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Transient Behaviour of Pump as Turbine Coupled to Self-Excited Induction Generator Under Variable Load Conditions

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ABSTRACT

The transient behavior of the Pump as Turbine (PAT) coupled to Self-Excited Induction Generators (SEIGs) under variable load conditions is one of the critical aspects in small-scale hydro generation systems. This paper investigates the behavior of the PAT-SEIG system during load variations and explores the impact of transient phenomena on system performance. Simulation studies are conducted using MATLAB/SIMULINK and the effects of various loading conditions are investigated and the results are analyzed and discussed. The research findings contribute to a deeper understanding of the transient behavior of PAT-SEIG operating under variable load conditions. The study offers valuable insights for optimizing the performance and stability of PAT-SEIG system applied in small-scale stand-alone hydropower systems.

Keywords: renewable energy sources, pump as turbine, self-excited induction generator, energy systems, micro hydropower systems

NONMENCLATURE

PAT	Pump as Turbine
BEP	Best Efficiency Point
SEIG	Self Excited Induction generator

1. INTRODUCTION

Energy remains one of the critical economic and development challenges facing the world today. It is reported that about 1.06 billion people, which is about 13% of the population living in rural areas, still have no access to electricity. Access to clean, reliable, and affordable electricity transforms the quality of life including access to basic services like health and education [1].

The use of pumps working in reverse as a turbine (PAT) coupled with a self-excited induction generator (SEIG) has gained much focus in recent years. It is a way of increasing electricity access in rural and hard-to-reach areas that cannot be connected to the grid [2].

PAT has been explored in Europe and other Asian countries as an energy recovery strategy applied in water distribution networks with a focus on isolated hydropower systems [3]–[5].

PATs and SEIGs play a crucial role in harnessing the kinetic energy of water flow into electrical energy. In addition, PAT-SEIGs are a cost-effective option for replacing conventional turbines in small-scale hydropower generation in isolated areas away from main electricity grid. Conventional turbines are site-specific and hence expensive to manufacture [6], [7]. These conventional turbines also require extensive infrastructure, making them unsuitable for small-scale applications. On the other hand, SEIGs do not require an excitation, making them suitable for applications in remote or off-grid areas. The PAT-SEIG output voltage and frequency are influenced by rotational speed, load resistance, excitation capacitance, and load variations [8], [9].

The performance of the PAT-SEIG is very critical as we require the machine to operate at the best efficiency points. This helps to harness maximum power from the site. The available challenge is that the pump and induction machine has been researched in isolation, independent of the other. This brings the challenge when evaluating the overall efficiency of the system. From the literature, the efficiencies of the PAT and SEIG lie at different points [10], [11]. It is imperative that careful matching is done when selecting a pump and generator to be applied at a particular site.

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This study investigates the operating behavior of the PAT-SEIG system when supplying power to a variable load through simulation in MATLAB/SIMULINK. The focus is on the starting characteristics and the variations in voltage and frequency when the load varies with changes in head.

2. MATERIALS AND METHODS

To study the behavior of the PAT-SEIG, a SIMULINK model was built as indicated in Figure 1 for PAT and Figure 2 for SEIG.

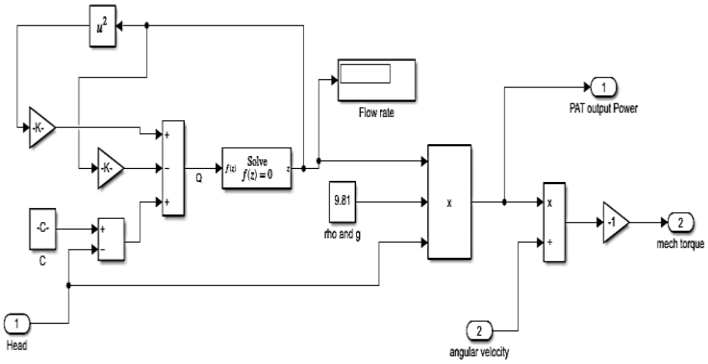

Figure 1: PAT Simulink model

The pump working in reverse was modeled in SIMULINK using the experimental results obtained from testing the pump at the Waterpower laboratory NTNU in Norway [12]. The pump specifications at BEP are shown in Table 1.

Table 1: Pump and Turbine specifications

FG32/160B	Pump mode
Head (m)	6.2
Flowrate (m3/hr)	8.7
Efficiency (%)	55
Specific speed (Ns)	27.6
Speed (N)	1450

Through the experiment, head vs flow rate characteristics were obtained and through regression, a polynomial approximation of the PAT was obtained and implemented as shown in Figure 1.

The model for a 3-phase SEIG feeding a three-phase load shown in Figure 2, is based on 3-MOT 7AA90L04, 1.5kW, 4 poles, 1500rpm induction motor model. The impedance data was entered into the asynchronous machine block and the magnetization characteristic for the block was updated with the experimental data.

When head which is an input to the PAT is adjusted, a system flow rate is calculated, followed by the calculation of the available power to the SEIG. Depending on the speed of the SEIG, the torque input to the generator is calculated. The generator is excited by a 50µF capacitor and is used to supply a variable resistive load.

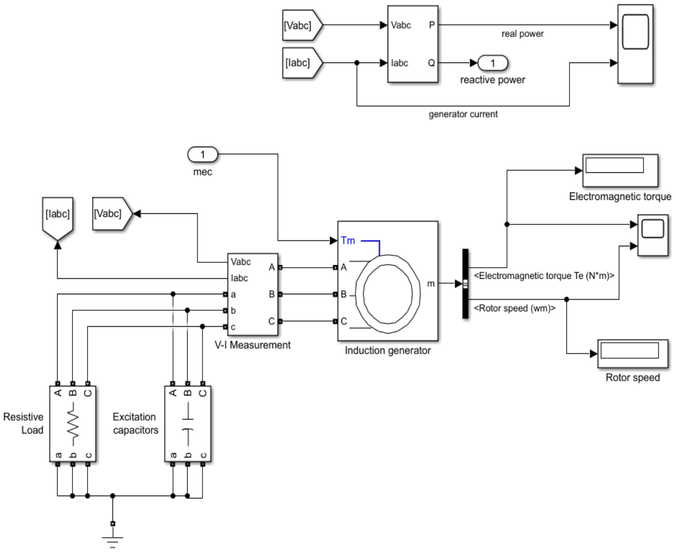

Figure 2: SEIG Simulink model

To investigate the transient and steady-state characteristics, the model was subjected to a varying head $(8m \leq H \leq 20m)$ and variable load $(70\Omega \leq R_L \leq 300\Omega)$ while the excitation capacitance was kept constant at 50µF.

3. RESULTS AND DISCUSSION

The presentation of results is divided into two sections, first section looks at the starting characteristics and the transient of the generator to changes in head. The second section discusses the steady state characteristics.

To ensure the accuracy of the PAT coupled to the SEIG model, a comparison was made of its output to experimental data. Furthermore, the model results were compared with those of other researchers. We observed similar trends in the SEIG model's performance to the findings of other researchers [10], [11], [13] .

3.1 Transient characteristics

The model was run at a low head of 8m while the load resistance was varied between 80Ω and 300Ω. For low values of head, the generated voltage does not reach a steady state for all loads. Figure 3 indicates the speed and voltage swings that decay with respect to time for H = 8m, Q = 9.629m3/s, and Pt = 755.7W.

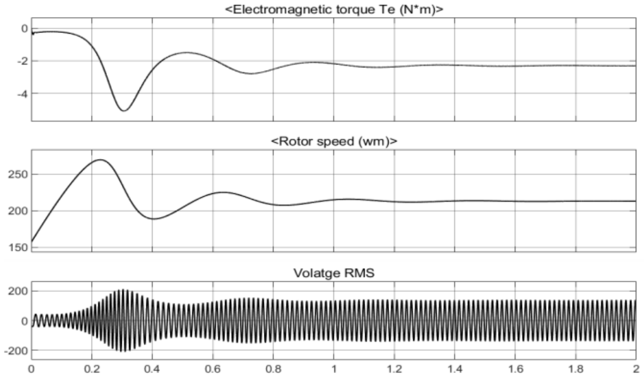

Figure 3: Starting characteristics at low head low resistance

The unstable response of the system is attributed to the low available power to drive the induction generator by the PAT and was overcome by increasing the head. Secondly, the head for the PAT was increased to 20m and the load was varied as in the previous setting. The results are shown in Figure 4. There is a developed torque ripple in the machine. This is caused by the overexcitation of the machine resulting in saturation of the core. The torque ripple will affect the control of the machine and the long-term performance of the generator [14].

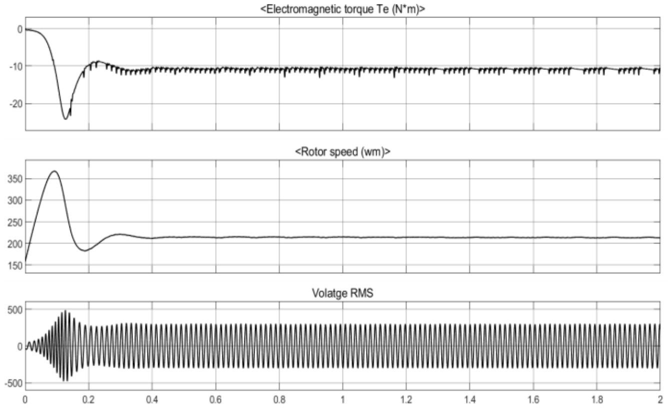

Figure 4: Starting characteristics at high head low resistance

Through a thorough investigation, the SEIG can accommodate a head between 10m and 14m for safe operation of the machine connected to a load range between 80Ω and 240Ω without generating torque ripples. The speed and hence frequency is constant for a particular load regardless of the change in input power.

With a high head, the available power was above the rating of the generator hence causing over-saturation of the core which results in pulsating of the torque and speed of the generator.

3.2 *Steady-state characteristics*

The simulation investigating how head affects voltage and frequency was conducted on the model. Head was adjusted from 8m to 20m and the flow rate, voltage, and frequency values were recorded when the system reached a steady state.

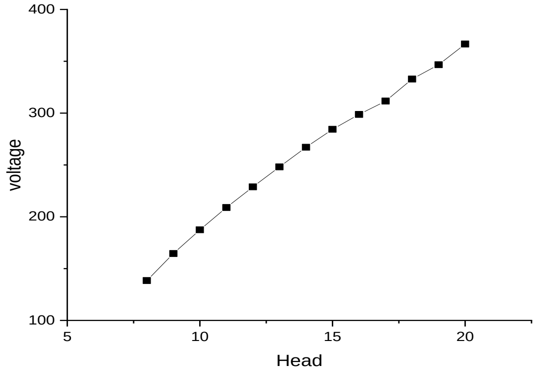

Figure 5: Variation of head versus voltage

Figure 5 shows a plot of the variation of head vs phase voltage. It is observed that voltage is directly proportional to head. Any increase in head results in an increase in voltage, and the machine produces a voltage of 240V with a head of 13.4m which falls within the safe operating zone to avoid torque ripple.

4. CONCLUSIONS

This study has explored and discussed the transient behavior of the PAT-SEIG operating at different heads has been explored through simulation. The PAT can only be run in reverse from a certain range of heads. The SEIG can also handle loads within the saturation range. In conclusion, understanding the dynamic behavior and control strategies of SEIGs is crucial for optimizing their performance and stability under different load conditions. Therefore, since the efficiencies of the PAT and the SEIG are not coincident hence careful consideration must be made when selecting a pump for a particular site.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Liu D, Liu H, Wang X, and Kremere E. (2023, August 6) World Small Hydropower Development Report 2019. United Nations Industrial Development Organization; International Center on Small Hydro Power; 2019. www. smallhydroworld.org.

[2] Kumawat RK, Chourasiya S, Agrawal S, and Paliwalia DK. Self excited induction generator: A review. International Advanced Research Journal in Science, Engineering and Technology, vol. 2, no. 1; 2015, doi: 10.17148/IARJSET.

[3] Carravetta A, Giudice D, Fecarotta O, and Ramos HM. PAT Design Strategy for Energy Recovery in Water Distribution Networks by Electrical Regulation. Energies 2013, Vol. 6, Pages 411-424, vol. 6, no. 1, pp. 411–424, Jan. 2013, doi: 10.3390/EN6010411.

[4] Alberizzi JC, Renzi M, Righetti M, Pisaturo GR, and Rossi M. Speed and pressure controls of pumps-as-turbines installed in branch of water-distribution network subjected to highly variable flow rates. Energies (Basel), vol. 12, no. 24, Dec. 2019; doi: 10.3390/en12244738.

[5] Stefanizzi M, Capurso T, Balacco G, Binetti M, Camporeale SM, Torresi M. Selection, control and techno-economic feasibility of Pumps as Turbines in Water Distribution Networks. Renew Energy, vol. 162, pp. 1292–1306, Dec. 2020; doi: 10.1016/j.renene.2020.08.108.

[6] Jain SV and Patel RN. Investigations on Pump Running in Turbine Mode: A Review of the State-of-the-art. Renewable and Sustainable Energy Reviews, vol. 30. Elsevier Ltd, pp. 841–868, 2014. doi: 10.1016/j.rser.2013.11.030.

[7] Kaunda SC. Energy Situation, Potential and Application Status of Small-Scale Hydropower Systems in Malawi. Renewable and Sustainable Energy Reviews, vol. 26. Elsevier Ltd, pp. 1–19, 2013. doi: 10.1016/j.rser.2013.05.034.

[8] Choudhary R and Saket RK. A critical review on the self-excitation process and steady state analysis of an SEIG driven by wind turbine. Renewable and Sustainable Energy Reviews, vol. 47. Elsevier Ltd, pp. 344–353, 2015. doi: 10.1016/j.rser.2015.03.043.

[9] Faisal-Khan M and Rizwan-Khan M. 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, 2016, doi: 10.1504/IJPEC.2016.076521.

[10] Fernandes JFP, Pérez-Sánchez M, da Silva FF, López-Jiménez FA, Ramos HM, Branco PJC. Optimal Energy Efficiency of Isolated PAT Systems by SEIG excitation Tuning. Energy Convers Manag, vol. 183, pp. 391–405, Mar. 2019, doi: 10.1016/j.enconman.2019.01.016.

[11] Capelo B, Pérez-Sánchez M, Fernandes JFP, Ramos HM, López-Jiménez PA, and Branco PJC. Electrical Behaviour of the Pump Working as Turbine in Off Grid Operation. Appl Energy, vol. 208, pp. 302–311, Dec. 2017, doi: 10.1016/j.apenergy.2017.10.039.

[12] Andersson A and Bye E. Analysis of Self-Excited Induction Generator for Use in Rural Areas with Electronic Load Controller and Additional Compensation Methods. 2016. Accessed: Jan. 30, 2023. [Online]. Available: Analysis of Self-Excited Induction Generator for use in Rural (Doctoral dissertation, Master's thesis). Department of Electric Power Engineering: NTNU. 1 SEIG with loads).

[13] Madeira FC, Fernandes JFP, Pérez-Sánchez M, López-Jiménez A, Ramos HM, and Cost- Branco PJ. Electro-Hydraulic Transient Regimes in Isolated Pumps Working as Turbines with Self-Excited Induction Generators. Energies (Basel), vol. 13, no. 17, Sep. 2020, doi: 10.3390/en13174521.

[14] De Santana MP, De Paula GT, De Oliveira CMR, Borges FDA, Paredes HKM, and De MonteiroJRB. Vector Control Applied to Mitigate the Electromagnetic Torque Ripple in Doubly Fed Induction Generator. IEEE Transactions on Energy Conversion, vol. 36, no. 4, pp. 2977–2986, Dec. 2021, doi: 10.1109/TEC.2021.3075933.