Performance Assessment of Controlled Organic Rankine Cycle System

Jianhua Zhang\textsuperscript{a}, Fuli Shui\textsuperscript{a}, Man Jiang\textsuperscript{a} and Junghui Chen\textsuperscript{b}\textsuperscript{*}

\textsuperscript{a}School of Control and Computer, North China Electric Power University, Beijing 102206
\textsuperscript{b}Department of Chemical Engineering, Chung-Yuan Christian University, Chung-Li, Taiwan 320

Abstract

It is necessary to investigate performance assessment of controlled Organic Rankine Cycle (ORC) systems because the characteristics of controlled process are coupling, time-varying, stochastic disturbances and nonlinearities. In particular, stochastic disturbances occurring in ORC systems are not necessarily Gaussian. A novel control performance assessment (CPA) method based on the entropy of controlled output is developed to evaluate the ORC system controlled by PI and Modeling Predictive Control (MPC). The simulation results indicate that the proposed method is effective and meaningful in the process of actual operation.

Keywords: Control Performance Assessment; Entropy; Organical Rankine Cycle; Non-Gaussian Disturbances.

1. Introduction

With energy depletion, Organic Rankine Cycle (ORC), which is efficiency in converting low temperature heat source into electric power \cite{1}, has obtained more and more attention in past few decades. Some researches on ORC systems have been done, such as modeling \cite{2}, control \cite{3}, operation optimization \cite{4}, and so on. Very few attempts on CPA of ORC systems have been done. However, controller’s performance directly affects the economy and safety of whole system. Proper control performance assessment can monitor real-time status of controller and guide operators to make right decisions. So, it is necessary and meaningful to assess control performance for complex ORC systems.

CPA is originated in MVC theorem \cite{5} proposed by Astrom in 1967. Only routine closed-loop output data and a priori knowledge of process time delay were used by Harris to estimate the control performance of MVC \cite{6} in 1989. CPA based on MVC criterion is under assumption that the disturbance obeys Gaussian distribution. However, the mass flow rate and temperature of waste heat in ORC process are not necessarily Gaussian. So, it calls for further research on CPA using a novel approach rather than

* Corresponding author. Tel.: 010-61772106; fax: +0-000-000-0000 .
E-mail address: zjhncepu@163.com
MVC based CPA method. In this work, entropy which is a more general measure of uncertainty is utilized to develop a CPA method. The quadratic Renyi’s entropy of random variable $X$ with length $M$ is

$$H_2(X) = -\ln \sum_{i=1}^{M} p_i^2$$

where $p_i$ is the corresponding probability density.

2. Model Description

The ORC system considered in this paper is shown in Fig. 1. Organic working fluid, R245fa, absorbs waste heat from exhaust gas in the evaporator. The vapor of working fluid exiting the expander drives the generator to produce electric power. The working fluid condensed into liquid in an air-cooled condenser. The liquid is then pumped back to the evaporator.

![Fig. 1. The Simplified Scheme of ORC System](image1)

![Fig. 2. A Simplified ORC Process Control Loop](image2)

In this paper, we take a temperature control system in ORC processes as an illustrative example to investigate CPA for ORC processes. The superheated vapor temperature at evaporator outlet $y_t$ is closely related to the efficiency of ORC systems. A simplified discrete-time temperature closed-loop control system is shown in Fig. 2. The pump speed $u_t$ is selected to regulate the superheated vapor temperature at evaporator outlet $y_t$. $a_t$ stands for a stochastic disturbance induced by exhaust gas. $G_c$, $z^{-d}G_p$, and $G_d$ are transfer functions of controller, controlled plant with time delay $d$ and disturbance respectively. The influence of disturbance $a_t$ on the output $y_t$ can be described by

$$y_t = \frac{G_d}{1+z^{-d}G_c G_d} a_t$$

3. Control Performance Assessment Based on Minimal Entropy Control

In order to study CPA of the controlled temperature system, the disturbance transfer function $G_d$ can be decomposed. The superheated vapor temperature at evaporator outlet $y_t$ can then be formulated by

$$y_t = F a_t + L a_{-d} = (a_t + n a_{-d} + \cdots + n d a_{-d}) + (n_a a_{-d} + n_d a_{-d} + \cdots)$$

where $F(z^{-d})$ and $L(z^{-d})$ can be further described as moving average models respectively. $F(z^{-d})$ is feedback-invariant and merely depends on the process time delay and the disturbance transfer function. $L(z^{-d})$ is feedback-dependent.
Since stochastic disturbance $a_i$ induced by exhaust gas is not necessarily Gaussian, the quadratic Renyi entropy of the controlled temperature $H_2(y_i)$ shown in following equation is investigated instead of its variance.

$$H_2(y_i) = H_2(Fa_i, La_i, a)$$

(4)

Assume that the disturbance variables $a_i, i=1,2,\cdots,t-d$ are bounded and independent of each other. The minimum entropy of output variables ($H_{2\text{min}}(y_i)$) can be obtained when $L=0$.

$$H_2(y_i) \geq H_{2\text{min}}(y_i) = H_1(Fa_i) = H_1(a_i) + H_1(n,a_i) + \cdots + H_1(n,a_{t-d-1})$$

(5)

As a result, the following performance index of CPA is presented.

$$\eta_e = \frac{H_{2\text{min}}(y_i)}{H_2(y_i)} (0 \leq \eta_e \leq 1)$$

(6)

Based on above analysis, the new performance index from Eq.(6) can be calculated easily if the time delay of the process, the disturbance sequences and the feedback invariant are known. As a matter of fact, minimum entropy filter (MEF) [9] and minimization of entropy with the estimation of distribution algorithm [10] can be used to identify the system model between disturbance and controlled output data.

4. Simulation

In this simulation, the proposed CPA method is applied to evaluate the control performance of a superheated temperature control system using the PI control and Modeling Predictive Control (MPC) [11] respectively. Matlab NCD toolbox is utilized to tune optimal PI parameters, and the transfer function of the PI controller ($G_c(z)=12.3+0.42/(z-1)$) is then obtained. When the MPC algorithm is applied to control superheated vapor temperature at the evaporator outlet for the ORC plant, the sampling period of the MPC algorithm is 0.2s, predictive horizon 39, control horizon 5 and the constraint of control input \([-2 \ 2]\) respectively. The simulation results are shown in Fig. 3- Fig. 6.
It is found from Fig. 3 that the disturbance from waste heat is non-Gaussian based on the cumulative distribution function of the actual disturbance. Fig. 4 and Fig. 5 indicate that the estimated disturbance from the PI control loop and the MPC loop respectively. It is found that the estimated non-Gaussian disturbance can approximate the actual disturbance well. The first figure in Fig. 6 shows the distribution of the actual disturbance. The middle figure in Fig. 6 indicates the distribution of the disturbance estimated by a MEF integrated into the PI control loop. The last figure in Fig. 6 indicates the distribution of disturbance estimated by a MEF integrated into the MPC closed loop. The performance index $\eta_e$ for PI and MPC controlled loops are calculated from Eq. (6) respectively. Their performance indices are 0.9086 and 0.9441 respectively. It is obvious that the two controllers can implement the control task; furthermore, the performance of MPC is better than PI control.

5. Conclusion

A new performance assessment method based on Renyi’s quadratic entropy is proposed to evaluate the control performance of the superheated vapor temperature control loop in an ORC system with non-Gaussian disturbance. The simulation results show that the MEF is a reliable method in estimating non-Gaussian disturbance from system output. From the estimated disturbance sequence and corresponding distribution probability, the CPA index can be calculated. The comparison between PI control and MPC shows that MPC is a better control law than PI.

Acknowledgements

This work was supported by the National Science Council, R.O.C., the China National Science Foundation under Grant (60974029) and National Basic Research Program of China under Grant (973 Program 2011 CB710706). They are gratefully acknowledged.

References


