

COB-2023-0757

THE STATE-OF-THE-ART OF HYDROSTATIC TRANSMISSIONS IN MICRO-HYDROPOWER PLANTS

Marina Baldissera de Souza
Sabrina Knoll Godoy Ilha
Leticia Renata de Carvalho
Ruben Dario Solarte Bolaños
Daniel Martins
Antonio Carlos Valdiero

Universidade Federal de Santa Catarina, Departamento de Engenharia Mecânica, Centro Tecnológico, Campus Universitário – Trindade, 88040-900, Florianópolis - SC, Brazil
marina.bs@posgrad.ufsc.br - sabrina.knoll.ilha@grad.ufsc.br - leticia.renata@grad.ufsc.br - ruben.solarte@posgrad.ufsc.br - daniel.martins@ufsc.br - antonio.valdiero@ufsc.br

Luís Antônio Bortolaia

Universidade Federal de Ouro Preto, Departamento de Engenharia Mecânica, Campus UFOP - Morro do Cruzeiro – Bauxita, 35400-000, Ouro Preto - MG, Brazil
luis.bortolaia@ufop.edu.br

Abstract. *Due to Brazil's large territory, rural areas often face power supply interruptions, leading to financial losses for agricultural activities. Micro-hydropower plants (MHPs) offer an eco-friendly solution to generate electricity during these interruptions. MHPs require a variable-speed technology connecting the turbine to the generator when there are significant flow rate variations. One perfect candidate for variable-speed technology is a hydrostatic transmission. This paper aims to present a survey on the state-of-the-art of the leading technologies used in micro-hydropower plants, focusing on evaluating the prevalence of hydrostatic transmission as a speed regulator device. To achieve this objective, academic works, patents, and commercial products were surveyed and analysed. Until now, no commercial MHP containing a hydrostatic transmission nor a patent of a hydrostatic transmission developed specifically for a MHP has been found. Among the academic works scrutinized, there is only one paper on the hydrostatic transmission design for an MHP. Using a hydrostatic transmission as a variable-speed technology has innovative potential and is a promising solution for designing a modular MHP, reducing costs and reaching a larger public.*

Keywords: *micro-hydropower plants, hydrostatic transmission, renewable energy, rural electrification.*

1 INTRODUCTION

Due to the extension of the Brazilian territory, rural areas are usually subject to problems with interruptions in the electric power supply. The lack of electricity for long periods of time leads to financial losses for rural producers since some agricultural economic activities rely heavily on electricity, such as dairy farms, whose products need to be refrigerated constantly, or poultry and pig farms, which use fans and lamps almost 24 hours a day for the rapid growth of the animals (Santos Junior and Sanches, 2020).

A popular solution for emergency electricity generation is stand-alone diesel generators. This option has the benefit of generating power on demand and has a very low investment cost. However, their permanent dependence on diesel fuel for operation, as well as the emission of pollutants, makes this option very expensive and environmentally unfriendly (Kusakana, 2014).

Micro hydroelectric power plants (MHPs), belonging to a category of small hydroelectric power plant (SHP), are an environmentally friendly solution for generating electricity during power supply interruptions. According to the Agência Nacional de Energia Elétrica (ANEEL)'s classification, SHPs are enterprises intended for self-production or independent power production, whose power output is greater than 3 MW and less than 30 MW (ANEEL, 2023). Eletrobras (2019) classifies SHPs based on installed capacity and design head: MHPs are a class of SHP that produce up to 100 kW of power and have a hydraulic head of up to 50 meters. MHPs have the advantage that they can be installed in remote areas where centralized power supply is not available and there is no other possibility of electricity supply (Azimov and Avezova, 2022).

The main components of an MHP are a device that transforms the energy of flowing water into rotational energy (e.g., a turbine or a waterwheel) and a generator that converts the rotational energy into electricity. A variable-speed

technology connecting the rotational energy device to the generator is required for significant flow rate variations. The prevalent variable-speed technologies in MHPs are "V" or wedge belts with pulleys, timing belts with sprocket pulleys, and gearboxes. These methods come with certain drawbacks. Despite their relatively low initial construction expenses, belt and pulley systems are not as effective as gearboxes. Nevertheless, gearboxes entail greater costs linked to maintenance and alignment (Kunwor, 2012). Besides, these technologies provide a fixed speed ratio that does not compensate for speed fluctuations.

A hydrostatic transmission is a perfect candidate for variable-speed technology as it provides a stepless gear ratio that is adjustable to flow rate fluctuations, without demanding an extensive infrastructure, and can be built using off-the-shelf components. According to Costa and Sepehri (2015), hydrostatic transmissions are devices between two rotating shafts whereby a hydraulic motor is the output and is directly controlled by the prime mover, a hydraulic pump, the motor itself, or by any combination of the three elements. The use of hydrostatic transmission enables the conversion of the mechanical energy generated by the turbine, resultant of torque and angular velocity, into oil-hydraulic energy represented by the product of flow and pressure, by means of a compact hydraulic pump that is easily installed in the turbine itself. Through pipes and hoses, this fluid energy can be transmitted to a suitable location for the electric generator. Then, by means of an appropriate hydraulic motor, this energy is converted into mechanical energy to drive the electric generator with a speed controlled by control elements present in the oil-hydraulic system. Associating a hydrostatic transmission with an automation system ensures that the micro-hydropower plant operates at maximum efficiency and produces a consistent amount of power.

In light of that, this paper aims to present a survey on the state-of-the-art of the leading technologies used in MHPs, focusing on evaluating the prevalence of hydrostatic transmission as a speed increaser device. To achieve this objective, academic works, patents, and commercial products were surveyed and analyzed. The remaining of this paper is structured as follows. Sec. 2 describes the materials and methods applied in the survey. Sec. 3 shows the results of the survey and the analysis of the technologies. Finally, Sec. 4 makes a summary of the findings and draws some conclusions.

2 MATERIALS AND METHODS

This paper focuses on conducting a comprehensive survey to explore the current studies and solutions related to renewable energies, MHPs, and speed increasers at both national and international levels. However, Brazilian solutions are given priority. The survey of the state-of-the-art of MHPs' technologies comprises academic works, patents, and commercial products.

The research of academic works was done in renowned scientific and academic sources, especially doctoral theses in the area of power generation, master's dissertations, course completion papers, and lastly, articles published in congresses and journals. The research of academic works was conducted in journals and annals, aside from some bases of academic papers, such as Google Academic and Science Direct. Brazilian journals in agricultural engineering, such as SBEA - Revista Engenharia Agrícola (SBEA, 2023) and Revista Brasileira de Energias Renováveis (UFPR, 2023), were scrutinized. Additionally, the annals of the Congresso Brasileiro de Engenharia Agrícola (CONBEA, 2023), were thoroughly examined. In brief, the analysis incorporated 34 academic sources, comprising 24 scientific papers, 9 undergraduate course conclusion works, and one thesis. In this paper, the academic works were explored in two languages. Academic works written in Portuguese were searched with the search terms listed in Tab. 1 and works in English were searched using the keywords stated in Tab. 2.

Table 1. Portuguese terms applied in the search engine of Google Academic database.

Search terms
Pequenas centrais hidrelétricas
Microgeração hidrelétrica
Central mini-hídrica
Hidrogerador
Turbina de ultra-baixa queda
Micro central hidrelétrica
Mini central hidrelétrica
Turbina Kaplan
Gerador elétrico de baixa potência
Transmissão hidrostática

The patent search performed in this paper aims to find concepts of MHPs that possess a hydrostatic transmission as a speed increaser connecting the turbine to the generator. In the absence of MHPs containing such power transmission technology, patents of other plants that generate electricity from the motion of a fluid, such as wind and tidal turbines, are included in the search.

Table 2. English terms applied in the search engine of Google Academic and Science Direct database.

Search terms
Micro-hydropower plant
Low head turbines
Ultra-low-head hydroelectric technology
Kaplan turbine
Low power electric generator
Hydrostatic transmission

The patent search method adopted in this work is an adaptation of the method developed in the Laboratory of Applied Robotics (LAR), from the Federal University of Santa Catarina (UFSC). In the LAR's method, the patent search is divided into four steps: preliminary search, preliminary search analysis, detailed search, and detailed search analysis (Hoeltgebaum, 2016).

The goal of the first step is to identify general terms related to the patent's title and/or abstract. Search parameters, including keywords, filters, and the database, must be recorded. The search parameters are evaluated by considering the number of results and their relevance. Then, the preliminary search results are analyzed to determine which combination of search parameters gives the best results. Information such as the priority date (date when the invention was first submitted) and the International Patent Classification (IPC) (WIPO, 2022) are extracted from the patents in the second phase. The analysis of the preliminary search defines the optimized search parameters of the detailed search, resulting in more relevant patents. Finally, the patents found in the detailed search are scrutinized, aiming to detect the potential of innovation for a given device.

In this paper, the patent search is carried out in two databases. Brazilian patents are searched in the database of the Instituto Nacional da Propriedade Industrial (INPI) (INPI, 2023) using the Portuguese search terms listed in Tab. 3. The number of patents found for each search term is shown in the second column of Tab. 3:

Table 3. Portuguese terms applied in the search engine of INPI's database.

Search terms	Results
Central mini-hídrica	0
Microgeração hidrelétrica	0
Mini central hidrelétrica	0
Turbina Kaplan	3
Transmissão hidrostática	51
Micro central hidrelétrica	1
Hidrelétrica	80
Geração energia elétrica	343

The second database used in this study is the PATENTSCOPE, from the World Intellectual Property Organization (WIPO) (WIPO, 2023), to seek out non-Brazilian inventions. The search terms used in PATENTSCOPE are listed in Tab. 4, alongside the number of results given by the search engine.

Table 4. Search terms applied in the search engine of PATENTSCOPE.

Search terms	Results
Micro-hydropower plant	11
Generation low head turbines electric energy	42
Hydrokinetic energy	282
Generation kaplan turbine electric energy	1050
Generation hydrostatic transmission electric energy	2
Hydrostatic transmission hydroelectric	3
Power generation hydrostatic transmission	30
Small hydropower plant	150
Mini hydropower plant	8

The numbers of Tabs. 3 and 4 demonstrate that not many patents were found in the preliminary search. Therefore, the first and the third steps of LAR's method are merged in this work. Nonetheless, a criterion is adopted to filter the results and select the patents that will be analyzed in detail. The patents gathered in the preliminary search are classified

into “patents of micro-hydropower plants” and “patents of hydrostatic transmissions”. Then, they are graded from 1 to 4 according to the criteria shown in Tab. 5. The patents that received a grade below 3 are excluded, leaving 33 patents to be deeply scrutinized.

Table 5. Grade criteria for selecting the patents to be analyzed in detail.

Grade	Patents of micro-hydropower plants	Patents of hydrostatic transmissions
4	Complete micro-hydropower plant	Hydrostatic transmission for hydropower plants
3	Components for micro-hydropower plant	Hydrostatic transmission for wind turbines and wave power
2	Components for large hydropower plants	Hydrostatic transmission for power generation applications
1	Not related to the objective of the search	

Finally, the search of commercial products aims to recognize the current state of Brazilian merchandise related to MHPs. Products such as full working hydropower plants, hydro generators, and joint turbines/generator sets, among others, are included in the search. The search of commercial products conducted in this paper was done by online searching using the keywords: “Gerador” “Usina Hidrelétrica”, “Turbina Kaplan” e “Transmissão Hidrostática”. As the search focus was exclusively within Brazil, the keywords used were only in Portuguese.

3 STATE-OF-THE-ART OF MHPS TECHNOLOGIES

By employing a state-of-the-art methodology described in Sec. 2, we successfully mapped various studies and ongoing developments, allowing us to uncover the potential for innovation and gain profound insights into the use of hydrostatic transmissions in MHPs. The results of the survey are presented hereafter, categorized as “academic works”, “patents” and “commercial products”.

3.1 Academic works

About 68% of the searches were conducted on national works, aiming to focus on Brazilian research. The rotary mechanical devices of each 34 academic works were classified according to the type of flow machine. The chart of Fig. 1 presents the classification of turbine types according to the flow machine. Excelled in the first place, with 18,8% of the results, Water wheel and Centrifugal pumps, followed by Pelton, Francis, and pumps as turbines (PATs), with 12,5%.

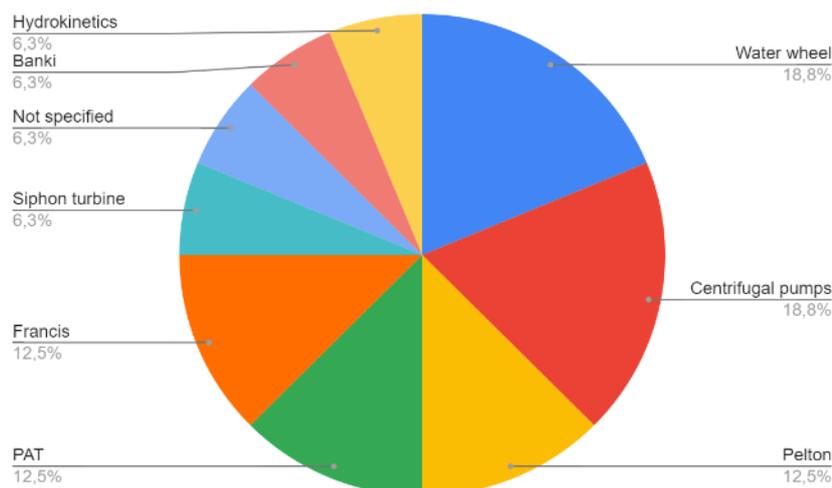


Figure 1. Distribution of the 34 academic works according to the type of flow machine.

Among the hydroelectric plants, 80% are over 100kW, around 13% are within 100 to 5 MW power range and about 6,66% are between 1 MW to 10 MW. Within the works analyzed, three-quarter of the academic works focused on rural properties. Furthermore, 25% of the studies did not have any power electronics components, while 75% had some converter, or controller, intended for regulating and controlling the flow of electrical energy. It was possible to identify three types of speed increasers between the turbine and the generator. Out of the 34 academic works, 2 of them contained a butterfly valve, one had a gear transmission and only one used a hydrostatic transmission.

Zielinski *et al.* (2022) suggest a new type of low-speed radial piston pump intended to be part of the hydrostatic transmission of a small hydropower plant. The proposed system is shown according to the numerical designations of Fig. 2. The invention is composed of a model of the low-speed radial piston pump (1) operated by a water wheel (2)

situated in a river (3). The pump delivers hydraulic fluid, through a hydraulic system (4), to a hydraulic motor (5), which drives an asynchronous generator (6). The invention has the possibility of changing the speed ratio during operation, through a mathematical model of the proposed pump.

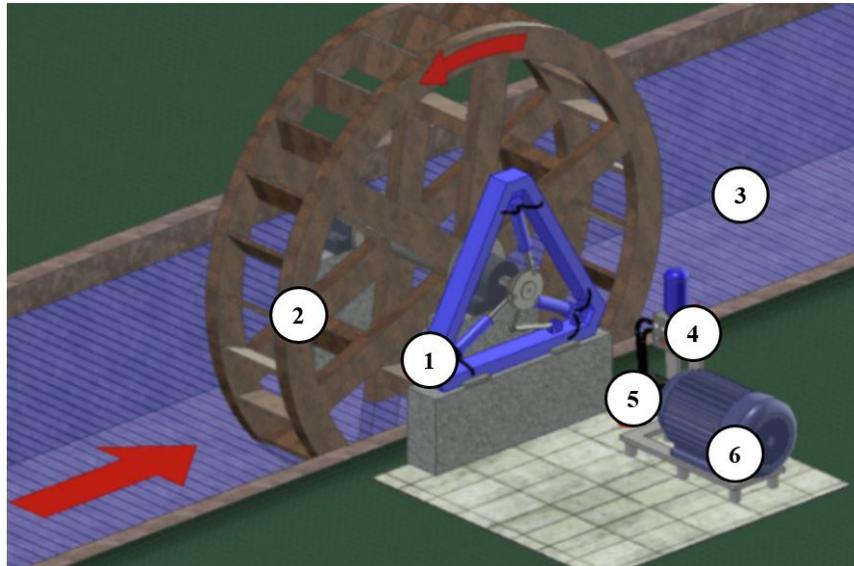


Figure 2. Example of micro-hydropower plant with the proposed hydrostatic transmission. Adapted from (Zielinski *et al.*, 2022).

Among the hydroelectric plants analyzed, a significant distribution of capacities was observed. The majority, corresponding to 80% of the total, has a capacity above 100 kW. About 13% of the plants are within the 100 kW to 5 MW range, while approximately 6.66% have a capacity between 1 MW and 10 MW.

When analyzing the related academic studies, it was found that three-quarters of them focus on the analysis of rural properties. With regard to power electronics components, 75% of the studies included converters and controllers for regulating and controlling the flow of electricity, while 25% did not feature any of these elements.

Furthermore, during the analysis of the papers, three types of speed governors were identified, responsible for the transmission between the turbine and the generator. Among the 34 academic studies examined, only two of them mentioned the presence of a butterfly valve, one reported the use of a gear ratio, and only one study mentioned the use of a hydrostatic transmission.

3.2 Patents

Among the 33 documents that received a grade of 3 or 4, Brazil holds the top spot for the most patents filed with a total of 12 inventions, followed by the United States with 8 patents, and China with 6 patents. The remaining patents come from European countries, Australia, and India. The oldest patent is an American invention from 1977, while the most recent patents were filed in 2022. The patent filed in 1977, numbered US 4 158 780, presents a power generation system for generating electrical power from wave motions of the sea (Wood, 1977). The system is described according to the numerical designations of Fig. 3, where the designation of the elements cited in the description is highlighted in red. The invention is composed of a pear-shaped floating structure, called “duck” (36), shown in Fig. 3(a). The waves rock (34) the duck, which drives a hydraulic pump (78) composing a hydrostatic transmission, whose hydraulic circuit is shown in Fig. 3(b). The pump (78) is coupled to a variable displacement hydraulic motor (79) that drives an electrical generator (80).

The 33 patents are classified according to the invention patented: “power plant”, when a patent protects a complete power plant concept (whether hydro, wind, or tidal); “hydrostatic transmission”, and “devices for converting water energy into rotational energy”. Intellectual properties which do not correspond to any of these categories are classified as “others”. More than half of the patents describe a complete power plant, while nearly a quarter of the documents discloses a device for converting the motion of the flowing water into rotational motion, such as turbines or water wheels. The class “hydrostatic transmission” contains only one patent.

The single patent belonging to the “hydrostatic transmission” category has the number CN 101 350 589 and describes a hydraulic transmission system for an ocean current power plant (Zhejiang University, 2008). The hydraulic transmission system is described following the numbers designating its elements in Fig. 4, which shows the schematic diagram of the transmission. The numbers cited in the description are in red in Fig. 4. The impeller’s (1) main shaft is linked to a variable displacement pump (4) that transmits high-pressure oil to both an energy storage device (9) and a variable motor (10). The

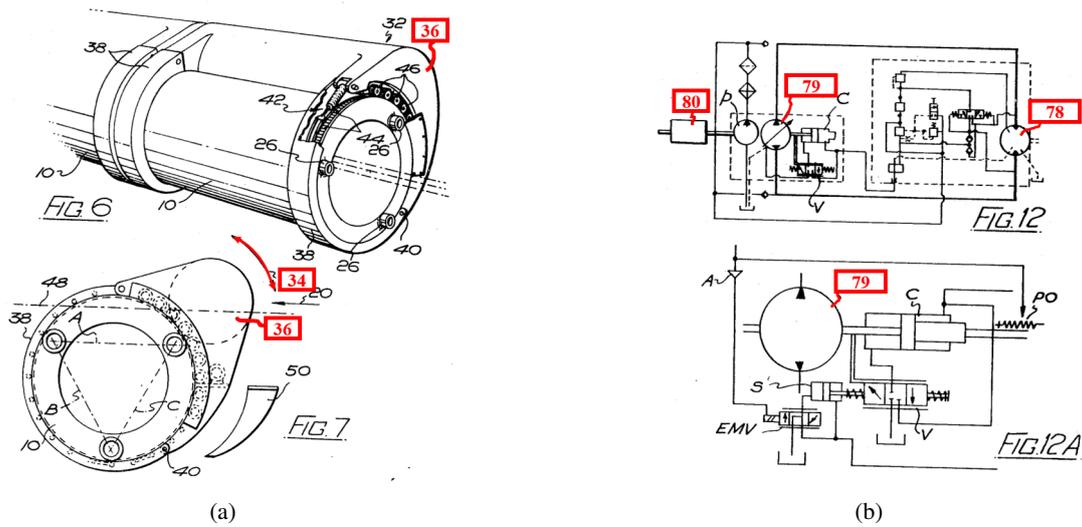


Figure 3. (a) One duck mounted a spine and its side view and (b) hydraulic circuit of the hydrostatic transmission of the patent US 4 158 780, Adapted from (Wood, 1977)

variable motor drives a permanent magnet synchronous generator (13), which is then connected to the power grid (14).

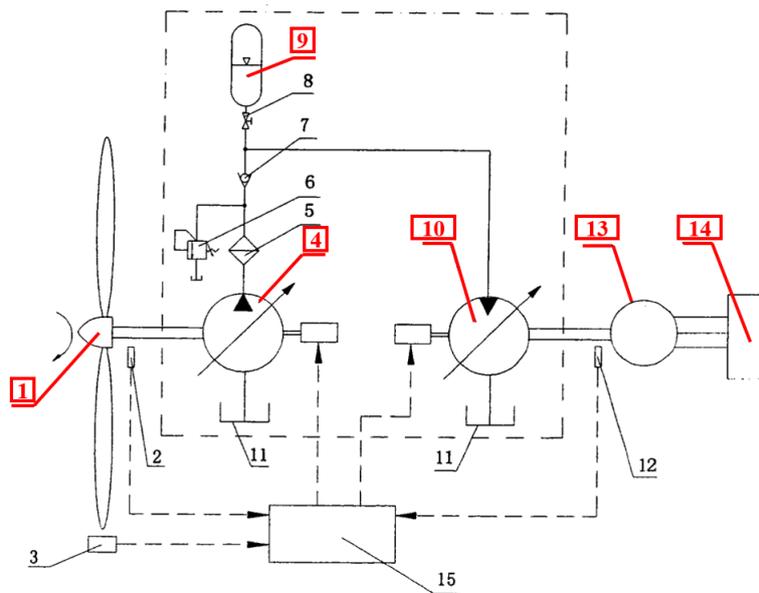


Figure 4. Schematic diagram of the hydrostatic transmission protected by the patent CN 101 350 589. Adapted from (Zhejiang University, 2008).

Out of the 20 patents categorized as "power plants," half of them do not provide details about whether there is a speed increaser device connecting the turbine to the generator. The turbines of two power plants are directly connected to the generator, while the turbines of the other eight power plants are coupled to the generator via a speed increaser. The technologies that multiply the turbine speed in these eight power plants are classified into four categories: "gears"; "gears, clutches or brakes"; "gears and hydrostatic transmission"; and "hydrostatic transmission". 5 out of 8 speed increasers described in the patents protecting power plants belong to the categories "gears" and "gears, clutches or brakes".

The "hydrostatic transmission" class comprises the speed increaser devices of two power plants, protected by the patents US 4 158 780 (Wood, 1977) and AU 2011 310 935 (Mitsubishi Heavy Industries, 2011). The power plant disclosed by patent US 4 158 780 and its hydrostatic transmission are described previously in this section and are represented in Fig. 3.

The patent AU 2011 310 935 protects a plant concept that can be applied to extract energy from the motion of the wind, tides, waves, and rivers. Fig. 5 contains an embodiment of the invention for wind power generation, showing the diagram of the hydrostatic transmission, which is described following the numbers designating its components in the figure, highlighted in red. The main shaft (2C) of the rotor drives the hydraulic pump (20) via a ring cam (42) and

a plurality of pistons (44i) and working chambers (45i). The working chambers (45i) are each connected to the high-pressure oil line (24) and the low-pressure oil line (26) through a high-pressure valve (70) and a low-pressure valve (72), respectively. The ring cam (42) controls the opening and closing of these valves. As the ring cam (42) moves, the low-pressure valve (72) opens and allows operating oil to enter the working chamber (45i) from the low-pressure oil line (26). The piston (44i) then raises the pressure of the operating oil in the working chamber (45i). Finally, the high-pressure valve (70) opens and allows the operating oil to discharge from the working chamber (45i) into the high-pressure oil line (24). The hydraulic motor (22) is driven by the high-pressure oil flowing through the high-pressure oil line (24). As a result, the generator (6), which is connected to the hydraulic motor (22), produces electrical power (Mitsubishi Heavy Industries, 2011).

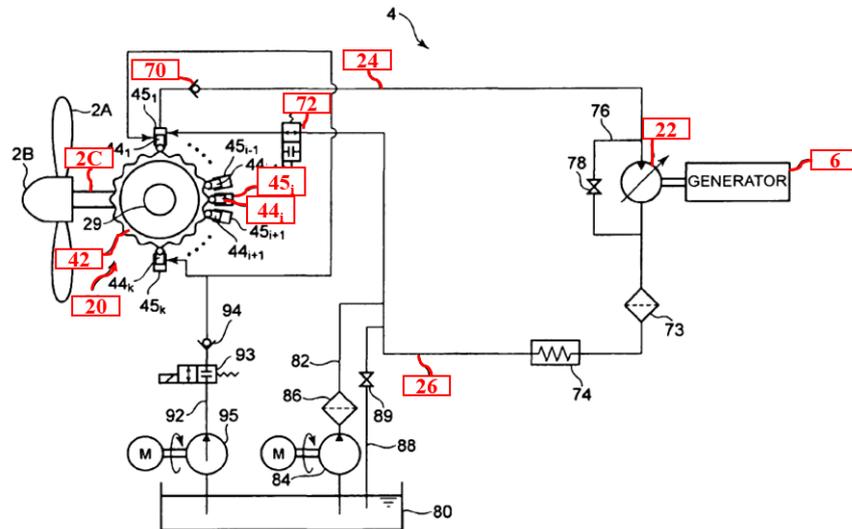


Figure 5. Embodiment of the invention disclosed by the patent AU 2011 310 935. Adapted from (Mitsubishi Heavy Industries, 2011).

A single speed increaser device belongs to the category “gears and hydrostatic transmission” and is protected by patent RO 126581 A2 (Petrea, 2008). Two figures of the patent are shown in Fig. 6, whose main designating numbers, written in red, are used to assist the description of the speed increaser device. Fig. 6(a) illustrates the working principle of the power plant, while Fig. 6(b) shows the whole power plant.

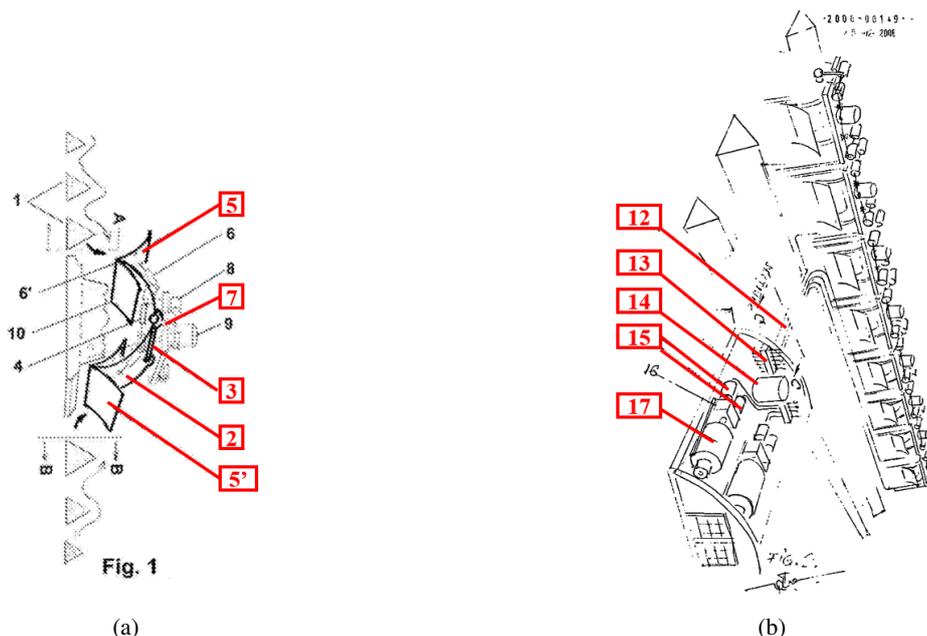


Figure 6. (a) Swinging metal frames device and (b) whole marine hydropower plant on the seafront described in patent RO 126581 A2. Adapted from (Petrea, 2008)

Patent RO126581A2 discloses a marine hydroelectric power station that generates electricity from the swinging motion of some metal frames (2), with one end hinged on a central shaft (3) and with the other end connected to two large blades (5). The blades extract the energy of the moving fluid mass as well as of the vertical pressure of sea waves. A lever (7) controls the high-pressure pumps of the hydrostatic transmission. The pumps are connected to some high-pressure pipes (12) that carry the fluid to the collector (13), which feeds a central reservoir of fluid under pressure (14). The high-pressure fluid drives the hydrostatic motors (15), which are coupled to the generator (17) through a gearbox.

In the patent survey carried out in this work, no concept of an MHP that employs a hydrostatic transmission to multiply the turbine speed was found. Four architectures of hydrostatic transmissions were described in this section and they regulate the speed either of wind or tidal turbines. From the sample of patents analyzed in this section, it can be inferred that the use of a hydrostatic transmission as a speed increaser device in micro-hydropower plants is an innovative approach that has not been extensively explored in the realm of renewable energy technology.

3.3 Commercial products

Thoroughly examining various energy generators manufacturers and catalogs related to hydropower energy generation, 21 relevant commercial products were compiled. The 21 products are fabricated in either the Southeast or South regions of Brazil, with 12 being in the south and 9 in the southeast, as illustrated in Fig. 7(a). Within the 21 products, three categories were defined. 9 products were categorized as generators, 3 as full hydropower plants, and the following 9 were joint turbines/generator sets. The category distribution is represented in Fig. 7(b).

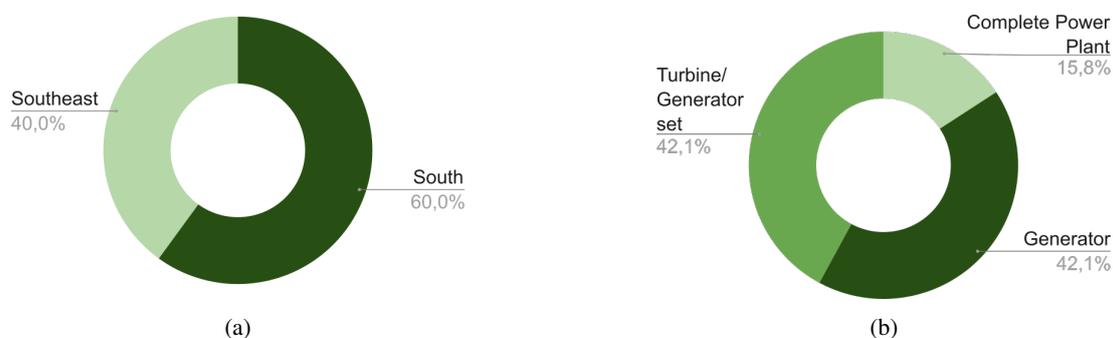


Figure 7. (a) Percentage of manufacturers per Brazilian regions and (b) Percentage of each category products manufactured in Brazil

Among the generators, about 20% are over 15000kVA, around 20% are within 5000 to 15000kVA power range and 60% are under 5000kVA, as indicated by the chart of Fig. 8.

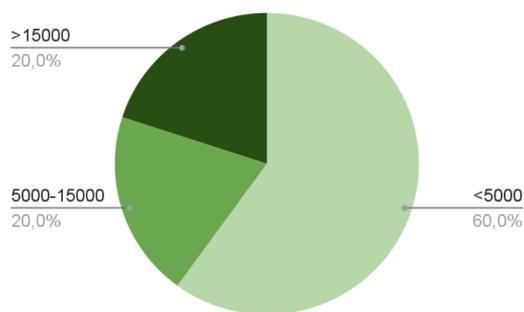


Figure 8. Power Range for Generators in kVA

Within the complete power plants, around 33% are under 1 kW power range while the remaining are above 5kW, as illustrated in the chart of Fig. 9(a). As for the turbine/generator sets, half are under 0.5kW and the other half are within 0.5 to 2 kW power range, as represented in Fig. 9(b).

It is also possible to observe some varied characteristics present in some products that are relevant to the hydropower plant in development. Out of the 21 products, 4 have been designed with a focus on rural properties; 9 can be considered MHPs (under 100kW); and 9 of them do not require a water reservoir. These numbers are illustrated by the chart of Fig. 10.

Throughout the searching process, none of the commercial products found contained hydrostatic transmissions. Out of the 21 products, 5 explicitly contained some kind of power transmission and all were described as either a gear set or a strap and pulley system.

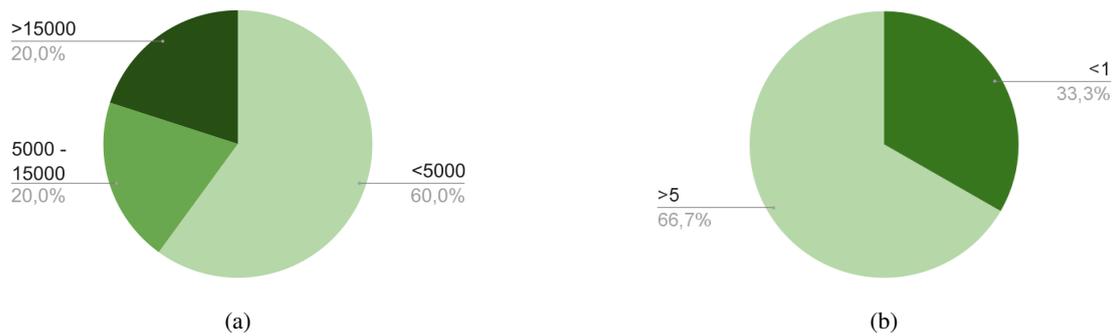


Figure 9. (a) Power range for complete power plants in kW and (b) turbine/generator set power range in kW

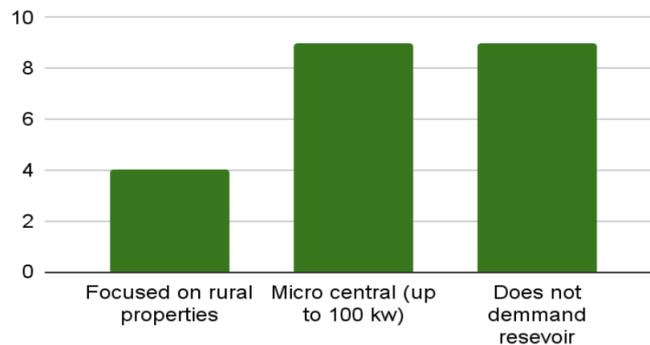


Figure 10. Similar characteristics met in different products

4 DISCUSSION AND CONCLUSIONS

The integration of hydrostatic transmissions presents a promising approach to enhance the performance of micro-hydropower plants. By utilizing the continuous gear ratio and flow rate adjustment, the integration of hydrostatic transmissions with automation systems can effectively harness these features, this technology enables better efficiency and power generation. Furthermore, the utilization of off-the-shelf components and the reduction in power electronics expenses further contribute to its practicality and economic viability.

In conclusion, the analysis of hydroelectric plants revealed a varied distribution of capacities, with the majority having capacities above 100 kW. Academic studies predominantly focused on analyzing rural properties, with a significant portion incorporating power electronics components for flow regulation. The investigation of speed governors highlighted the limited mention of butterfly valves, gear ratios, and hydrostatic transmissions in the examined literature.

Additionally, the patent survey indicated a lack of hydrostatic transmission implementations for multiplying turbine speed in micro-hydropower plants. The use of hydrostatic transmissions in renewable energy technology remains largely unexplored. Notably, commercial products surveyed did not feature hydrostatic transmissions, with power transmissions predominantly described as gear sets or strap and pulley systems.

Overall, these findings underscore the potential for innovative applications of hydrostatic transmissions in micro-hydropower plants, providing an avenue for further research and development in the renewable energy sector.

5 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Department of Mechanical Engineering at UFSC (Federal University of Santa Catarina) for the support of this project (SIGPEX Number: 202222878) and to CNPq (National Council for Scientific and Technological Development) for supporting the research project (CNPq process number: 406936/2022-6) through financial aid and scholarships for scientific initiation, masters and doctorate, which contributed to the design of this research in the area of training human resources in Engineering.

6 REFERENCES

- ANEEL, 2023. "Quantidade de empreendimentos de geração de energia em operação". URL <https://dadosabertos.aneel.gov.br/dataset/empreendimentos-em-operacao>. Accessed: 17 apr 2023.
- Azimov, U. and Avezova, N., 2022. "Sustainable small-scale hydropower solutions in central asian countries for local and

- cross-border energy/water supply”. *Renewable and Sustainable Energy Reviews*, Vol. 167, p. 112726.
- CONBEA, 2023. “Congresso brasileiro de engenharia agrícola”. URL <https://conbea.org.br/>. Accessed in: 30 jan 2023.
- Costa, G. and Sepehri, N., 2015. *Hydrostatic transmissions and actuators: operation, modelling and applications*. John Wiley & Sons.
- Eletrobras, 2019. “Manuais e diretrizes para estudos e projetos”. URL <https://eletrobras.com/pt/Paginas/Manuais-e-Diretrizes-para-Estudos-e-Projetos.aspx>. Accessed in: 31 jan. 2023.
- Hoeltgebaum, T., 2016. *VARIABLE COMPRESSION RATIO ENGINES: A MECHANISM APPROACH*. Master’s thesis, Universidade Federal de Santa Catarina.
- INPI, 2023. “Consulta à base de dados do inpi”. URL <https://busca.inpi.gov.br/pePI/jsp/patentes/PatenteSearchBasico.jsp>. Accessed in: 09 may 2023.
- Kunwor, A., 2012. *Technical specifications of micro hydropower system design and its implementation feasibility analysis and design of Lamaya Khola Micro Hydro Power Plant*. B.S. thesis, Bachelor’s Degree Program in Industrial Management, Arcada University of Applied Sciences, Helsinki, Finland.
- Kusakana, K., 2014. “A survey of innovative technologies increasing the viability of micro-hydropower as a cost effective rural electrification option in south africa”. *Renewable and Sustainable Energy Reviews*, Vol. 37, pp. 370–379.
- Mitsubishi Heavy Industries, L., 2011. “Power generating apparatus of renewable energy type and method of attaching and detaching blade”. Patent, Australian Patent Office, Registry number: AU-2011310935-A1, Deposit: September 22, 2011, Publication date: April 04, 2013.
- Petrea, S., 2008. “Marine hydroelectric power station”. Patent, State Office for Inventions and Trademarks, Romania, Registry number: RO-126581-A2, Deposit: February 25, 2008, Publication date: August 30, 2011.
- Santos Junior, L.A.d. and Sanches, M.S., 2020. *Análise de viabilidade de pequenas centrais geradoras renováveis em propriedades rurais*. B.S. thesis, Universidade Tecnológica Federal do Paraná.
- SBEA, 2023. “Revista engenharia agrícola: edição especial energia na agricultura”. URL <http://www.engenhariaagricola.org.br/>. Accessed: 12 fev. 2023.
- UFPR, 2023. URL <https://revistas.ufpr.br/rber/about>. Accessed: 15 fev. 2023.
- WIPO, 2022. *International Patent Classification (IPC)*. World Intellectual Property Organization. Accessed in: 09 may 2023.
- WIPO, 2023. “Patentscope”. URL <https://www.wipo.int/patentscope/en/>. Accessed in: 9 may 2023.
- Wood, E., 1977. “Power generation systems in buoyant structures”. Patent, United States Patent and Trademark Office, Registry number: US-4158780-A, Deposit: April 20, 1977, Publication date: June 19, 1979.
- Zhejiang University, 2008. “Ocean current generation speed-changing constant frequency method and apparatus base on hydrostatic transmission”. Patent, China National Intellectual Property Administration, Registry number: CN-101350589-A, Deposit: September 08, 2008, Publication date: January 21, 2009.
- Zielinski, M., Myszkowski, A., Pelic, M. and Staniek, R., 2022. “Low-speed radial piston pump as an effective alternative power transmission for small hydropower plants”. *Renewable Energy*, Vol. 182, pp. 1012–1027.

7 RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.