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Recent developments of control strategies for organic Rankine cycle (ORC) systems

Jianhua Zhang [1,]*, Kang Li [2] and Jinliang Xu [3]

[1]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing, 102206, China;
E-Mail: zjhncepu@163.com

[2]School of Electronics, Electrical Engineering and Computer Science Queen's University Belfast, Belfast, UK;

[3]The Beijing Key Laboratory of New and Renewable Energy, North China Electric Power University, Beijing 102206, China

Abstract

Organic Rankine cycle (ORC) is one of the most rapidly growing approach to utilizing low grade thermal energy. This paper deals with the main control problems existed in ORC systems and overviews the main approaches presented in literature. The main ORC operating modes are introduced, the control strategies of ORC systems are then surveyed. Thus, this paper presents a comprehensive review of overall control strategies for ORC energy conversion systems and points out research trend on ORC control systems.

Keywords

Organic Rankine cycle, control, operation

Nomenclature

ADRC	Active disturbance rejection controller	LQI	Linear quadratic integral
CV	Controlled variable	MV	Manipulated variable
EKF	Extended Kalman Filter	MVC	Minimum variance control
DP	Dynamic programming	MPC	Model predictive control
FCL	Following the connected load	NC	Neural control
FFC	Feedforward control	OC	Optimal control
FOPTD	First order plus time delay	ORC	Organic Rankine cycle
FTE	Following the thermal energy	PID	Proportional-Integral-Derivative
GSC	Gain scheduling control	PWM	Pulse-width modulation
LPV	Linear parameter varying	RC	Robust control

1. Introduction

Organic Rankine cycle (ORC) is a well-known approach to recovering low grade thermal energy. The available low temperature heat sources include geothermal energy, biomass products, waste heat from industrial processes and internal combustion engine, surface seawater, solar energy and so on (Tchanche et al., 2013; Tchanche et al., 2011; Lecompte et al., 2015; Colonna et al., 2015; Hung et al., 1997; Qiu et al., 2015; Sprouse et al., 2013).

Some literature has been published on control of ORC systems, but no recent comprehensive review has been reported on control theories and applications of ORC systems except reference (Tona and Peralez, 2015) where the control schemes designed for ORC systems on board heavy-duty vehicle was surveyed. A number of research publications have reviewed architectures (Lecompte et al., 2015), principles (Tchanche et al., 2013; Liu et al., 2015; Shi et al., 2017), working fluid and expander selections (Bao and Zhao, 2013), modelling (Ziviani et al., 2014; Zhang et al., 2017), Techno-economic analysis (Quolin et al., 2013; Velez et al., 2012), applications in waste heat recovery (Hung et al., 1997; Qiu et al., 2015; Sprouse et al., 2013), ORC based power systems (Colonna et al., 2015; Markides, 2015).

Control system plays an important role in ORC systems, effective control scheme may ensure ORC systems operating over a wide range meet the process operation efficiency, safety and reliability. This paper presents a comprehensive review of overall control strategies for ORC systems and aims at providing a reference for further research in the field of ORC systems.

The rest of the paper is organized as follows. Section 2 gives a brief introduction of the operation modes of ORC systems. Section 3 devotes to overview control strategies applied to ORC systems operating in following the connected load mode (FCL). Section 4 focuses on a review of control strategies applied to ORC systems operating in following thermal energy (FTE) mode. Section 5 gives some concluding remarks and some challenges of improving control performance.

2. Operation modes for ORC systems

ORC based low grade thermal energy conversion systems are usually operated using two basic strategies: FCL and FTE (Zhang et al., 2014c). The difference between two operating modes are: 1) Is the mass flow rate or temperature of heat source a manipulated variable (MV)? 2) Does the rotating speed of the expander vary with hot source?

The ORC based power generation system operating in FCL and FTE modes are shown in figure 1 and figure. 2, in which the operation strategy of ORC systems concentrates on load following and maximum thermal energy conversion efficiency respectively. The control objectives of the ORC systems are closely related to their operation modes.

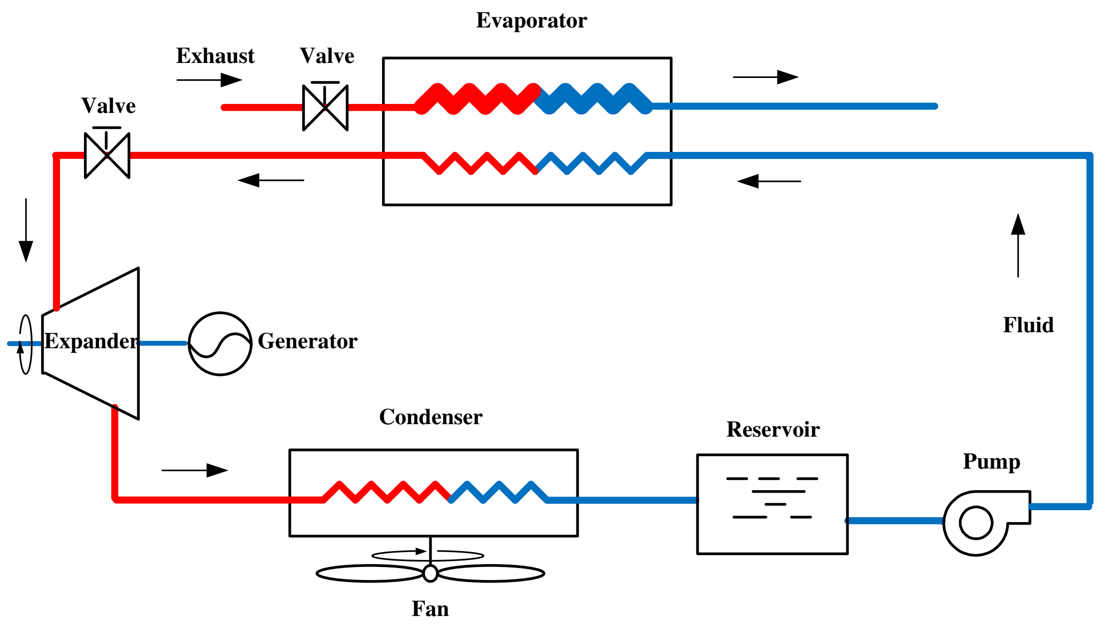


Figure 1. An ORC system in FCL operation mode (Zhang et al., 2014c)

2.1 FCL mode

Figure 1 shows an ORC based system operating in FCL mode, in which the expander and the generator are linked with the same shaft, and the generator is connected to power grid without a power converter interface. In essence, the ORC power generation system need meet load requirement as soon as possible. The maximum energy conversion efficiency of the ORC system in this operating mode is not required, namely, low grade thermal energy that is not utilized by ORC system may be bypassed. The rotating speed of the generator (or the expander) is determined by grid frequency and the number of poles of the stator winding. The produced electric power is required to follow the variations of the load demand while the primary ORC process variables must be maintained within safe operating limits. The mass flow rate or the temperature of the low grade thermal energy sources is usually manipulated to match the varying load.

The control tasks of the ORC system under this kind of operating mode are similar to that of the conventional fossil fired power plants. The set-points of the controlled ORC systems may change substantially due to changes in load requirements. The primary ORC process variables (the evaporating pressure, the superheating and the subcooling) must be maintained within appropriate ranges.

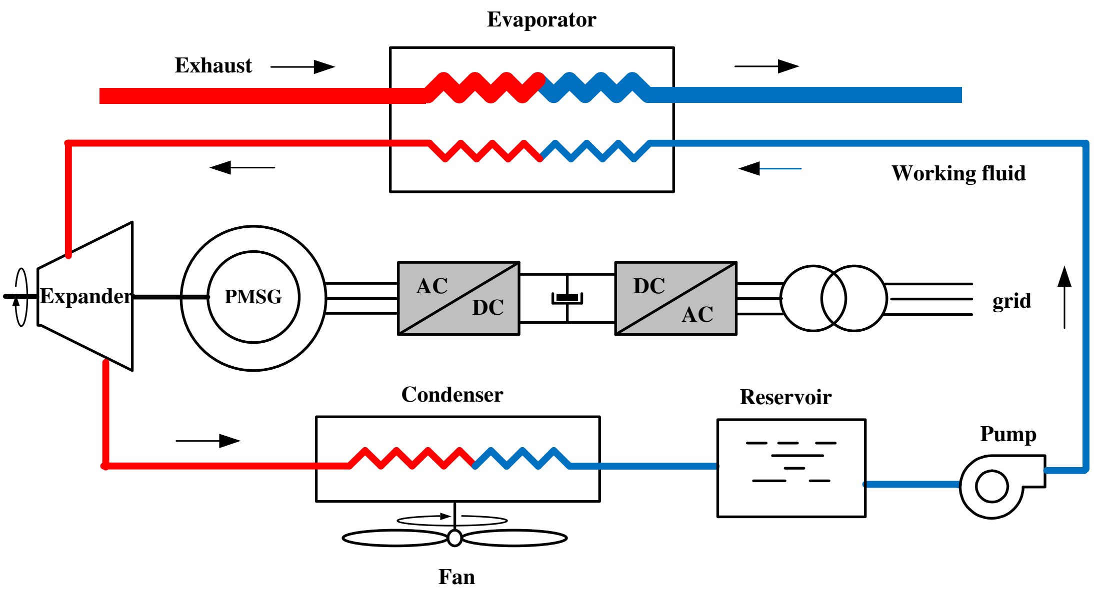


Figure 2. An ORC system in FTE operation mode (Zhang et al., 2014c)

2.2 Following utilized thermal energy mode

With regard to the ORC system operating in FTE mode (shown in figure 2), where the generator is connected to the grid via a full-capacity converter system. The electric power from the generator follows the variations of the utilized thermal energy so as to guarantee the efficient utilization of thermal energy while the ORC process variables must be maintained at desired levels. The mass flow rate or the temperature of the low grade thermal energy sources is usually not used as an MV. The set-points of the controlled ORC systems may change substantially because of variations in the mass flow rate or the temperature of heat source entered to the evaporator.

The ORC system operating in FTE mode aims at efficiently utilizing low grade thermal energy, namely, maximum energy conversion efficiency is expected to achieve under this circumstance. The energy conversion efficiency of the ORC system operating in FTE mode was investigated in (Zhang et al., 2014c). It is pointed out that the overall energy conversion efficiency can be reformulated by

$$\eta_{overall} = \frac{\int_{t_1}^{t_2} \left(\frac{ff \cdot V_s \cdot N_{\exp}}{60 \cdot \upsilon_{exp,i}} \cdot \left(w_1 + w_2 \right) \cdot \eta_{\exp} - W_p \right) dt}{\int_{t_1}^{t_2} \dot{m}_a \cdot \left(h_{su,a} - h_{a,ref} \right) dt} \tag{1}$$

where $\eta_{\exp}$ and $\eta_{overall}$ stand for efficiency of the expander and overall energy conversion efficiency. $N_{\exp}$, $\dot{m}_a$ and h_a are the rotating speed of the expander, the mass flow rate and the enthalpy of heat source respectively. $\upsilon_{exp,i}$ and $h_{a,ref}$ are the reference enthalpy of heat source at 25°C and the specific volume of working fluid respectively. ff is the filling factor and V_s the swept volume. W_p is the pump consumption power. w_1 and w_2 are the specific work of the expander during Isentropic expansion and Constant volume expansion respectively. It can be observed from Eq. (1) that the energy conversion efficiency of a given ORC system is closely related to the rotating speed of the expander, the mass flow rate and the enthalpy (or the temperature) of heat source.

As far as the ORC system operating in a specific operating point is concerned, its current operating condition is determined by the mass flow rate $\dot{m}_a$ and the enthalpy h_a (or the temperature) of the heat source together. Therefore, the rotating speed of the expander should be manipulated in order that the maximum energy conversion efficiency is obtained.

In figure 2, the generator connects to power grid through double pulse-width modulation (PWM) converters and transformer. The permanent magnet synchronic generator (PSMG) allowed for four quadrant operations can realize variable-speed and constant frequency control by using double PWM converters. Since the expander and the generator are linked together with the same shaft, speed regulation of the expander can then be achieved by manipulating the generator torque. Accordingly, the maximum energy conversion system can be achieved.

In summary, the control tasks of the ORC system in FTE operating mode are similar to that of the wind power plants operating in low wind speed region. Seeking the maximum energy conversion efficiency is equivalent to capturing maximum thermal energy. The optimal set-points of the controlled ORC system can be calculated on basis of both the mass flow rate and the temperature of heat source. The primary ORC process variables must be kept within appropriate ranges. Moreover, the rotating speed of the expander is manipulated so that the produced electric power can adapt to varying thermal energy inputting into the ORC system.

3. Control strategies for the FCL mode

When an ORC system is operating in FCL mode, the rotating speed of the expander might keep within a proper range. The set-points of the evaporating temperature, superheating and subcooling vary with the load demand. The mass flow rate or the temperature of the heat source at the inlet of the evaporator is selected as one of MVs.

This kind of ORC power plant is required to deal with some problems encountered in conventional thermal power plants.

3.1 Traditional PID

Three PI controllers were designed for an ORC system that recovers waste heat of heavy-duty diesel powertrain in (Luong and Tsao, 2015). Two independent PI controllers are designed to control the evaporating and condensing pressures and the third one to follow the load demand. The mass flow rate of the condensing fluid and two throttle valve positions are selected as the MVs. The controlled automotive ORC system operating in following base/varying load mode is investigated. The controlled ORC system cannot meet both the power demand and pressure set-points in presence of infeasible power demand. Obviously, it is necessary to improve control performance by adding decoupling or adopting other advanced control laws. Although PI or PID controller is the most intuitive and easiest to implement, it is unable to achieve satisfactory control performance due to nonlinearities, uncertainties, coupling, varying load demand.

3.2 LQI

Two-input two-output (2 x 2) and Three-input two-output (3 x 2) multivariable LQI control scheme were employed for an ORC system respectively (Luong and Tsao, 2014a). LQI control algorithm incorporates linear quadratic regulation technique and integral action so as to reject the steady state tracking error. Two controlled variables (CVs) are the evaporating and condensing pressures. The MVs are chosen as the mass flow rate of the condensing fluid and the throttle valve (before the evaporator) positions in the 2 x 2 multivariable ORC control system. Another throttle valve position becomes a new MV in the 3 x 2 multivariable ORC control system.

A control oriented nonlinear state space model was built for ORC system operating in FCL mode (Zhang et al., 2012a), a four-input four-output (4 x 4) multi-variable LQI control method was presented. The CVs include the net power, throttle pressure, superheated vapor temperature at the outlet of the evaporator and the working fluid temperature at the outlet of the condenser. These CVs are controlled by corresponding MVs: the throttle valve position, rotating speed of the pump, condensing air velocity and exhaust gas velocity. The controller is designed for the ORC system operating in a nominal operating point with the aid of the linearized model. The control performance will degrade when the ORC system deviates the nominal operating point. In addition, the last two CVs, condensing air velocity and exhaust gas velocity, should be replaced by the mass flow rates of exhaust gas and condensing air for improving their measurement in practice.

3.3 MVC

In order to tackle stochastic disturbances from heat source and measurement noises, a multivariable generalized minimum variance control (MVC) algorithm was employed in an ORC system (Hou et al., 2014). The MVC controller can be obtained by minimizing the following performance index

$$\begin{aligned} J_{MVC} = E\{&[H(q^{-1})y(k+d) - R(q^{-1})y_r(k+d)]^T[H(q^{-1})y(k+d) \\ &-R(q^{-1})y_r(k+d)] + [\lambda(q^{-1})u(k)]^T[\lambda(q^{-1})u(k)]\} \end{aligned} \tag{2}$$

where the vector y_r represents the set points of the CVs. $H(q^{-1})$, $R(q^{-1})$ and $\lambda(q^{-1})$ are weight polynomials corresponding to the CVs, set-points of the CVs and MVs, which penalizes the tracking errors and control efforts. Compared with PID controller, generalized MVC obtains better performance (Hou et al., 2014). It should be pointed out that the disturbances and measurement noises are not necessarily Gaussian in practical ORC systems, so it is necessary to do further research on stochastic control theory for ORC systems.

3.4 OC

Optimal control is one of promising control strategies for ORC control systems. Peralez et al. (2014a) employed an adaptive-grid dynamic programming (DP) algorithm to obtain the optimal control law, a fraction of engine exhaust gas and condensing air flow, by maximizing the net power. Constraints on wall temperature and pressure are taken into account as well.

Additionally, the adaptive grid DP algorithm was extended to design an optimal control strategy for an ORC based engine waste heat recovery system in (Peralez et al., 2015). Dynamic real-time optimization is used to produce the optimal set-points for the

ORC pressures in high-level. While DP algorithm is used to calculate the optimal control signals in low-level. A fraction of engine exhaust gas and condensing air flow are obtained by maximizing the recovered energy. In addition, the condensing air flow can be calculated by maximizing the net power as well. The optimal control input of the ORC system can be solved by minimizing following performance index:

$$J_{OC} = \int_0^{t_f} \left(-P_{turb}(t) + P_{pump}(t) + P_{fan}(u,t)\right)dt \tag{3}$$

where $P_{turb}(t)$ is the produced power by the turbine. $P_{pump}(t)$ and $P_{fan}(u,t)$ are the powers consumed by the pump and the cooling system respectively. The bounds on the control inputs (4) and security constraint on pressure (5) is also considered for the proposed optimal control approach.

$$u(t) \in [0,1] \times [0,4], \quad \forall \mathrm{t} \in [0, t_f] \tag{4}$$

where the fraction of exhaust gas is bounded by $[0,1]$, whereas the air mass flow provided by the fan is limited to $[0, 4\mathrm{kg/s}]$.

$$p_1(t) \le 25\mathrm{bar}, \quad \forall t \in [0, t_f] \tag{5}$$

Although the net power or the recovered energy of the ORC system might be maximized, however, numerical calculation burden increases with time, because the cost function to be optimized is an accumulative index rather than an instant index. Moreover, the control algorithm depends on the model of the ORC system. Two state model might not completely characterize the dynamics of real ORC systems.

The optimal control algorithm obtains an optimal control law by minimizing a certain cost function (performance index). The objectives of optimization in ORC systems are generally energy consumption, net power, control effort, closed loop tracking error. In addition, some constraints on CVs and MVs can be considered by solving optimization problem with constraints.

3.5 MPC

MPC has been applied in ORC processes due to its efficient control of multivariable systems with strong couplings, disturbances and operating constraints. A set of control signals are obtained by optimizing a proper cost function over the prediction horizon based on predicted model. The first element of the calculated control vector at current sampling instant is sent to the actuator.

A four-input four output (4x4) generalized predictive control strategy was presented for ORC systems (Zhang et al., 2013a), in which the dynamics of the ORC plant is formulated by a controlled autoregressive integrated moving average (CARIMA) model. The optimal control law can be solved by minimizing the following cost function

$$J_{MPC} = \sum_{j=1}^{N_y} \left\| \hat{y}(k+j|k) - y_r(k+j) \right\|_R^2 + \sum_{j=1}^{N_u} \left\| \Delta u(k+j-1) \right\|_Q^2 \qquad (6)$$

where $\hat{y}(k+j|k)$ is an optimal j-step ahead prediction of the CVs up to time k sampling periods, $y_r(k+j)$ a future set-points of the CVs. N_y and N_u are prediction horizon and control horizon respectively. R and Q are positive definite weighting matrices respectively.

Simulation results are given to test the load following capability and set-points tracking performance of the throttle pressure, the superheated vapor temperature and working fluid temperature at the outlet of the condenser. Additionally, disturbance rejection capabilities are also testified. However, constraints on both CVs and MVs are not taken into account in the proposed MPC strategy. The simulation tests are designed for the ORC system operating around a specified nominal operating condition, no further research on wide range control is reported.

In a different study, a four-input four output (4x4) constrained model predictive control strategy was applied into an ORC based solar thermal power plant in (Rahmani et al., 2015). A nonlinear state space model is identified for the ORC power plant, its linearized state space model is then established and provided for the MPC with constraints on 6 process variables. There are some differences in choosing CVs and paired MVs between two schemes presented in (Zhang et al., 2013a; Rahmani et al., 2015). The selected CVs are the net power, superheating, the temperature of the working fluid at the inlet of the turbine and the pressure at the outlet of the turbine. The corresponding MVs includes rotational frequency of the motor pump, volume flow rate of hot heat source, rotating speeds of both the ventilator and the circulation pump. Although nonlinear MPC strategy is effective in ORC control systems, but it requires system identification or complex mathematical analysis.

Grelet et al. (2015) employed an explicit multiple MPC to control the fluid temperature at the inlet of the expander in an ORC based waste heat recovery system mounted on a heavy duty truck engine. The fluid temperature at the inlet of the expansion machine is controlled by manipulating the working fluid mass flow rate entering the evaporator. The model of the controlled plant is identified and represented by a series of first order plus time delay (FOPTD) models. Simulation results illustrate that multiple MPC is satisfactory based on two FOPTD models which describe the dynamics of the ORC system operating in high/low load operating points respectively. Indeed it is a fast control algorithm without online optimization. Wide range control based on the proposed multiple MPC strategy is not reported.

A switching MPC strategy was presented to reject disturbances caused by the diesel engine waste heat of Euro-VI heavy-duty truck in real on-road driving conditions (Feru et al., 2015). The ORC based waste heat recovery system operating area is divided into three regions, in which MPC controllers are assigned respectively. Two parallel evaporators provide thermal energy to one expander in this ORC system, two bypass valves manipulate the ethanol flow rate simultaneously, such that the vapor state at the outlet of the evaporators is maintained in the presence of engine disturbances. CVs are the vapor fraction after the exhaust gas recirculation and exhaust evaporator. Simulation results show that the proposed switching MPC can achieve better control performance than nonlinear MPC and PI controller. In order to put the proposed control algorithm into practice, the vapor fraction measurement equipment or an estimator is needed to measure the CVs.

3.6 Compound control

Compound control strategies are obtained by the fusion of different control techniques. Several compound controllers have been presented for ORC control systems.

3.6.1 MPC +EKF

Since not all system states are available for measurement, it is reasonable to estimate unknown system states using filtering algorithms. A three-input two-output (3x2) multivariable MPC with extended Kalman filter (EKF) was utilized in ORC systems in (Luong and Tsao, 2014b). EKFs are designed for estimating the states of both the evaporator and the condenser. MPC can obtain better control performance than both PI and LQI in terms of reducing pressure regulation errors and incorporating constraints on control law. However, further research on wide range control is needed.

3.6.2 Cascade control + ADRC

Shi et al. (2016) applied a compound control strategy, combined cascade control with two active disturbance rejection controllers (ADRCs), to an ORC based engine waste heat recovery system, in which the primary CV, the superheating, is controlled by manipulating the mass flow rate of the engine exhaust gas and the secondary CV (the opening of each valve in exhaust gas mixture recirculation) by the corresponding valve voltage. The ADRC strategy is utilized in both outer and inner loops. The external heat source disturbance and the internal parametric uncertainties can be restrained efficiently. The ADRC obtains promising results, but tuning the controller parameters is cumbersome. This work only investigate superheating control law for ORC systems, control method of other key process variables are not reported.

3.6.3 PID + FFC + Compensator

An improved scheme based on proportional-integral, feed-forward and lead-lag compensator was proposed for an ORC control system in off-grid island mode in (Usman et al., 2017). Experimental investigation has been done for an off-grid ORC system subjected to load disturbance, the rotating speed of the expander can track its set-point quickly while the inlet pressure of the expander varies with load demand.

In addition, a compound control scheme combined PID control with FFC was used for an ORC based engine waste heat recovery system in (Torregrosa et al., 2016), although the FFC algorithm wasn't revealed in detail.

The controlled system shown in figure 3 is a section of a geothermal ORC power plant (Padula et al., 2012). The mechanical side of the ORC plant is mainly composed by the two turbines and the relative piping and valves. The control of the turbine speed is of main concern when the ORC power plant connects to the grid (normal) or a stand-alone load (island mode). The turbine inlets are regulated by the valves HT-V1, HT-V2, LT-V1, LT-V2 and HT-V3. The first four valves are kept completely open when the plant delivers electric power to the grid. When the ORC power plant is working in island-mode, the first four valves are completely closed and the low temperature/ pressure turbine is switched, the control valve HT-V3 is used to control the plant. A compound controller that combines an event driven PI controller with FF controller send the control signals to the valve motors.

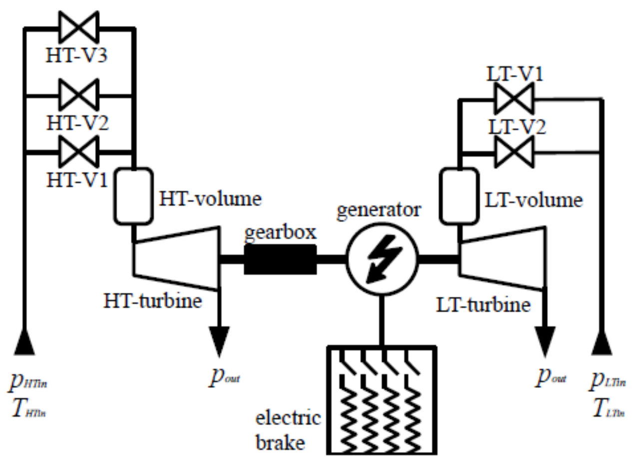


Figure 3. Diagram of the ORC Plant power section (Padula et al., 2012)

When the ORC power plant is switched from the normal operation mode (grid connected) to the island one (stand-alone), the electric brake regulated by nonlinear FF controller dissipates the excess of power produced in order to avoid excessive turbine speed overshoot.

3.6.4 GSC+PID+FFC+EKF

A compound control strategy was proposed for regulating the superheating of an ORC based engine waste heat recovery system by combining PID feedback controller with feedforward controller in (Peralez et al., 2013). Dynamic FFC term is obtained from a nonlinear reduced model of the high-pressure part of the ORC system while a gain-scheduling (GS) PID controller is tuned based on identified model. The superheating control performance is improved, nevertheless, it needs an extensive investigation on system identification so as to obtain a reliable, concise and low time-consuming model. In addition, the control method of other main process variables is not introduced.

Later, this compound control strategy was extended to a two-input two-output (2 x 2) ORC system in (Peralez et al., 2014b), moreover, the unmeasurable states are estimated using an implicit EKF. Simulation results indicates that both the superheating and the evaporating pressure have been successfully controlled.

Recently, more details have been demonstrated in (Peralez et al., 2016), some experimental results on superheating control testify the effectiveness of the proposed compound algorithm that integrates gain scheduling PID, FFC and EKF together. Simulation results on pressure control have been illustrated rather than experimental results. It is not easy to tune the parameters of the proposed compound control strategy.

3.6.5 ADRC + Decoupling

Zhang et al. (2012b) proposed a compound control strategy, combined a linear ADRC with a static decoupling compensator, for an ORC based waste heat recovery system, whose model is obtained by applying the system identification technique. The disturbances existed in the ORC system are estimated through an extended linear state observer and then compensated by a linear feedback control strategy. The decoupling compensator, designed based on the simplified linear ORC model, can alleviate the interactions among process variables, hence, it is easier to tune the parameters of the proposed ADRC strategy. The temperature of the working fluid at the outlet of the condenser can be easily controlled by a single closed-loop control system, therefore, a three-input three-output (3 × 3) multivariable control system is investigated for the ORC system. Simulation results show that the proposed control strategy can provide satisfactory set-point tracking performance and disturbance rejection. The proposed control strategy without requiring an accurate mathematical model for the waste heat recovery system is a significant progress for this type of processes. This practical control strategy is easy to understand and implement, making it an appealing method to real applications. Nevertheless, it is still necessary to investigate the methods to tune the parameters of the nonlinear ADRC for ORC control systems in future.

4. Control systems for the FTE mode

When an ORC system is operating in FTE mode, it can be observed that the rotating speed of the expander is usually varying with the heat source. In addition, the mass flow rate and the temperature the heat source at the inlet of the evaporator are not selected as MVs or CVs.

This kind of ORC power plant is required to deal with some problems encountered in wind plants or solar plants rather than conventional thermal power plants. The objective of the control system is to maintain the outlet temperature (or the superheating) of the evaporator, the outlet temperature (or the sub-cooling) of the condenser and the evaporating pressure at desired set-points in spite of the disturbances induced from fluctuations in the low grade thermal energy source, the pump and the expander. Thus, when the pump rotating speed for adjusting working fluid, the expander rotating speed (or the shaft torque) for adjusting evaporating pressure (or temperature) and the pump (or the fan) rotating speed for adjusting water (or air) entering the condenser are manipulated during operation, the expected transient response might be obtained.

4.1 PI Control

Three control schemes were proposed in (Quoilin et al., 2011), the superheating is controlled with the pump flow rate and the evaporating temperature with the expander speed. Two independent single PI control loops are employed in scheme 1. Adding the optimal set-point of the evaporating temperature to scheme 1 leads to scheme 2. In scheme 3, the evaporating temperature PI control loop is same as that in scheme 1. A faster reaction of the pump can be achieved to deal with varying operating conditions due to the FFC adopted in the superheating control loop, where the correlated optimal pump flow rate regarded as the FFC signal, is defined by a linearly combined formula whose coefficients need be identified in advance. The linear regression formula to predict the optimal evaporating temperature in scheme 2 is determined by studying the ORC system in many operating points, so is the optimal working fluid flow rate in scheme 3. The control performance degrades if the operating conditions vary from nominal condition.

4.2 GSC

A gain scheduling control (GSC) strategy was proposed for ORC base waste heat recovery systems over a wide range of operation conditions in (Zhang et al., 2016a). The nonlinear dynamics of the ORC system is formulated by an affine linear parameter varying (LPV) system whose scheduling parameters are selected as the mass flow rate and the temperature at the inlet of the evaporator. The LPV controller should guarantees the quadratic H_∞ performance $\overline{\gamma}$ for the closed-loop system T_{zw} as follows

$$\|T_{zw}\|_\infty < \overline{\gamma} \tag{7}$$

Simulation results illustrate that the gain scheduling controller based on the LPV model can achieve satisfactory control performance over a wide range operating region. The comparisons between GSC and conventional PI control has been investigated in (Zhang et al., 2016a). Take the robustness test as an illustrative example, figure 5 show variations of CVs and MVs when the operating condition of the ORC system varies as shown in Fig. 4. The responses of the CVs achieve smaller deviation from its set-point and settling time using the gain scheduling controller based on LPV model. It is clear from Fig. 5 that the GSC requires less energy than PI controller by comparing the MVs. Figure 6 shows the superiority of GSC by comparing net output power and overall efficiency of the ORC system.

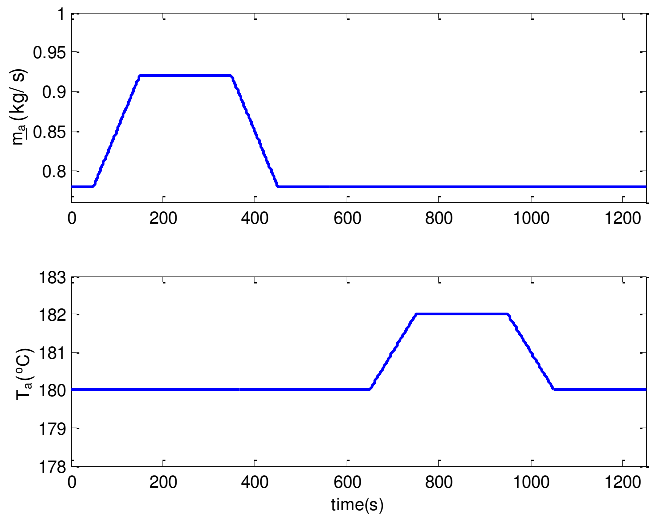


Figure. 4 Variance of operating condition (Zhang et al., 2016a)

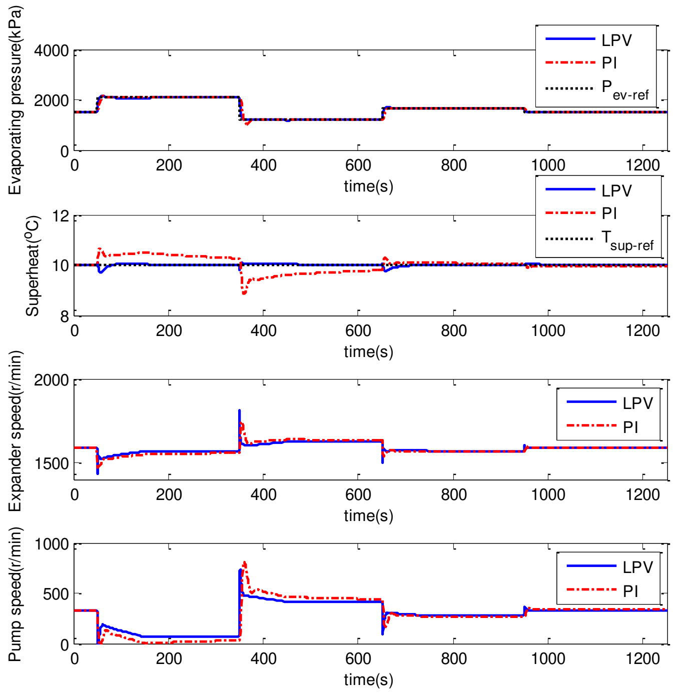


Figure. 5 Variations of CVs and MVs (Zhang et al., 2016a)

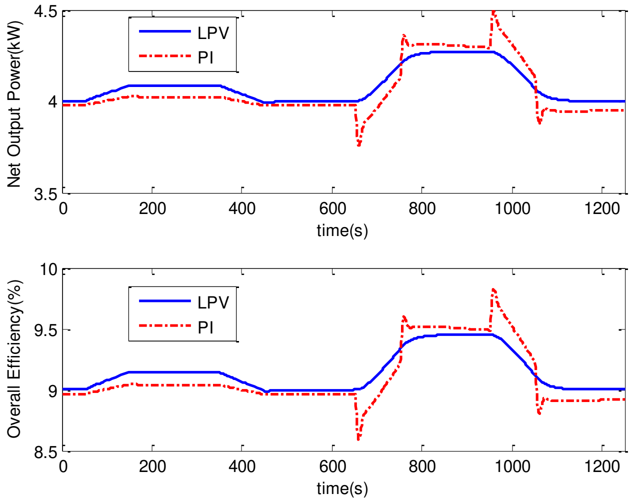


Figure. 6 Net output power and overall efficiency (Zhang et al., 2016a)

However, ORC control systems over entire operating range are not reported in (Zhang et al., 2016a), more appropriate LPV models should be built to improve control performance in future.

4.3 MPC

A constrained MPC strategy shown in figure 7 was presented for an ORC system operating in FTE mode in (Zhang et al., 2014c). This three-input three-output (3 x 3) multivariable system obtains satisfactory control performance. In this work, the temperature at the outlet of the condenser (the subcooling) becomes a CV regulated by the mass flow rate of the condensing fluid for improving the energy conversion efficiency. The constraints on both CVs and MVs are included to guarantee the controlled ORC system operating within safe operating region. There are two kinds of MV constraints shown as inequalities (8) and (9) in this control system. In addition, CV constraints shown in inequality (10) are critical to guarantee the controlled ORC system within the safe operating region.

$$-\Delta u_{max} \leq \Delta u(t) \leq \Delta u_{max} \tag{8}$$

$$\underline{u} \leq u(t) \leq \bar{u} \tag{9}$$

where Δu_{max} is maximum rate of the control input. $\bar{u}$ and $\underline{u}$ are maximum and minimum input values respectively.

$$\underline{y} \leq y(t) \leq \bar{y} \tag{10}$$

where $\bar{y}$ and $\underline{y}$ are maximum and minimum output values respectively.

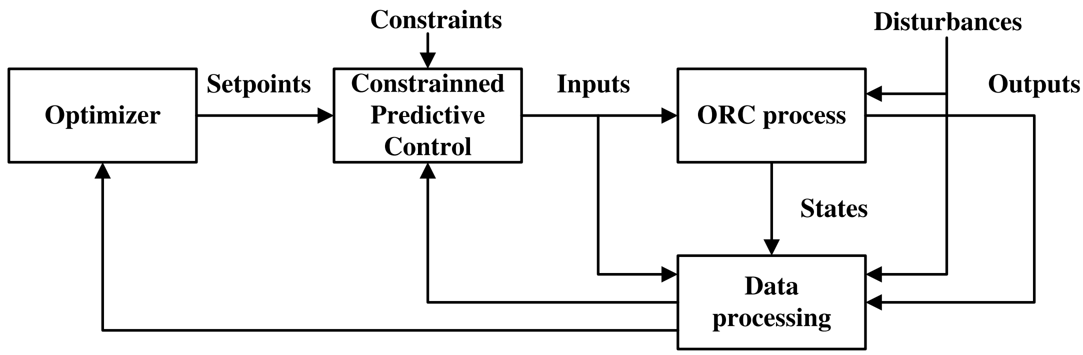


Figure 7. Constrained MPC of ORC systems (Zhang et al., 2014c)

The disturbances from the waste heat source shown in Fig. 8, the temperature T_{ai} and the flow rate $\dot{m}_{ai}$, are imposed during the test. The controlled ORC system may adapt to the variations of the temperature and flow rate, hence, the waste heat can be deeply recovered.

The variations of MVs shown in Fig. 9 (a) demonstrate that the manipulated signals lie within the feasible region. In Fig. 9 (b), the dash lines represent the set-points corresponding to each CVs. It is clear that the CVs are kept within proper ranges despite the fluctuations of the temperature and flow rate of waste heat source.

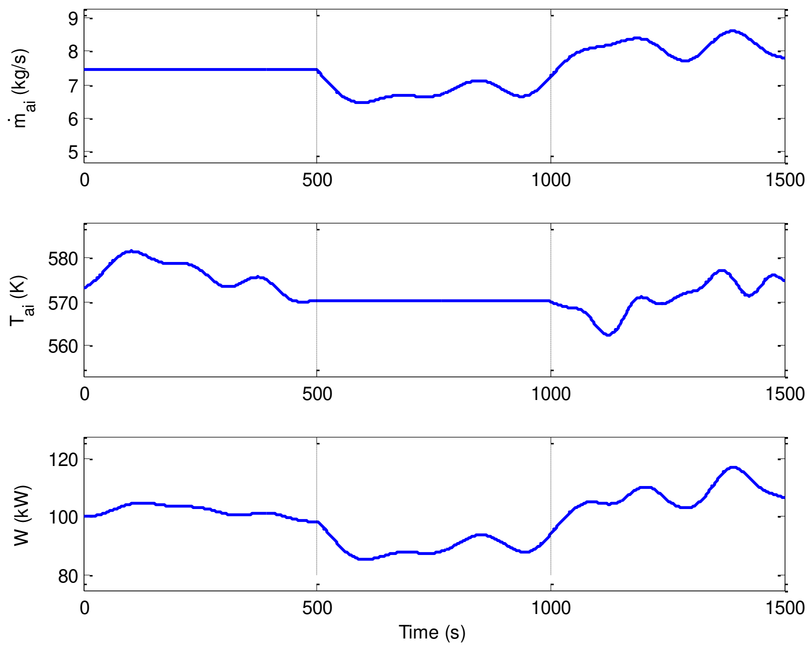
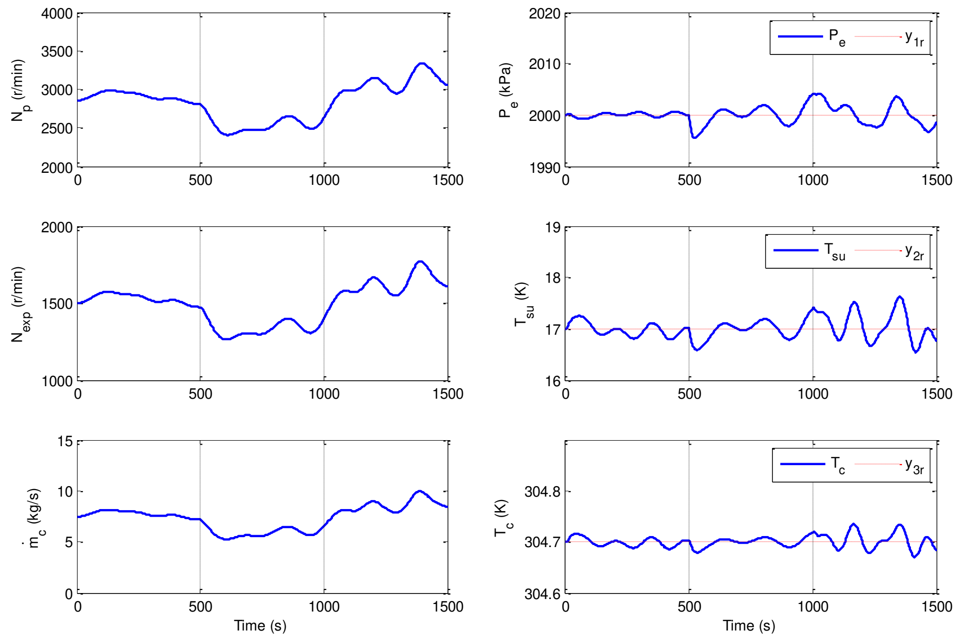


Figure 8. Fluctuation of waste heat and response of output power (Zhang et al., 2014c)



(a) Variations of MVs (b) Responses of CVs

Figure 9. Evolutions of MVs and CVs (Zhang et al., 2014c)

The dynamics of the ORC process is identified and formulated by controlled auto-regressive integrated moving average model, it is necessary to investigate nonlinear MPC for ORC systems in future.

A two-input two-output MPC strategy was applied into an ORC waste heat recovery system for increasing its efficiency in (Hernandez et al., 2014). Two CVs, the superheating and the evaporating temperature, are regulated by manipulating the rotating speeds of both the pump and the expander respectively. Compared with a decentralized PI controller, the extended prediction self-adaptive control algorithm can achieve a higher average efficiency (Hernandez et al., 2014) , that is to say, a higher average net power can be obtained with less control effort. However, wide range control is not studied in this work.

Later, the MPC strategy was improved by optimizing the set-points of the CVs in (Hernandez et al., 2015). Considering the variations in heat source, an optimizer is explored to produce the optimal set-point of the controlled superheating. Compared with switching PI control, the ORC system under the improved MPC strategy produces more net power. The optimal set-point act on the superheating rather than another CV (the evaporating temperature). In addition, wide range control is not studied.

Recently, a multiple MPC strategy was proposed for ORC system to deal with nonlinearity and varying operating conditions in (Zhang et al., 2016b). A model bank is built to describe the ORC system operating in some typical operating points. The control signal is obtained based on the prediction outputs of all sub-model and their corresponding weights. Simulation results testify the effectiveness of the ORC system over a wide operating range. This practical control strategy is easy to understand and implement, moreover, it can deal with nonlinearity, constraints both on CVs and MVs and varying operating points. Hence, it is suitable for real ORC systems after obtaining the proper weights corresponding to sub-models.

4.4 RC

A multivariable robust control (RC) algorithm was designed for an ORC system in (Zhang et al., 2013b). Simulation results show that the proposed control strategy can obtain satisfactory performance in set-point tracking and disturbance rejection. This simple structured and easy-to-realized controller does not require a precise math model, it can deal with generalized disturbances that include the internal unmodeled dynamics, the external uncertain disturbance and the modeling errors and make it an appealing method to real applications.

4.5 Neural control (NC)

A single neuron controller was presented to control the working fluid temperature at the outlet of the evaporator (Ren et al., 2016). The survival information potential criterion is used to optimize the controller parameters in order that the randomness and magnitude of the closed-loop tracking error are as small as possible. The weights of the neural controller can be determined by minimizing following performance index

$$J_{NC} = S_{\alpha}(e_k) + \lambda S_{\alpha}(u_k) \tag{11}$$

where $\lambda > 0$ is the weight. $S_{\alpha}(e_k)$ and $S_{\alpha}(u_k)$ are the survival information potential of the tracking error and the MV at k_{th} instant respectively.

Simulation results show some encouraging results have been achieved. The proposed neural control algorithm doesn't depend on the model of the controlled ORC process. In essence, this control algorithm is a data driven control algorithm which can be implemented easily and reject stochastic disturbances.

4.6 OC

In order to deal with stochastic disturbances in ORC systems, optimal control algorithm which needn't make any assumptions on stochastic disturbances has been used in ORC systems. A minimum error entropy controller was developed for control the superheating of an ORC system in (Zhang et al., 2016c). The optimal controller is obtained by minimizing an improved entropy criterion which combines the entropy of the tracking error and mean value of the squared tracking error. In addition, constraints on the rotating speed of the pump is also considered. Similarly, a multi-objective estimation of distribution algorithm was adopted to obtain all the possible optimal control inputs to control the working fluid temperature at the outlet of the evaporator of an ORC system (Zhang et al., 2014b). However, it is necessary to determine the best control inputs from all candidates. The proposed optimal algorithm isn't extended to multivariable ORC control systems.

Set-points optimization is very important in order that the controlled ORC system operates optimally. The optimizer shown in figure 4 produces optimal set-points for the constrained MPC in the lower level on basis of optimal operation strategies or data mining techniques (Zhang et al., 2014c). A more detailed supervisory control system was presented for ORC systems in (Zhang et al., 2014a). In supervisory level, the optimal set-points are determined for superheating and evaporating pressure by combing support vector machine with genetic algorithm. Following the mass flow rate and temperature of heat source, the optimal set-points make controllers produce optimal control signals which drive the expander operating at optimal rotating speed, accordingly, the energy conversion efficiency can be achieved.

It was pointed out that the optimal evaporating temperature correlated to the heat source temperature, the condensing temperature and the working fluid mass flow rate in the second control strategy presented by Quoilin et al. (2011). A line regression formula for predicting the optimal evaporating temperature was obtained using the golden section search method for 31 operating points and specified operating conditions.

5. Conclusions

Control strategies play an important role in harvesting energy efficiently from low grade thermal energy. This paper overviews different control techniques and outcomes of many research work in the area of ORC control systems. Advantages and disadvantages of different control techniques and their limitations are analyzed and discussed.

Some important points of development for ORC control systems can be summarized as follows:

1) Some attractive control strategies are available for ORC control systems in the form of conventional PID control, FFC, GSC, ADRC, LQI, OC, NC, RC, MVC, MPC and some compound control strategies. These techniques were reviewed and highlighted their features. Compared with most of the other control techniques,

MPC and improved MPC (multiple MPC, switching MPC) generally provides better control performance because they can deal with nonlinearities, constraints on process variables, disturbances and varying operating condition.

2) Most of the control strategies proposed for ORC systems depend on model, although some control oriented models have been built for ORC systems, for example, two state model (Peralez et al., 2015), (simplified) physical model (Quoilin et al., 2011; Zhang et al., 2012, 2016a), LPV model (Zhang et al., 2016a), FOPTD (Grelet et al., 2015) and transfer functions (Hernandez et al., 2014). Modelling of ORC systems should be studied via system identification techniques or analyzing physical models. Some state estimation methods, filter or observer design approaches, can be employed to improve control performance.

3) Maximum energy conversion efficiency tracking algorithm is crucial for ORC systems so as to deeply utilize low grade thermal energy. Associated with the mass flow rate and temperature of heat source, there exists a specific generator (expander) speed which captures maximum power. Hence, it is necessary to investigate both the machine side and grid side controller for ORC power generation systems.

4) In order to ensure ORC systems operate in optimal condition, it is necessary to investigate supervisory control strategy to produce optimal set-points for ORC control systems.

5) Because the dynamics of ORC systems is complex in terms of nonlinearity, coupling and time varying disturbances, advanced control algorithms should be

investigated. In addition, performance comparison of different control strategies should be performed via both simulation and experimental test. Some comparison metrics can be employed to compare the performances of different controllers, for example, energy conversion efficiency, steady state response improvement (alleviating tracking error), transient response improvement (decrease in overshoot, rise time, settling time and peak time), robustness to disturbances and changes in operating points, handling constraints on operation variables, reduction of computation time, implementation in practice.

6) The ORC control system over a wide (or entire) operating range should be studied to adapt to variances induced by heat source or connected load.

7) Because ORC systems operating in different modes have different control objectives, it is necessary to investigate proper control algorithms to follow load demand or heat source.

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