Tanzania Journal of Engineering and Technology 2024, **43**(4):22 - 35

Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v43i4.1000

Regular Research Manuscript

A Bibliometric Analysis of PAT-SEIG Evolution as an Alternative Energy Generation Method

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ABSTRACT

Pumps as Turbines (PATs) coupled with Self-Excited Induction Generators (SEIGs) as an alternative energy generation method have been the subject of significant research in recent years. This paper presents a bibliometric analysis of the evolution of PAT-SEIG technology as an alternative energy generation source. An analysis of a comprehensive dataset of peer-reviewed journal articles, conference proceedings, and patents related to PAT-SEIG systems, using advanced bibliometric techniques and PRISMA to identify key research themes, influential authors, the growth of the field and patterns of collaboration, and changes in research focus over time. Over a publication period of 32 years, a total of 949 documents were reviewed using the PRISMA checklist, resulting in the selection of 77 documents for analysis. The findings indicate an increasing interest in PAT-SEIG technology, with an impressive annual growth rate of 9.45%. However, gaps have been identified which provide areas for further studies. These include the PAT prediction methods, voltage and frequency fluctuations in SEIG, and the overall efficiency of the PAT-SEIG system. The study provides insights into the current state of research and highlights areas that require further investigation as a way of contributing to the advancement of the technology.

ARTICLE INFO

Submitted: **Apr. 24, 2024**

Revised: **Nov. 13, 2024**

Accepted: **Dec. 20, 2024**

Published: **Jan. 2025**

Keywords: *Alternative energy sources, micro-hydro, pump as turbine (PAT), and self-excited induction generator (SEIG).*

INTRODUCTION

Access to electricity is one of the catalysts for social and economic development in rural communities. Small and medium industries thrive with access to electricity (UNIDO, 2022). Conventional electricity is generated using a synchronous generator primed by conventional turbines (Francis, Kaplan, Pelton, etc) controlled by a governor. This use of conventional methods makes economic sense for hydro generation from 100 kW and above. For small streams with lower potential below 100 kW, the electromechanical equipment cost becomes significant, reaching up to 40% of the total project cost (Binama *et. al*., 2017; Choudhary and Saket, 2015; Kumawat *et. al*., 2015).

In a quest to find cheaper alternative energy generation methods, a pump working in reverse as a turbine coupled to an induction motor working in reverse as a generator has gained research attention in recent years. Using PAT offers several advantages over conventional water turbines for stand-alone micro-hydropower systems. These benefits include a wide availability of centrifugal pumps with varying capacities and heads, cost-effectiveness, and easy access to spare parts like bearings and seals. Unlike some conventional turbines that need to be custom-made based on specific site parameters, PATs are readily accessible and can be quickly deployed (Derakhshan and Nourbakhsh, 2008; Yang *et al*., 2012). This makes PATs a viable option, especially for very low-power plants (below 100kW), as they offer a shorter capital payback period, typically within two years. Additionally, PATs can be designed to maintain a constant flow rate even with minimal annual water availability, and multiple PATs can be installed in parallel to manage demand fluctuations by turning them on and off as needed. Pumps are readily available on the market and are mass-produced. The study of pumps working as turbines started (Fernández et al., 2005; Kandi *et al*., 2021; Mdee *et. al*., 2016).

There are different types of induction motors, but the squirrel cage-type induction machine is of interest because it is rugged, readily available, and requires little maintenance (Rana & Meena, 2018). SEIG is a type of electric generator that operates without a separate source of excitation. It is commonly used in small-scale renewable energy systems, such as wind turbines and hydroelectric generators. A prime mover, such as a wind turbine rotor or a water turbine, is connected to the generator's shaft (Chauhan *et. al*., 2013; Singh, 2004; Bonert and Rajakaruna, 1998). When a mechanical prime mover powers a standalone induction machine, the machine's residual magnetism induces a voltage in the windings of the stator at a frequency that is directly proportional to the rotor speed. The induced voltage appears across the capacitors connected to the stator terminals, causing a reactive current to flow in the stator windings. Consequently, a magnetizing flux is created inside the machine (Kumawat *et. al*., 2015). The magnetic saturation inside the machine restricts the stator voltage's final value. Because the induction machine is singly excited, the electrical system connected to it needs to be able to supply the reactive VAR required to create the air-gap flux. The induction machine can operate in two modes. One is that it can be connected to the grid, and the second is in isolated mode. No matter which mode the machine operates, it will always be a VAR consumer. When the machine is grid-connected, it draws the reactive power from the grid, and when in isolation, the reactive power is drawn from the shunt-connected capacitors (Choudhary and Saket, 2015; Khalaf and Ali, 2020; Khan and Khan, 2016). SEIGs are known to exhibit poor voltage and frequency regulation, making them less suitable for sensitive electronic loads (Chauhan, Jain, et al., 2010). Voltage and frequency control mechanisms are often needed to stabilize the output. SEIGs may exhibit a poor transient response to load changes, which can affect their ability to supply power reliably (Giuliani *et. al*., 2015; Haque, 2008).

A pump working in reverse as a Turbine coupled to the induction generator (PAT-SEIG) is becoming a potential solution to the high cost of developing the potential micro hydro sites. The PAT-SEIG system is composed of a conventional pump run in reverse as a generator (Calgan *et. al*., 2020; Paliwal *et. al*., 2017). The self-excited induction generator is a crucial component in renewable energy production. It offers a cost-effective and straightforward solution for hydroelectric and wind energy applications. The induction generator has some drawbacks, as its excitation typically requires an external power source. In this mode of operation, the prime mover supplies the real power demand of the terminal load while the capacitor bank is used to supply the reactive power requirement of the load and generator (Mdee et al., 2020). PATs and SEIGs have been the subject of various review works (Giudicianni et al., 2023; Liu *et. al*., 2022a; Amelio et al., 2021; Binama *et. al*., 2017; Jain & Patel, 2014; Agarwal, 2012). This paper provides a systematic literature analysis of the following (i) an overview of micro hydro plants, (ii) a research evolution of SEIG and PATs, and (iii) current trends in research and research fronts.

MATERIALS AND METHODS

The review followed a systematic review protocol drawn using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) on articles retrieved from SCOPUS. It is established that Google Scholar, Scopus, Web of Science and Dimensions are the most used publication databases (Page *et. al.*, 2021). An inclusion/exclusion criterion was created to eliminate journal articles that were not pertinent to the current inquiry. The requirements were established, along with where to find the information and how to do searches. The snowballing technique was used to collect additional pertinent information from all of the chosen articles' references to clarify the primary inclusion criteria (Wohlin, 2014). Figure 1 indicates the systematic literature survey using PRISMA.

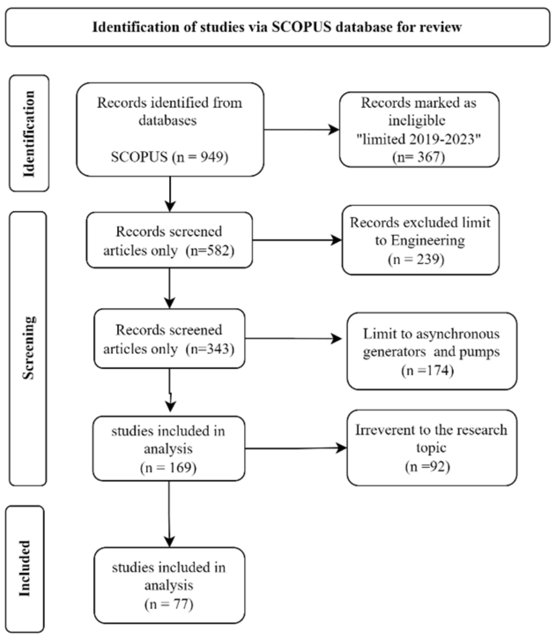

Figure 1: PRISMA Flowchart.

Database Search Criteria

The phrase: pump as a turbine and self-excited induction generator is used in the database search as indicated in Table 1. Results from 1991 to 2023 show a total of 5921 records. The search was improved to only capture peer-reviewed articles. Peer-reviewed articles cover the following keywords for inclusion in the analysis: asynchronous generators, self-excited induction generators, and pump as turbines. The outcome of the criteria for inclusion resulted in 949 articles being qualified for analysis.

The data was analysed by VOSviewer and Rstudio bliometrix and biblioshiny software. VOSviewer and R studio are software tools for the construction and visualization of bibliometric networks at a cumulative level and they use two visualizations. The level 1 clusters are shown in one visualization, along with the citation relationships between these clusters, and the topics covered by a level 1 cluster are shown in the second visualization using a term map indicating the topics for the level 1 cluster (Page *et. al.*, 2021; van Eck and Waltman, 2017).

Table 1: Inclusion criteria for the database search.

Option	*Inclusion criteria applied*
Language	English
Search phrase	"Pump as a turbine" AND "self-excited induction generator"
Keywords	asynchronous generators, self-excited induction generators, and pump as turbines
Source type	Journal articles
Document Type	Articles

RESULTS AND DISCUSSION

This section presents the results from the systematic review of the bibliometric search. After applying relevant restrictions, the database search yielded 949 documents for review as shown in Figure 2. The publication years span a range of 32 years, exhibiting an impressive annual growth rate of 9.45%.

Since 1991, 1,737 authors have contributed to the research topic. However, this number may represent only a portion of the overall contributions, as not all journals have been included in the analysis.

Keywords Concurrence

Figure 3 shows the concurrence map obtained by Vioswier linking the keywords in the research articles under consideration. The size of the circle represents the frequency of use of the keyword in the most relevant themes, and the circle's placement suggests a correlation in publications in this network visualization of keyword co-occurrence. The colour indicates the year range in which the keyword was most researched.

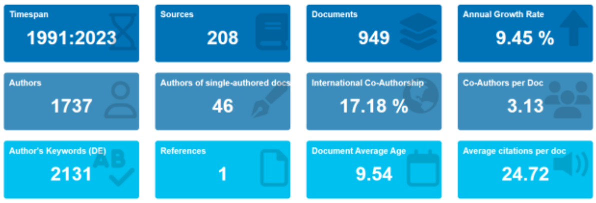

Figure 2: Summary information for the Scopus search.

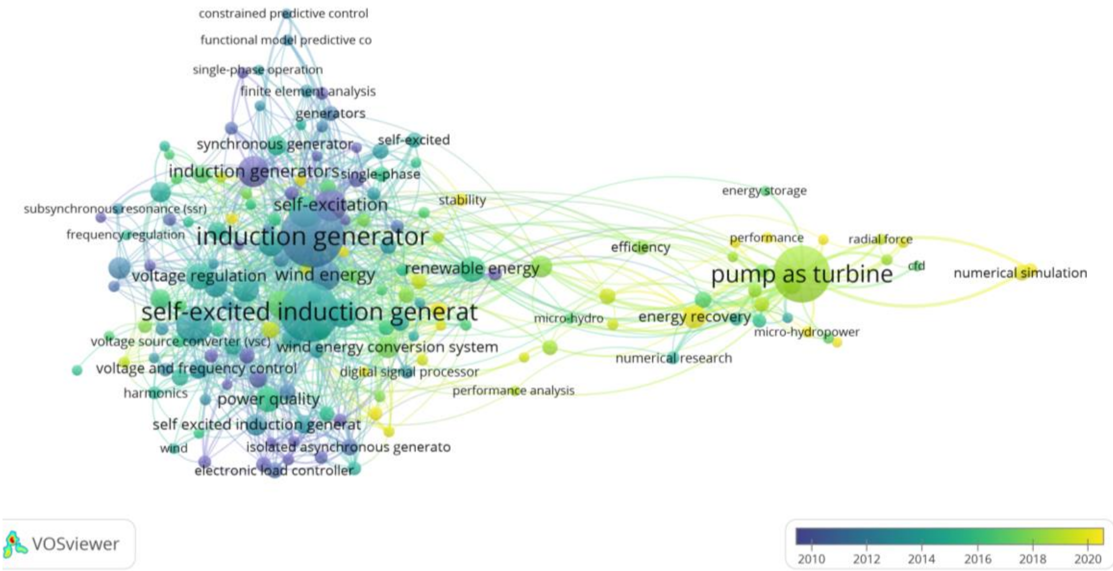

Figure 3: Map of keywords indicating research progress.

The induction generator has been a highly researched area where the machine is connected to the grid. The development of wind energy generation of electricity led to more research in induction generator applications.

From the graph, it is observed that the "pump as a turbine" has gained popularity in recent years. It can also be observed that the study of induction generators gained much attention in early 2000. This was in a quest to diversify renewable energy sources and search for alternative energy generation methods. Research in favour of induction generators has grown so far because induction machines are readily available, cheap to construct, and require little maintenance (Abdel-Aziz *et. al*., 2017). In rural areas, the electrical loads are primarily single-phase, which means that a single-phase induction generator (IG) can often adequately meet the demand. However, three-phase induction generators have several advantages, including higher efficiency, a more compact design, and cost-effectiveness, making them a more favourable option compared to single-phase generators. One of the primary challenges of using a three-phase induction generator for single-phase loads is the potential for current imbalance in the system.

Main Authors Contributions

The information presented in Figure 4 highlights the contributions of authors who have published two or more articles between 2002 and 2020. Notably, Singh B. and Murty S.S. have made substantial contributions to the analysis of induction generators. Meanwhile, Yang S.S. and Derakhshan S. have established a foundational base for further research on pumps as turbines with their key publications.

Murthy (1982) described a new analytical technique that used the Newton-Raphson method to identify the saturated magnetizing reactance and generated frequency of the

SEIG under steady-state conditions, given specific values for capacitance, speed, and load. The technique set the foundation for other researchers to improve on.

Singh et al. (2004) Tested several centrifugal pumps (Ns < 60) and using experimental data, relationships were derived to predict the BEP of the PAT. The model was validated using referenced experimental data. Two equations were derived to estimate the complete characteristic curves of PAT based on the best efficiency point. A procedure was presented for selecting a suitable pump to work as a turbine in a small hydro-site.

Bansal (2005) provided a literature survey for the previous 25 years on SEIG operating in isolation, covering classifications, parallel operation, and voltage control. The article highlights SEIGs' advantages over synchronous generators, like affordability, simplicity in design, and ease of maintenance. However, it also acknowledges challenges such as reactive power compensation, voltage regulation, and parameter variations.

Derakhshan and Nourbakhsh (2008) tested several centrifugal pumps ($N_s < 60$) as turbines. Based on experimental data, approximation equations were developed to predict the BEP of a pump operating as a turbine. The validity of the model was established using experimental data. Two equations were derived to estimate the characteristic curves of the PAT at the BEP. A procedure was presented for selecting a pump that is best suited to work as a turbine at a particular micro hydro site.

Amelio *et. al*., (2021) reviewed methods used for predicting PAT performance, with the main objective of aiding the designer of hydroelectric plants suitable for the use of PAT. The analysis of 1D, 2D and simulation models was presented indicating their advantages and drawbacks.

Yang *et. al*., (2012) presented various methods for predicting the performance of PATs. Theoretical analysis is first conducted to develop relationships between pump and turbine characteristics, head, flow rate and efficiency followed by empirical correlation. Computational fluid dynamics (CFD) simulations are used to model the behaviour in both pumping and turbine modes. The theoretical method and CFD predictions are found to provide more accurate estimates of PAT performance characteristics at the best efficiency point compared to some other existing prediction techniques.

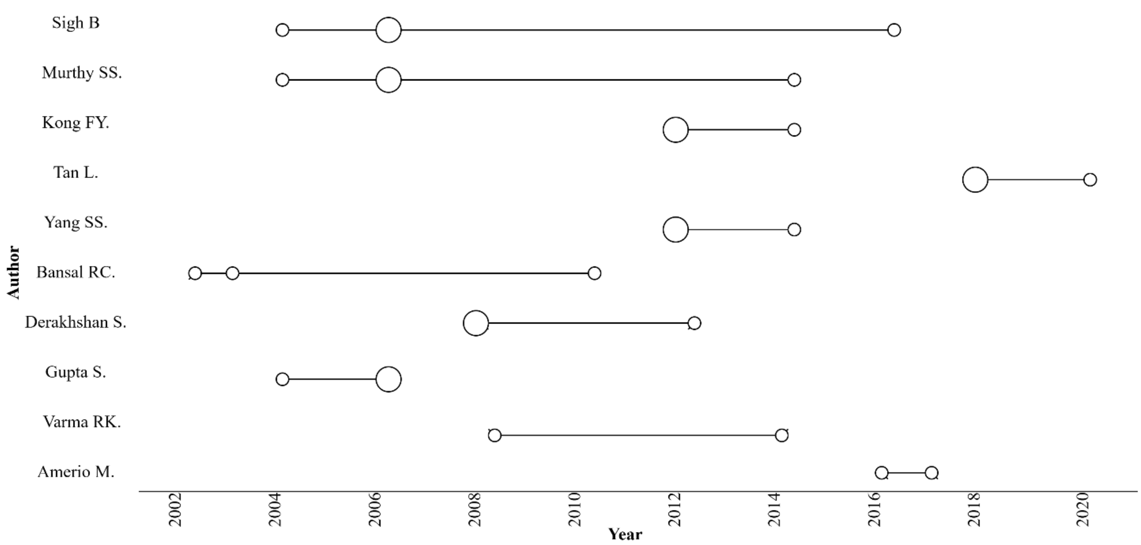

Figure 4: Authors' production over time.

Abdel-Aziz *et. al*., (2019) evaluated the SEIG connected to a single-phase load. The study established that although three-phase generators offer higher efficiency and are smaller in size, they are not ideal for supplying single-phase loads. This is due to current imbalances, leading to issues like pulsating torque and machine overheating. The study proposed a novel approach, employing a three-phase generator excited by two capacitors, with capacitor values determined through the Ruth-Hurwitz stability criterion.

From the analysed literature, there are still no models and methods able to predict PAT characteristic curves. Research is ongoing to find the best model to predict PAT behaviour. Considering the SEIG, the excitation and loading conditions for the machine are not fully understood, and some gaps need further research. From the highlighted literature, it is observed that PAT and SEIG's initial research was mutually exclusive.

Contribution to Research Based on Countries

Figure 5 identifies the various research groups from different countries and their research contribution with respect to time. It is observed that India has contributed significantly to the growing research on Induction generators. India spearheaded the analysis of the equivalent circuit and estimation of the excitation capacitance based on the steady-state equivalent circuit analysis (Bonert and Rajakaruna, 1998; Yadav, *et. al.*, 2013; Malik *et. al.*, 1982; Singh, 2004).

Italy and Spain have been conducting research on energy recovery systems, with notable contributions from Carravetta *et. al.*, (2013) and Stefanizzi *et. al.*, (2020), who look at energy recovery from water distribution networks using PATs. The researchers emphasize the significance of examining the interactions between energy recovery and water management, including the types of machinery installed, the economic and environmental effects of large and small hydropower systems, and how hydropower can be used in water distribution networks to achieve sustainable improvements in the performance of irrigation water networks.

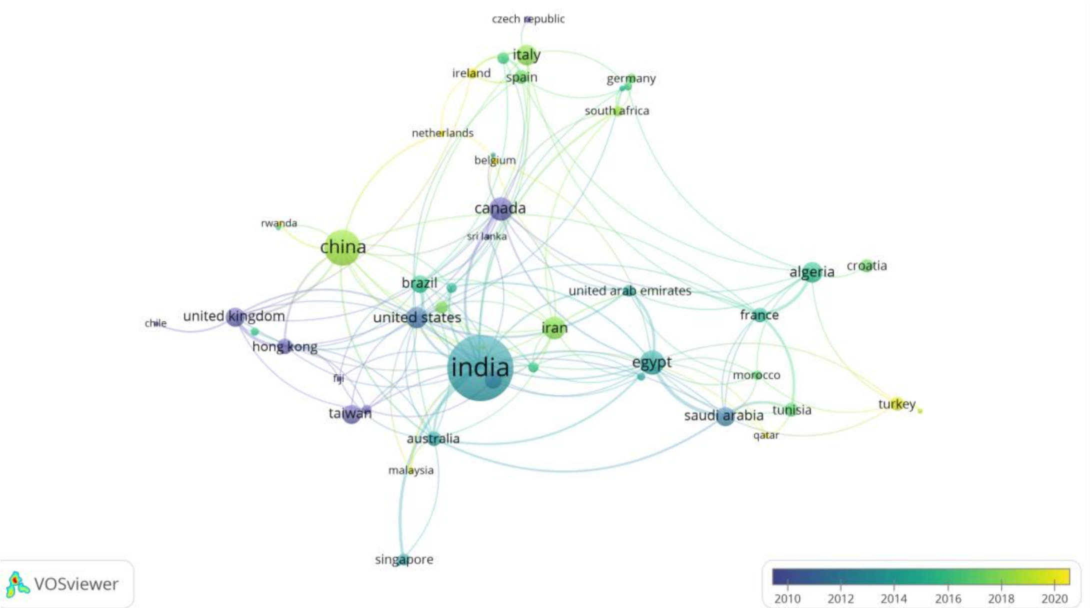

Figure 5: Research contribution based on countries.

Word Cloud Map

Keywords were analysed directly from the published documents, taking into account the frequency of appearance of the most used keywords, as shown in Figure 6. In this way, it was evident that the most used keywords were asynchronous generators, pumps as turbines, and wind power. The development of induction generators has led to significant leaps in harnessing wind power. Currently, further applications of these generators are being made in micro-hydro applications as the search for alternative energy generation methods is ongoing. Pump as turbines is an emerging technology being studied for applications in energy recovery solutions for water distribution networks and as stand-alone systems supplying power to isolated loads.

Figure 6: Keywords word cloud.

Research development and trends

A research front is typically understood as a circumstance in which societal needs and interests align with the most recent scientific findings. The groups of scientific publications and their relationships are the main subjects of analysis when determining research fronts. A research front is, by definition, a network of recently published papers that are heavily cited. A research front is defined in more detail as a collection of recently published articles with a common topic that are strongly connected through a network of citations and weakly connected to publications outside the group (Mazov *et. al*., 2020; Nederhof and Van Wijk, 1997).

Figure 7 shows the research trends in pumps as turbines and self-excited induction generators. Pumps as turbines and self-excited induction generators are at the top of the research trends. This area is growing as the world focuses on decentralized energy generation methods and energy recovery systems.

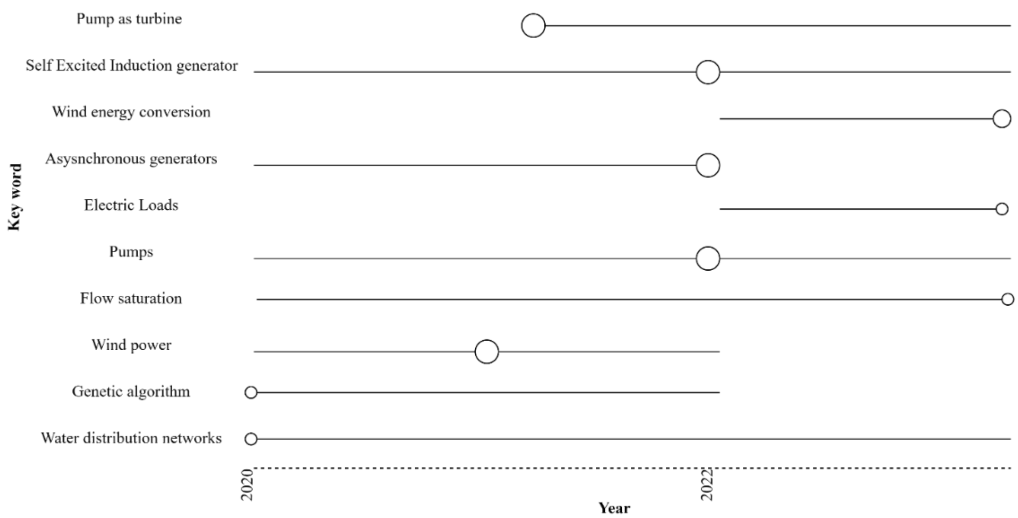

Figure 7: Current research trends

In the early stages of research, investigations focused on the fundamental principles of reverse operation for pumps and induction (asynchronous) motors, with a distinct emphasis on studying each system independently. Given the necessity for excitation in integrated generators, the research subsequently expanded to explore both grid-connected and stand-alone generator configurations. This included the derivation of formulas for determining excitation capacitor values and the development of conversion factors relevant to PAT.

Current research in the field concentrates on enhancing the efficiency and optimizing the performance of pump-as-turbine (PAT) systems under varying operational conditions, alongside leveraging advanced material technologies. Additionally, there is a notable emphasis on performance prediction utilizing various modelling approaches, including polynomial fitting, curve analysis, and non-dimensional methodologies. A key gap identified is the lack of operating curves from manufacturers for pumps functioning in reverse mode; consequently, researchers are leveraging computational fluid dynamics (CFD) simulations coupled with experimental studies to formulate robust predictive models for PAT applications (Nasir *et. al.*, 2023a; Wang *et. al.*, 2022; Fontanella *et. al.*, 2020; Jain, *et. al.*, 2013; Ibrahim and Metwaly, 2011; Chauhan *et. al.*, 2011).

Researchers are actively working to address the challenges associated with Self-Excited Induction Generators (SEIGs) and improve their performance for various applications. Their focus is on developing control strategies and power electronics solutions to enhance voltage and frequency regulation in SEIGs. Additionally, they are investigating methods to improve the transient behaviour of these systems, making them more responsive to sudden changes in load. Studies are also being conducted on how SEIG-based systems can be integrated into microgrids and distributed energy systems to enhance overall stability and resilience (Aree, 2018; Khan *et. al.*, 2022; Perez-Sanchez *et. al.*, 2020).

Overall, ongoing research aims to make SEIGs more efficient, reliable, and suitable for a wide range of applications, particularly in renewable energy systems, where they can play a vital role in harnessing clean energy. Table 3 summarizes the thematic areas of research and the research gaps.

Table 2: Research areas and gaps

Issues with SEIG	**Papers**	**Observation/ gap**
Voltage and Frequency regulation Selection of excitation capacitors	Taghikhani and Farahani, (2017), Bonert and Rajakaruna, (1998), Capelo *et. al*. (2017), Fernandes *et. al*. (2019), Marra *et. al.* (2000), Nigim *et. al.*, (2004), Özer et al. (2022), Paliwal *et. al.* (2023), Qureshi *et. al.* (2022)., Chakraborty *et. al.* (2021)	When the load connected to the SEIG is increased, the frequency and voltage decrease. Research is ongoing to determine the optimal excitation values for the capacitor. Different approaches are used to calculate the minimum capacitance.
Issues with PAT		
Operating point and efficiency prediction methods and selection of Pump as Turbine	(Amelio *et. al.* (2021), Barbarelli *et al.* (2017); Manservigi *et. al.* (2021), Mdee et. al. (2021), Liu *et. al.* (2022b), Qin *et. al.* (2023); Zhang et al. (2023), Stefanizzi et al. (2020), Venturini *et. al.* (2018), Nasir *et. al.* (2023)	The process involves the calculation of conversion factors and using non-dimensional analysis, Statistical analysis, and experimentation The different approaches can be compared to select the one predicting the BEP of the PAT
Global issues		

Selection of PAT-SEIG machine combination for a particular site and overall efficiency	Fernandes *et. al.* (2019), Fernández García *et. al.* (2022), Pagaimo et al. (2021), Renzi M, *et. al.* (2019) Venturini *et. al.* (2018), Madeira *et. al.* (2020)	Considering site parameters and the expected load to be supplied by the PAT-SEIG, the selection of the appropriate size of the pump is crucial. Research is ongoing on the best selection methods for the PAT-SEIG for the best efficient operation at a particular site.

CONCLUSION AND RECOMMENDATIONS

The study of PATs and SEIGs has witnessed a significant evolution over the years. From its early stages, where fundamental principles were explored by developing the equivalent circuits and calculation of the excitation capacitors, to the contemporary focus on efficiency enhancement and predictive modelling, researchers have continually adapted their investigations to contribute to decentralized energy generation and sustainable practices. Current trends focus on:

a. Making PATs and SEIG more efficient, research is ongoing focusing on the loading and efficiency of the SEIG
b. Reliability of the PAT-SEIG to supply power at standard voltage and frequency with minimal transients
c. Adaptable, thus contributing substantially to the advancement of renewable energy systems and the broader quest for a sustainable future.

The selection of a PAT to couple to SEIG for a specific site involves crucial considerations for optimal performance. Mathematical correlations between site characteristics and pump hydraulic data aid in choosing the most suitable pump for power generation applications. The methodology for selecting the best PAT focuses on maximizing energy production based on efficiency points and hydraulic parameters of the site. Incorporating micro-hydro turbines in water systems can enhance energy efficiency, especially in off-grid recovery systems, where the PAT-SEIG combination plays a vital role. Analysing transient regimes of the PAT-SEIG system under sudden changes in hydraulic or electrical components is crucial for understanding efficiency variations. Overall, the proper selection and analysis of the PAT-SEIG combination are essential for achieving high efficiency in micro-hydropower applications.

ACKNOWLEDGMENTS

The study was facilitated with funding from the NORHED II initiative, specifically through its Energy and Network (ENET) Project at the University of Dar es Salaam (UDSM) in Tanzania and the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

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