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Low-head Pico-hydro Plant using the Pump as Turbine (PaT) and Permanent Magnet Synchronous Generator (PMSG) for Isolated Loads: Experimental Studies

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ABSTRACT

Pico hydropower is a versatile power source providing electricity access for the world's poorest living in isolated locations. Though on a global scale, a significant market for such pico hydro systems exists in many countries, they are not widely used because they are not easily available, and the available head is low. One solution to address these issues comprehensively is using a pump as a turbine. However, in the case of a pump as turbine, studies on the performance of pico hydro systems are generally available only for heads above 10 m. To assess the technical feasibility of pico hydro plant at very low heads (less than 6 m), experimental studies were conducted using a pump as turbine (PaT) with a modified impeller vane coupled with a permanent magnet synchronous generator (PMSG). A power conditioner provided a stable output voltage of 220 V and a frequency of 50 Hz. The Pico hydro plant was evaluated with a test setup of a storage tank with a facility to have heads less than 6m and flow rates ranging from 6 to 9 liters per second. The results of the experiments at different heads – with and without power conditioner - are presented in tables and graphs, giving the output and efficiency of the different components of the system. Overall, it was demonstrated that this PaT could work at heads ranging from 2 to 4.5 m and at 4.5 m head with a flow rate of 7.5 l/s, the Pico hydro plant could generate a maximum power of 1.48 kW with an efficiency of 42%. The experimental setup was also used to power typical residential loads to demonstrate the effective applicability of this renewable energy resource. Overall, the results indicate the potential of Pico hydro systems that can help electrify communities to achieve SDG 7.1 using low-head hydropower resources.

1. INTRODUCTION

Energy plays an important role in all areas of human and commercial activities and is an important economic input. According to Tracking SDG7 (2021), energy access could be defined as providing sustainable and modern energy services to meet end-users' energy needs, and from the perspectives of households and businesses, the most common energy needs are cooking, lighting, heating/cooling (where applicable), and other productive energy use. Other than for cooking, electricity is an important resource for all these energy needs. Though the number of people without access to electricity fell by 36% from about 1.2 billion to about 759 million - from 2010 to 2019 - the access rate for electricity services was 90% of the global population in 2019. It is estimated that more than 750 million people worldwide do not have access to electricity. The number of people without access to clean cooking solutions declined by 9% - from 3 billion to 2.6 billion—from 2010 to 2019 - and more than 2.5 billion people do not have access to clean cooking facilities.

The strides in improving electricity access were due to the availability and application of various electrification options, namely, the expansion of grids and the deployment of mini-grids and off-grid solutions. Though the grid connection route is estimated to be the least-cost option for serving the unelectrified population, the decentralized renewable energy-based mini-grids and off-grid technologies driven by innovation, enabling policies, and finance have demonstrated their reliability in providing high-quality electricity for the community and have become the backbone of accelerated electrification strategies (Tracking SDG7 (2021)). Though off-grid solar technologies provide the fastest and lowest-cost path for closing the 'last mile' gap to reach the most remote populations, other renewables also fulfill the task of where their resource is available. The areas that do not have access to electricity are mainly the world's rural regions. The *International*

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Energy Agency (IEA) also suggests that for rural households, this minimum threshold of electricity use is 250 kilowatt-hours (kWh) per year, while for an urban household, it is 500 kWh per year (IEA, 2016).

The rural regions without energy access typically comprise islands, hills and forest areas, as well as rural and sparsely populated areas. In these areas, grid extension is often not cost-effective. Though small, standalone energy technologies, such as simple solar home systems (of a few tens of Watt capacities), can meet the basic electricity needs of rural communities, very small hydropower systems are versatile alternatives for electricity generation, where small streams, rivers, and canals are available. Some suitable locations are low-head sites, such as irrigation canals and streams in both hilly and plain areas. The lack of electricity access in developing countries is in rural households, and they have little hope for grid connection in the foreseeable future. Though the COVID-19 pandemic during the initial third decade of the 21st century has clearly exacerbated the status quo, in such locations where appropriate, Pico hydro systems could provide electricity for households, commercial installations, battery charging stations, *etc*. The running cost of these small hydro plants is low, though the initial capital cost could be relatively high. One option to reduce the equipment cost is using a pump in reverse mode, ie. pump as a turbine (PaT).

However, plants with this type of pump as a turbine setup are few and detailed performances of PaT systems are also not available for low-head systems. Mariano Arriaga (2010) has described theoretically the design and feasibility of a Pico turbine in Lao PDR for a community of upto 400 people. The electrical characteristics of the PaT, as well as the cost implications and the social factors involved in the installation and operation of the system, have been presented. The net head for the turbine operation is 10.6m. Studies on Pico turbines have also been carried out in Kenya, Thailand and Vietnam. The head requirement for these turbines is generally greater than 10 m. Therefore, using a pump as a turbine at heads lower than 10 m is a challenge. Another major issue is in choosing and applying this technology since pump manufacturers provide only the hydraulic machine's specifications in pump mode and not in turbine mode (Akbar Telikani *et al*. (2023)).

For a pump as a turbine to be effectively used, the machine's (pump) performance when it operates as a turbine needs to be ascertained. Mose Rossi and Massimiliano Renzi (2018) have shown that there are studies that have considered the empirical, theoretical and analytical relations to identify the best efficiency points and performance in turbine mode using data obtained by laboratory tests.

The major issues, therefore, that need to be addressed for deployment of PaTs are: working (demonstration) of PaT at low heads (less than 10 m), finding the operational characteristics of very low head PaTs in turbine mode, controller system effectiveness and the evaluation of the Pump as Turbine's best efficiency points at off-design operating conditions when they are operating in turbine mode. Also, to the authors' knowledge, usage of such a system to supply typical residential loads has not been done.

The options to convert the turbine mechanical output to electricity include induction, synchronous and permanent magnet synchronous generators (PMSG). Among these, PMSGs are stable and have additional advantages due to their compact size, high power density, reliability, and robustness. However, they are more expensive. To the knowledge of the authors, there has not been any experimental study that has demonstrated the applicability of a PatT-PMSG system for low heads. Therefore, a study was conducted to experimentally measure a PaT system's performance, and its results are presented in this paper. Specifically, the objectives of the study were to (a) demonstrate the development and applicability of a PaT-PMSG system that can be used for low head conditions (<6m) and (b) find the performance and efficiency of the PaT-PMSG system at different heads. In this process, we describe a Pico hydro plant's design, installation and performance. This particular system, where the Pump as Turbine is coupled with a Permanent Magnet Synchronous Generator (PMSG), is designed for very low heads, ranging from 2m to 4.5m. Through this approach, it will be demonstrated that the considered system could generate power that can be used to power isolated communities without voltage fluctuations for conventional electrical equipment used in households and commercial sectors. The details regarding the above are presented below.

The paper is organized as follows: we first present general details of the Pico hydro generation technology, tracing its origins and subsequent developments, and more specifically, the development of Pump-as-Turbines. Details of the electrical components, especially the permanent magnet synchronous generator (PMSG), power conditioning system (PCS), electronic load controller (ELC) and dumping load, are then given. The next section presents the details of the experimental setup and the materials and methods (methodology) adopted in carrying out the experimental studies. Details of the experimental observations of two different experimental conditions are then presented, followed by a discussion of the observations and the results. The conclusion section summarizes the work done and gives the novelty of this research.

2. PICO HYDRO GENERATION TECHNOLOGY

Hydropower plants can be classified based on power generation capacity, as shown in Table 1. The large hydro generation is based on the dam's potential energy, and the electricity generated is typically connected to the national grid. However, small hydro plants are independently installed and connected to the microgrid. Pico hydro plant has low standalone power generation (<5kW) capacity. Hydropower systems of this size benefit in terms of cost and simplicity from different approaches in the design, planning and installation than those which are applied to larger hydropower. In many circumstances, Pico hydro technology is a versatile power source and could provide a low-cost option for off-grid electrical power.

Pump-as-Turbine (PaT) are pumps that are used in reverse mode (of the pump's action). Its main advantages are its low initial cost and low operation and maintenance costs because of its easy/widespread availability in the market. These advantages result in their short payback period and the availability of spare parts for various sizes and dimensions. Additionally, they can also find applications in many water-related sectors, such as water supply systems, water distribution networks, wastewater plants, and irrigation systems (Rossi *et al*. (2019); Morabito and Hendrick (2019)).

Table 1: General classification of hydropower generation based on the capacity.

Hydro generation	Capacity	Feed to
Large	More than 100MW	National power grid
Small	Up to 25MW	National power grid
Mini	Below 1MW	Micro power grid
Micro	6kW to 100kW	Isolated industrial loads and isolated communities
Pico	Up to 5kW	Domestic and small communities

Source: Ahmed M.A. Haidara *et al.* (2012)

Many Pico hydro schemes have been successfully implemented in remote regions of the world to supply electricity to remote areas relatively far from grid areas. In a conventional Pico hydropower scheme, water is diverted from the river through an intake weir. A weir is a structure constructed across the river, maintaining continuous flow through the intake. The water is fed into a forebay tank. It is sometimes enlarged to form a small reservoir. A reservoir can be a useful energy store if the water available is insufficient in the dry season. The water flows from the forebay tank or reservoir down a long pipe (penstock). At the end of the penstock, water comes out of a nozzle as a high-pressure jet. The power in the jet is transmitted to a turbine runner, which changes it into mechanical power. The turbine runner has blades or buckets, which cause it to rotate when they are struck by water. The turbine is attached to a generator. The purpose of the generator is to convert rotating power into electrical power. Thus, the energy of water flowing in a small stream is converted to electricity. The power available is proportional to the product of the head and discharge. The mechanical power produced at the turbine shaft, P (in W), can be estimated from Equation (1).

$$P = \eta \times \rho \times g \times Q \times h \qquad (1)$$

where, η is the hydraulic efficiency of the turbine, ρ the density of the water (kg/m³), g is the acceleration due to gravity (m/s²), Q is the discharge (m³/s) and h is the head of the water acting on the turbine (m).

For the case of Pump as Turbine, the first published work regarding the use of standard pumps running in reverse mode was more than nine decades ago (Thoma and Kittredge (1931)), and it was much later, in 1984, when Tjode and Azbill (1984) outlined the use of standard pump running in reverse mode for electric power generation. Later, in 1996, Williams presented a guide for sizing pumps as turbine units, giving empirical equations to calculate the expected output and a brief troubleshooting guide. The guide also discussed the alternative of reducing the impeller's diameter to attain the optimal operating point for the pump running in reverse mode. Pumps (rotational fluid machines) are reversible and can run effectively like a turbine (Williams, 1996). However, the behavior of the real fluid flow, including friction and turbulence, results in different rules for the design of pumps as turbines.

When a pump is used as a turbine, it operates under variable head and flow conditions. So, the hydro system flow must be adjusted to accommodate seasonal variations or adjust the power output according to the consumer's demand. The flow through the turbine is accelerated with less turbulence. Therefore, runner passage must be relatively shorter, reducing friction losses and ensuring high efficiency. It is less sensitive to cavitations since friction losses in the draft tube increase the turbine's backpressure. As the flow is reversed in PaT, the pump casing (volute) determines the energy transfer. So, the pump design and manufacturing details will affect the performance. Machines may have similar performance in pump mode with a similar impeller but will not necessarily yield the same performance in the turbine mode. A control valve must be incorporated into the penstock line to start and stop the PaT. Conventional turbines have effective hydraulic control (adjustable guide vanes, nozzles, or runner blades) to control the available flow or the required output. If PaTs are operated at other than the design flow, i.e., below their best efficiency point, a relatively rapid efficiency drop will occur. So, it is important to select a suitable pump as a turbine, based on a flow rate and a gross head, with an objective of converting the pump curves and best efficiency points to its turbine equivalent. Equations (2) and (3) are used to calculate the flow rate and head when running the pump in reverse mode, as

$$Q_t = (n_t \times Q_{bep}) / (n_p \times \eta_{max}^{0.8}) \qquad (2)$$

$$H_t = (n_t / n_p)^2 \times (H_{bep} / \eta_{max}^{1.2}) \qquad (3)$$

where, Q_{bep} and H_{bep} are the best efficiency points of the pump, η_{max} is the pump's maximum efficiency, and n_p, n_t

are the rotational speed (rpm) when running as pump and turbine, respectively.

These equations are based on the standard pump affinity laws. Since the equations are empirical, the actual PaT performance can potentially differ by (+) or (-) 20%.

For the design of the electric system to be installed with the PaT, a choice must be made concerning the type of generator and control to use. Induction, synchronous and permanent magnet synchronous generators (PMSG) are the options for converting hydraulic energy to electrical energy. Among them, there is growing interest in PMSGs, as they are stable and secure during normal operation and do not need an additional DC supply for the excitation circuit of generators. Its other advantages include its compact size, high power density, high reliability, and robustness. Moreover, the simple rotor design without field windings, slip rings and excitation system also increases the efficiency of the overall machine. However, when a PMSG is coupled to a PaT, the electricity generated has variable amplitude and frequency, which varies highly as a function of hydraulic energy input and load on the system. Due to the fixed excitation of the PMSG, it is difficult to maintain the operating speed constant at all load points. Therefore, control devices such as a solid-state power conditioning system comprising a rectifier and inverter and Electrical load controller are needed to stabilize the power output to 220 V, 50 Hz.

The experimental performance of a self-excited induction generator (SEIG) and permanent magnet synchronous generator (PMSG) for renewable energy-based standalone applications has been studied (Murali Krishna *et al*., 2022a). The same constant speed-prime mover (motor) was used for evaluating the performance. The results indicate that if cost is not a consideration to the customer, then PMSG is suggested to avoid extra capacitor arrangement for self-excitation and reactive power compensation, while the size and weight can be reduced through special machine design of PMSG for dedicated loads.

In another study, a three-phase PMSG was designed and tested for the resistor and induction motor load applications while maintaining the voltage, frequency and voltage total harmonic distortion (THD) values within the permissible level. The results indicate that the voltage, frequency and voltage THD values of the PMSG system are within the acceptable level at rated loading conditions (Murali Krishna *et al.*, 2022b).

Another study using PMSG considered the (theoretical) modeling and control of a small hydropower plant for a DC microgrid. The system is made up of a turbine, a permanent magnet synchronous generator (PMSG), a voltage source converter and a DC microgrid. The electrical, mechanical and hydraulic dynamics were studied by employing a nonlinear controller based on passivity. The simulation results show better performance of the proposed controller when compared with a PI controller (Walter Gil-González, 2020).

An Electronic Load Controller (ELC) replaces the speed governor and aims to maintain the frequency of a power generation constant by controlling the generator output power between the consumer and dummy load. Ofosu *et al.* (2019) designed and implemented a cost-effective ELC using Magnetostrictive Amorphous Wire as a frequency sensor. An amplifier and a signal conditioning circuit were designed to convert the analog signal from the MAW to a digital signal that is fed to the microcontroller. Experimental test results using a motor - generator (as a hydropower plant) show the effectiveness of the ELC in dumping excess power to the damper load (for which incandescent lamps were used) when the consumer load changes and in maintaining the supply frequency between 49.5 and 50.5 Hz.

Though there are studies in recent years on PaT, PMSG and controllers, a survey of the above literature indicates the lack of comprehensive studies that (a) demonstrate the use of PMSG coupled to PaT, (b) demonstrate the working of a system at low heads (less than 10 m) and (c) evaluates the performance of such a system for varying operating conditions. This has been addressed in this study.

3. EXPERIMENTAL SET-UP OF THE PICO HYDRO GENERATION SYSTEM

The Pico hydro installation was designed and constructed to evaluate the performance of the pump as turbine – coupled with a permanent magnet synchronous generator (PMSG) with an objective to regulate the generated power so as to supply electricity to isolated loads. The details of the experimental setup stand are given below:

The general arrangement of the test stand installed is shown in Figure 1. It consists of a water tank which is connected to a turbine (PaT) by a penstock. Control valves and overflow pipes are placed to arrange the desired flow of water. The turbine is coupled to a PMSG connected to a power conditioner. Typical residential loads were used. The specifications of the system's individual components, namely, feeder pump, pump-as-turbine, PMSG, power conditioning system, electronic load controller, *etc.,* are listed in Table 2. The feeder pump pumps the water into the tank of volume 3.6 m x 2 m x 2 m, which can maintain a maximum head of 4.8 m with a penstock arranged from the tank acting as a weir for the flow of the water to the turbine. Control valve 1 near the feeder pump controls the back flow of the water to the pump, while control valve 2 controls the inflow to the tank and control valve 3 near the penstock is used to control the flow rate to the turbine. Two overflow pipes of 100 mm diameter each are arranged with control valves 4 and 5 to control the outflow from the tank to maintain the head at particular levels, allowing the evaluation of the Pico hydro system’s performance at variable heads. By controlling the valves, the head of the storage tank is maintained at a particular head and the system is evaluated. Figure 2 shows the schematic of the basic system without the power conditioning components.

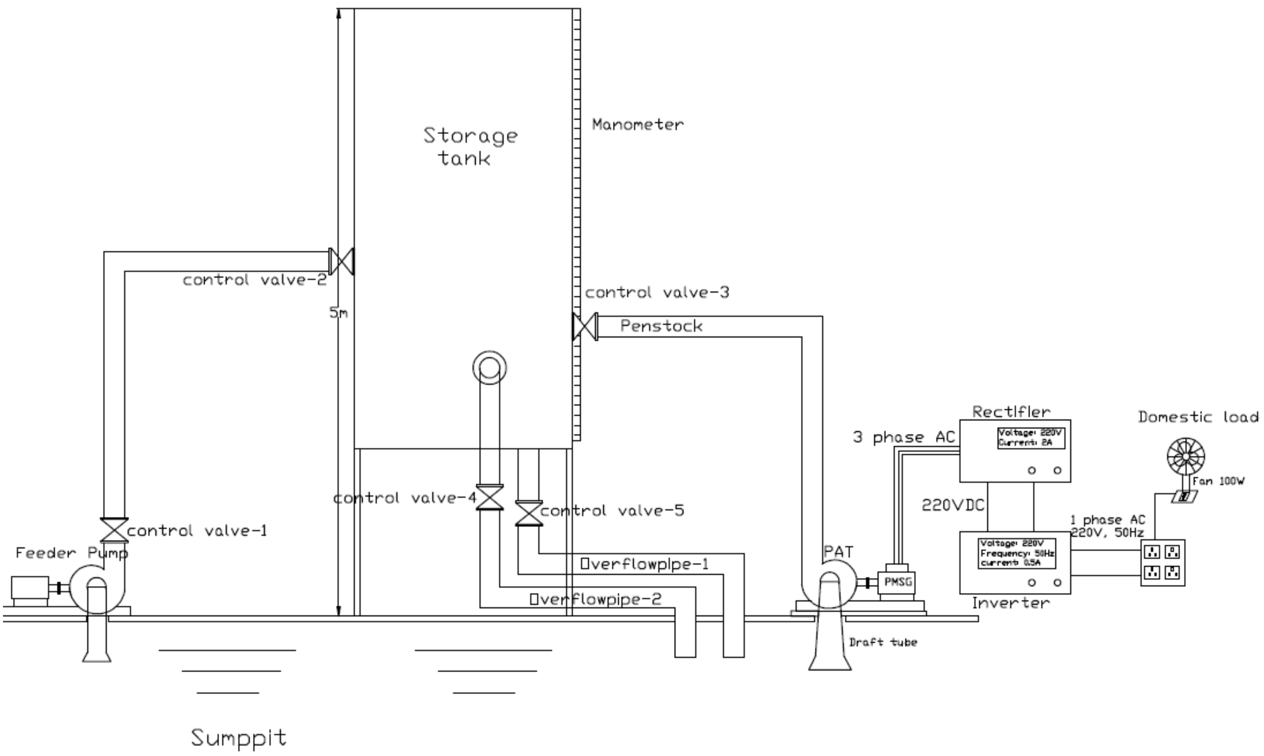

Fig. 1. General arrangement of the Pico hydro experimental test stand.

Table 2: Specification of the various components of the Pico hydro system.

Equipment	Specifications / Capacity
Feeder pump	6.4 (m^3/min) x 6.2m x 1unit (Ebara model: 250SZ x 1060rpm x 11KW)
Pump as turbine (PaT)	Mixed flow type pump (Ebara model: 200SZ) with flow rate of 0 - 0.11 m^3/s, output range of 0-4.8 kW and speed range of 0 – 1200 rpm
Permanent magnet synchronous generator (PMSG)	Rated power: 5.5 KVA, Rated speed: 1500 rpm, Rated voltage: 400V, rated current 7.9A (Komel Manufacturing Plant, Poland)
Electric load controller (ELC)	3-Phase, with the function of voltage control at 210V, with dummy load (Tan Nan Trading and Production Joint Stock Company, Vietnam)
Power conditioning system (PCS)	DC Rectifier KY31H15, Input: 180V~360Vac, 23~50Hz, Output: 310V15A Off grid Inverter KY-5KVA, Input: 100~780VDC, Output: 5KVA, single-phase 220Vac

The electrical system consists of the 3-phase generated power from PMSG connected to a power conditioner, which controls the generated power to a regulated power output that can electrify isolated loads (Figure 1). The power conditioning system consists of a rectifier and inverter unit. The rectifier is designed for a wide range of input voltage (100-360 V AC) and a wide range of input frequencies (20 to 50 Hz). The function of the rectifier is to convert three-phase AC voltage to DC Voltage (which is adjustable from 0 to its maximum value of 350 V DC where the generated DC can be used to charge the batteries for energy storage). The DC output of the rectifier is supplied as input to the inverter with a DC voltage input range of 180 to 300 V DC and with an output of single phase 220V AC, 50Hz that can be directly connected to isolated loads. The inverter used is a BND series sine wave inverter with advanced pulse-width modulation of the sine wave technology.

The type of dump load used is variable pure resistive load made of coils with a maximum capacity of 3 kW.

4. METHODOLOGY

The following methodology was adopted to address the objectives of the study. The experimental studies were designed to understand the working of the PaT-PMSG and of the controllers, and hence they were conducted in two phases, as follows:

- The first phase of experiments aimed to demonstrate the PaT-PMSG working with variable frequency and voltage output by connecting it to a 3-phase variable resistive load of 3 kW. A known head of water was first maintained, and for this specific head for a given resistive load, the performance parameters of the Pico hydro system were measured by using an ultrasonic flowmeter, 3-phase wattmeter, voltmeter and frequency meter. Based on the measurements, the efficiency was calculated. The experiment was repeated for various heads (see Figure 2).

- In the second phase of the experiment, which was to find the efficiency of PaT-PMSG-PCS-ELC with 220 V_{ac}, 50Hz single phase power output, similar experiments were conducted by varying single phase 3 kW resistive load (as per experimental setup in Figure 1) for the various heads, and the procedure was similar to what was described above.

For each of the two phases of the experimental study, the head ranged from 2 m – 4.5 m, and experiments were conducted at intervals of 0.5 m. Experimental studies specifically carried out on the PMSG showed that it delivered voltage from about 100V to 320V in a speed range of 400 rpm to 1100 rpm. Accordingly, the power output characteristics of the PMSG ranges from 1.2 kW - 3 kW for a speed of 500 rpm-1100 rpm, which is proportional to the head range of 2 to 6m. So, during the two experimental phases, the PMSG speed was maintained within the speed limits.

The data collected during the experiments were: flow rate of the water in the penstock using an ultrasonic flow meter, net head using a manometer, voltage, frequency, load current and power output of the PMSG using a 3-phase wattmeter. The designed hydraulic efficiency of the PaT is 77.5%, which was obtained based on experimental tests of the PaT by the manufacturer and was used to calculate the PaT power output, and the net head was used to calculate the mechanical power output of the PaT.

Based on these observations, it could be seen that the Pico hydro system was evaluated in two steps for its performance. Firstly, the system was evaluated for its power output at a particular head and studying the function of voltage, frequency and current outputs, and this was repeated for other heads (because of the PMSG). Secondly, an electronic load controller and standalone solid-state controller were used as a power conditioner to get a stable voltage of 220V and frequency of 50Hz and the performance of the Pico hydro system was then evaluated for its applicability. The observations, calculations and results are presented in the next section.

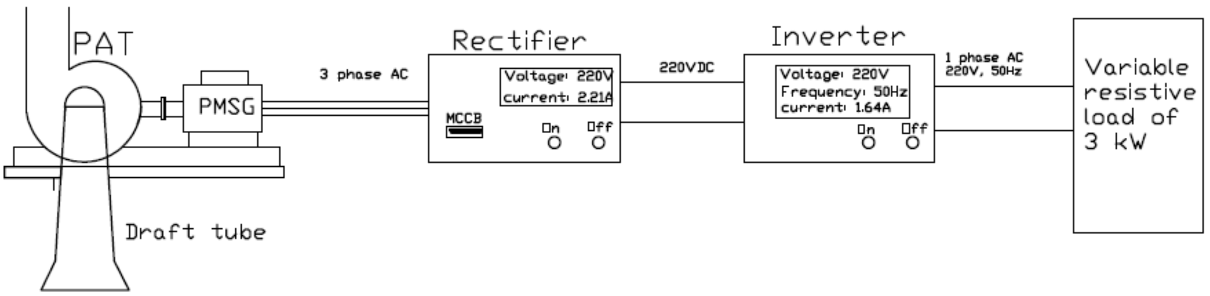

Fig. 2. Schematic arrangement for the evaluation of the Pico hydro system with Electric Load Controller (ELC) and Power Conditioning System (PCS).

5. EVALUATION OF THE PICO GENERATION SYSTEM

As noted above, the Pico hydro system was evaluated in two steps for its performance. This was done by conducting the experiment at specific heads and measuring the other desired parameters.

These were then used to calculate the output, efficiency and other related output parameters. Firstly, the system was evaluated for its maximum power outputs at a particular head, using 3 phase resistive load of 3 kW, and secondly, the evaluation was done for its performance with a power conditioner with a regulated power output of 220 V, 50 Hz on single phase 3 kW resistive load. The PaT-PMSG system was arranged at the test stand for evaluation (for the first set of experiments) without the Electric Load Controller (ELC) and the power conditioning system (PCS). The head was varied from 2 m to 4.5 m at an interval of 0.5 m for each step for evaluating the system performance. The data collected and the calculated results are shown in Table 4. Head, flow rate, voltage, frequency, current and the PMSG output are the measured parameters, while the PaT output and the PaT-PMSG system efficiency have been calculated. Based on these observations, the output power curves of PaT & PMSG at each head for variable load have been drawn in Figure 3. It can be seen from Table 3 and Figure 3 that the flow rate varies between 0.05 to 0.078 m3/sec, while the PaT output varies between 0.76 (at 2 m head) and 2.67 kW (at 4.5 m head). At 4.5 m head, the pico hydro unit can generate a maximum power of 2.08 kW without a controller with a variable voltage and frequency. A sample output calculation is given below:

The mechanical power, P (in W), produced at the turbine shaft (PaT output) can be estimated from Equation (1) as:

$$P = \eta \times \rho \times g \times Q \times h$$

where, η is the hydraulic efficiency of the turbine = 77.5%,
ρ = 1,000, the density of the water (kg/m³),
g = 9.81, the acceleration due to gravity (m/s²),
Q, is the discharge (m³/s), and
h is the head of the water acting on the turbine (m).

So, PaT output at 3.5 m head and 0.65 m3/s flow rate is 1.73 kW.

It can be observed from the data in Table 3 that the voltage and current generated by the PMSG varies from 93 V to 147 V and from 2.5 A to 4.5 A, respectively, with the maximum acceptable load on the PaT- PMSG. The frequency also varies from 19 to 31 Hz. The overall efficiency of the PaT-PMSG system varies between 60-70%.

Table 3. Experimental and calculated performance parameters of PaT-PMSG system at various heads (without power conditioning system (PCS)).

Head (m)	Flow rate (m^3/s)	PaT Input (kW)	PaT Output (kW)	Voltage (V)	Current (Amp)	Frequency (Hz)	PMSG output (kW)	PMSG η (%)	PaT-PMSG η (%)
2.0	0.050	0.981	0.760	93	2.5	19.53	0.69	90.8	70.3
2.6	0.055	1.403	1.087	102	3.5	21.07	0.99	91.1	70.6
3.0	0.059	1.736	1.346	108	4.0	22.62	1.20	89.2	69.1
3.5	0.065	2.232	1.730	116	4.0	24.41	1.47	85.0	65.9
4.0	0.075	2.943	2.281	128	4.5	27.33	1.83	80.2	62.2
4.5	0.078	3.443	2.669	147	4.5	31.05	2.08	77.9	60.4

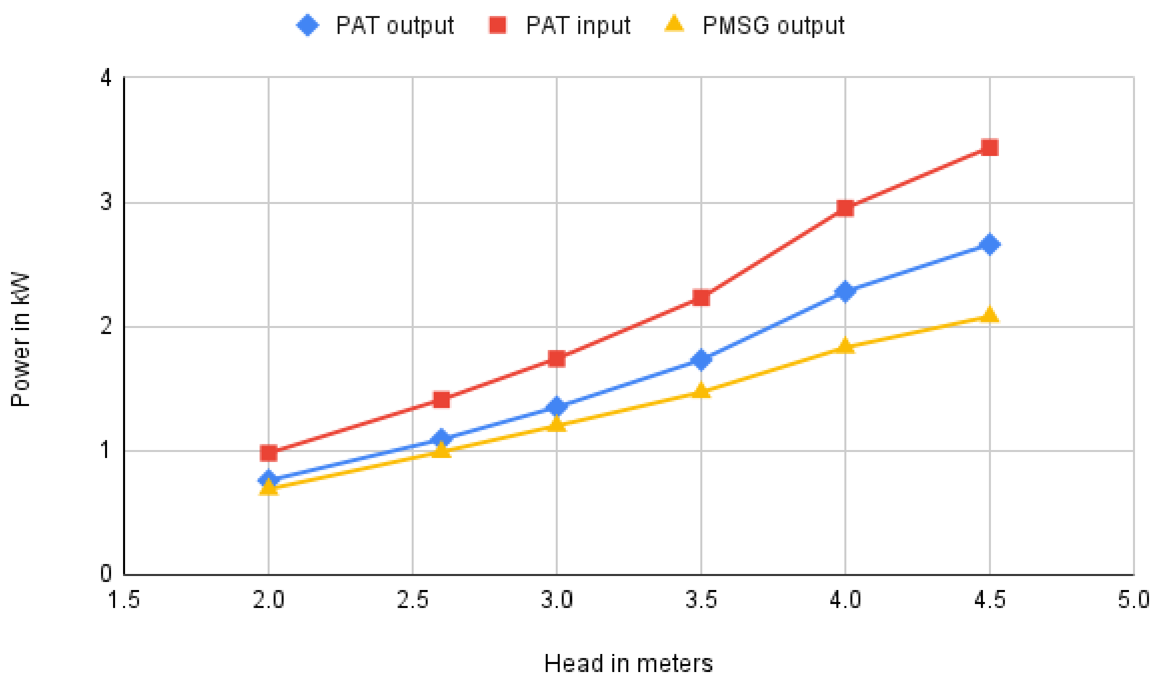

Fig. 3. PaT and PMSG power outputs of the Pico hydro system at different heads (without ELC and PCS).

Due to wide changes in the voltage and frequency, the generated power cannot be directly supplied to the consumers and has to be regulated to 220 V and 50 Hz. So, a power conditioner comprising a rectifier (3-phase AC to DC) and inverter (DC to single-phase AC) is needed to regulate the power supply to isolated loads and the voltage and frequency. So, as a second step of evaluation, aiming to provide electricity at a stable voltage of 220 V and frequency of 50 Hz, a power conditioning system and an electronic load controller were added, and experiments were conducted at various heads. The experimental observations are shown in Table 5. The efficiency of the power conditioner used is 70%, which contributes to the reduction in the final power output. Accordingly, the Pico hydro system installed could generate a maximum power of 1.48 kW at 4.5 m head with an efficiency of 42%, at a stable voltage of 220 V and frequency of 50 Hz from PCS that can power isolated loads. The output power curve of each equipment is shown in Figure 4.

Table 4. Experimental and calculated performance parameters of the complete Pico hydro system at various heads.

Head (m)	Flow rate (m^3/s)	PaT Input (kW)	PaT Output (kW)	Overall system output (kW)	PaT-PMSG η (%)	Overall system η (%)
2.3	0.050	1.128	0.874	0.490	61.2	43.4
3.0	0.065	1.913	1.483	0.880	54.9	46.0
3.5	0.070	2.403	1.863	1.040	49.1	43.3
4.0	0.070	2.747	2.129	1.150	52.8	41.9
4.5	0.080	3.52	2.73	1.480	46.0	42.0

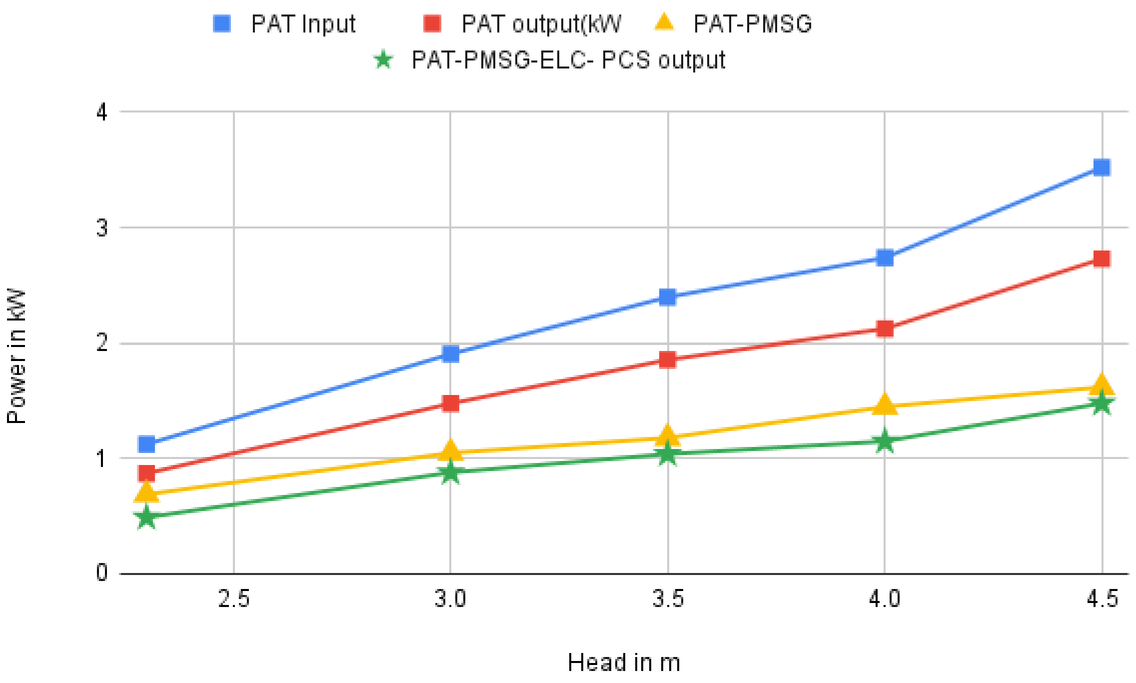

Fig. 4. PaT, PMSG and overall power outputs of the Pico hydro system at different heads.

Though the power conditioning system is connected to the PMSG to generate the final output with a voltage of 220 V and frequency of 50 Hz, the output voltage and frequency of PMSG are highly dependent on the input energy and load, which decides the speed of the PMSG. So, to control the effect of load fluctuations and no-load conditions (which causes runway speed) on PMSG, an electronic load controller (ELC) was installed at the output terminals of the PMSG. The frequency is variable for a PM generator as the frequency is proportional to speed. The electronic load controller is used to get a single phase 220V with a constant frequency of 50Hz output. As per the results obtained with PCS on the pico hydro system, installing ELC improved the system's stability and improved the performance of the PCS and, therefore, that of the overall system.

As per the "Pico hydro plant for village power, practical manual scheme," the system efficiency for electrical generation using a Pico hydro with a conventional turbine and controller is typically between 40 and 50% [Phillip Maher and Nigel Smith (2001)]. Their case study describes a Pico hydro plant using a 'pump-as-turbine' directly coupled to an induction motor as a generator with an electrical output of 2.2 kW. The net head was 18m and the flow into the turbine was 28 l/s. The electrical output of 2.2 kW corresponds to a turbine-generator efficiency of 45%. In the current study, the Pico hydro plant generates electric power with an efficiency of 42 to 46% for a head range of 2.3 m to 4.5 m, with a very stable output voltage of 220 V and frequency of 50 Hz that can be used for rural electrification.

- At 4.5 m head with a flow rate of 0.08 m^3/s, the pico hydro plant could generate a maximum power of 1.48 kW with an efficiency of 42%, and
- At a head of 3.5 m with a flow rate of 0.07 m^3/s, the pico hydro plant generated power of 1.04 kW with an efficiency of 43.3% with a stable output voltage and frequency independent of fluctuations in the load.

Tables 3 and 4 give the efficiencies of the PMSG, PaT – PMSG, and the overall system for various load currents at different heads. It is clear that for each head, there is an optimal load that provides the highest efficiency.

The (theoretical) potential of a Pico hydro system development considering 77.5% efficiency of pump as turbine and 80 to 85% of PMSG and with 70% solid-state power electronic controller efficiency is expected to provide an overall efficiency of 43-46%. The experimental efficiency of 61-71% of PaT-PMSG outputs validates the potential values ranging from 62-66%. The experimental PaT-PMSG-ELC-PCS efficiency of 40-45% validates the theoretical values. The experiments also show that the modified PaT, by rounding its runner inlet vanes by 2mm, improves its efficiency and moves the peak efficiency point to a smaller flow range of PaT, confirming its applicability for heads less than 6m. However, instead of PMSG, using a synchronous generator that has similar efficiency as PMSG would be more attractive and could improve the overall efficiency as a PCS will not be required.

The applicability of this type of PaT in an actual setting can be estimated by considering that the Pico hydro system generates regulated power of 1.48 kW for 24 hours a day, which amounts to approximately 36 kWh. For electricity requirements of 1.55 kWh per day, shown in Table 5 per household for rural communities, it could be estimated that about 20 households could be electrified by this system.

It should be noted that the PMSG is more expensive than the other options, but to use a system at low head and for remote locations, a reliable and robust system is necessary. Obviously, further work is necessary to improve the financial aspect as well as to improve the efficiency of power conditioners to make such systems attractive.

Table 5. The residential load considered for electrification purposes.

S. No.	Load	Watt/Load	Use (hours/day)	Wh/day
1	Lamp	50	6	300
2	Fan	50	12	600
3	Television	150	3	450
4	Miscellaneous	100	2	200
			Total Wh/day	1,550

6. CONCLUSION

The objective of this study was to show the applicability and working of a PaT at low heads and show its operational characteristics, as well as the controller system's effectiveness. The Pico hydro plant system described in this study using a pump as a turbine coupled with a permanent magnet synchronous generator (PMSG) for very low heads ranging from 2m to 4.5m was demonstrated to generate electric power with an efficiency of 41 to 47%. It could generate unregulated power of 2kW with efficiency of 60% at a head of 4.5m. At the same head, PCS and ELC could generate regulated power of 1.48kW with a stable supply voltage of 220V and frequency of 50Hz at an overall efficiency of 42%. These values are similar to the Pico hydro plants using conventional turbines. The potential of a Pico hydro system development using 77.5% efficiency of pump as turbine and 80 to 85% of PMSG and with 70% solid-state power electronic controller efficiency, installed can be replicated for electrification of small communities with resource availability of very low head less than 5m and minimum flow rate of 6 l/s to 9 l/s. The research has also demonstrated that the standalone Pico hydro system with a pump as turbine coupled to PMSG is a good alternative in terms of its efficiency, robustness and minimum maintenance. The PCS used proves to be more justified for the purpose of generating a constant single-phase output of 220 V 50 Hz that can supply more reliable and stable power to the consumer. The Pico hydro plant's performance could be improved by using an ELC to maintain the speed of the PMSG, which depends on the load and energy input and would also improve the overall efficiency.

The main novelty of this work is the practical demonstration of a modified PaT that works at very low heads, less than 6 m, effectively. At the same time, though PMSG is quite robust and efficient in terms of operation, there are challenges of cost and high losses due to the additional controller to generate AC power at 50 Hz frequency.

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