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An appraisal of proportional integral control strategies for small scale waste heat to power conversion units based on Organic Rankine Cycles

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ABSTRACT

Despite the increasing number of Organic Rankine Cycle (ORC) installations at megawatt scale, the waste heat rejected by industrial processes can vary substantially from a few kWh to many megawatt hours. Hence, ORC units with a power output in the range of tens of kilowatts should be developed to tackle the heat recovery and business opportunities that can arise from this market segment. In the current research activity, a dynamic model of a small scale ORC system was developed using a commercial software platform. The unit is equipped with two plate heat exchangers, a centrifugal pump and a radial turbine designed and optimized using an in-house code and a commercial 1D modelling tool. The off-design behaviour of the ORC system has been characterized by varying the inlet conditions of heat source and sink, and the revolution speed of the turbomachines. Moreover, the response to transient thermal inputs at different time scales has also been investigated. Finally, four control strategies have been compared from the performance and energy efficiency perspectives. The results show that the turbine based regulation strategies achieve better control performance while pump based controls are able to regulate the system by maintaining the net power output closer to the design point.

1. Introduction

The growing energy demand, the scarcity of fossil sources, and the increasing stringent regulations on the pollutants and the greenhouse gas emissions are driving academia and industry to seek new solutions for a sustainable power generation and to increase the overall energy efficiency of existing industrial facilities. Among the Waste Heat Recovery (WHR) technologies, heat to power conversion systems represent one of the most effective methods to reduce the industrial net energy consumption and enhance the re-use of the heat recovered in a flexible and profitable way. Usually these waste heat sources are available at low temperatures and are widespread in industry. For such cases, the Organic Rankine Cycle (ORC) technology has proven to be a reliable, cost-effective and easy to maintain technology [1–3], especially for large capacities ranging from a few hundreds of kW_{th} to a few MW_{th} [4–7].

When smaller units are considered in the power input range of a few kilowatts up to 100 kW_e, there are aspects which have not been fully investigated yet. Among them, one of the most relevant topics is the accurate modelling of the system dynamics for design and optimization purposes [8], and the development of suitable and effective control strategies, to ensure safe and optimal operation of the unit even when sudden changes in the operating conditions occur. The latter is strongly needed in several applications, as the automotive ones or distributed stand-alone units, where flexibility and reliability in different working points are fundamental. In such applications, the heat load supplied to the system can change rapidly in a periodic, random and unexpected way, as it occurs for example in automotive ORC systems under transient driving cycles [9]. For these reasons, the proper modelling and analysis of transients, together with the design of suitable control systems is crucial and requires further attention.

In Ref. [10] Desideri et al. developed a model of a 11 kW_e ORC system equipped with a screw expander. The model was validated in steady-state and transient conditions by imposing step change in the pump revolution speed of 5 Hz and 15 Hz. The results showed a

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good accuracy in predicting the system transients even if difficulties were found to handle the zero-flow conditions occurring when shut down and start-up operations are considered. An even smaller system has been analyzed by Kosmadakis at al. in Ref. [11], who studied a supercritical 3 kW ORC engine equipped with a volumetric scroll expander. The system was tested in on design and off-design conditions and the effect of the turbomachines' revolution speed on the unit performance was assessed. Another low capacity ORC system using a volumetric expander as power conversion unit was modelled by Quoilin et al. in Ref. [12]. The aim of the work was to test three different control strategies able to optimize the system overall efficiency when the hot source inlet temperature was varied from 120 °C up to 300 °C. The control variables adopted were the pump and the expander revolution speeds. It has been found that the regulation of the evaporating temperature of the working fluid, accomplished by setting the revolution speed of the volumetric expander, achieved the best performance. Similar control strategies have been developed by Ni et al. in Ref. [13] for a larger ORC system recovering heat through a solar parabolic collector. Even in this case only the transient dynamics of the heat exchangers were reproduced, while steady state models were used for the turbomachines. A model for a much higher capacity ORC system was proposed by Mazzi et al. [14]. The ORC unit was designed to recover heat from a stream of exhaust gases of 58.9 kg/s at 300 °C. The authors were able to reproduce the behaviour of the system at off-design and transients conditions. The results showed that the performance of the unit was affected by the change of the inlet temperature of the heat source. A decrease in the oil temperature of 30 °C resulted in a system efficiency drop from 24.6% to 23.6%.

Similar work was carried out by Casella and Mathijssen [15] on a 150 kW_e ORC system using a turbo-generator as power conversion device. The model was successfully validated, showing an uncertainty of nearly 3% between the experimental measurements and model predictions. The authors also designed a Proportional-Integral (PI) controller to regulate the turbine inlet temperature acting on the pump revolution speed. The feed-back controller showed good performance but more complex regulation systems may be required to handle a wider range of operating conditions. A Proportional-Integral-Derivative (PID) scheme coupled with a feed-forward and a lead-lag compensator was implemented and compared to more conventional PID controllers by Usman et al. [16]. The results showed that the controller was able to track the expander speed and cope well with electric load disturbances. Another work on the control of the turbine generator of an ORC system was carried out by Padula et al. [17], focused in particular on the switching of the unit from the grid operating mode to stand-alone mode through a series of throttle valves placed at the inlet of the high and low temperature/pressure turbines. Usman et al. [16] also presented strategies oriented at controlling the power output of a small scale off-grid ORC unit equipped with a scroll expander [16].

More advanced control strategies have been proposed by Hernandez et al. [18,19]. The authors compared the model predictive and extremum-seeking control techniques against the more conventional PID regulations. They reported that more advanced strategies, thanks to a more efficient control action, allow an increase of the energy recovery compared to PID schemes. However, when the objective is to manage reduced time scale disturbances introduced by temperature and flow fluctuations of the waste heat source rather than optimize the power output of the ORC unit for different heat load conditions, the added complexity of these control methods may represent an obstacle to their widespread use in industrial WHR applications, which demand simple and cost-effective solutions.

For these reasons, the aim of this work was to investigate several control strategies, each one characterized by different complexity, to assess their performance and suitability for small scale ORC systems for stationary WHR applications. The novelty of the study involved the testing of the control strategies on a fully dynamic ORC model, considering the transient behaviour of all the components of the system, including turbomachines, valves and system piping. The model refers to a 40 kW ORC power unit equipped with a radial turbine whose design has been accomplished by means of a novel approach additionally reported in the paper. After the description of the modelling methodology, the off-design behaviour of the ORC unit is presented and the transient responses of both the uncontrolled and controlled system are assessed with reference to a series of heat load profiles at different time scales (200s, 350s, 600s and 1100s). Four different control strategies are also implemented and compared. All the strategies adopt a Proportional-Integral (PI) control law to maintain constant the Turbine Inlet Temperature (TIT) for different control parameters.

2. Dynamic model

The research methodology herein presented is applicable to any ORC based heat to power conversion unit. The transient and control studies performed, instead, mostly refer to stationary power generation systems. In particular, the applications where the conclusions presented in this study can be transposed are the ones where water is either the waste heat stream (e.g. geothermal ones) or the heat transfer fluid from a heat recovery exchanger. With regards to the second case however, the current modelling approach discards the thermal inertia of the heat recovery loop, which in turn can damp high frequency fluctuations of the heat load at the ORC evaporator.

With reference to the plant scheme in Fig. 1, the heat recovery takes place through a plate heat exchanger having water on the hot side and the working fluid of the system, which is R245fa, on the cold side. After being pressurized in a multi-stage centrifugal pump, the working fluid undergoes to a full vaporization during the heat recovery process and it is expanded in a turbine, where the useful energy conversion process takes place from a slightly superheated state. After the expansion, the working fluid is eventually condensed in a second plate heat exchanger using water as heat sink. A refrigerant receiver is eventually positioned between the condenser and the pump such that thermal expansion during start-up or large transients can be absorbed, and any cavitation phenomenon at the pump inlet is prevented.

The commercial software platform in which the modelling has been carried out is GT-SUITE™. This tool includes model templates for the components employed in the plant configuration considered. Nevertheless, accurate input data are of paramount relevance for the overall implementation and accuracy of the approach. These inputs can result either from an experimental campaign or, as in the current case, from more detailed or complex models. Finally, connections between these devices are made through piping sub-models. The electric machines connected to pump and turbine are not modelled in this work, which means that the power quantities considered are purely mechanical. In the following paragraphs, a more detailed description of each sub-model is provided.

The boundary conditions imposed in the simulations are revolution speeds of pump and turbine as well as inlet temperatures and flow rates of hot and cold sources. The equations are solved with an implicit numerical method that approximates the system of algebraic differential equations to a system of nonlinear algebraic ones, which are eventually solved iteratively. The solution values at the next time step are simultaneously provided to all the sub-volumes of a given model (e.g. pipes divisions, heat exchangers