Purdue University
Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2018

Model-free Control and Automatic Staging of Variable Refrigerant Flow System with Multiple Outdoor Units

Liujia Dong
The University of Texas at Dallas, United States of America, lxd122030@utdallas.edu

Yaoyu Li
University of Texas at Dallas, United States of America, yaoyu.li@utdallas.edu

Tim Salsbury
timothy.i.salsbury@jci.com

John M. House
Johnson Controls, Inc., john.m.house@jci.com

Model-free Control and Automatic Staging of Variable Refrigerant Flow System with Multiple Outdoor Units

Liujia Dong[1*], Yaoyu Li[1], Timothy I. Salsbury[2], John M. House[2]

[1]University of Texas at Dallas,
Richardson, TX, USA
lxd122030@utdallas.edu; yaoyu.li@utdallas.edu

[2]Johnson Controls International PLC, Building Technologies & Solutions Research Group,
Milwaukee, WI, USA
Timothy.I.Salsbury@jci.com; John.M.House@jci.com

* Corresponding Author

ABSTRACT

This paper describes a model-free control and automatic staging strategy for the operation of a variable refrigerant flow (VRF) system with multiple outdoor units (ODUs). The strategy maximizes energy efficiency in real time and handles ODU operation during load changes. Extremum seeking control (ESC) is used to minimize power consumption in real time while the thermal load is regulated with inner loop controllers. In addition to the compressor pressure setpoints and ODU fan speeds, the manipulated inputs of ESC include the openings of suction-side bypass valves in order to optimize load sharing among multiple ODUs. An integrated ODU staging-off strategy is proposed, for which the compressor shaft power normalized by the rated capacity is adopted as the feedback signal for ESC. Under decreasing load, it is desirable to turn off the least efficient ODU in a model-free fashion. The ODU compressor speed is proposed as the indicator variable for turning off the least efficiency ODU(s). In this study, with online optimization of ODU load sharing based on the normalized compressor power, ESC can drive less efficient compressor(s) to operate at lower speed/capacity.

1. INTRODUCTION

Variable refrigerant flow (VRF) air conditioning systems are typically multi-split ductless configurations with multiple indoor units (IDUs) and one or more outdoor units (ODUs) (Thornton *et al*. 2012). VRF systems are capable of controlling the amount of refrigerant flow to the evaporators of multiple IDUs, typically via the use of variable-capacity compressors and electronic expansion valves (EEV), thus enabling variable capacity for individual IDUs. VRF systems offer many advantages, such as the elimination of duct loss associated with air distribution, design and installation flexibility, compactness, integrated controls, quiet operation and reduced maintenance cost (Aynur 2012). The heat recovery mode can dramatically improve the energy efficiency compared to the cooling-only and heating-only modes (Shi *et al.* 2003). The past three decades have seen dramatic developments in VRF systems for cooling and heating of commercial and residential buildings. In particular, the VRF system can be configured into the so-called Multi-functional VRF (MFVRF) system to achieve simultaneous heating and cooling for different zones (Goetzler *et al*. 2007; Xia *et al*. 2002; Hai *et al*. 2006; Park *et al*. 2001; Shi *et al*. 2003; Xia *et al*. 2004). Using combinatorial actuations of control valves in the Mode Change Unit (MCU), the IDUs and ODU can switch operation between evaporating and condensing depending on the nature of the thermal load of individual zones and the overall system (Goetzler *et al*. 2007; Xia *et al*. 2002; Massuda *et al*. 1991).

Similar to the situation for many other heating, ventilation and air conditioning (HVAC) systems, controls of VRF systems faces the challenge of significant nonlinearity and large variation of ambient and load conditions, which increases the cost for deployment of model-based control and optimization strategies for real-time operation. This problem is exacerbated for MFVRF systems due to the diversified operational modes. Therefore, model-free approaches have received great attention. Weiss *et al.* (2014) present a hybrid control scheme for VRF system, combining an outer-loop ESC with model predictive control (MPC). Recently, the authors have proposed a multi-input extremum seeking control (ESC) based strategy for VRF system with four IDUs and one ODU (Dong et al., 2017a). The IDU zone temperature is regulated by EEV opening, and the compressor pressure is regulated by compressor speed. The feedback signal for the ESC is the total power consumption of the system, and the manipulated inputs are the compressor pressure setpoints, ODU fan mass flow rate, and superheat (SH) setpoints for individual IDUs. A simulation study of different operational modes showed that ESC can drive the manipulated inputs to neighborhoods close to the optimum found using an offline simulation-based optimization procedure. Also, using a normalized ODU temperature gradient, we have developed a strategy for automatically switching the ODU between evaporator and condenser operation as load conditions change.

The focus of this paper is on VRF systems with multiple ODUs. In addition to managing transitions between numerous operation modes that are typical for VRF systems, controls of multi-ODU VRF systems need to ensure reasonable load sharing among operating ODUs as well as turning on and off particular ODU(s) under fluctuating loads such that the system can operate efficiently. In other words, for any given operating condition, the most efficient combination/subset of ODUs should be used. This objective is relatively straightforward to achieve with readily available model based optimization algorithms if the characteristics of the ODUs and IDUs are known and all the operational variables can be measured. However, as mentioned above, this requirement is not easily satisfied without the significant cost of model construction and calibration. It is desirable to realize the ODU on/off logic via a model-free approach.

In this paper, for a multi-ODU VRF system, we describe an automatic ODU staging controller integrated with a penalty function based multivariable ESC strategy. To optimize load sharing among multiple ODUs in operation, a set of bypass valves (BPVs) are added at the suction side of the compressors to manipulate refrigerant flow distribution among different compressors as needed. The performance index as the ESC feedback is the total power of the compressors, the ODU fans and the IDU fans, augmented with penalties for achieving minimum superheat at the suction side of compressors. The manipulated inputs include the compressor suction pressure setpoint, the openings of BPVs at the suction side of the compressors, and a common fan speed setpoint for all ODUs. As for the ESC feedback, the compressor shaft power is normalized by its maximum capacity.

A set of control strategies for staging on/off particular ODUs is developed based on the compressor speed of the operating ODUs. Under increasing load, if the operating compressor(s) speed exceeds the higher limit of operation speed range, an additional ODU is turned on to meet the load demand. Under decreasing load, it is desirable to turn off the least efficient ODU in a model-free fashion. If the compressor speed of an ODU falls below a preset lower limit for sufficient time, this OSU will be turned off.

The proposed control and ODU staging strategy is evaluated with an MFVRF system consisting of 12 IDUs and three ODUs. A dynamic simulation model of this illustrative system is developed with Dymola (Dassault Systèmes, 2017) and the TIL Library (TLK-Thermo, 2017). Simulation studies have been performed to evaluate the proposed ESC strategy for energy efficient operation during constant load patterns, and the control logic for staging on and off ODU(s) during load increases and decreases. The system modeling will be described in the next section, followed by the description for the proposed control strategies. Then, the simulation results are presented. The last section concludes the paper with discussion on future work.

2. CONFIGURATION AND MODELING FOR MULTI-ODU VRF SYSTEM

Fig. 1 shows the schematic of the 12-zone multi-ODU VRF system, which consists of three ODUs, one mode change unit (MCU) and 12 IDUs. The $i^{\text{-th}}$ (i = 1, 2 and 3) ODU includes a variable speed compressor, bypass valves (BPV_i, $BPV_{Comp,i}$), a heat exchanger, and an EEV (EEV_{Oi}). For each zone, the temperature is regulated by controlling the EEV opening in each IDU with a proportional-integral (PI) controller. For each ODU, the compressor suction pressure is regulated by the compressor speed with a PI controller. The setpoint for each compressor suction pressure is identical. In order to optimize load sharing for multi-ODU operation, a set of bypass valves are introduced in this study at the suction side of the compressors to manipulate the refrigerant flow distribution among different ODU compressors. To evaluate the proposed control strategy, a Modelica based dynamic simulation model is developed, using Dymola 2014, TIL Library 3.4 and TIL Media Library 3.4.

In this study, the compressor model uses an isentropic efficiency that varies as a function of the refrigerant mass flow rate. The original efficiency based compressor model in TIL library is based on volumetric efficiency λ_{eff}, effective isentropic efficiency $\eta_{eff,is}$, and isentropic efficiency η_{is}. For known values of the displacement volume V and compressor speed n, the compressor shaft power is calculated with

$$P_{shaft} = \frac{\lambda_{eff}}{\eta_{is} \times \eta_{eff,is}} \times \rho_d \times n \times D \times (h_d - h_s) \tag{1}$$

where n is the compressor speed, and ρ is the refrigerant density as a function of the pressure and temperature.

Subscripts '*d*', '*s*', '*is*' and '*eff*' denote discharge side, suction side, isentropic process, and effective value, respectively.

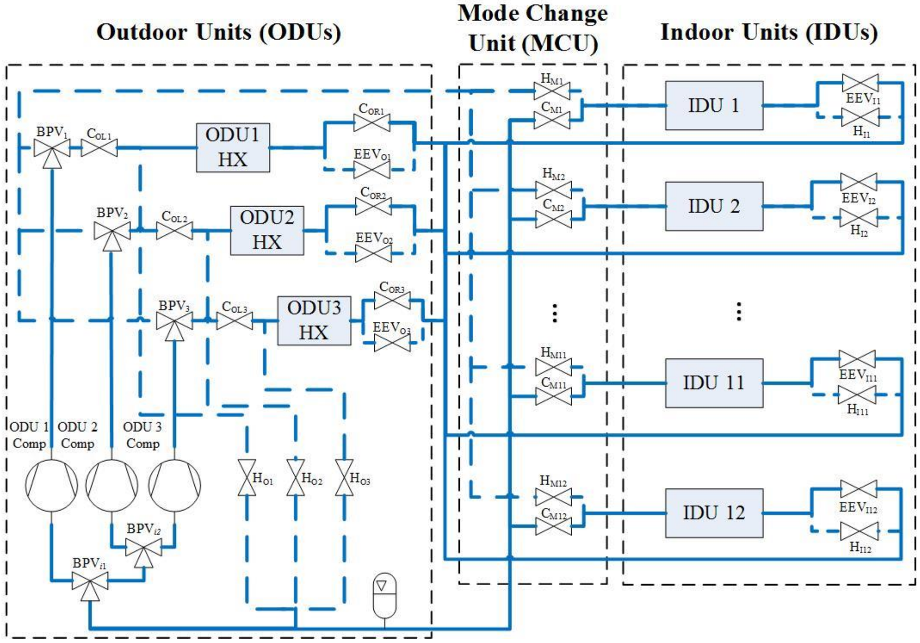

Figure 1. Schematic diagram of a multi-ODU VRF system.

In practical operation of a heat pump compressor, the efficiency often varies with the mass flow rate of refrigerant. In this study we have formulated the compressor isentropic efficiency as a 4th-order polynomial of the inlet-port refrigerant mass flow rate:

$$\eta_{is}(\dot{m}) = c_4\dot{m}^4 + c_3\dot{m}^3 + c_2\dot{m}^2 + c_1\dot{m} + c_0 \quad (2)$$

where c_i (i = 0, 1, …, 4) are coefficients. For the three ODU compressors, without loss of generality, the isentropic efficiency maps as a function of refrigerant mass flow rate are shown in Fig. 2.

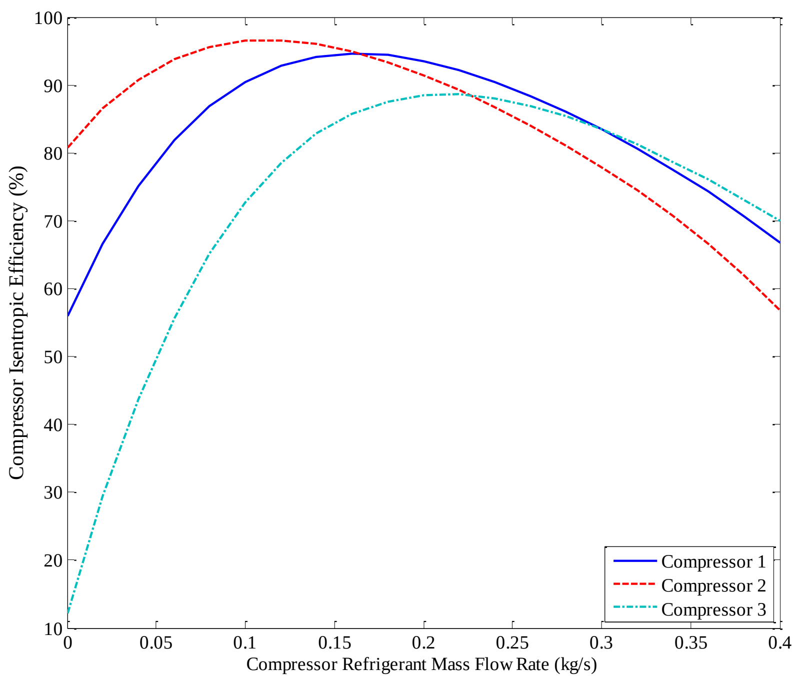

Figure 2. Compressor isentropic efficiency with respect to refrigerant flow rate.

The compressor shaft power is then calculated by replacing the constant isentropic efficiency in Eq. (1) with the mass flow rate based isentropic efficiency shown in Fig. 2. The heat exchangers of the IDUs and ODUs are modeled with the *HeatExchangers.FinAndTube.MoistAirVLEFluid.ParallelFlowHX* module in the TIL Library which is a fin-and-tube parallel flow heat exchanger model. The pipes are all copper and the refrigerant used is R410A, for which the medium properties are computed via the TIL Media Library. The EEVs are modeled with the orifice valve module *VLEFluidComponents.Valves.OrificeValve* in the TIL library. The linear directional control valve module *VLEFluidComponents.Valves.LinearDirectionalControlValve* is used to model the BPV and as the basis for the model of the solenoid valves. The zones served by the IDUs are modeled by the *GasComponents.Volumes.Volume* model from the TIL library.

3. ESC AND ODU STAGING STRATEGY FOR MULTI-ODU VRF SYSTEM

3.1 Penalty-function Based Multivariable Extremum Seeking Control

ESC is a class of model-free adaptive control, which aims to search for the optimizing input $u_{opt}(t)$ for the generally unknown time-varying cost function $l(t, u)$, where $u(t) \in \mathbb{R}^m$ is the input parameter vector (Ariyur and Krstic 2003). As shown in Fig. 3, the measurement of the cost function $l(t, u)$, i.e. $y(t)$, is corrupted by noise $n(t)$. $F_I(s)$ and $F_O(s)$ denote the linear time-invariant approximations of the input and output dynamics, respectively. Signals $d_1^T(t) = [a_1 \sin(\omega_1 t) \quad \cdots \quad a_m \sin(\omega_m t)]$ and $d_2^T(t) = [\sin(\omega_1 t + \alpha_1) \quad \cdots \quad \sin(\omega_m t + \alpha_m)]$ denote the dither and demodulation inputs, respectively, where ω_i are the dithering frequencies for each input parameter channel, a_i are the dither amplitudes, and α_i are the phase angles introduced intentionally between the respectively dither and demodulation signals. With small-amplitude dither, the perturbed output, based on Taylor series expansion, contains the gradient information in the first-harmonics term. After filtering the DC component of the dithered output by band-pass filters $F_{BPi}(s)$, the resultant signal is multiplied (demodulated) by d_2, which shifts the gradient term to the DC term. Applying low-pass filters $F_{LPi}(s)$ will produce a vector-valued signal proportional to the gradient of the cost function at the input of the integrator array. In this study, the multi-variable ESC design follows the guidelines provided in (Krstic 2000).

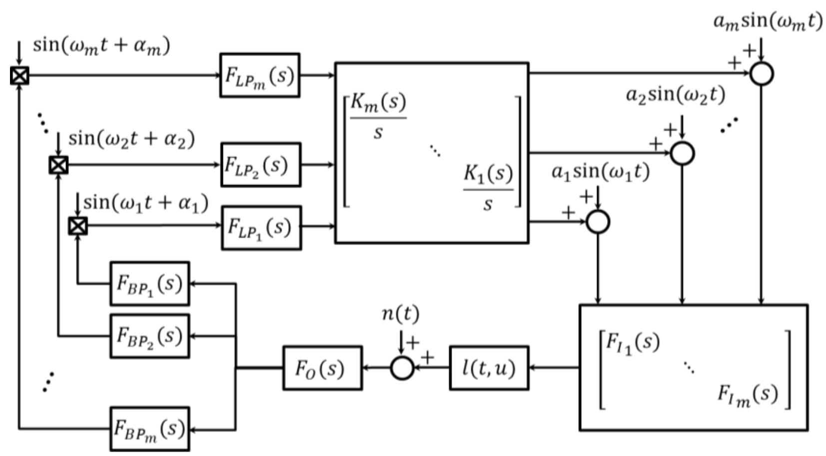

Figure 3. Block diagram of multivariable ESC based on dither-demodulation scheme.

In addition to the compressor pressure setpoints and ODU fan speeds, the manipulated inputs of ESC also include the openings of suction-side BPVs in order to optimize load sharing among the multiple ODUs. For efficient operation of building HVAC systems, a typical choice of performance index for the ESC feedback is the power consumption of the whole system. However, beside the objective of maximizing energy efficiency, there are operational constraints (e.g. inputs and states) imposed on some process variables. Recently, the authors have investigated several forms of constrained ESC by formulating penalty-function based performance indices, via augmentation with penalty terms reflecting constraint reinforcement (Dong *et al.* 2018). In this study, the performance index for the ESC of multi-ODU VRF system is proposed as the summation of normalized values of compressor shaft powers and fan powers, augmented with the penalty for securing minimum superheat at the inlet of ODUs, i.e.

$$J=\sum_{i=1}^{N}\left(\frac{P_{Comp,i}}{P_{Comp,i,rated}}+\frac{P_{fan,i}}{P_{fan,i,rated}}\right)+\frac{a}{\left|T_{SH}-T_{SH,\lim}\right|} \tag{3}$$

where a is the weight factor of penalty term, N is the number of ODUs, $T_{SH,lim}$ is the preset lower limit of the superheat temperature, and subscript 'rated' indicates the rated power value of an equipment. The manipulated inputs include the compressor suction pressure setpoint, the openings of BPVs at the suction side of the compressors, and a uniform setpoint of fan speed for all ODUs.

3.2 ODU Staging Logic for Multi-ODU VRF System

A model-free ODU staging control strategy is proposed for operation of the multi-ODU VRF system described earlier. Assume the VRF system contains N ODUs, and n ($n<N$) of them are in operation, then the $(n+1)^{th}$ ODU will be turned on if the speed of one of the operating compressors exceeds an upper threshold (e.g. 80%) of the rated speed for a specific time duration. For ODU staging-off, an ESC integrated logic is proposed. As shown in Eq. (3), the compressor shaft power normalized by the rated capacity is part of the ESC feedback. With online optimization of ODU load sharing based on the normalized compressor power, ESC can drive less efficient compressor(s) to operate at lower speed/capacity. If the compressor speed of an ODU falls below a preset lower threshold (e.g. 20% of the rated speed) for sufficient time, this ODU will be turned off.

4. SIMULATION STUDY

The ESC and ODU staging strategies proposed in Section 3 are evaluated with the Modelica based simulation model described in Section 2. The system is assumed to operate with all IDUs in cooling mode. The ambient temperature and relative humidity are set to be 35ºC and 40% RH, respectively.

Case #1: Scenario of ODU Staging-On with Increasing Load

Initially, the system is operated at a low load, with each IDU having an identical load of 0.9kW. At this load, the master ODU has sufficient capacity to service the load by itself. Later, the cooling load increases in two steps as shown in Figure 4. Also shown in Figure 4 are the trajectories of the zone temperature and the superheat at the compressor suction port, as well as those of the ESC inputs and output.

Segment 1 of Figure 4 shows the ESC process for the initial level of cooling load. ESC is turned on at t = 30 minutes and begins searching for the optimal values of the ODU fan mass flow rate and compressor suction pressure setpoint. A simulation based optimization procedure using a genetic algorithm (GA) method is applied to find the global optimum for the inputs and the total power consumption. The optimum obtained by the GA method is shown as red dashed lines in the plots. The GA method finds the globally minimum total power at 2934.5 W, with P_{CS} at 13.75bar and the ODU fan mass flow rate at 0.97kg/s. ESC converges to an average total power of 2950.8 W in steady state, with P_{CS} approximately equal to 13.6 bar and ODU fan mass flow rate approximately equal to 0.95kg/s. Compared to the GA results, the steady error is about 0.6%. The power consumption of single-ODU operation period was decreased from 5034.8 W to 2950.8 W, i.e. by 41.3%, with the 2% settling time of about 50 minutes.

Next, in segment 2, the zonal load increases linearly from 0.9kW to 1kW per IDU over a 60-minute period starting at t = 270 minutes. ODU #2 is turned on following the proposed ODU staging-on logic described earlier. Segment 2 shows the transition period for the startup process for staging on ODU #2, in which ESC is turned off and all input channels are reset to their initial values before ESC is applied. After the startup process of ODU #2, the ESC for two-ODU operation is turned on to find the optimum point of the manipulated inputs, shown as segment #3 in Figure 4. The GA method finds the global minimum of total power at 3650.3 W, with P_{CS} at 13.69 bar, the BPV#1 opening at 0.78 and the ODU fan mass flow rate at 1.13 kg/s. ESC converges to an average total power of 3674.5 W in steady state, with the P_{CS} around 14 bar, the BPV#1 opening around 0.78 and ODU fan mass flow rate around 1.25 kg/s. Compared to the GA results, the steady error is about 0.6%. The power consumption of two-ODU operation period decreased from 6917.5 W to 3774.5 W, i.e. by 45.1%, with the 2% settling time of about 50 minutes.

Finally, another load increase from 1kW to 2.2kW per IDU is applied at t = 780 minutes following a 60-minute ramp as shown in segment 4 in the figure. After the startup process of turning on ODU #3, the ESC for three-ODU operation is applied, shown as segment 5 in the figure, and the new optimum of the manipulated inputs are obtained. The GA method finds the global minimum of total power at 5352.2 W, with P_{CS} at 12.48bar, BPV#1 opening at 0.79, BPV#2 opening at 0.63 and the ODU fan mass flow rate at 1.37kg/s. ESC converges to an average total power of 5440.5 W in steady state, with P_{CS} around 12.7 bar, BPV#1 opening around 0.5, BPV#2 opening around 0.7 and ODU fan mass flow rate around 1kg/s. Compared to the GA results, the steady error is about 1.6%. The power consumption of three ODUs operation period was decreased from 8627.1 W to 5440.5 W, i.e. by 34.2%, with the 2% settling time of about 60 minutes.

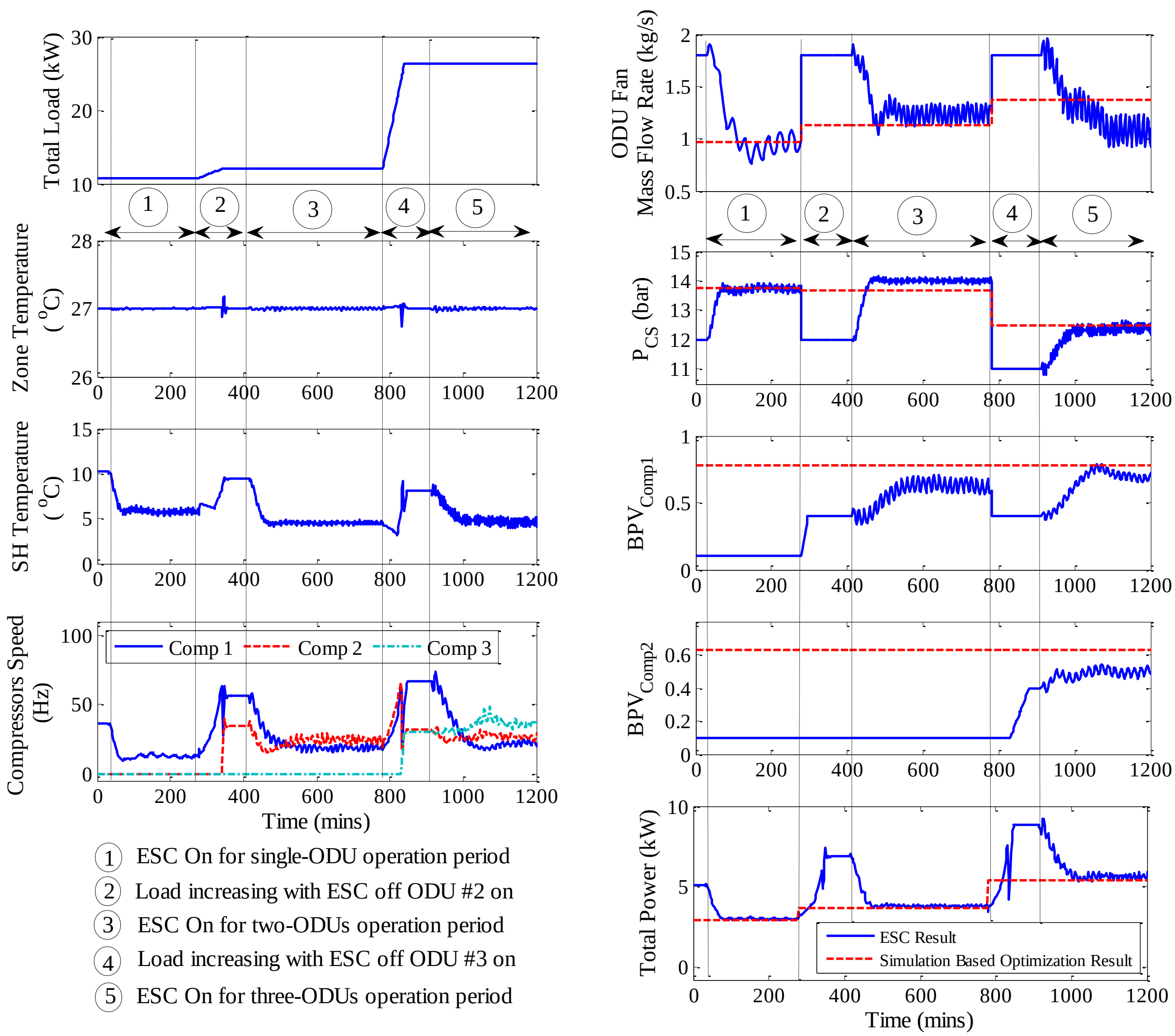

Figure 4. Total load, zone temperature, superheat temperature and ESC inputs outputs profiles for Case #1.

Case #2: Scenario of ODU Staging-off with Decreasing Load

The ODU staging-off scenario is then simulated. Figure 5 plots the simulation results in the same manner of Figure 4. The system is initially operated in a high level of cooling load demand, with the cooling load of each IDU set as 2.2kW. All three ODUs are operated to meet the load requirement. The ESC for three-ODU operation is turned on at t = 30 minutes to search for the optimum of the ODU fan mass flow rate, BPV#1 and BPV#2 openings, and compressor suction pressure setpoints, with the results shown in segment 1. The GA results are again shown in red dashed line in the plots, which finds the global minimum of total power at 5910.4W, with P_{CS} at 12.4bar, BPV#1 opening at 0.67, BPV#2 opening at 0.45 and the ODU fan mass flow rate at 0.9kg/s. ESC converges to an average total power of 5945.3W in steady state, with P_{CS} around 12.6 bar, BPV#1 opening about 0.7, BPV#2 opening around 0.48 and ODU fan mass flow rate around 1.1kg/s. Compared to the GA results, the steady error is about 0.6%. The power consumption of three-ODU operation period was decreased from 12039.2 W to 5945.3W, i.e. by 50.6%, with the 2% settling time of about 50 minutes.

Then, the cooling load is decreased from 2.2kW to 1.5kW per IDU with a 60-minute down ramp starting at t = 30 minutes, the least efficient ODU is turned off following the proposed ODU staging-off logic. In this case ODU#3 is the least efficient ODU. Segment 2 shows the duration when the load decrease turns off ODU#3 following the staging-off logic. During this period, ESC is turned off as in the previous case. After the transient of the staging-off process, the ESC for two-ODU operation is used to find the optimum of the manipulated inputs as shown in segment 3. The GA method finds the global minimum of total power at 4680.4 W, with P_{CS} at 13.4 bar, the BPV#1 opening at 0.67 and the ODU fan mass flow rate at 0.75 kg/s. ESC converges to an average total power of 4703.2 W in steady state, with the P_{CS} around 13.2 bar, the BPV opening around 0.7 and ODU fan mass flow rate around 0.8kg/s. Compared to the GA results, the steady error is about 0.5%. The power consumption of two ODUs operation period was decreased from 6288.9 W to 4703.2 W, i.e. by 25.1%, with the 2% settling time of about 50 minutes.

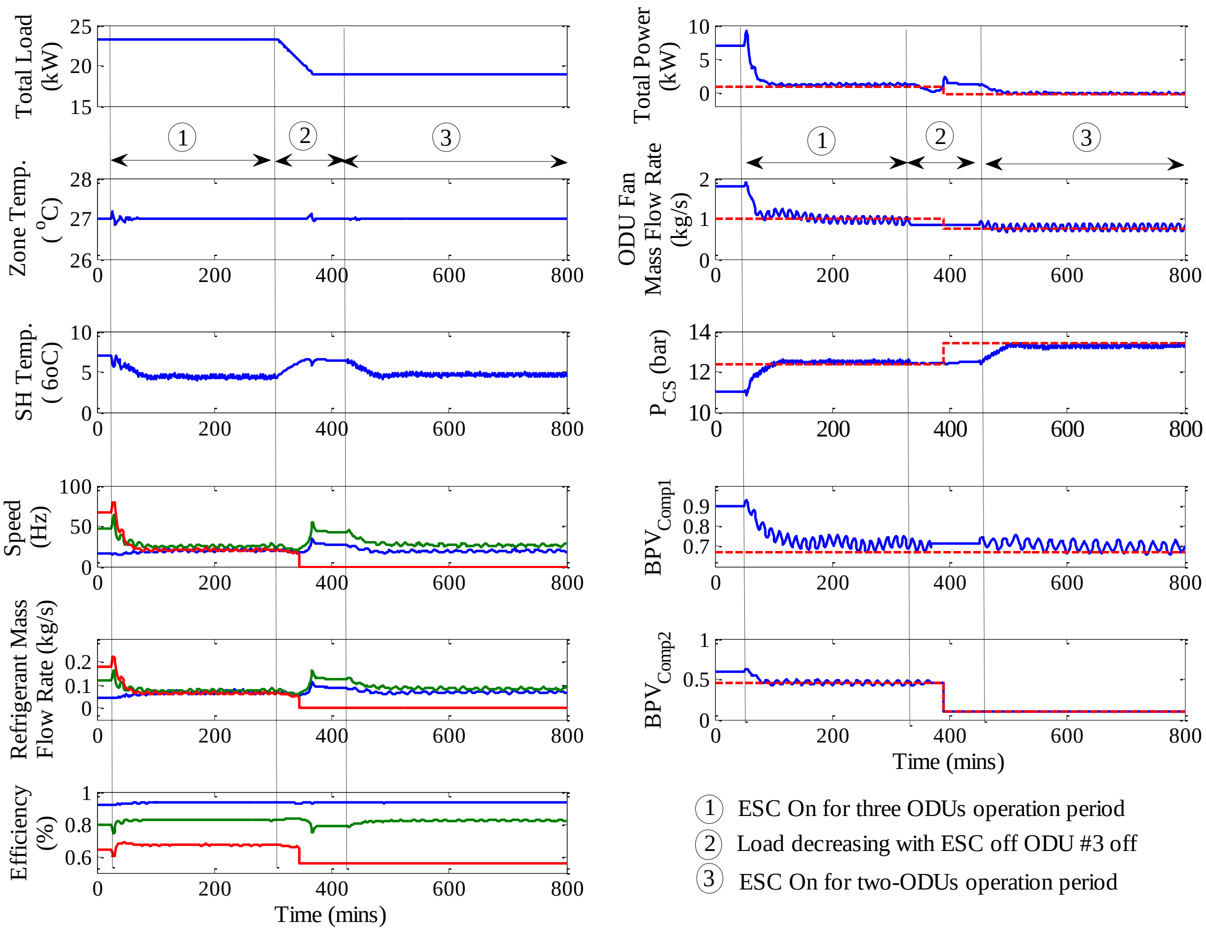

Figure 5. Total load, zone temperature, superheat temperature and ESC inputs outputs profiles for Case #2.

5. CONCLUSIONS

An ESC integrated ODU staging strategy is proposed for a multi-ODU VRF system, which is validated with an all-cooling Modelica simulation model of a 12-IDU three-ODU system. By incorporating the normalized compressor power into the objective function for ESC, the ODU staging-off operation can automatically turn off the least efficient ODU without the need for model knowledge when the cooling load decreases. In addition,
the ESC results under different number of ODUs have shown good convergence with reasonable settling time to the optimum found by a simulation-based global optimization process.

ACKNOWLEDGMENTS

The authors are grateful of the financial support by Johnson Controls Inc. We appreciate TLK-Thermo for their permission of accessing the TIL Suite products and their assistance for using the software.

REFERENCES

Ariyur, Kartik B., and Miroslav Krstic. *Real-time Optimization by Extremum-seeking Control*. John Wiley & Sons, 2003.

Aynur, T.N., Variable refrigerant flow systems: A review, Energy and Buildings 42(2010), 1106-1112.

Dassault Systèmes, Dymola: Multi-engineering Modeling and Simulation, 2017. http://www.3ds.com/products/catia/portfolio/dymola

Dong, L., Li, Y., Mu, B., Xiao, Y. 2015. "Self-optimizing control of air source heat pump with multivariable extremum seeking," *Applied Thermal Engineering* 84 (2015) 180-195.

Dong L., Li, Y., Salsbury I. T., House M. H., 2018 "Constraint handing in ESC control strategies with application to HVAC systems," accepted by American Control Conference, June 27-29, Milwaukee, WI, USA.

Goetzler, W., Variable refrigerant flow systems, ASHRAE Journal, 49 (4) (2007) 24–31.

Hai, X.H., Jun, S., Hand, Z.Y., T.C. Bin, Design and research of the digital VRV multi-connected units with three pipes type heat recovery system, Proc. 11th Int. Refri. Air Cond. Conf. Purdue, 2006.

Krstic, M. "Performance Improvement and Limitations in Extremum Seeking Control," Systems & Control Letters, Vol. 39, pp. 313–326, 2000.

Li, P., Li, Y., Seem, J.E. 2010. "Efficient Operation of Air-side Economizer Using Extremum Seeking Control," *ASME Transactions - Journal of Dynamic Systems, Measurement and Control*, Vol. 132, No. 3, pp. 031009 (10 pages).

Li, X., Li, Y., Seem, J.E. 2013. "Dynamic Modeling and Self-optimizing Operation of Chilled Water Systems Using Extremum Seeking Control," *Energy and Buildings*, 58, pp. 172-182.

Masuda, M., Wakahara, K., Matsui, K., Development of a multi-split system air conditioner for residential use, ASHRAE Transactions 97 (2) (1991) 127–131.

Park, Y.C., Kim, Y.C., Min, M.K., Performance analysis on a multi-type inverter air conditioner, Energy Conversion and Management, 42(13) (2001) 1607–1621.

Rotea, M.A. "Analysis of Multivariable Extremum Seeking Algorithms," Proc. 2000 Am. Control Conf., Vol. 1, pp. 433 – 437, Chicago, IL, June 28-30, 2000.

Shi, W., Shao, S., Li, X., Peng, X., Yang, X., A network model to simulate performance of variable refrigerant volume refrigerant systems, ASHRAE Transactions 109 (2) (2003) 61–68.

Thieriot, H., Nemer, M., Torabzadeh-Tari, M., Fritzson, P., Singh, R. and Kocherry. J.J., "Towards Design Optimization with OpenModelica Emphasizing Parameter Optimization with Genetic Algorithms," Proc. 8th Int. Modelica Conference, pp. 756-762, Dresden, Germany, 2011.

Thornton, B. and Wagner, A. Variable Refrigerant Flow Systems, Prepared for the General Services Administration by Pacific Northwest National Laboratory, December 2012.

TLK-Thermo, GmbH. 2017. TIL Suite – Simulates thermal systems. https://www.tlk-thermo.com/index.php/en/software-products/til-suite

Xia, J., Winandy, E., Georges, B., Lebrun, J., Experimental analysis of the performances of variable refrigerant flow systems, Building Services Engr. Research & Tech. 25 (1) (2004) 17–23.

Xia, J., Winnady, E., Georges, B., Lebrun, J., Testing methodology for VRF systems, Proc. 9th Int. Refri. & Air Cond. Conf. at Purdue, 2002.

Xiao, Y., Li, Y., Dong, L., Seem, J.E. 2014 "Multi-variable Extremum Seeking Control for Mini-split Air-conditioning System." *Proc. the 15th Int. Refri. & Air Cond. Conf. at Purdue*, July 14-17, 2014.