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# Enhanced-efficiency operating variables selection for vapor compression refrigeration cycle system

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ABSTRACT

In this paper, a novel enhanced-efficiency selection of operating variables based on self-optimizing control (SOC) method for the vapor compression refrigeration cycle (VCC) system is proposed. An objective function is proposed to maximize the energy efficiency of the VCC system while meeting with the demand of indoor thermal comfort. With the detailed analysis of operating variables, three unconstrained degrees of freedom are selected among all the candidate operating variables. Then two SOC methods are applied to determine the optimal individual controlled variables (CVs) and measurement combinations as CVs. The model predictive control (MPC) method based controllers and PID controllers are designed for different sets of CVs, and the experimental results indicate that the proposed selection of CVs can achieve a good trade-off between optimal (or near optimal) stable operation and enhanced-efficiency of the synthesized control structure.



## 1. Introduction

The significantly increasing energy consumption of the heating, ventilating, and air-conditioning (HVAC) systems has attracted many scholars' attention during the past decades. Numerous researchers have focused on the optimization and control strategies of HVAC systems for enhancing the energy efficiency (Thompson and Dexter, 2005; Schurt et al., 2009; Elliott and Rasmussen, 2013; Kamar et al., 2013; Afram and Sharifi, 2014; Fallhsohi et al., 2010; Salazar and Méndez, 2014). The effective control strategies adjust the operating variables of the system to ensure the system reliability and reduce the energy consumption.

The vapor compression refrigeration cycle (VCC) system, which is a complex multivariable system, is a core component in HVAC system. As the essential step in controller design of VCC system, appropriate selection of controlled variables (CVs) and manipulated variables (MVs) not only affects the control system performance but also influences the overall plant operation and costs (Rangaiah and Kariwala, 2012; Van De Wal and De Jager, 2001). However, the selection of operating variables is based on practice experience in most of the previous studies. It seems that less attention has been devoted to the influence of different sets of CVs for the operation stability and system efficiency of the VCC system.

The researches focused on the selection of operating variables can be classified into relative gain array (RGA) based criterion and SOC method. Jain et al. (2010) analyzed a reduced set of CVs for VCC system, and then proposed a decentralized feedback structure by using RGA number to choose input–output (I/O) pairs. He and Cai (2009) developed the relative normalized gain array (RNGA) algorithm as variable selection criterion which provided more accurate selection results than RGA did. Based on the RNGA method, Shen et al. (2010) proposed a decoupling control strategy to the temperature control of HVAC systems. The experiment results above proved the effectiveness of I/O pairs, while the choices of effective CVs did not take the energy efficiency into account.

Recently, SOC method is widely applied in industrial process systems. "Self-optimizing control" is defined as a tradeoff between economic performance and acceptable loss achieved without re-optimization when disturbances occur. Skogestad and Postlethwaite (1996) provided an analysis of minimum singular value within configuration of SOC to choose the optimized CVs. Halvorsen et al. (2003) proposed a local optimization rule to minimize the loss of worst-case with which to choose the optimized CVs. Kariwala et al. (2008) further improved this optimization rule and presented an approach to minimize the average loss for SOC. Alstad and Skogestad (2007) proposed null space method to select optimal measurement combinations as CVs, the advantages

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**Nomenclature**

| | |
|---|---|
| $a, b, c$ | coefficient |
| $s$ | disturbance |
| $A$ | cross-sectional area ($m^2$) |
| $C, D$ | coefficient |
| $C_p$ | specific heat capacity at constant pressure (kJ/kg/°C) |
| $F_{com}$ | frequency of compressor (Hz) |
| $G$ | gain of the selected measurement |
| $H$ | selection or combination matrix |
| $h_{cri}$ | enthalpy at inlet of condenser (kJ/kg) |
| $h_{cro}$ | enthalpy at outlet of condenser (kJ/kg) |
| $h_{eri}$ | enthalpy at inlet of evaporator (kJ/kg) |
| $h_{ero}$ | enthalpy at outlet of evaporator (kJ/kg) |
| $J$ | cost function |
| $L$ | loss in the self-optimizing method |
| $\dot{m}_{ca}$ | air flow rate of condenser (kg/s) |
| $\dot{m}_{com}$ | mass flow rate of refrigerant through compressor (kg/s) |
| $\dot{m}_{ea}$ | air flow rate of evaporator (kg/s) |
| $\dot{m}_{eri}$ | mass flow rate of refrigerant at inlet of evaporator (kg/s) |
| $\dot{m}_{ero}$ | mass flow rate of refrigerant at outlet of evaporator (kg/s) |
| $\dot{m}_r$ | mass flow rate of refrigerant (kg/s) |
| $\dot{m}_v$ | mass flow rate of refrigerant through expansion valve (kg/s) |
| $MSS$ | minimal stable superheat of evaporator (°C) |
| $n$ | measurement and implementation error |
| $P_e$ | evaporating pressure (bar) |
| $P_c$ | condensing pressure (bar) |
| $\dot{Q}_e$ | evaporator energy transfer rate (kJ/s) |
| $T_{amb}$ | environment temperature (°C) |
| $T_{cai}$ | air temperature at inlet of condenser (°C) |
| $T_{cri}$ | refrigerant temperature at inlet of condenser (°C) |
| $T_{cro}$ | refrigerant temperature at outlet of condenser (°C) |
| $T_{crsat}$ | condensing temperature (°C) |
| $T_{csc}$ | subcool degree of condenser (°C) |
| $T_{csh}$ | superheat degree of condenser (°C) |
| $T_{eai}$ | air temperature at inlet of evaporator (°C) |
| $T_{eri}$ | refrigerant temperature at inlet of evaporator (°C) |
| $T_{ero}$ | refrigerant temperature at outlet of evaporator (°C) |
| $T_{ersat}$ | evaporating temperature (°C) |
| $T_{esh}$ | superheat degree of evaporator (°C) |
| $u$ | system input |
| $\dot{W}_{com}$ | power consumption rate of compressor (kJ/s) |
| $y$ | system output |
| $v_o$ | opening of expansion valve |
| $\eta_{com}$ | delivery coefficient of compressor |
| $\rho$ | density (kg/$m^3$) |

*Subscripts*

| | |
|---|---|
| $a$ | air |
| $c$ | condenser |
| $com$ | compressor |
| $e$ | evaporator |
| $i$ | inlet |
| $o$ | outlet |
| $r$ | refrigerant |
| max | maximal value allowed |
| min | minimal value allowed |

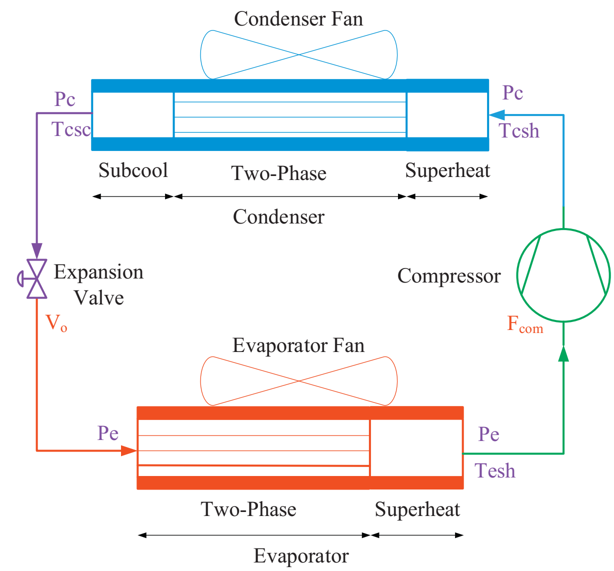


**Fig. 1.** Vapor compression refrigeration cycle system.

of which were simple in computing and realizing. Cao and Kariwala developed branch and bound methods for SOC and applied to large-scale processes to demonstrate the computational efficiency (Cao and Kariwala, 2008; Kariwala and Cao, 2009, 2010). Zumoffen and Musulin (2013) proposed a novel CVs selection approach based on spectral graph theory by which the energies were related to the deviations in manipulated and controlled variables. While there are few researches on the application of SOC could be found when it comes to select the CVs of actual VCC systems. Jensen and Skogestad (2007a,b) considered the steady-state operation of two different refrigeration cycles. Five degrees of freedom were considered and 2% savings of compressor power had been obtained with the proposed selection of CVs, while only one unconstrained degree of freedom was used to optimize the operation.

In this paper, the objective is to select the CVs for the VCC system to enhance the energy effectiveness and disturbance rejection for VCC system. According to the dynamic model of VCC system, the relationship among operating variables is analyzed and the constraints for the optimal operation are detailed. Three unconstrained degrees of freedom are selected among all the candidate operating variables. The objective function is proposed to minimize the energy consumption of the VCC system while meeting with the cooling demands. Then the optimal individual CVs and measurement combinations as CVs are selected by applying the SOC methods. The effectiveness of the proposed selection is verified by the control performance of the MPC controllers and PID controllers which are designed for different structures of operating variables.

The remainder of the paper is organized as follows. Section 2 details the dynamic model of the VCC system. Section 3 provides the analysis and optimization based on SOC method for VCC system. Section 4 selects the optimal individual CVs and combined CVs of VCC system, and the experimental results indicate the efficiency of the proposed selection. Section 5 summarizes the main conclusions.

## 2. Description of VCC system

A typical VCC system fully utilizes a circulating refrigerant as the medium which absorbs and removes heat from the spaces and subsequently achieves the desired objectives. It includes four main components: evaporator, compressor, condenser, and expansion valve (see Fig. 1). The relationship between pressure and enthalpy