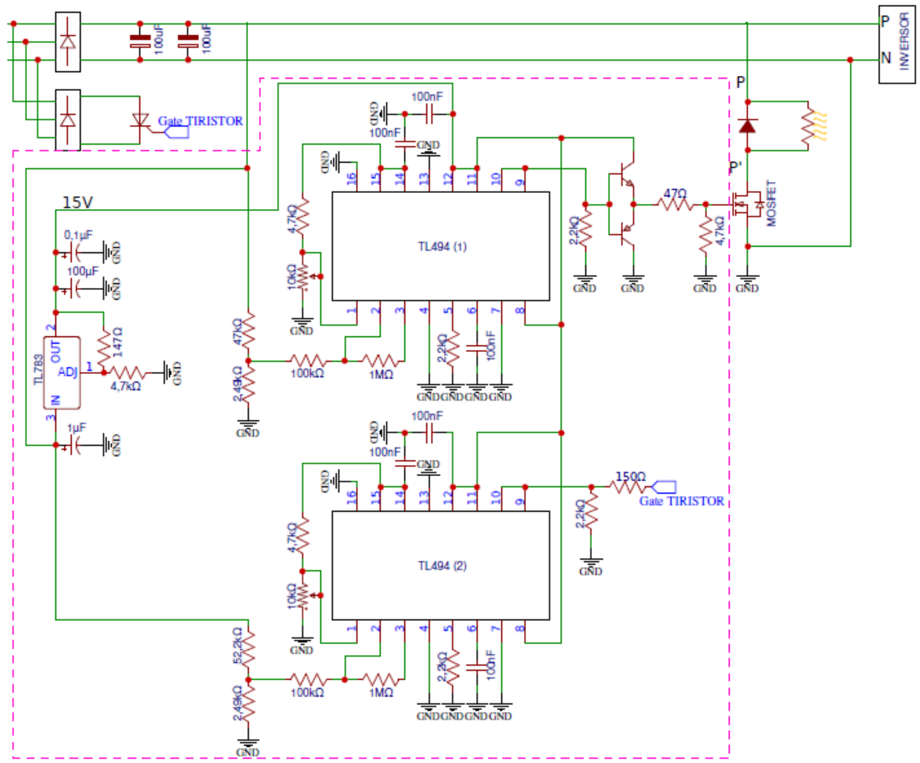


Fig. 3. Over-voltage protection circuit schematic.

The protection circuit schematic is shown in Fig. 3. It is based on a step-down converter with a power MOSFET and a free-wheeling diode to dissipate the energy in a power resistor. The control is performed by Pulse-Width-Modulation (PWM) using the PWM controller TL494(1). A voltage divider (at pin 1), with a 4k7 resistor and a 10k potentiometer, sets the threshold voltage for which the TL494(1) starts the generation of pulses. Another voltage divider (at pin 2) is used to measure the DC output voltage of the generator. The deviation between these two inputs is amplified by one of the two error amplifiers of the TL494. The error controls the generated duty-cycle. The resistor and capacitor connected to pins 5 and 6, respectively, set the switching frequency at approximately 4,54 kHz.

The microinverters used in this work have a V_{DCmax} of 50 V and the V_{MPP} is 40 V as it will be presented later. Therefore, upon reaching a voltage value equal to 45 V on the DC bus, the TL494(1) starts generating pulses with a duty-cycle proportional to the DC voltage. The MOSFET activates the part of the circuit that dissipates the energy in an external resistor R to avoid the no-load operation of the generator and, thus, limiting the DC output voltage. The power resistor must be sized to withstand the P_{DCmax} and at V_{DCmax}, hence:

$$R = \frac{V_{DCmax}^2}{P_{DCmax}}. \quad (1)$$

However, if the PMSG speed or power continues to increase and, therefore, the voltage goes beyond 48 V on the DC bus, a second PWM controller, TL494(2), starts generating pulses, triggering a power thyristor. This action short-circuits the generator and, thus, avoids the destruction of the microinverter by over-voltage. This crowbar protection is a second level of protection and it is expected to operate only in extreme conditions. In normal operating conditions the protection is ensured by the over-voltage protection described above.

3 Experimental Results

This section presents the experimental results achieved with the proposed over-voltage protection circuit. Different operating conditions requiring protection were tested: (a) during the inverter synchronization with the grid, moving from no load to load operation; (b) when the microinverter disconnects from the grid due to a grid failure; (c) when generated power is above P_{DCmax}; and (d) when the PMSG short circuit is required.

For the first two cases, (a) and (b), the test is done using an emulation platform for pico-hydro systems. This structure has a water reservoir, at the height of 3,5 m and 4 pipes with a total water flow of 40 l/s [4]. The pipes have their outlets equally spaced around the blades of a horizontal water wheel prototype. The wind generator 1 (gen. 1), with the characteristics presented in Table 1, is coupled to the water wheel by a 1:5 mechanical transmission.

Table 1. PMSG technical data.

Gen.	**Speed** (rpm)	V_{DCo} (V)	V_{DC} (V)	I_{DC} (A)	P_{DC} (W)
1	300	45	28	10.7	300
2	630	30	24	12.5	300

In the third and fourth cases, (c) and (d), the tests were done on a workbench that has a three-phase induction motor driven by a conventional frequency converter. The PID macro, usually available in the frequency converters, was used to perform a closed-loop control of the shaft (mechanical) power of the generator. For these tests, it was used the wind generator 2 (gen. 2) presented in Table 1. This PMSG was directly connected to the shaft of the induction motor.

The microinverters presented in Table 2 were used in both experimental platforms.

Table 2. Microinverter technical data [2], [12] and [7].

Characteristic	Unit	Microinverter		
		1	**2**	**3**
P_{DCmax}	W	300	300	280
I_{DCmax}	A	11.5	9.5	10
V_{DCmax}	V	50	50	50
V_{DCmin}	V	20	18	22
V_{MPPrange}	V	24-40	20-40	28-40
P_{ACmax}	W	250	235	245

3.1 Results Obtained With an Emulation Platform

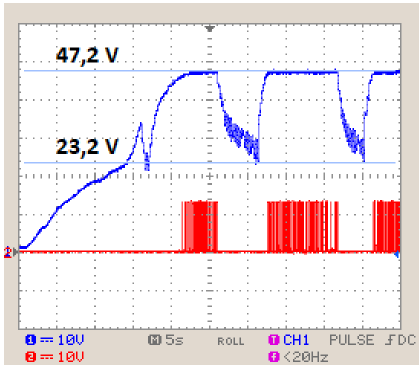
As said above, an emulation platform for pico-hydro systems, consisting of a horizontal water wheel, was used for evaluation tests in real conditions. The synchronization test (a) aims to show the performance of the protection circuit when the generator starts with no load and the microinverter initiates the synchronization procedure before connecting to the grid. At first, the generator is loaded by the protection circuit while waiting for the PV microinverter to be able to process the power generated by the turbine (water wheel). During this synchronization time the protection circuit operates and limits the voltage set point as designed. The energy is dissipated in a power resistor preventing damage of the PV microinverter.

During the start-up of the generator shown in Fig. 4(a), the microinverter sought to connect a few times. However, it was unsuccessful at first and the protection circuit actions were required. The microinverter of Fig. 4(b), connects the generator to the grid after about 15 seconds. The protection circuit operates during the last 5 seconds, limiting the DC voltage to 47,2 V. Both figures show the PWM operating as soon as the DC voltage reaches 45 V. For Fig. 4(c), the microinverter was very agile as it started and achieved the steady-state voltage value of approximately 28,8 V, even before the protection circuit was activated.

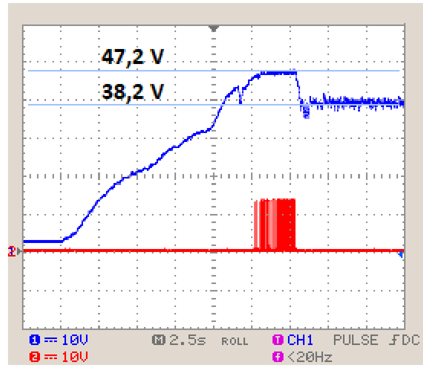
Similar to what occurs during grid synchronization, a grid failure causes the increase on generator voltage, unless the protection circuit limits the voltage. Test (b) is shown in Fig.5, where the voltage, which was being maintained at an approximately constant operating point by the microinverters, passed to the value limited by the protection circuit, immediately after the grid failure simulation.

3.2 Results Obtained With a Work Bench

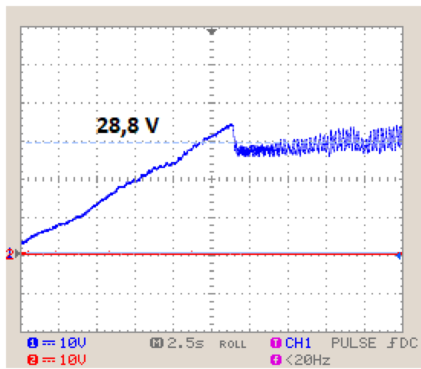
The over-power test (c), is performed with a generated power higher than the maximum input power of the microinverter. Fig.6 plots the power dissipated by the protection circuit in the resistive load and the power at the input of the microinverter. The tests were performed increasing the power. As soon as the



(a)



(b)



(c)

Fig. 4. Over-voltage protection circuit behaviour during generator start-up and grid synchronization tests with (a) Microinverter 1, (b) Microinverter 2 and (c) Microinverter 3.

input power of the microinverter reaches its limit, the protection circuit starts dissipating in the power resistor.

The crowbar test (d) was performed increasing the power until the voltage reached the value designed to short circuit the generator.

Fig.7 illustrates the moment when the short-circuit occurs. First, PWM pulses (in blue) are generated by the over-voltage protection when the DC voltage reaches 45 V. Subsequently, when it catches up 47,2 V, the thyristor is turned on and the voltage falls drastically to a value corresponding to a voltage drop across the thyristor (2,4 V). The final value of short circuit current (for the maximum generated power) was 18 A.

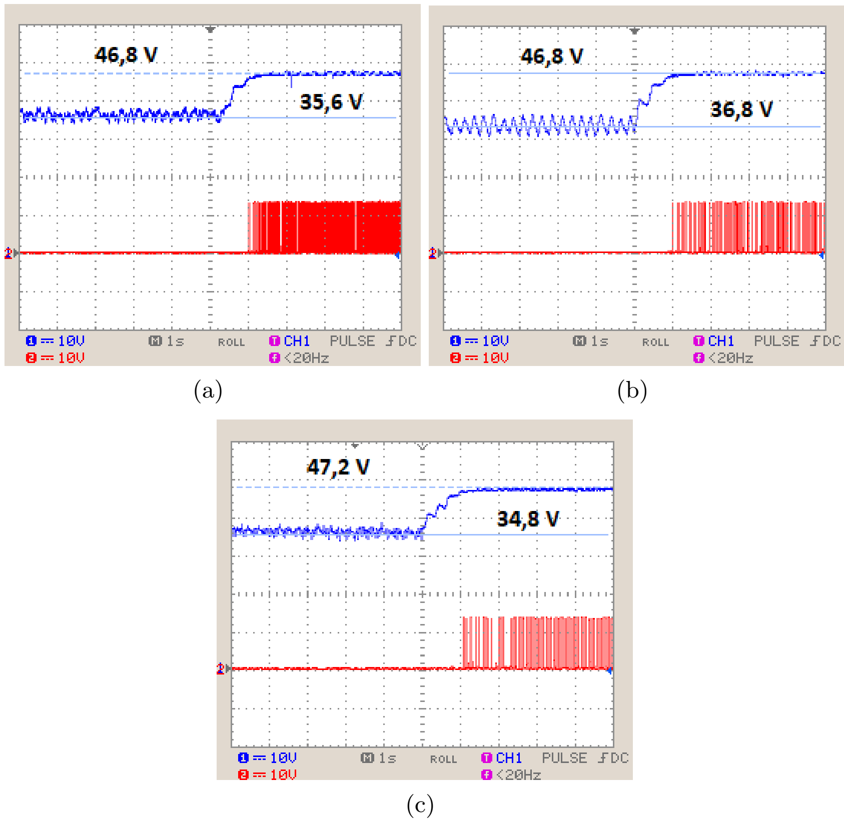
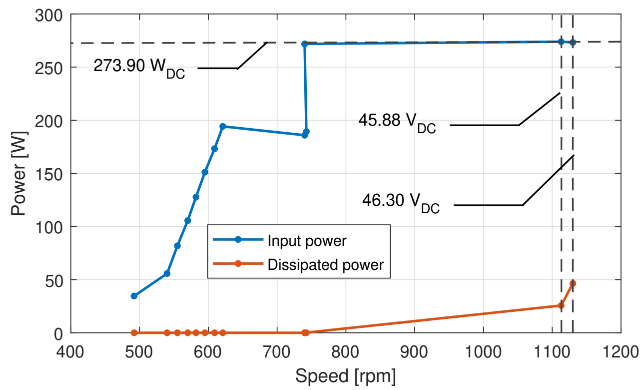


Fig. 5. Over-voltage protection circuit behavior in failure tests with (a) Microinverter 1, (b) Microinverter 2 and (c) Microinverter 3.

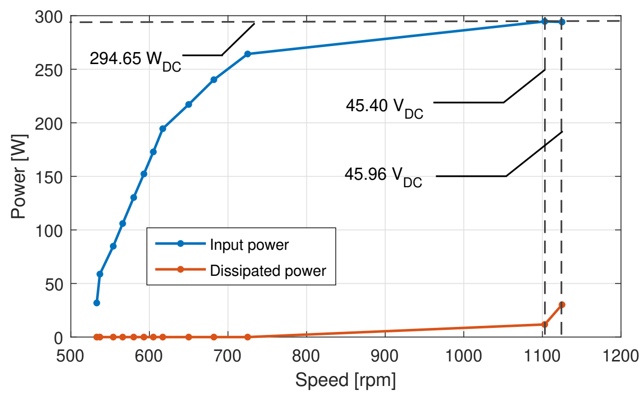
4 Discussion

The evaluation results using a benchwork and real emulation platform proved the effectiveness of the protection circuit. Tests with the emulation platform, consisting of a horizontal water wheel, showed that the start-up of the generator (and water wheel) is slow enough for the Microinverter 3 to connect to the grid, even before the protection circuit action is required. Microinverter 2 connected to the grid after about 15 s, but the action of the protection circuit was required during about 5 s to limit the voltage. Microinverter 1 took several seconds to connect to the grid. In this case, the protection circuit limited the DC voltage conveniently.

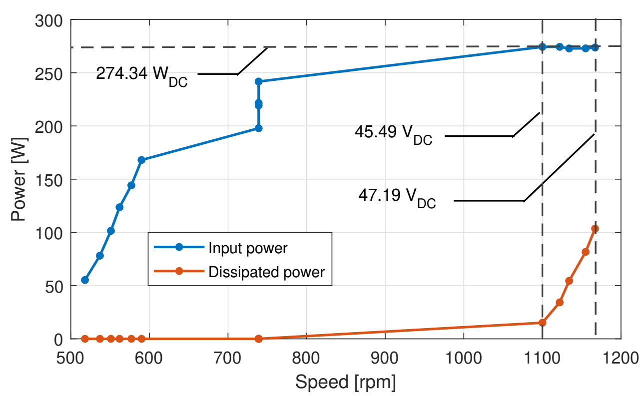
The performance of the protection was demonstrated when the DC voltage reached the value of 45 V and then limited it to 47,2 V, waiting for the Microinverters 1 and 2 connect the generator to the grid. After the starting transient all microinverters operated with a DC voltage defined by the MPP tracking algo-



(a)



(b)



(c)

Fig. 6. Over-voltage protection circuit behaviour with over-power generation tests with (a) Microinverter 1, (b) Microinverter 2 and (c) Microinverter 3.

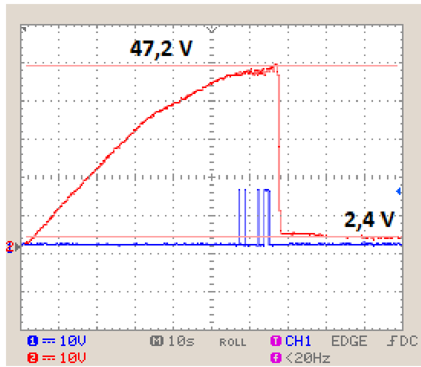


Fig. 7. Over-voltage protection circuit behaviour with a short-circuit test.

rithm (below the protection threshold) and the action of the protection circuit was terminated.

When simulating the grid failure, the protection circuit limited the DC voltage to 46,8 V with the first and second Microinverters and to 47,2 V with the third one. Once again, the developed circuit has proved effectiveness in protecting the devices.

Tests made on a workbench, showed that as the generator power increased, the speed and, therefore, the DC voltage also rose, as seen in Fig. 6. At a certain point, a P_{DCmax} value was reached and the microinverters were no longer able to process the generated power. In this case, the excess was dissipated in the auxiliary power resistor. Notably, the moment when maximum input power is reached, the resistor starts to dissipate. For all cases, the DC voltage protection threshold was approximately 45,50 V.

Moreover, when the generated power (and voltage) is too high, further protection is needed. This is done by short-circuiting the generator. During the test (d) it was demonstrated two protections (dissipation in the resistor and the short-circuit itself) working properly. The generator breaks and the speed is significantly reduced. The voltage in the DC bus is limited to the voltage on the thyristor. This additional protection prevents damage of the devices in extreme situations. In this situation, for the system to resume normal operation, operator intervention may be required. In effect, the thyristor will no longer turn off while there is voltage on the DC bus.

5 Conclusion

Small-scale pico-hydro systems are an interesting energy generation opportunity because they run 24 hours a day. These systems can be easily exploited if standard technology widely available on the market is used, such as generators designed for small wind turbines and photovoltaic microinverters. The integration of this equipment, as distributed energy sources connected to the grid, is possible with the over-voltage protection circuit proposed and developed in this work. Experimental tests were performed for validation purposes, both in real context with a water wheel or on a workbench. The results demonstrated the usefulness and efficacy of the developed circuit. Two permanent magnet synchronous generators were connected to the grid using three different microinverters. The protection has proved to be effective in the expected situations: during the turbine (generator) starting, while the microinverter is connecting to the grid; when the generator is at no load due to grid failures; and in cases of excessive power. Thus, the developed circuit effectively protects the generator against too high speeds and, consequently, it limits the DC voltage at the input of PV microinverters, whenever these are used for grid connection of pico-hydro turbines.

Acknowledgments. The authors would like to thank FCT (Foundation of Science and Technology, Portugal) for the financial support through the contract SAICT-POL/24376/2016 (POCI-01-0145-FEDER-024376), and to the partnership among IPB, CEFET/RJ and UTFPR in the teaching and research program.

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Appendix C

Paper: Grid Connection Approach for Very Small-Scale Pico-Hydro Systems Using PV Microinverters

Grid Connection Approach for Very Small-Scale Pico-Hydro Systems Using PV Microinverters

Gabriela Moreira Ribeiro
Electronic Engineering Department
CEFET/RJ
Rio de Janeiro, Brazil
gribeiro.eletronica@gmail.com

Wellington Maidana
Research Centre in Digitalization and
Intelligent Robotics (CeDRI)
Instituto Politécnico de Bragança
Bragança, Portugal
maidana@ipb.pt

Vicente Leite
Research Centre in Digitalization and
Intelligent Robotics (CeDRI)
Instituto Politécnico de Bragança
Bragança, Portugal
avtl@ipb.pt

Ângela Ferreira
Research Centre in Digitalization and
Intelligent Robotics (CeDRI)
Instituto Politécnico de Bragança
Bragança, Portugal
apf@ipb.pt

***Abstract*—The use of renewable energy sources has grown significantly in recent decades, with emphasis on resources that have a low environmental impact in the energy production process. Small-scale pico-hydro systems have great potential and are also in line with increasing environmental requirements. Microgrids can integrate this type of solution into self-supporting systems and electrification of remote locations. This paper presents and discusses an approach for very small-scale pico-hydro systems, up to 300W, for grid connection, using photovoltaic microinverters recently launched on the market. Experimental validation was performed on a test workbench and a laboratory platform. The results were carried on applying different input power values. The laboratory platform consists of a water wheel prototype with specific water flow and head. Data from two generators, three microinverters, and a passive load were collected during the laboratory experiments. This approach presents encouraging results for the exploration of the emerging energy potential of pico-hydro systems of very small pico-hydro systems, with power available 24 hours per day. This work is a contribution to the dissemination of this approach, which can be easily widespread and contribute to environmentally friendly energy production.**

***Index Terms*—Photovoltaic Inverters, Pico-hydro Systems, Distributed Generation, Microgrid.**

I. Introduction

The need for energy access to locations far from urban centers and increasing energy demand in developed regions make sustainable energy production a continuous effort. Distributed production has been considered a feasible application solution in order to reduce environmental impact and have lower economic expenses [1, 2]. Renewable energy plants have been an ally of small-scale production and a good solution for microgrid creation. Within this field, low power hydroelectric plants have their potential located in rural properties and riverside populations [3]. For instance, in Portugal, Brazil, China, India and Bangladesh exist examples of standardized technologies applied by small consumers [4–7].

A huge number of applications can also be exploited in developed regions such as in household water supply [8], wastewater treatment facilities [9] and to improve control systems and optimize generation as a part of integrated water management systems [10, 11].

Pico-hydroelectric plants have their primary energy source from rivers, streams, small water reservoirs, water channels of low depth and relatively small water flow, and they are usually classified as pico-hydro for powers up to 5 kW [12, 13].

In many cases, microgrids form isolated systems of the conventional grid, called off-grid, to supply small consumers or villages. In these conditions, there is a need for voltage and frequency regulation to suit the electrical supply of the conventional equipment. On the other hand, in circumstances where the microgrid is exploited connected to the utility grid, called on-grid, the direct connection of generators to the grid must have one more concern: the synchronization with the grid.

A way to regulate voltage and frequency for power generation systems based on synchronous generators is to control the rotation speed of the generator shaft by mechanical means, equipment construction or hydraulic control. The frequency of the generator is proportional to the speed of rotation (n_m), and the voltage is also proportional to the magnetic flux (ϕ). According to [14], it is also frequency dependent, as shown by (1) and (2) where P is the number of poles, k is a constant related to generator construction and ω is the angular velocity of the rotor. These operating characteristics are added to control and manage load demand providing balance between generation and consumption. Therefore, for off-grid systems, the speed variation must be greatly reduced for different water heads and flows.

$$f_e = \frac{n_m \cdot P}{120} \quad (1)$$

$$E = k \cdot \phi \cdot \omega \quad (2)$$

Another approach for the generator connection to the grid, which does not require mechanical or hydraulic control is the use of photovoltaic (PV) inverters. In this case, the inverter device compensates voltage and frequency fluctuations of the synchronous generator and establishes the interface with the grid.

In real contexts, seasonal changes cause frequent variations in hydraulic conditions of the local geography. From [15, 16], the best way to work a pico-electric system, with the highest energy capture, is to allow the generator to work at variable speed operation (VSO). Under these conditions, a reliable approach that provides connection of hydroelectric systems to the grid is the use of PV inverters [17], based on their current state of development and cost-effectiveness when compared with dedicated inverters.

Previous works [17, 18] had their focus on a power range of the conversion system 1 to 2 kW. In this context, the current work presents the feasibility of the integration of very low power water systems, using generators up to 300 W with PV microinverters for connection to the conventional grid. It is a generic approach, hence it may integrate a permanent magnet synchronous generator (PMSG) working at variable speed to a grid which requires a constant frequency and regular voltage.

II. Grid Connection of Pico-hydro Systems

The conventional mini and micro hydro systems and large energy production plants from the water source, usually have a generator operating at constant speed. The methods for speed and frequency regulation are found in [16, 17, 19]. On the other hand, in order to enable cheaper and widespread pico-hydro systems solutions to communities and small companies, some grid connection methods using PMSG working at VSO:

- Integration using specific power converters for hydraulic plants;
- Integration using wind converters;
- Integration using PV converters.

The uniqueness related to the topography of each site and its hydraulic dynamics difficult the widespread of pico-hydro systems using specific power converters. Indeed, each site requires a specific generator, with suitable power and speed (or voltage). Therefore, the availability of standardized systems, as it happens with PV systems, has not been possible so far. These factors make the development, replication, and marketing of the first approach costly.

The second alternative is the wind inverter connected to the generator with a three-phase rectifier. These inverters are available on the market but they need to be parameterized, which involves the knowledge of the power curve coefficients.

The third approach presents the possibility of using a PV inverter after the rectifier circuit as illustrated in Fig. 1.

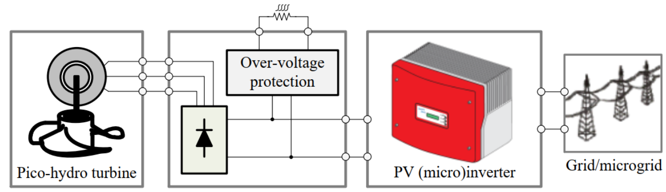

Fig. 1. Practical approach for grid-connected pico-hydro systems, adapted from [18]

According to [17], this strategy complies with the prerequisites of grid connection, and has a wide spectrum of products available on the market in the power range of pico-hydro systems. In addition, PV inverters have a maximum efficiency up to 98% of the rectified power. Considering that hydro-systems may operate 24 hours per day, much higher than in PV applications, this solution has an high energy efficiency potential.

Whatever the approach, an over-voltage protection circuit must be implemented [17]. This device acts in cases the inverter is switched off, during synchronization and grid failure, low energy demand while there is a high power supply or natural phenomena which may raise the power drastically.

A. *Procedure for integration of permanent magnet generators and PV inverters*

PV inverters are widely available on the market, with competitive prices and relative ease installation. It may endorse a turnkey solution and does not require parameterization by installers. However, the PV inverter and the generator must be compatible since the dynamics of the PV modules is different from the PMSG. The conditions for integration these devices were studied and proposed in [17, 18]. Once again, an over-voltage protection circuit is required to prevent damage to the generator and inverter, due to the increase of generator's speed under no load conditions.

The integration is done by overlapping characteristic curves of the generator and PV inverter as shown Fig 2. The maximum power point tracking (MPPT) algorithm imposes different operation points for PMSG. As an example, if a PMSG starts from ”Speed 5”, its current will increase up to the maximum rectified rated current or it will be limited by the internal generator impedance (point 2). In contrast, if it slowly decreases to ”Speed 1”, the new working operation will be point 4. Nonetheless, for initial operation, the rotational speed needs to achieve a minimum value, to which it will correspond a DC voltage to start the PV inverter.

Additionally, the rectified voltage of the generator (V_{DC}) must be within the MPP range of the PV inverter ($V_{MPP_{min}} \leq V_{DC} \leq V_{MPP_{max}}$), while the rectified current (I_{DC}) should not exceed the maximum permissible inverter input current.

When the generator voltage is greater than the corresponding value given by (3), the current required by the PV microinverter is smaller and it is able to process the ongoing power [17].

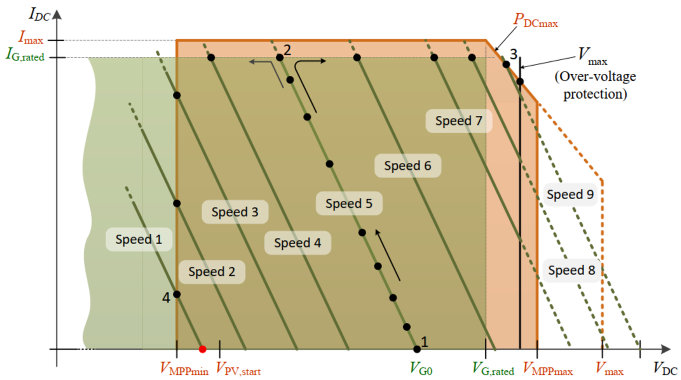

Fig. 2. Overlapping of the operating areas of PV inverter and generator [17]

$$V_{DC} = \frac{P_{DCmax}}{I_{DC_{max}}} \tag{3}$$

Finally, to a successful integration, the generator DC voltage with no load, during initial operation, must be higher than minimum PV inverter voltage ($V_{DC_{start}}$).

It should also be mentioned that the execution period of the MPPT algorithm is about 1 or 2 seconds, which means a high time constant for generator variation. Favorably, the dynamics of the hydraulic system is relatively low.

III. Experimental Results

This section presents experimental results obtained with a laboratory workbench and a water wheel prototype, using PV microinverters and PMSG. The proposed approach was tested with: a) two PMSG, presented in Table I; and b) three commercial PV microinverters, with the characteristics presented in Table II.

For this purpose, the emulation of a water wheel was implemented in the laboratory using a 3 kW squirrel cage rotor induction motor controlled by a frequency converter [17]. Typically, the water turbines present low speed dynamics due to the high damping and inertia factor. It is thus possible to consider the speed control of the electric drive, as previously done in [18]. However, in order to emulate flow variations, different heads and flow rates, the power control of the primary unit was adopted, which results in a variable speed (DC output voltage) and torque (DC output current) operation. The PV microinverter connected to the grid processes the power available from the PMSG, i.e. the DC output voltage and current, and is responsible for the MPPT and the interface with the grid [17].

TABLE I
PMSG TECHNICAL DATA

Gen.	**Speed** (rpm)	V_{DCo} (V)	V_{DC} (V)	I_{DC} (A)	P_{DC} (W)
1	630	30	24	12.5	300
2	300	45	28	10.7	300

TABLE II
MICROINVERTER 1 [20], 2 [21] AND 3 [22] TECHNICAL DATA

Characteristic	**Unit**	**Microinverter**		
		1	**2**	**3**
P_{DCmax}	W	300	300	280
I_{DCmax}	A	11.5	9.5	10
V_{DCmax}	V	50	50	48
V_{DCmin}	V	20	18	22
$V_{MPPrange}$	V	24-40	20-40	28-40
P_{ACmax}	W	250	235	245

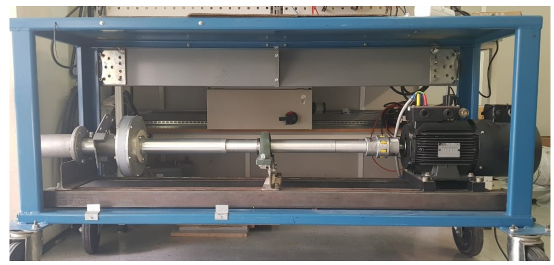

Fig. 3. Motor and generator 1

A. Experimental validation using a laboratory workbench

The experimental validation of the methodology under analysis, using PV microinverters of Table II, is demonstrated with generator 1 of Table I. A squirrel cage induction motor was used for the emulation of the the water turbine. The motor was power controlled using the PID macro available with the frequency converter. By this way, different heads and water flows can be emulated [17]. The generator was directly coupled to the shaft of the motor, as depicted in Fig. 3.

The three-phase generator output voltages are rectified and a protection circuit is used for over-voltage protection. The protection circuit was configured to dissipate power to a power resistor when V_{DC} reaches 46 V.

Figures 4, 5 and 6 show the obtained results. The power is decreased with steps of about 25 W.

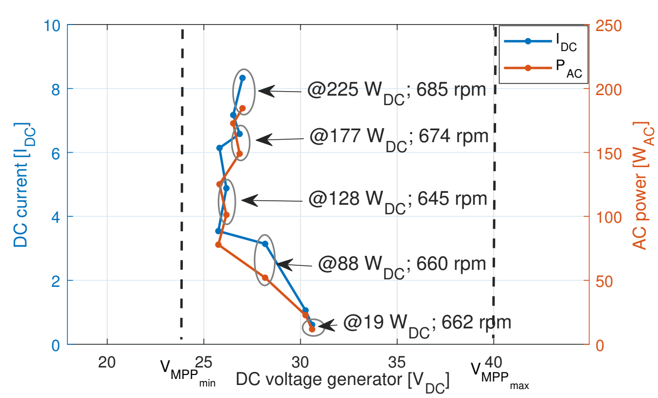

Fig. 4. Grid connection using Gen. 1 and microinverter 1

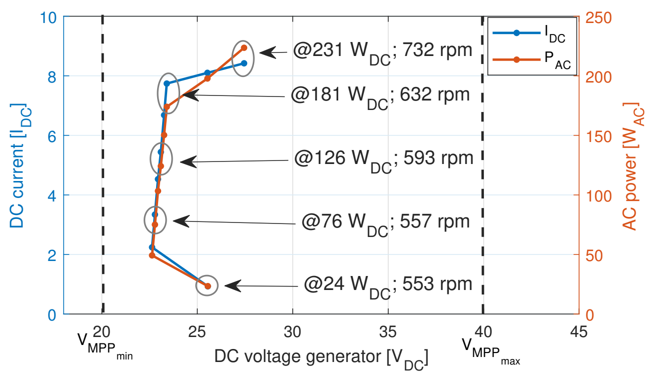

Fig. 5. Grid connection using Gen. 1 and microinverter 2

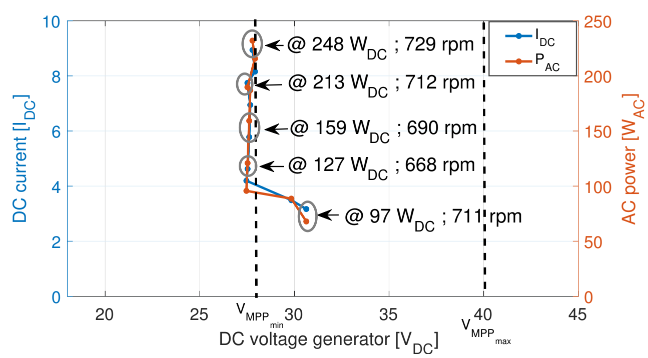

Fig. 6. Grid connection using Gen. 1 and microinverter 3

B. Validation using an experimental platform

An experimental setup was used for validation in real conditions. This platform consists of an horizontal water wheel prototype and was developed in the scope of an ongoing project [23]. This system, shown in Fig. 7, includes:

- a conventional frequency converter;
- a 5.5 kW motor-pump group;
- a secondary water tank, located up to water wheel;
- a water wheel prototype;
- a mechanical transmission (1:5) between the water wheel and PMSG;
- a PMSG (gen. 2 from Table I);
- an over-voltage protection circuit with a power resistor;
- the PV microinverters of Table II.

The water wheel prototype is coupled to the PMSG 2 through a mechanical transmission (timing belts) as shown in Fig. 7.

The horizontal water wheel has 32 paddles and a diameter of 1.2 m, which is determined by the space available in the House of Silk, a small museum where there was form a mill. This is part of the activities of the SilkHouse Project [23] and is intended to recover this historical heritage.

There are 4 water jets, with diameter of 50 mm, spaced 90 degrees. The preliminary results are presented in Table III. The values correspond to the steady state operation as in the

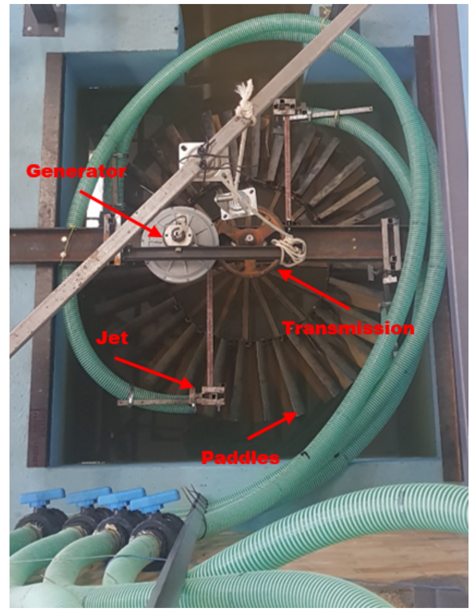

Fig. 7. Experimental platform and water wheel prototype

House of Silk. The water flow is about 40 l/s (4 jets) and the available head is 3.5 m. Additionally, Table III also presents the results obtained with a variable resistive load.

TABLE III
WATER WHEEL GRID CONNECTION RESULTS WITH GEN.2, DIFFERENT MICROINVERTERS AND A PASSIVE LOAD.

	Microinverter			
	1	2	3	Passive Load
V_{DC}(V)	40.2	29.9	39.5	18.7
I_{DC}(A)	1.4	2.8	1.4	5.4
P_{DC}(W)	57.0	82.9	56.8	100.4
V_{AC}(V)	233.7	234	233.7	-
I_{AC}(A)	0.24	0.33	0.23	-
P_{AC}(W)	55	77.1	53.7	-

IV. DISCUSSION

According to the obtained results in steady state operation, presented in Fig. 4, Fig. 5 and Fig. 6 as well as in Table III, the PV microinverters are able to process the power generated by the generators of very small-scale pico-hydro turbines and inject the energy into the grid.

From the experimental results obtained with the water wheel, and varying the power resistor, Table III shows that the maximum output power achieved was 100.4 W. The operating point, with 18.7 V_{DC} and 5.4 A_{DC}, is in accordance with the closest one provided by the manufacturer, respectively 107.6 W, 18 V_{DC} and 6 A_{DC} (at 444 rpm). In this case, the microinverter 2 was able to extract a DC power of 83 W, 17% less than the one obtained with the power resistor (100.4 W). In fact, the optimum operating point of the generator is outside the MPP range of the microinverter (20-40V) and, therefore, the microinverter is not able to extract the maximum power. Better results would be obtained if the available power was close to the rated value, as shown in Fig. 4, Fig. 5 and Fig. 6. These figures, with Gen. 1 and microinverters 1, 2 and 3, respectively, show the first two working inside of the MPP range, and the third approximately at the lower limit of the MPP range, i.e., 28 V. Indeed, this limit is higher than the rated voltage of the Gen. 1 for the power range up to 250 W.

All the obtained results demonstrate that, for perfect integration, the DC operating point of the generator (and, therefore, the turbine) should be inside the MPP range of the microinverter. In other words, for the rated power of the microinverter, the generator DC output voltage should be of the order of magnitude of 30 V. Indeed, it is not the case of Gen. 1 since it was a lower rated voltage, namely 12 V for battery charging (wind turbine DS-300).

Furthermore, it may be necessary to add a DC-Link capacitor between the generator and microinverter to improve compatibility between them, as is the case with Gen. 1 and microinverter 3. In fact, this compatibility also depends on the dynamics of both: the small turbine and the microinverter MPPT algorithm.

V. Conclusion

This paper presents a practical approach for pico-hydro systems, specifically those that integrate low power wind generators up to 300 W of magnitude, and conventional photovoltaic microinverters. Experimental tests were performed in the laboratory, using two emulation platforms. The obtained results allow to validate the integration under analysis, even with the microinverters presenting different performances due to different MPPT algorithms and not perfect match between the generator operating point and the MPP range of the microinverter, for the available power. The integration of pico-hydro systems in the grid, using conventional PV microinverters, offers an economically efficient solution, since they can operate 24 hours a day in opposition to PV systems, which depend on solar irradiation. PV inverters are a mature and ready-to-use technology, which can be used in small pico-hydro applications. Pico-hydro systems, including very low power (300 W) applications, have an emerging potential to be exploited, both in developed and undeveloped countries due to increased energy demand and isolated communities without access to the main grid, respectively.

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