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Electrical behaviour of the pump working as turbine in off grid operation

Bernardo Capelo[b], Modesto Pérez-Sánchez[a,*], João F.P. Fernandes[b], Helena M. Ramos[c], P. Amparo López-Jiménez[a], P.J. Costa Branco[b]

[a] Hydraulic and Environmental Engineering Department, Universitat Politècnica de València, Valencia 46022, Spain
[b] Mechanical Engineering Institute (IDMEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa 1049-001, Portugal
[c] Civil Engineering, Architecture and Georesources Department, CERIS, Instituto Superior Técnico, Universidade de Lisboa, Lisboa 1049-001, Portugal

HIGHLIGHTS

- Self-excited induction generator is an excellent solution to operate isolated to grid.
- PAT system shows lower efficiencies when the SEIG is not optimized.
- Tuning methodology to optimize the capacitance is crucial to increase the efficiency.
- PAT isolated to grid can be operated under variable operation strategy.
- PAT-SEIG is a novelty tested solution to operate isolated to grid.

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ABSTRACT

The use of pumps working as turbines (*PATs*) connected to the electric system, in the replacement of pressure reduction valves to reduce the excessive pressure in water distribution networks, have been studied for the last years. The introduction of *PATs* is very important in the water-energy nexus to promote the increase of the energy savings. As consequence, the majority of the water systems does not have access to the electrical grid and, therefore, the need to study the *PATs* operation off-grid is necessary. In this line, the novelty of this research is the application and optimization of a *PAT* in water systems when the recovery solution is off-grid type. To operate correctly, the induction machine requires an external source of reactive power, which is typically provided by the electrical grid. To supply the required reactive power, a bank of capacitors is installed at the machine terminals, so-called self-excited induction generator (*SEIG*). The analytical model, simulation and experimental works were performed, to analyse the *SEIG* behaviour. The results were applied in a *SEIG-PAT* system obtaining the global efficiency of the system for different speeds and loads. The global efficiency decreases 47% when off-grid operation, showing the need to optimize the electrical parameters of the generator to operate as off- grid with acceptable efficiency levels. In this framework, a tuning methodology for the *SEIG* capacitor bank values was developed to be automatically adjusted according to the operating point of the *PAT* to maximize its efficiency.

1. Introduction

In some contexts, such as the case of rural and remote areas, the installation of micro-hydro power sources to generate and store energy can be a good alternative to supply or complement the energy demand of these areas [1,2]. Possible applications of these solutions are huge, as water distribution systems are present in any infrastructure and public works all around the world. For example, in Vallada's network (Valencia, Spain), studies indicate to be possible to recover up to 188 MWh/year for 910,000 m^3/year (0.201 kWh/m^3) [3] that is being wasted in the WDS. If this recovery potential is extended to the worldwide irrigate consumption, that is currently 117 km^3/year in drip irrigation, the energy saved in irrigation water systems would be significant. These values can contribute to reduce the consumption of non-renewable energy that are currently used, such as the use of diesel generator [4]. In supply networks, the energy recovery was similar with obtained values oscillating between 1 and 5% of the provided energy in the network [5]. Other examples are the pressurized water networks

* Corresponding author.
E-mail addresses: bernardo.capelo@ist.utl.pt (B. Capelo), mopesan1@upv.es (M. Pérez-Sánchez), joao.f.p.fernandes@tecnico.ulisboa.pt (J.F.P. Fernandes), helena.ramos@tecnico.ulisboa.pt (H.M. Ramos), palopez@upv.es (P.A. López-Jiménez), pbranco@tecnico.ulisboa.pt (P.J.C. Branco).

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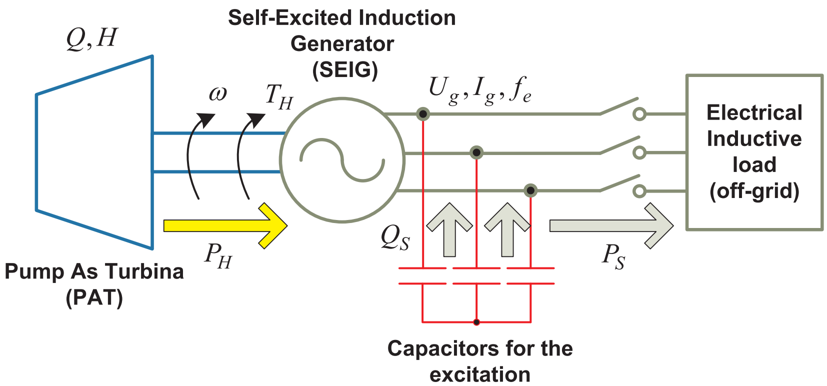

Fig. 1. Illustrative scheme of the self-excited induction generator system for a stand-alone PAT system.

(irrigation and drinking) [5,6] and wastewater treatment plants, which can improve its energy efficiency by the installation of the energy recovery in the sludge line [7,8].

One viable solution is the installation of a pump working as turbine (*PAT*) [4,9–11], which can operate under the variable operation strategy (*VOS*) to maximize the recovered energy used in the pumping water system [12,13] and to provide balancing in the response of water distribution systems (WDS). Particularly, the impact in the overall energy efficiency of the system is great, as PATs replace valves (which lose the energy) by turbines (which recover this energy). This kind of energy recovery, complemented by energy storage units, presents a well-known technology and offers a low cost solution, easy installation and also maintenance [14], mainly for energy systems without a power grid connection.

One of the main concerns about the PAT are the lack of pump information given by the manufacturer for the turbine mode. Several mathematical studies have been focused on estimating the PAT curves from the available information Dario [15] for different types of turbines, as Turgo, Cross-flow and Agnew turbines Mosè [16].

In parallel, the most typical electrical machines used in WDS systems are the induction ones, which are also capable of operating as generator. In off-grid cases, when the induction generator (IG) is not connected to the power grid, it requires a minimum capacitance to keep it excited for different loads [17]. The behaviour of a self-excited induction generator (SEIG) system off-grid type is not new. This is only valid for cases where its load impedance is relatively constant and generator motive power is characterized by small fluctuations. For example, micro-hydro run-of-the-river power plants are the ideal example mainly due to its use in rural activities [18]. On the other hand, low power and off-grid wind induction generators are characterized by large fluctuations that also demand capacitance values to be adjusted to the maximum power extraction [19]. For PATs, recent applications as substituting pressure reducing valves [20] and even for energy recovery in WDS [21], the electric load and/or hydraulic power change by large flow fluctuations and therefore, the analysis acquires sense.

PAT systems with off-grid operation are characterized by different operating modes that will have an impact in the global efficiency of the energy recovery system, due to the SEIG and the hydraulic turbine efficiencies. Therefore, the electric and hydraulic regulation should be considered to maximize the recovered energy in the pressurized water system [21–23]. A symbiosis between hydraulic and electric system is necessary in terms of excitation and regulation of the rotational speed. This application will play an important role in the future due to the high number of opportunities to install them in pressurized water systems to improve the energy recovery and reduce the energy losses.

The aim of this work is to analyse the connection between hydraulic and electric systems to regulate it for its best overall efficiency. This is not currently analysed deeply in the expert literature since there is only analysis for the hydraulic system or connected to the grid [24]. Therefore, knowing the actual deficit in this framework, this paper presents an off-grid system of a self-excited induction generator (*SEIG*), in which the analytical development and computational model are used to solve the system dynamic. Once these numerical analyses were defined, an experimental application of the *SEIG* was developed. Finally, as novelty, the *SEIG* was applied on a hydraulic facility to analyse the behaviour of this hydraulic system when connected to a recovery electrical machine and to regulate it to the best system efficiency. The hydraulic analysis enabled to determine the global, hydraulic and electric efficiencies when it operates as off-grid connection. These values were then compared with the ones obtained when connected to the grid.

2. Material and methods

This section describes the methodology for an automatic tuning of capacitor bank in self-excited induction generators to maximize energy efficiency in the *PAT*. The system will be off-grid and a standard induction motor will be used. Specifically, using an induction motor as generator significantly diminishes the cost of the *PAT* electrical equipment.

2.1. Self-excited induction generator. Proposed automatic tuning design for PATs

Standard squirrel-cage induction motors of small power (up to 1 or 2 kW), operating as low-voltage generators, today, have their cost lower than synchronous generators, requiring not only less complex control (reduction in maintenance costs) but also showing a great robustness due to its simple form of construction. Since its inherent reversible motor/generator characteristic, when the induction machine is mechanically coupled to a prime mover, the rotor exceeds the synchronous speed and becomes generator of active power, standing out why it does not require any synchronization equipment and also having a good over-speed capability and short-circuit protection.

Fig. 1 shows a scheme of the *PAT* and a self-excited induction generator system. The system is composed by a variable capacitor bank connected at the induction machine terminals to supply its required reactive power. When the machine starts rotating, driven by the hydraulic turbine, a small voltage is induced in the stator coils with a frequency proportional to the rotor angular speed (ω_r), due to the angular variation of the machines' magnetic reluctance. With this small voltage, the capacitor bank starts producing reactive currents, thus providing reactive power (Q_S), increasing the voltage and magnetizing the induction machine.

Table 1 lists the rated values of the induction generator. The hydraulic turbine, considered in this work was an Etanorm 32-125 KSB (Fig. 2a), with a rated speed equal to 1020 rpm and a rated flow of 4.2 l/s, as Fig. 2b shows in the turbine characteristic. However, one must notice that according the KSB turbine efficiency graph in Fig. 2c, the maximum efficiency for 1200 rpm takes about 62%, but for a less