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Potential use of Pump as Turbine Coupled to Self-Excited Induction Generator for Micro-hydro Cooking and Cooling Applications

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ABSTRACT

Clean cooking and efficient cooling in developing countries have recently become areas of great focus. Further, the environmental impact of flooding in high-capacity hydroelectric plants has become a major concern. As a result, there is growing emphasis on developing sustainable and decentralized energy solutions, focusing on the potential of micro-hydro systems, especially in rural and remote areas. Although there are several alternative energy generation methods, their application is not straightforward. One of the latest technologies under research is using pumps as turbines coupled to an induction generator. This paper explores through a rigorous experimental approach the possibility of using a pump as turbine (PAT) coupled with a self-excited induction generator (SEIG) as an alternative energy source for heating, lighting, and cooling applications. The 1.5 kW delta-connected induction generator was excited by three 50 µF star-connected capacitors. The cooking and cooling apparatus was represented by a resistive element with a fixed resistance and inductance seen by the generator. The results show that the PAT-SEIG system produced the required 240 V, which is sufficient to power ten 50 W LED bulbs or power a compressor for a cooling system. The study has demonstrated that PAT-SEIG can offer an alternative, cost-effective solution for generating electricity to power cooking or cooling appliances.

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INTRODUCTION

In rural off-grid communities, cooking is a daily domestic activity reliant primarily on polluting fuels like paraffin, wood, and animal waste. These fuels contribute significantly to harmful emissions which are detrimental to human health and the environment. As of 2023, approximately 2.3 billion people worldwide still lack access to clean cooking technologies and fuels (Nydal, 2023). Despite significant progress made over the last decade, it is unlikely that universal access to clean cooking will be achieved by 2030 at the current rate of progress. The continued use of polluting fuels and inefficient cookstoves negatively impacts the environment, health, and human livelihoods (IRENA, 2019; IRENA, 2023a).

The need for clean and sustainable cooking energy is crucial in areas where polluting fuels are the primary source of cooking energy. Current humanitarian efforts prioritize the need for clean cooking and allocate resources to promote the related technologies. These efforts primarily concentrate on improving fuel-based cookers to be more energy-efficient or using alternative, cleaner fuels to reduce health risks associated with open-fire cooking. Clean cooking often involves switching from biomass to Liquid Petroleum Gas (LPG) or using electric cookers instead of traditional combustion methods (Lentswe et al., 2022; Nydal, 2023). Addressing the electricity needs of rural areas is of paramount importance in fulfilling essential development objectives. Reliable electricity access contributes to improved lighting, more efficient cooking methods, enhanced security, increased productivity, and facilitates productive applications for value addition. Prioritizing these needs is vital for fostering sustainable growth and development in these communities (Kaunda, 2013; UNIDO, 2022). Microgrids are particularly well-suited for remote, off-grid rural areas with low energy demand, as they can be deployed in various sizes tailored to specific community needs and local conditions (Jain & Patel, 2014).

Different energy sources have unique advantages and disadvantages. Fossil fuels such as coal, oil, and natural gas are reliable and provide high energy density. However, they significantly contribute to pollution and climate change. Renewable sources like solar, wind, and hydro offer sustainability and have minimal environmental impact, though they can be intermittent and require substantial upfront investment for infrastructure. Nuclear energy produces low emissions and provides a steady energy supply, but it poses risks related to radioactive waste and potential accidents. Balancing energy demand with environmental and economic concerns is essential in determining the right energy mix (Ang et al., 2022; Arshad, 2017; Zalengera et al., 2014). Table 1 compares selected renewable energy technologies based on availability. The highlighted technologies can be applied in mini or microgrids.

Table 1: Comparison of selected energy technologies

Energy source	***Availability***
Wind	Unpredictable/seasonal
Solar without storage	12 hrs and seasonal
PAT-SEIG	Site-specific / 24hrs

Source: (Toumi et al., 2023)

Various researchers have studied cooking and cooling technologies for off-grid and microgrid systems. Leach et al. (2021) discussed off-grid modern cooking technologies, highlighting the cost-effectiveness and environmental impacts of transitioning to electric cooking services using solar PV-battery systems. Upadhyay et al. (2013) explored the use of off-grid modern cooking technologies, such as biogas plants and solar cookers, which could transform rural lives by replacing traditional fuels. Lombardi et al. (2019) evaluated the techno-economic feasibility of off-grid electric cooking using PV microgrids, proving cost-competitiveness compared to conventional fuels. Kuś et al. (2019) simulated a solar-driven absorption cooling system with PV modules and found that the design offers off-grid refrigeration solutions for underdeveloped regions to ensure continuous cooling for medications and food with minimal environmental impact. Kuś et al. (2019) developed a battery-free solar refrigerator that integrated solar PV power with thermal storage. The system used a vapour compression cycle and a control system, offering an efficient off-grid refrigeration solution. Katutsi et al. (2024) explored how convenience, cultural compatibility, and social reputation influence the sustained use of clean cooking technologies in Ugandan households, highlighting factors crucial for adoption and continued usage. It has been observed that the researchers have mostly looked at the use of solar in providing the energy source for these cooking and cooling technologies, but Africa also has a huge potential for micro-hydro systems (Kaunda, 2013; Mdee et al., 2018; Nyirenda et al., 2024).

Cooking system

Figure 1 shows the arrangement for a cooking unit with heat storage. The power source, which can be solar, wind, or PAT-SEIG is connected to the heating element immersed in oil in a container. Thermal energy storage presents a promising solution to the cooking challenges in sub-Saharan Africa, where reliance on fuelwood is prevalent. The region's frequent power outages due to insufficient electricity generation hinder using electric cooking appliances (IRENA, 2023b; Nydal, 2023). The intermittent nature of the power supply can be mitigated by integrating thermal energy storage, such as using oils, pebbles, or phase change materials like paraffin wax (Khatri et al., 2022).

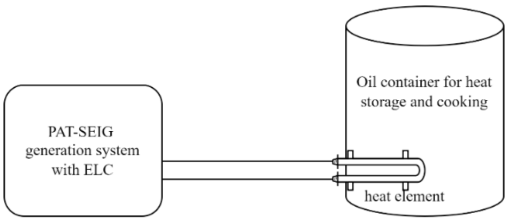

Figure 1: proposed set-up of a cooking unit.

The power supplied by the generator is given by Equation (1).

$$P = VI \tag{1}$$

Where P is power, V is voltage, I is current, and the energy supplied to the heating element in the cooking unit can be calculated from Equation (2)

$$E_G = P\Delta t = VI\Delta t \tag{2}$$

Where E_G is the energy supplied by the generator, V is the terminal voltage, and Δt is the time taken while supplying the power. The energy supplied to the energy storage pot is converted to heat and causes the temperature of the oil to rise (Lentswe et al., 2022). The relation relationship between the temperature rise and energy supplied is shown in Equation (3)

$$E_P = \rho v c_p \Delta T \tag{3}$$

where E_P is the energy supplied to the pot, ρ is the density of oil, c_p is the specific heat capacity and ΔT is a temperature change. Assuming direct contact between the heating element and the oil, the losses can be neglected; thus, the energy supplied to the cooking pot is equal to the generated power per unit of time as shown in Equation (4).

$$E_G = \eta E_P \tag{4}$$

Cooling system

Small-scale off-grid refrigeration systems, particularly in developing countries, face challenges in determining energy requirements. Research on off-grid ice-making operations in remote areas highlights the increased demand for cooling systems that require reliable energy sources (Sertsoz and Fidan, 2021). A refrigeration system is designed to transfer heat from one area to another, thereby cooling the first area. Figure 2 shows a refrigeration system consisting of four key components: a compressor, a condenser, a capillary tube (expansion valve), and an evaporator. The compressor compresses refrigerant gas, which moves to the condenser to release heat and condenses into a liquid. This liquid refrigerant flows through the expansion valve, where the pressure drops and liquid evaporates in the evaporator coil, absorbing heat from the surrounding environment. The cycle repeats, effectively maintaining a lower temperature in the refrigerated spaces (Albaghdadi et al., 2021; Sossan et al., 2016; Leon-Ballester et al., 2012).

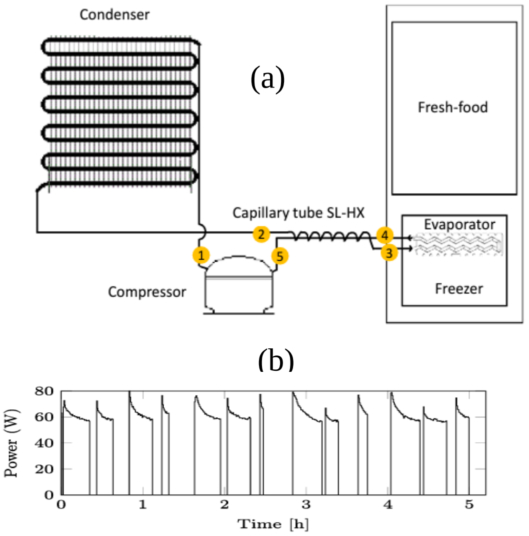

Figure 2: Arrangement of a two-door domestic refrigerator (Sossan et al., 2016).

There are factors to consider when selecting a compressor, such as capacity, efficiency, noise level, and application requirements. The efficiency of a refrigeration system is quantified by its coefficient of performance (COP), a dimensionless metric that assesses system effectiveness. A higher COP signifies greater efficiency, reflecting the system's ability to deliver a greater amount of cooling per unit of energy consumed.

$$COP = \frac{Q_e}{P_{el}} = \frac{q_e}{w} \quad (5)$$

where Q_e is the required cooling capacity, q_e is the specific cooling power, P_{el} is the effective electrical power on the compressor shaft and w is the specific compression work. Table 2 shows an extract of the compressor selection chart. The compressor rating in watts increases proportionally with the space to be cooled.

Table 2: Domestic refrigeration selection chart

Type	*Box size in liters*	*BTU*	*Watts*	*HP*
Single door fridge	-	212	62	1/12
	-	256	75	1/10
	226-254	317	93	1/8
	283-370	423	124	1/6
	226-340	509	149	1/5
Double door fridge	370-461	635	186	1/4

(Source: Zubair, 2020)

PAT-SEIG system

Current research focuses on the potential of using a pump as a turbine (PAT) coupled with a self-excited induction generator (SEIG) for micro-hydropower systems. This approach offers several advantages over traditional water turbines, including lower cost, wider availability, and easier maintenance (Dalei et al., 2023; Nyirenda et al., 2024). PATs can be quickly deployed and are suitable for low-power plants, typically below 100 kW. They can operate with minimal water availability and can be easily scaled by adding more units in parallel. The SEIG requires external excitation from externally connected capacitors and is a good match for the PAT due to its simplicity and low maintenance requirements. Overall, the combination of PAT and SEIG presents a promising solution for small-scale hydropower generation (Chauhan et al., 2010; Jain and Patel, 2014; Pawowoi et al., 2022; Pivetta et al., 2022). The PAT harnesses the potential energy of water to supply to a variable load as illustrated in Figure 3. The PAT is installed on a perennial stream where the minimum flow Q_{min} is determined to be adequate for power generation. The PAT and IG can be selected and bought off the shelf. The PAT converts the potential energy of water to rotational energy and the SEIG converts the rotational energy to electrical energy.

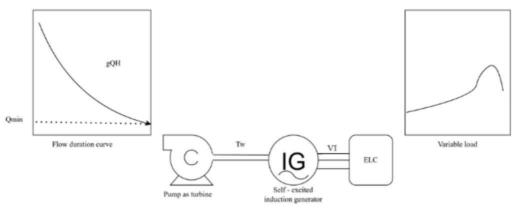

Figure 3: PAT-SEIG energy generation system.

Potential energy available from the site is given by $PgHQ_{min}$ is converted to rotational energy $T\omega$ by the PAT which drives the self-excited induction generator to generate a terminal voltage to supply a variable load. The electronic load controller monitors the generated power and the demand. Any excess energy is diverted to a dump load.

This paper aims to experimentally investigate the potential of utilizing a pump-as-turbine system coupled with a self-excited induction generator as an alternative energy source for heating, lighting, and cooling applications. The study involves conducting a series of experiments to analyze the system's dynamic response to changes in load.

MATERIALS AND METHODS

This section presents the materials and procedures used to perform the experiments. Table 1 indicates the compressor ratings for a certain BTU and horsepower, which means the power absorbed by a resistive element can represent the power supplied to the refrigeration and cooking systems. Thus, during experimentation, a resistive element is used to represent the power absorbed by the refrigeration system. The peak power demand from the generator side is taken as a constant.

Materials

The study used the Pedrollo pump FG 32/160B, rated at 1450 rpm for a head of 6.2 m and flow rate of 8.7 m3/hr at an efficiency of 55%. The pump was coupled to the generator with an induction motor model number 3-MOT 7AA90L04, 1420 rpm, 4-pole. Three 50 µF excitation capacitors were used to excite the generator. The generator fed a variable resistive load through an electronic load controller.

Methods

The experimental setup was conducted at the Water Resources Laboratory of the College of Engineering and Technology at the University of Dar es Salaam. An induction generator was coupled to a pump as a turbine (PAT), as shown in Figure 4. The PAT is fed from a 7.5 kW feed centrifugal pump through a 50 mm diameter pipe. The 50 mm pipe is reduced to 32 mm before feeding the PAT through a gate valve. The IG is connected to an ELC box, which houses the excitation capacitors and a thyristor-controlled dump load switching mechanism. The output of the ELC was connected to a variable resistive load used to represent the heating element for the cooker and the compressor for the cooling system. A data logger was used to record the speed of rotation, voltages, and currents of the PAT.

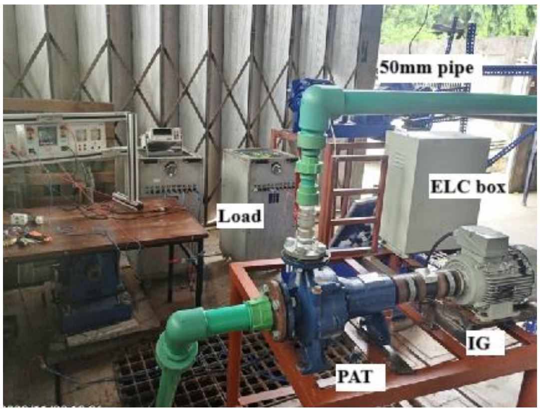

Figure 4: PAT-SEIG experimental setup.

Step 1

The PAT-SEIG was run at a constant flow rate, providing constant power input to the IG. To represent the heating element, a variable resistance was varied with values ranging between 90 Ω and 500 Ω. At random points, spot measurements were done, and the frequencies, speeds, and resistance values were recorded. Further, the resistors were replaced with ten LED light bulbs resistors were replaced with ten LED light bulbs.

Step 2

The PAT-SEIG was run at a constant speed, and the load of 158.4 Ω was connected to the generator. The generator was started on No-Load, and after 30 seconds, the load was switched ON. At 39 seconds, the load was switched OFF, and later at 44 seconds, the SEIG was restarted on load. At 68 seconds, the load was switched OFF, and the machine was run at No-Load.

RESULTS AND DISCUSSION

The steady-state performance of the machine obtained through experiments conducted in Step 1 of PAT-SEIG experiments is the, as shown in Figure 5. It was observed that the speed and frequency varied with the load resistance. The frequency increased directly proportional to the resistance and speed. When there was a high load resistance of 500 Ω, the frequency was 50.2 Hz. As the load connected to the generator was decreased, the frequency and speed decreased correspondingly.
With the resistor replaced with the bulbs, the PAT SEIG system powered a load of ten 50 W LED lights connected to the circuit. The voltage and frequency were recorded, as shown in Figure 6. The recorded voltage was 242.3 V at a frequency of 51.3 Hz. The generator speed did not fluctuate and was measured at 1600 rpm.
From step 2, the Start-stop transient characteristic with a load of 158.4 Ω connected to the circuit as the load was obtained, as shown in Figure 7. The generated no-load voltage was 242.3 V at a speed of 1600 rpm. The load was switched ON at 20 seconds, and the speed and voltage were reduced to 1385.33 rpm and 220 V, respectively. The generator was switched OFF at 38 seconds by cutting the water feed to PAT.

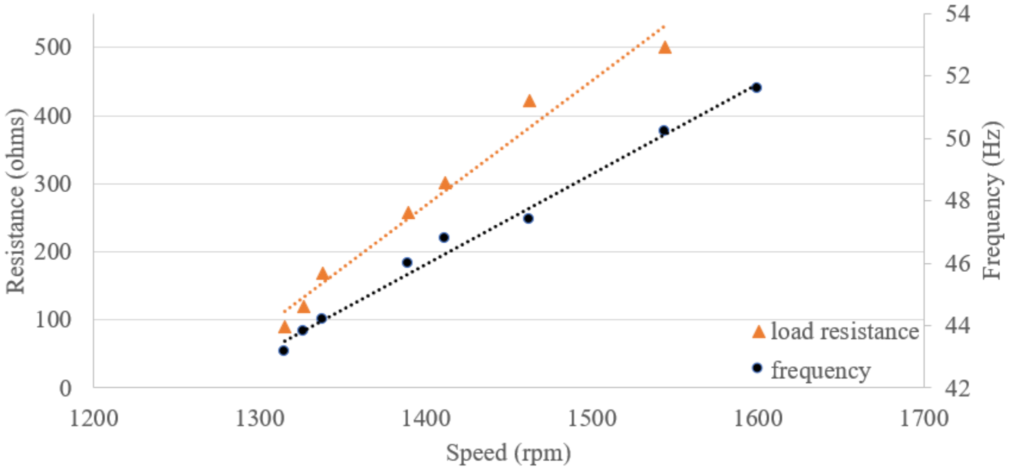

Figure 5: variation of speed and frequency with resistance.

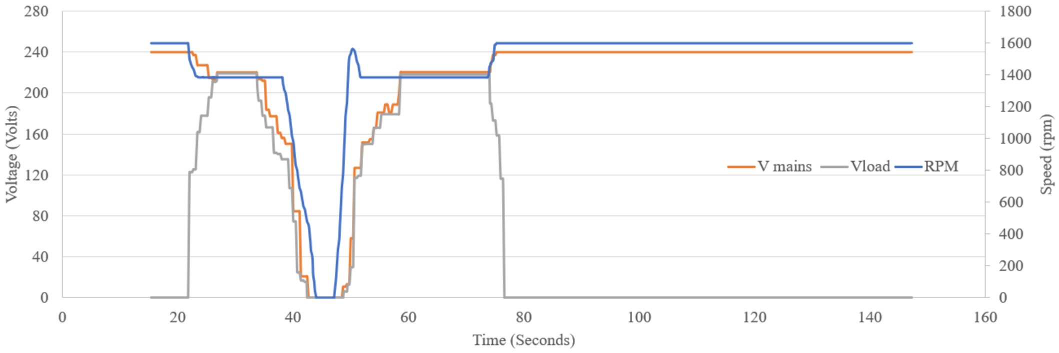

Figure 6: Stop-start generator transient characteristics.

Figure 7: Induction generator supplying a load.

It was observed that the speed and voltages fell to zero. At 48 seconds, the water supply to the PAT was restored, and the speed of the machine increased following a transient characteristic. The generated voltage and load voltage increased to reach the previous ON load values of 1385.33 rpm and 220 V. At 73.93 seconds, the load was switched OFF, and the machine ran at No-Load values of 1600 rpm and mains voltage of 242.3V.

It has been shown that the produced voltage and frequency can achieve the standard levels of 240 V, and the generated power depends on the rating of the induction motor operated as a generator. The voltage output fluctuates with changes in load impedance. Experimental results indicate that this generated voltage is sufficient to power a single-phase 500 W heating element. Additionally, this voltage could potentially power up to a 0.5 hp single-phase refrigerator compressor.

CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated that the PAT-SEIG system is capable of meeting practical power demands, such as those for heating, cooling, and lighting, by delivering a stable 240 V output sufficient to power multiple LED bulbs. Unlike intermittent renewable sources like solar and wind, this system provides continuous power, though challenges related to voltage variation and harmonic distortion persist. The observed transient characteristics, particularly the changes in speed and frequency with varying load resistances, underscore the need for careful management of operating conditions to maintain optimal performance. Ensuring the system operates near the target frequency of 50 Hz is crucial for maintaining high efficiency, especially when powering resistive loads. Another advantage is that Pumps and induction motors can be sources off the shelf hence cheaper compared to panels at the same rating. Future research should focus on improving voltage stability and reducing frequency fluctuations, possibly through the integration of series capacitors or other stabilization techniques which is essential to maximizing the reliability and overall effectiveness of PAT-SEIG systems in diverse and dynamic energy applications.

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NOMENCLATURE

COP	Coefficient of Performance
PAT	Pump as turbine
SEIG	Self-Excited Induction Generator
LED	Light Emitting Diode
BTU	British Thermal Unit

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