Tanzania Journal of Engineering and Technology 2024, **43**(1):133-143
OPEN ACCESS articles distributed under Creative Commons
Attribution Licence [CC BY-ND]
Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v43i1.909

Regular Research Manuscript

Optimization Pump as Turbine Coupled to a Self-Excited Induction Generator Using Multi-Objective Genetic Algorithm

Emanuel J. Nyirenda[1,2†], Joseph H. Kihedu[2], Cuthbert Z.M. Kimambo[2], Torbjorn K. Nielsen[3]

[1]Mechanical and Industrial Engineering Department, University of Dar es Salaam, Tanzania
[2] Electrical Engineering Department, Malawi University of Business and Applied Sciences, Malawi
[3]Department of Energy and Process Engineering, Norwegian University of Science and Technology, Norway.
[†]Corresponding author: enyirenda@mubas.ac.mw

[†]ORCID: https://orcid.org/0000-0003-0622-5860

ABSTRACT

As a way of accelerating the deployment of affordable and clean renewable energy generation technologies, applying a pump working as a turbine coupled to a self-excited induction generator is gaining popularity in various areas including energy recovery and micro hydro systems. However, it is currently challenging to predict the performance of the PAT-SEIG system and there is no agreed-upon rule on the selection of the appropriate system to be installed at a particular site. This paper has presented multi-objective optimization to select the best operating point of the PAT-SEIG system. The results show that the peak efficiencies for the PAT fall between 39.9% and 40.08% and for SEIG they fall between 69.78% and 69.84% and are not coincident. Thus, when selecting the operating point, a trade off on one element is necessary. Gamultobj optimization outputs the Pareto solutions and FMINCON locates the BEP within the Pareto solutions.

ARTICLE INFO

Submitted: **Feb. 26, 2024**

Revised: **March. 14, 2024**

Accepted: **March, 30, 2024**

Published: **Apr., 2024**

Keywords: *Pump as Turbine, SEIG, energy recovery, energy sources, genetic algorithm, optimization*

NOMENCLATURE

PAT	Pump as Turbine
BEP	Best efficiency point
SEIG	Self-Excited Induction Generator
MOO	Multi-objective optimization
FMINCON	Function minimization with constraints
Gamultobj	Genetic Algorithm multi-objective optimization function

INTRODUCTION

To contribute to the achievement of Sustainable Development Goal 7 by 2030, there is a need to accelerate the deployment of new, affordable, clean renewable energy generation technologies to isolated and hard-to-reach areas (Liu et al., 2019). Clean energy conversion technologies refer to technologies that are designed to generate electricity or useful energy from renewable and low-carbon energy sources, with minimal environmental impact. These technologies are critical to the transition to a low-carbon economy and the reduction of greenhouse gas emissions, as they assist in reducing reliance on fossil fuels and mitigating the impacts of climate change (Arshad, 2017; REN21, 2022).

Hydropower is a form of renewable energy that is widely available and currently provides electricity to over 16% of the world's population. However, the electromechanical units used for power generation are the most expensive components of conventional hydropower systems. This is because they are custom-made and site-specific. Researchers are currently exploring non-conventional energy sources such as wind, biomass, and solar as alternatives to address the shortage in power generation and meet the rising global demand for electricity. With the rapid depletion of fossil fuels and increasing fuel costs, distributed power generation schemes that produce small amounts of power and distribute it to local networks are taking center stage (Jain and Patel, 2014; Kaunda, 2013; Singh et al., 1990). Conventional hydro turbines and the associated governing equipment have a high cost and hence are unaffordable, especially for distributed power generation in rural off-grid areas. To reduce the electromechanical equipment cost, the use of pumps operating in reverse as turbines coupled with self-excited induction generators is becoming increasingly popular as an alternative energy generation method. The PAT-SEIG system offers a low-cost solution that can replace commercial micro-hydro turbines. (Subramanian and Sabberwal, 2014).

Squirrel cage induction motor types are preferred because of their simple rotor design, inherent ruggedness, and cost-effectiveness for relatively small machines. When driven above the synchronous speed, the induction motor operates as a generator. The prime mover can be a turbine, an engine, a wind turbine, or any other device that provides the necessary torque and speed to drive the generator. For micro-hydro installations the use of pumps working in reverse as turbines is gaining momentum (Ali and Davoudabadi, 2017; Khan and Khan, 2016; Fernandes et al., 2019). Pumps and induction motors are readily available on the market and can be bought off the shelf. The challenge is matching the Pump and the generator for electricity production at a particular site. Several issues including the load to be supplied, the available power from a stream, and the efficiency of the generation system are worth considering (Kandi et al., 2021; Manservigi et al., 2021; Stefanizzi et al., 2020).

The efficiency of the PAT-SEIG system depends on the efficiencies of the individual machines. Therefore, the selection of the best operating point is crucial in designing the generation system, especially when using off-the-shelf machines (Fernandes et al., 2019). Several studies have looked at the efficiency curves and prediction of the efficiency curves of the Pump as Turbine. There are four categories of PAT performance prediction methods: those using BEP, those using specific speed, loss modeling, and polynomial fitting. Each method has its advantages and disadvantages (Liu et al., 2022; Wang et al., 2023).

There are various optimization methods available, each with its strengths and limitations, making them more suitable for certain types of optimization problems. Single-objective optimization is straightforward and efficient but can't handle multiple conflicting objectives. Evolutionary algorithms are adaptable and can handle complicated problems, but they may be computationally expensive. Gradient-based methods are efficient for convex optimization, but they may struggle with non-convex problems (Abed-alguni et al., 2022; Grosan, 2004). Multi-Objective Optimization involves optimizing multiple objectives that may conflict with each other. Instead of finding one solution, MOO aims to determine a set of solutions that includes all conflicting objectives. The method used depends on the problem. Multi-objective optimization provides insights into trade-offs between conflicting objectives, but it may require more computational resources and analysis effort. The selection of the optimization method depends on the problem characteristics, objectives, constraints, and available computational resources (Rahimi et al., 2023).

Several researchers have contributed to the area of optimization of PAT and SEIG. The use of a genetic fuzzy algorithm to optimize the guide vane shape of a turbine, resulting in improved stability and performance of the pumped storage hydro was developed by (Zhang et al., 2023). The optimization strategy combined fuzzy logic and a genetic algorithm to adjust probabilities and weight factors and optimize control parameters. Filo (Filo, 2023) and Wang (Wang et al., 2022) Optimized the geometric parameters of the impeller in the PAT to reduce energy losses and improve efficiency under three different typical flow conditions. To improve energy recovery, a study by (Fernández García et al., 2022) focused on determining the number and placement of PATs in irrigation networks. The methodology was assessed in two networks with significant flow variation while considering the theoretical PAT curves. (Qin et al., 2023; Zhang et al., 2023) examined turbine performance at different speeds and analyzed head loss, pressure distribution, and other factors. Results indicated that as rotational speed increased, the high-efficiency area of the turbine widened, but there was little variation in maximum efficiency across speeds. Wang et al. (2020) proposed a MOO strategy for pump-as-turbines, using one-dimensional theory and analysis of geometrical parameters. The optimization of the impeller geometry was performed with a genetic algorithm and resulted in increased efficiencies for both the pump and optimized variables of PAT. Ramos et al. (2022) proposed a MOO approach using genetic algorithms to recover excess hydraulic energy and reduce water losses in water networks. The use of PAT as pressure-reducing valves (PRV) to regulate pressure, generate electricity, and ensure system feasibility was explored.

There are few studies considering the optimization of PAT coupled with SEIG. Several researchers (Hassan, 2011; Ibrahim and Metwaly, 2011) have analyzed the performance of a three-phase SEIG using different optimization algorithms including genetic algorithm and particle swarm optimization to minimize the generator's total impedance equation. Comparing the results, it was determined that GA is the most effective algorithm for analyzing SEIG. current discussions of performance optimization include types of induction generators, modeling techniques, capacitance requirements, and optimization techniques for voltage regulation and frequency control (Fracassi et al., 2022; Khan and Khan, 2016; Khan et al., 2022).

The efficiency of the PAT and the SEIG are not coincident hence it requires an optimization tool to get the best operating point (Fernandes et al., 2019; Madeira et al., 2020). This study presents a methodology for selecting an optimal PAT-SEIG system operating point for installation at a site with known site parameters and load profile. The selection process uses multi-objective optimization to find the optimal operating point for the PAT-SEIG system by finding the Pareto solutions from the efficiency equations of the PAT and SEIG. The paper further explores the characteristics of a Pump and an Induction generator that were separately acquired from the market via experimentation and optimization algorithms. Efficiency relationships were developed from experimental data to provide input for the genetic algorithm optimization model.

METHODS AND MATERIALS

This section describes the materials and methods used to achieve the study objective. The study focuses on two main components, a pump and an induction motor. The components were sourced online due to their easy accessibility. An experimental study was conducted on each component to determine their characteristics, and the results of this experiment were used as input for MATLAB.

Pump as turbine characteristics

The pump used in the study is Pedrollo FG 32/160P with the following specifications: - 1450rpm speed, head of 6.2m, and flow rate of 8.7m3/hr at an efficiency of 55%. During the turbine testing process, water flows down from a tank through a 600mm diameter pipe. A gate valve is used to regulate the flow into the next section of piping where the diameter is reduced to 200mm. The pipe diameter is further tapered down to 50mm through the flow sensor before it is reduced to a diameter of 32mm. From there, the pipe is directed to the inlet of the PAT. The water passes through the impeller and is then discharged through a 50mm diameter pipe into the reservoir.

The lab used a pressure tank to supply water for PAT testing and the bottom reservoir for pump operation testing. The water flow into the pipe was controlled with a gate valve and the flow rate was measured using the flow sensor model Optiflux 2000 C. Two pressure sensors were used to log inlet and outlet pressures. The HBM T22/200Nm sensor measured torque to calculate efficiency. An rpm sensor was also used to count every passing of a small reflector tape on the shaft.

To obtain the H-Q characteristic for the PAT, the gate valve is adjusted gradually from fully closed to fully open positions. The flow rate and the pressure at the input at the PAT input and tailrace. The flow rate range is between 0 and 23m3/hr.

SEIG Characteristics

The equivalent circuit of the SEIG is shown in Figure 4 circuit is divided into three parts: the inductive load (R_L, X_L), the capacitive reactance (X_c) and the equivalent electric circuit of the induction generator. The parameters R_S and $R_r^{/}$ represent the stator resistance and the rotor resistance referred to the stator respectively, $X_S$and $X_r^{/}$ represent the stator leakage reactance and the rotor leakage reactance referred to the stator, respectively. The remaining $R_m$and $X_m$are parameters representing iron losses and the air-gap magnetic energy in the induction machine. s is slip $(= \frac{n_s - n_r}{n_s})$.

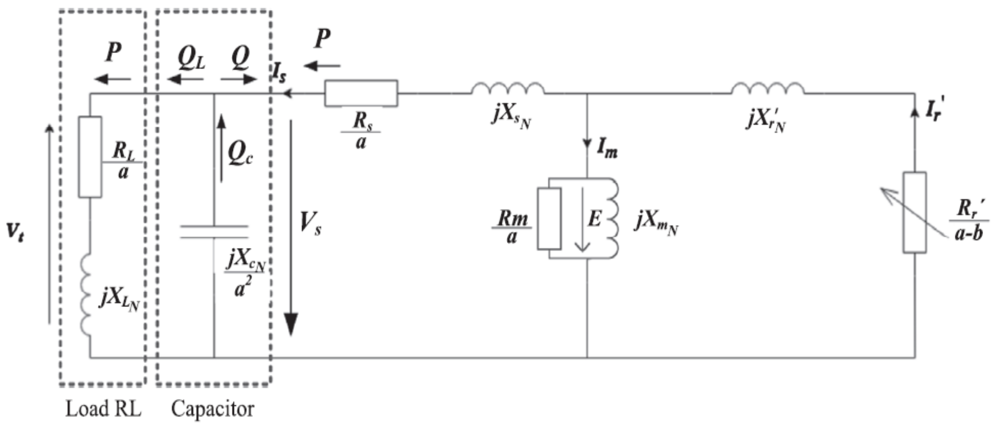

Figure 1: Equivalent circuit of an induction generator (Source: Fernandes et al., 2019).

The parameters defined in the circuit will appear in the SEIG formulae for calculating excitation capacitance and efficiencies. The normalized circuit parameters done by dividing all circuit parameters by the per unit frequency $a = \frac{f}{f_b}$ are shown from equations 1-5.

$$X_s = 2\pi a f_b L_s \rightarrow \frac{X_s}{a} = 2\pi f_b L_s = X_{sb} \quad (1)$$

$$X_L = 2\pi a f_b L_s \rightarrow \frac{X_s}{a} = 2\pi f_b L_s = X_{sb} \quad (2)$$

$$X_m = 2\pi a f_b L_m \rightarrow \frac{X_m}{a} = 2\pi f_b L_m = X_{mb} \quad (3)$$

$$X_r^{/} = 2\pi a f_b L_r \rightarrow \frac{X_r^{/}}{a} = 2\pi f_b L_r = X_{rb} \quad (4)$$

$$X_c = \frac{1}{2\pi a f_b C} \rightarrow \frac{X_c}{a} = \frac{1}{2\pi f_b C a^2} = \frac{X_{cb}}{a^2} \quad (5)$$

$$s = \frac{N_s - N}{N_s} = 1 - \frac{N}{N_s} = 1 - \frac{N}{N_{sb} a} = 1 - \frac{b}{a} = \frac{a-b}{a} \quad (6)$$

To ensure the self-excitation of the induction generator, the total admittance (or impedance) of the equivalent circuit must be zero.

$$Z_t I_s = 0 \quad (7)$$

$$Z_t = Z_1 + \frac{Z_c Z_L}{Z_c + Z_L} + \frac{Z_2 Z_m}{Z_2 + Z_m} \quad (8)$$

where:

$$Z_1 = R_s + jaX_s$$

$$Z_c = -j\frac{X_c}{a}$$

$$Z_2 = \frac{aR_r}{a-b} + jaX_r$$

$$Z_L = R_L + jaX_L$$

$$Z_m = jaX_m$$

The voltage generated by a self-excited induction generator depends on several factors, including the speed of the rotor (Paliwal et al., 2023), the excitation capacitance since the machine requires reactive power to start generating, the load impedance which determines the operating speed, and the magnetization characteristics that indicate the critical capacitance and resistance for voltage buildup in the machine (Choudhary and Saket, 2015; Haque, 2008; Zhang and Haugland, 2019).

A no-load test was conducted to establish the magnetization curve of the machine operated as an induction motor. The induction machine tested in this study is a model 3-MOT 7AA90L04 induction motor with the following specifications; - rated speed of 1420rpm, 4-pole, 3-phase, 1.5kW at a power factor of 0.81.

Induction generator self-excitation

The selection of the right size of the capacitor is crucial for the excitation of the stand-alone generator. Together with the magnetizing curve, the capacitor determines the value of terminal voltage and the self-excitation process (Madeira et al., 2020; Singh et al., 2010). If the value of the connected capacitor is less than the critical capacitor value, then the generator would not excite as the capacitor would not supply the required reactive power for self-excitation (Masic et al., 2018). From the magnetizing curve and circuit parameters, the minimum excitation capacitance for the generator at no load can be calculated (Haque, 2012).

When the generator is loaded, the reactive power requirement will increase (Rana & Meena, 2018). The reactive power source has to supply both reactive requirements for the load and for the SEIG. The excitation capacitor for the test model was chosen to be 50µF which is higher than the minimum capacitance to maintain excitation at no load (Andersson & Bye, 2016). Figure 2 shows the arrangement of the experiments done at the Norwegian University of Science and Technology (NTNU).

Figure 2(a) shows an induction motor coupled to the PAT. The PAT is connected to an overhead tank through a series of pipes. The flow rate of the water from the tank is regulated using a gate valve, and a Krohne flow meter is used to measure the flow rate. The PAT system is connected to the induction generators through a torque sensor and an rpm sensor is also installed to monitor the rotational speed of the shaft. The induction generator is excited by three 50µF capacitors arranged in a 2C2 configuration. The capacitors excite the machine while feeding a variable single-phase load and a dump load through a thyristor-controlled ELC, as shown in Figure 2(b).

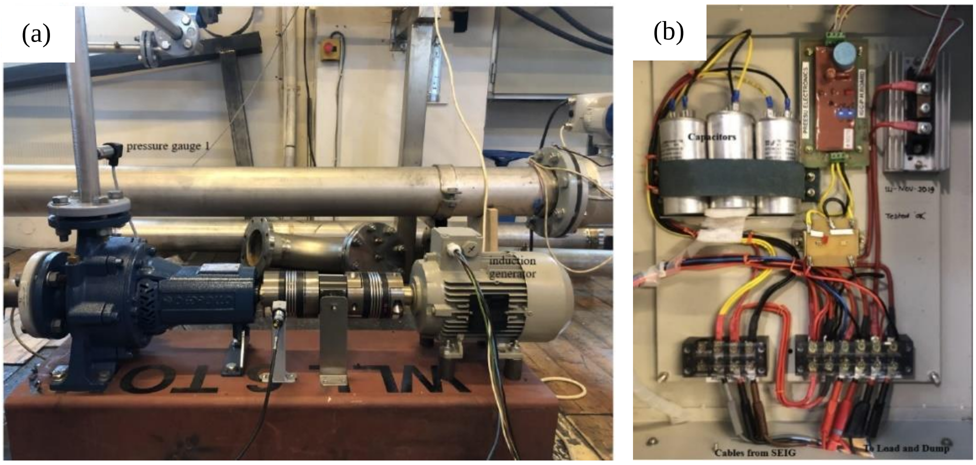

Figure 2: Test rig for the induction generator coupled to the driver motor (Source: Andersson and Bye, 2016).

The PAT is driven with a variable flow rate to vary the torque supplied to the induction generator. The flow rate varies from 0 and 23m3/hr. The generator is supplying a constant load of 120 **Ω**. The induction generator speed changes with load and the value of load. From the two experiments, the variation of efficiencies of the PAT and SEIG versus flow rate were obtained. SEIG, PAT, and the overall PAT-SEIG system efficiencies can be calculated for each electrical load using Equations (9) and (10) below.

$$\eta_{seig} = \frac{P_L}{P_m} \; ; \quad \eta_{pat} = \frac{P_m}{P_{hyd}} \tag{9}$$

$$\eta_{overall} = \eta_{seig} * \eta_{pat} \tag{10}$$

Optimization with MATLAB using Genetic algorithm

Genetic Algorithm is an optimization and learning technique inspired by Darwin's theory of evolution. They search the solution space of a function through simulated evolution, using mutation, crossover, and selection operations (Purohit et al., 2013). They are simple to construct and effective in solving linear and nonlinear problems. Advances in software technology have made GAs suitable for solving difficult problems in real-time (An et al., 2016; Kochenderfer and Wheeler, 2019; Messac, 2015).

Optimization techniques are used to determine the most optimal set of design parameters. The process involves minimizing or maximizing a system characteristic equation that is dependent on another variable. From (Messac, 2015), the objective function f(x) is subject to constraints in one or more of the following forms:

$$\min_{x} f(x) \quad \text{Objective functionSubject to}$$
$$g(x) \leq 0 \quad \text{Inequality constraints}$$
$$h(x) = 0 \quad \text{Equality constraints}$$
$$X_{lb} \leq x \leq X_{ub} \quad \text{Parameter bounds}$$

where x is the variable parameter, f(x) is the objective function and g(x) returns values of the equality and inequality constraints evaluated at x. In the optimization process for the current study, the efficiency equations for Pat and SEIG form the objective function. The efficiency equations are a function of flow rate and the flow rate is bounded in the region where the PAT and SEIG are operating close to their maximum efficiencies. The two objective functions are minimized using multi-objective optimization implemented in MATLAB.

RESULTS AND DISCUSSION

The results of the experiments are presented in this section. The first section presents validation of the results. Section 3.1 presents a comparison of results between what other researchers have found and the results from the current study, Section 3.2 presents the

PAT test results and Section 3.3 presents the SEIG test results followed by the optimization process in MATLAB.

Validation of PAT and SEIG results

The model was validated by comparing the output to other models in the literature. The efficiency of the SEIG and speed of rotation were compared with the results published by Capelo (Capelo et al., 2017). Figure 3 shows the variation of speed versus efficiency. It can be observed that for all loads, as the speed increases, the efficiency of the generator increases.

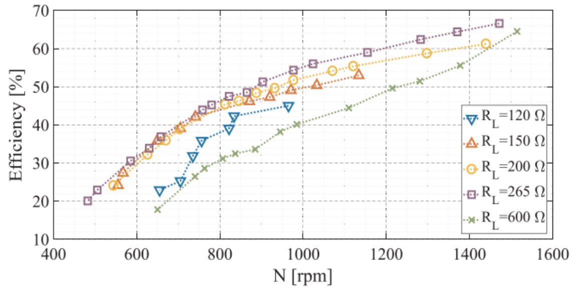

Figure 3: Variation of speed vs efficiency (Source: Capelo et al., 2017)

The results from the developed model are shown in Figure 4. It can be observed that there are similar trends in the behaviors of the two machines. The higher the connected resistance, the lower the efficiency of the machine. The second observation is that the plots converge to maximum efficiency at higher speeds.

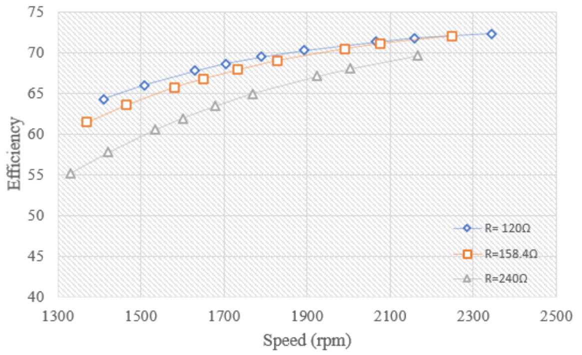

Figure 4: Variation of speed vs efficiency current experiments

PAT Test Results

The data obtained from the experiment was plotted as shown in Figure 5. It was observed that the PAT starts producing power at a flow rate of 9.54 m3/hr giving an efficiency of 2.5%. Through regression analysis, a trend curve approximating the data points was obtained. The relationship between the flow rate and PAT efficiency is polynomial to the power 2.

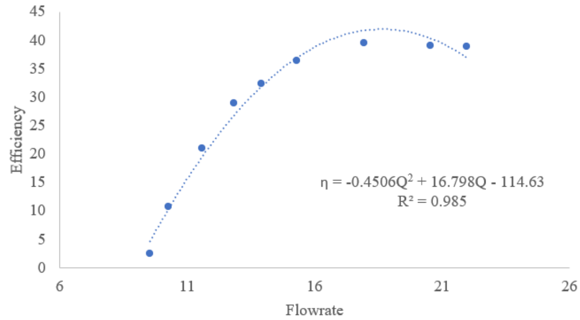

Figure 5: Plot of efficiency vs flowrate for PAT

SEIG results

The results from testing the generator at a constant load of 120 Ω and fixed excitation were plotted in Figure 6. The generator started to produce power at a flow rate of 9.54 m3/hr. it was observed that the efficiency grows from 55% to 70% as the flow rate increases to 18 m3/hr.

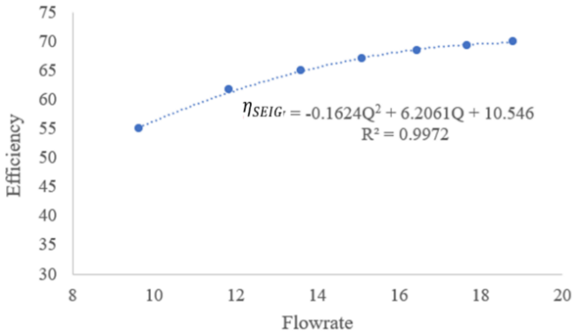

Figure 6: Plot of efficiency versus flow rate for SEIG

Selection and performance optimization

From the plot of flow rate and frequency for PAT and SEIG, it was observed that both efficiencies increase towards their peaks which are not coincident. Through optimization, the best operating points were identified. The equations representing the two efficiency curves are presented in Equation 1 and Equation 2.

$$\eta_{PAT} = -0.4506Q^2 + 16.798Q - 114.63 \quad (1)$$

$$\eta_{SEIG} = -0.1624Q^2 + 6.2061Q + 10.546 \quad (2)$$

The optimization process was implemented using gamultobj code in MATLAB. The search was constrained to between a flow rate of 10 m3/hr and 30 m3/hr.

The result after running the code is shown in Figure 7. The Pareto optimal solutions for PAT efficiency range from 39.9% to 40.07%, while for SEIG efficiency, the range is between 69.79% and 69.84%. Considering the Pareto front, it is evident that the BEP for the system does not align with maximizing the efficiencies of both machines. The PAT's highest efficiency is approximately 40.07%, while the SEIG can operate at an efficiency of 69.836%. by using this result, the designer can select the optimal balance between PAT and electrical efficiency when designing the PAT-SEIG system.

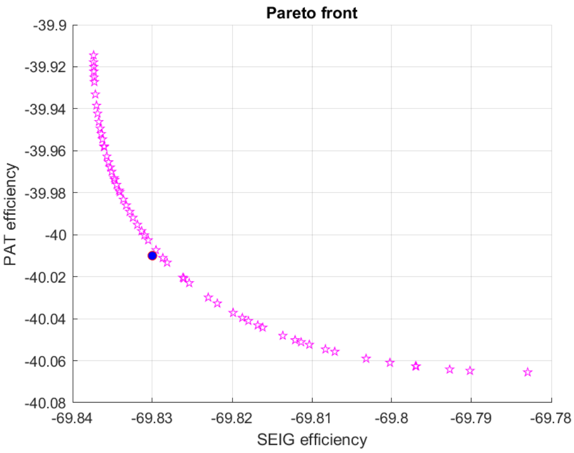

Figure 7: Pareto Front containing a set of solutions.

Operating point selection using FMINCON

When choosing the operating point, it is important to consider the machine's rating and magnetizing characteristics to avoid insulation failure due to electrical stresses on the machine (Masic et al., 2018). It is noted that in the PAT-SEIG setup, the peak of their efficiencies occurs at different values of shaft speed and hence flow rate. Therefore, when considering the point of operation, the SEIG being a sensitive equipment is required to operate close to the maximum efficiency point. The PAT has a low risk of failure at a higher speed.

The output of the multi-objective optimization was compared with the output of the FMINCON optimization function. The main aim is to maximize the SEIG efficiency; hence the objective function will be η_{SEIG} and the equality constraint will be η_{PAT}. The lower and upper bound of flowrate are defined as 10 m3/hr and 30 m3/hr respectively.

Table 3: Output from FMINCON function

Initial objective (efficiency)	56.367 %
Final objective (efficiency)	69.8374 %
Solution Q	19.1 m^3/hr
funcCount	17
Exit Flag	1

The result from the FMINCON gives the optimal SEIG efficiency of 69.83% and a flow rate Q of 19.1m3/hr. The initial objective was 56.367%, and it has improved to 69.83% through optimization. The results of the FMINCON optimization are described and the solutions are checked if they satisfy the constraints and are within the Pareto solutions. The result is plotted together with the Pareto solutions and indicated by a blue dot in Figure 6.

CONCLUSIONS

This paper has presented the methodology of using multi-objective optimization to select the best operating point of the PAT SEIG system where the pump and induction generator are bought from off-the-shelf for rural off-grid applications. The results show that the peak efficiencies for the PAT and SEIG are not coincident thus when selecting the operating point, a tradeoff on one element is necessary. In most applications, the selection of higher electrical efficiency is preferred to reduce overheating caused by the losses being converted to heat. The two optimization methods complemented each other in finding the BEP for the off-the-shelf PAT-SEIG system. The gamultobj optimization provided a range of efficiency combinations, from which the designer can select the system's operating point. The study shows that the peak efficiencies for the PAT fall between 39.9% and 40.08% and for SEIG they fall between 69.78% and 69.84%. Thus, when selecting the operating point, a tradeoff on one element is necessary. By using FMINCON, the best efficiency point can be located, and it has been demonstrated that it is within the Pareto solutions where the SEIG and PAT efficiency are at 69.83% and 40.01% respectively.

REFERENCES

Abed-alguni, B. H., Paul, D., & Hammad, R. (2022). Improved Salp swarm algorithm for solving single-objective continuous optimization problems. Applied Intelligence, 52(15), 17217–17236. https://doi.org/10.1007/S10489-022-03269-X

Ali Taghikhani, M., & Davoudabadi Farahani, A. (2017). A Reactive Power Based Reference Model for Adaptive Control Strategy in a SEIG. In Technology & Applied Science Research (Vol. 8, Issue 1). https://doi.org/10.48084/etasr

An, Z., Zhounian, L., Peng, W., Linlin, C., & Dazhuan, W. (2016). Multi-objective optimization of a low specific speed centrifugal pump using an evolutionary algorithm. Engineering Optimization, 48(7), 1251–1274. https://doi.org/10.1080/0305215X.2015.1104987

Andersson, A., & Bye, E. (2016). Analysis of Self-Excited Induction Generator for Use in Rural Areas with Electronic Load Controller and Additional Compensation Methods. (Master's thesis). hdl.handle.net/11250/2433751

Arshad, M. (2017). Clean and Sustainable Energy Technologies. Clean Energy for Sustainable Development: Comparisons and Contrasts of New Approaches, 73–89. https://doi.org/10.1016/B978-0-12-805423-9.00003-X

Capelo, B., Pérez-Sánchez, M., Fernandes, J. F. P., Ramos, H. M., López-Jiménez, P. A., & Branco, P. J. C. (2017). Electrical Behaviour of the Pump Working as Turbine in Off Grid Operation. Applied Energy, 208, 302–311. https://doi.org/10.1016/j.apenergy.2017.10.039

Choudhary, R., & Saket, R. K. (2015). A critical review on the self-excitation process and steady state analysis of an SEIG driven by wind turbine. Renewable and Sustainable Energy Reviews, 47, 344–353. https://doi.org/10.1016/J.RSER.2015.03.043

Faisal Khan, M., & Rizwan Khan, M. (2016). Analysis of voltage build-up and speed disturbance ride through capability of a self-excited induction generator for renewable energy application Multy Phase Machines View project Multi-phase SEIGs View project. International Journal of Power and Engineering. https://doi.org/10.1504/IJPEC.2016.076521

Fernandes, J. F. P., Pérez-Sánchez, M., da Silva, F. F., López-Jiménez, P. A., Ramos, H. M., & Branco, P. J. C. (2019). Optimal Energy Efficiency of Isolated PAT Systems by SEIG excitation Tuning. Energy Conversion and Management, 183, 391–405. https://doi.org/10.1016/j.enconman.2019.01.016

Fernández García, I., Perea, R. G., & Rodríguez Díaz, J. A. (2022). New Model for Determining Optimal PAT Locations: Maximizing Energy Recovery in Irrigation Networks. Journal of Water Resources Planning and Management, 148(11). https://doi.org/10.1061/(asce)wr.1943-5452.0001605

Filo, G. (2023). Artificial Intelligence Methods in Hydraulic System Design. Energies, 16(8). https://doi.org/10.3390/en16083320

Fracassi, A., De Donno, R., Ghidoni, A., & Congedo, P. M. (2022). Shape optimization and uncertainty assessment of a centrifugal pump. Engineering Optimization, **54**(2), 200–217. https://doi.org/10.1080/0305215X.2020.1858075

Grosan, C. (2004). A comparison of several algorithms and representations for single objective optimization. Springer, Berlin, **3102**, 788–789.

https://doi.org/10.1007/978-3-540-24854-5_80/COVER

Haque, M. H. (2008). Voltage regulation of a stand-alone induction generator using thyristor-switched capacitors. 2008 IEEE International Conference on Sustainable Energy Technologies, ICSET 2008, 34–39. https://doi.org/10.1109/ICSET.2008.4746968

Haque, M. H. (2012). Capacitance requirement in a three-phase SEIG under no-load and load conditions. 2012 IEEE International Conference on Power System Technology, POWERCON 2012. https://doi.org/10.1109/POWERCON.2012.6401268

Hassan I. (2011). Analysis of Self Excited Induction Generator using pso. 2011 Engineering conference, Scientific research doi:10.4236/eng.2011.38105

Ibrahim, H., & Metwaly, M. (2011a). Genetic Algorithm Based Performance Analysis of Self Excited Induction Generator. Engineering, 03(08), 859–864. https://doi.org/10.4236/eng.2011.38105

Ibrahim, H., & Metwaly, M. (2011b). Genetic Algorithm Based Performance Analysis of Self Excited Induction Generator. Engineering, 03(08), 859–864. https://doi.org/10.4236/eng.2011.38105

Jain, S. V., & Patel, R. N. (2014). Investigations on Pump Running in Turbine Mode: A Review of the State-of-the-art. In Renewable and Sustainable Energy Reviews, **30**, 841–868. https://doi.org/10.1016/j.rser.2013.11.030

Kandi, A., Moghimi, M., Tahani, M., & Derakhshan, S. (2021). Optimization of Pump Selection for Running as Turbine and Performance Analysis Within the Regulation Schemes. Energy, **217**. https://doi.org/10.1016/j.energy.2020.119402

Kaunda, C. S. (2013). Energy Situation, Potential and Application Status of Small-Scale Hydropower Systems in Malawi. In Renewable and Sustainable Energy Reviews, **26**, 1–19. https://doi.org/10.1016/j.rser.2013.05.034

Khan, & Khan, R. M. (2016). Analysis of voltage Build-up and Speed Disturbance Ride Through Capability of a Self-Excited Induction Generator for Renewable Energy Application. Under Science, **7**(2). https://doi.org/10.1504/IJPEC.2016.076521

Khan, M. F., Khan, M. R., & Iqbal, A. (2022). Effects of induction machine parameters on its performance as a standalone self-excited induction generator. Energy Reports, **8**, 2302–2313. https://doi.org/10.1016/J.EGYR.2022.01.023

Kochenderfer, M. J., & Wheeler, T. A. (2019). Algorithms for Optimization (1st ed.). Cambridge, MA : The MIT Press, ISBN 9780262039420.

Liu, D., Liu, H., Wang, X., & Kremere, E. (2019). World Small Hydropower Development Report 2019. United Nations Industrial Development Organization; International Center on Small Hydro Power. ISSN: 2706-7599Liu, M., Tan, L., & Cao, S. (2022). Performance Prediction and Geometry Optimization for Application of Pump as Turbine: A Review. Frontiers in Energy Research, **9**, 818118. https://doi.org/10.3389/FENRG.2021.818118/BIBTEX

M. Ramos, H., Silva Santos, R., López-Jiménez, P. A., & Pérez-Sánchez, M. (2022). Multi-objective optimization tool for PATs operation in water pressurized systems. Urban Water Journal, 19(6), 558–568. https://doi.org/10.1080/1573062X.2022.2048864

Madeira, F. C., Fernandes, J. F. P., Pérez-Sánchez, M., Amparo López-Jiménez, P., Ramos, H. M., & Costa Branco, P. J. (2020). Electro-Hydraulic Transient Regimes in Isolated Pumps Working as Turbines with Self-Excited Induction Generators. Energies, **13**(17). https://doi.org/10.3390/en13174521

Manservigi, L., Venturini, M., & Losi, E. (2021). Optimal Selection of Pumps as Turbines for Maximizing Electrical Energy Production. E3S Web of Conferences, **238**. https://doi.org/10.1051/e3sconf/202123801005

Masic, S., Samka, S., & Buljbasic, L. (2018). Model of the Stand-Alone Self Excited Induction Generator with Saturation Effects and Terminal Voltage Regulation. Proceedings: International Symposium on Power Electronics, Electrical Drives, Automation and Motion: Amalfi (Italy), Messac, A. (2015). Optimization in Practice with Matlab ® for Engineering Students and Professionals. www.cambridge.org/9781107109186

N.Purohit, G., Mohan Sherry, A., & Saraswat, M. (2013). Optimization of Function by using a New MATLAB based Genetic Algorithm Procedure. International Journal of Computer Applications, **61**(15), 1–5. https://doi.org/10.5120/10001-4212

Paliwal, S., Kumar Sinha, S., & Kumar Chauhan, Y. (2023). Standalone SEIG using Smart Meta-Heuristic Algorithm to Optimize its Performance and Loadability. Proceedings - IEEE International Conference on Device Intelligence, Computing and Communication Technologies, DICCT 2023, 546–551. https://doi.org/10.1109/DICCT56244.2023.10110158

Qin, Y., Li, D., Wang, H., Liu, Z., Wei, X., Wang, X., & Yang, W. (2023). Comprehensive hydraulic performance improvement in a pump-turbine: An experimental investigation. Energy, 284, 128550. https://doi.org/10.1016/J.ENERGY.2023.128550

Rahimi, I., Gandomi, A. H., Chen, F., & Mezura-Montes, E. (2023). A Review on Constraint Handling Techniques for Population-based Algorithms: from single-objective to multi-objective optimization. Archives of Computational Methods in Engineering, 30(3), 2181–2209. https://doi.org/10.1007/S11831-022-09859-9

Rana, K., & Meena, D. (2018). Self-excited Induction Generator for Isolated Pico Hydro Station in Remote Areas. 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES).

REN21. (2022). Renewables 2022 Global Status Report.

Singh, G. K., Senthil Kumar, A., & Saini, R. P. (2010). Selection of Capacitance for Self-Excited Six-Phase Induction Generator for Stand-Alone Renewable Energy Generation. Energy, 35(8), 3273–3283. https://doi.org/10.1016/j.energy.2010.04.012

Singh, S., Singh B, & Jain, M. (1990). Performance Characteristics and Optimum Utilization of a Cage Machine as Capacitor Excited Induction Generator. IEEE Transactions on Energy Conversion, 5(4), 679–685. https://doi.org/10.1109/60.63139

Stefanizzi, M., Capurso, T., Balacco, G., Binetti, M., Camporeale, S. M., & Torresi, M. (2020). Selection, control and techno-economic feasibility of Pumps as Turbines in Water Distribution Networks. Renewable Energy, **162**, 1292–1306. https://doi.org/10.1016/j.renene.2020.08.108

Subramanian, K., & Sabberwal, S. P. (2014). Regulated Voltage Operation of a Stand-Alone 3-Ø Self-Excited Induction Generator. https://doi.org/10.1109/ICAEE.2014.6838501

Wang, K., Wang, S., Meng, P., Wang, C., Li, Y., Zheng, W., Liu, J., & Kou, J. (2023). Strategies employed in the design and optimization of pump as turbine runner. Renewable Energy, **216**. https://doi.org/10.1016/j.renene.2023.119080

Wang, L., Asomani, S. N., Yuan, J., & Appiah, D. (2020). Geometrical Optimization of Pump-As-Turbine (PAT) Impellers for Enhancing Energy Efficiency with 1-D Theory. Energies, 13(16), 4120. https://doi.org/10.3390/EN13164120)

Wang, Luo, W., Zhang, B., Ntiri Asomani, S., Xu, J., Luo, Z., & Wang, L. (2022). Performance analysis of geometrically optimized PaT at turbine mode: A perspective of entropy production evaluation. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(24), 11446–11463. https://doi.org/10.1177/09544062221115105

Zhang, Lu, J., Yang, S., Liu, W., Tao, R., Zhu, D., & Xiao, R. (2023). Performance improvement of a pump as turbine in storage mode by optimization design based on genetic algorithm and fuzzy logic. Journal of Energy Storage, 62, 106875. https://doi.org/10.1016/J.EST.2023.106875

Zhang, S., & Haugland, T. (2019). System design and implementation of induction generators self-excited by capacitors for maritime diesel electric propulsion systems, IEEE Industry Applications Society.ISBN: 9781538664995