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Design and experimental validation of an adaptive control law to maximize the power generation of a small-scale waste heat recovery system

Andres Hernandez [a,b,d,*], Adriano Desideri [b], Sergei Gusev [c], Clara M. Ionescu [a], Martijn Van Den Broek [c], Sylvain Quoilin [b], Vincent Lemort [b], Robin De Keyser [a]

[a] Ghent University, Department of Electrical Energy, Metals, Mechanical Constructions and Systems, Dynamical Systems and Control Laboratory, Technologiepark 914, 9000 Ghent, Belgium
[b] University of Liege, Energy Systems Research Unit, Thermodynamics Laboratory, Campus du Sart Tilman B49, 4000 Lige, Belgium
[c] Ghent University, Department of Flow, Heat and Combustion Mechanics, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium
[d] Universidad de Ibagué, Facultad de Ingeniería, Programa de Ingeniería Electrónica, Carrera 22 Calle 67, 730001 Ibagué, Colombia

HIGHLIGHTS

- Determination of the conditions that challenge control design in ORC systems.
- Development of an adaptive predictive strategy to maximize ORC power generation.
- Comparison to the performance achieved by a gain-scheduled PID control strategy.
- Procedure to build an optimizer for evaporating temperature from experimental data.
- Experimental validation of the proposed control strategies on a 11 kW ORC unit.

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ABSTRACT

Increasing the energy efficiency of industrial processes is a challenge that involves, not only improving the methodologies for design and manufacturing, but optimizing performance during part-load operation and transient conditions. A well-adopted solution consists of developing waste heat recovery (WHR) systems based on Organic Rankine Cycle (ORC) power units. The highest efficiency for such cycle is obtained at low superheating values, corresponding to the situation where the system exhibits time-varying nonlinear dynamics, triggered by the fluctuating nature of the waste heat source. In this paper, an adaptive control law using the Model Predictive Control (MPC) framework is proposed. This work goes a step beyond most of the existing scientific works in the field of ORC power systems, since the MPC controller is implemented in a lab-scale prototype, and its performance compared against a gain-scheduled PID strategy. The experimental results show that the adaptive MPC outperforms the gain-scheduled PID based strategy, as it allows to accurately regulate the evaporating temperature, while keeping vapor condition at the inlet of the expander i.e., the superheating, in a safe operating range, thus increasing the net power generation.

1. Introduction

A growing interest in reducing the amount of world-wide industrial energy consumption has resulted in a number of studies, revealing the great potential for technologies able to recover heat at low temperatures [1]. Among the possible solutions for converting low temperature waste heat into electrical energy, Organic Rankine Cycle (ORC) systems loom up as suitable and attractive solutions [2], standing out for their reliability and cost-effectiveness [3].

While systems at power capacities in the range from hundreds kW_{el} to a few MW_{el} can be considered at a mature stage [4,5], the case of small-scale waste heat recovery (WHR) applications is still under development from fluid selection [6], covering cycle design [7,8], to specific component design methodologies [9].

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* Corresponding author at: Ghent University, Department of Electrical Energy, Metals, Mechanical Constructions and Systems, Dynamical Systems and Control Laboratory, Technologiepark 914, 9000 Ghent, Belgium.
E-mail address: Andres.Hernandez@ugent.be (A. Hernandez).

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Nomenclature

Acronyms

ORC	Organic Rankine Cycle
WHR	waste heat recovery
MPC	model predictive control
EPSAC	extended prediction self-adaptive control
PI	proportional-integral control
PSD	power spectral density

Subscript

el	electrical
ev	evaporator
exp	expander
pp	pump
hf	hot fluid
wf	working fluid
cf	cold fluid
sh	super-heated
eh	electrical heaters

symbols

N	rotational speed (rpm)
p	pressure (Pa)
T	temperature (°C)
$\dot{m}$	mass flow (kg/s)
$\dot{W}$	power (W)
Δ	difference
s	Laplace complex variable
η	efficiency
α	reference-trajectory time constant
ζ	robustness coefficient MPC
σ	frequency intelligent MPC filter
a	coefficient intelligent MPC filter

The highly fluctuating nature of the heat source (temperature and mass flow) makes WHR applications a challenging task [10]. In order to increase the commercial viability of this technology recent research has been focusing on optimizing the performance of small ORC units, adopting multi-objective optimization for the design stage [11,12], dynamic modeling to investigate the system dynamics [13,14] for stationary [15] and mobile ORC applications [16] and to test control strategies during transients conditions [17,18].

In order to achieve the desired optimal performance, control plays a major role [19]. The main challenges are twofold: (1) keep the cycle in a safe condition during operation and (2) maximize the net power generation. Safe operation of the ORC unit is important for the life expectancy of all components. In this regard, ensuring vapor state at the inlet of the expander machine, i.e, an accurate regulation of the evaporator superheating, is an important task for the controller. The regulator has to guarantee a minimum superheating in order to maximize the efficiency, and avoid the formation of liquid droplets at expander inlet that can damage the expansion machine [20]. In order to maximize the output power, the evaporating pressure represents the most relevant controlled variable [7].

Concerning safety and therefore regulation of superheating several controllers have been designed: based on thermodynamics' insight to obtain correlations that can be used as feed-forward action [21], or based on a supervisory predictive control [22], predictive functional control [23] or generalized predictive control as in [24]. A clear trend in the use of advanced model-based controllers, especially Predictive Controllers is confirmed in [25,26] where Model Predictive Control (MPC) outperforms PID strategies to regulate superheating for varying heat source profiles, and to deal with system nonlinearities [27,28]. Most of these studies aim to guarantee safety conditions by regulating the superheating but little attention has been paid to the performance of the power unit in terms of power generation. Recent studies on real-time optimization using MPC have demonstrated to be an attractive solution for optimal performance [29,30], with only few work including experimental work [31,32].

In this study, control strategies to optimally recover waste heat in ORC technology are investigated. The focus is not only on ensuring safety conditions but on maximizing the net power generation. Such situation is achieved when the system reaches the optimal evaporating temperature [33]; usually given by the optimizer, here derived from a steady-state model and as a function of the heat source conditions. The controller's task is then to follow the optimal setpoint generated by the optimizer, while ensuring a minimum superheating value for safe operation. A challenging situation is encountered when both temperature and mass flow rate conditions vary, since this triggers the nonlinear and time-varying dynamics present in the system. In order to deal with such situation, a single controller might not be sufficient. Therefore, a gain-scheduled switching PID and an Adaptive Model Predictive Controller are proposed to deal with the varying dynamics. The performance of the proposed strategies is experimentally evaluated on a low-capacity (11 kWe) waste heat recovery unit equipped with a twin-screw expander, which represents one of the major contributions of this work, since little work regarding the implementation of advanced controllers is available in literature [18,34].

The paper is structured as follows. Section 2 introduces the architecture and main characteristics of the ORC system. A description of the methodology to obtain a low-order dynamic model suitable for prediction is presented in Section 3. In Section 4 the Extended Prediction Self-Adaptive Control (EPSAC) approach to MPC used in this study is introduced. The control structure, design and tuning of the proposed PID and MPC based strategies are described in Section 5, where the experimental results are also presented and discussed. Finally, a conclusion section summarizes the main outcome of this contribution.

2. Organic Rankine Cycle experimental facility

2.1. The Organic Rankine Cycle system

The system considered in this study is the pilot plant available at Ghent University campus Kortrijk (Belgium). A schematic layout of the ORC system is presented in Fig. 1. The system based on a cycle with recuperator and R245fa as working fluid, has a nominal power of 11 kW$_{el}$. A twin-screw expander drives a synchronous permanent magnet generator connected to the electric grid through a four-quadrant inverter, which allows varying the generator rotational speed (N_{exp}). Although the maximum expander rotation speed is 10,000 rpm, generator rotating speed is kept below 5000 rpm for safety reasons. The circulating pump (N_{pp}) is a vertical variable speed 14-stage centrifugal pump with a maximum pressure of 14 bar and 2.2 kW$_{el}$ nominal power.

Starting from the bottom of the ORC installation in the middle of Fig. 1, it is possible to recognize the liquid receiver installed at the outlet of the condenser where the fluid is collected in saturated liquid condition. From the receiver outlet, the fluid (typically