2018

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Extremum-Seeking Control Optimizes VRF Energy Consumption

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ABSTRACT

To a VRF (Variable Refrigerant Flow) system, outdoor unit (ODU) energy consumption is the combination of the power consumption of compressors and outdoor fans. The combined power consumption changes with discharge pressures and other conditions. Discharge pressures are controlled to its' setpoint by manipulating fan speed. There are optimal discharge pressure points, where the combined power consumptions are at its' minimum.

Most common control approaches in industry on the discharge pressure is setting them to a constant value or calculating as a function of compressor speed and ambient temperature. Fixing it to a constant value is not a desired solution since the optimal pressure points change with load, ambient temperature and other operating conditions. Calculating as a function of compressor speed and ambient temperature, though two major factors are in the consideration, still needs lab tests and calibration to find the relation between the energy consumption and discharge pressure. Since VRF system consists multiple ODUs and IDUs (Indoor Units), the task of lab tests could be overwhelming.

In this work, ESC (Extremum Seeking Control) is used to automatically find the optimum discharge/suction pressure points when VRF is in cooling/heating operation. ESC algorithm is implemented into the VRF equipment control. When ESC is enabled, a small excitement signal applies to discharge setpoint, power consumption of compressors and fans is monitored. ESC will find the optimal discharge setpoints to minimize the combined power consumption. ESC is active in all normal operation conditions, it will optimize the energy consumption over all load ranges of heating/cooling and heat recovery operation. Simulation has been conducted to demonstrate the potential savings on the outdoor unit energy consumption.

1. INTRODUCTION

VRF systems have been used for over 30 years in commercial and residential buildings in Asia. VRF represents between 40-80% of HVAC market in Europe and Asia. It U.S. recent years, VRF is the fastest growing segment of HVAC industry. Compared to other HVAC system, VRF has serval advantages, ODU compact and modular design make it easy to install over wide range of capacity, long and small size piping occupies less space, high COP [Fig. 1] and concurrent heating and cooling.

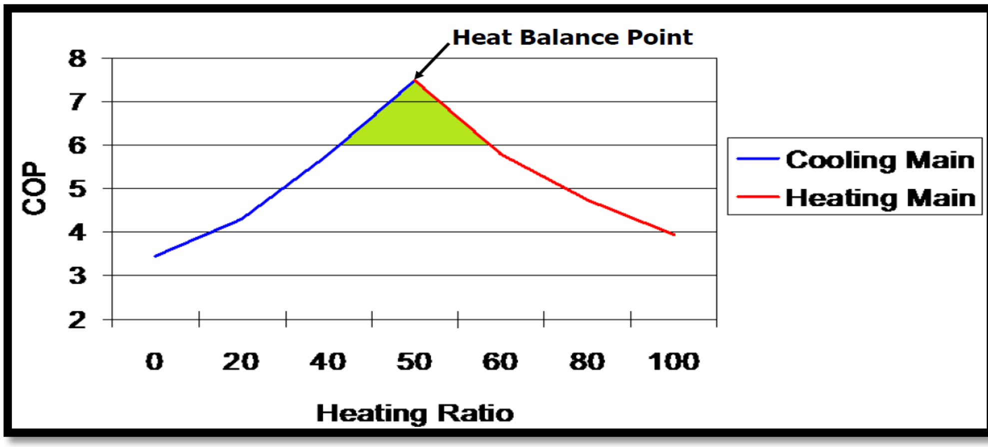

Figure 1. COP during Heat Recovery [1].

Fig. 2 is the top of the integrated Refrigerant Cycle Control (RCC) Model Based Design (MBD) environment in Matlab/Simulink. The environment includes VRF plant models, VRF RCC control, simulation/emulation automated test facilities, interactive I/O interfaces. RCC control system is designed and implemented in this environment, simulation tests against VRF plant models are conducted to test control logic and algorithm. After passing all simulation tests, RCC control code will be generated automatically. The generated code is integrated with embedded driver code and deployed to the hardware board for emulation tests. With simulation/emulation tests, most of the control logic and algorithms are tested with simulated VRF plant model. Therefore, lab tests, which takes time and resources, can be focused on testing the control features that are hard to model in the VRF plant model.

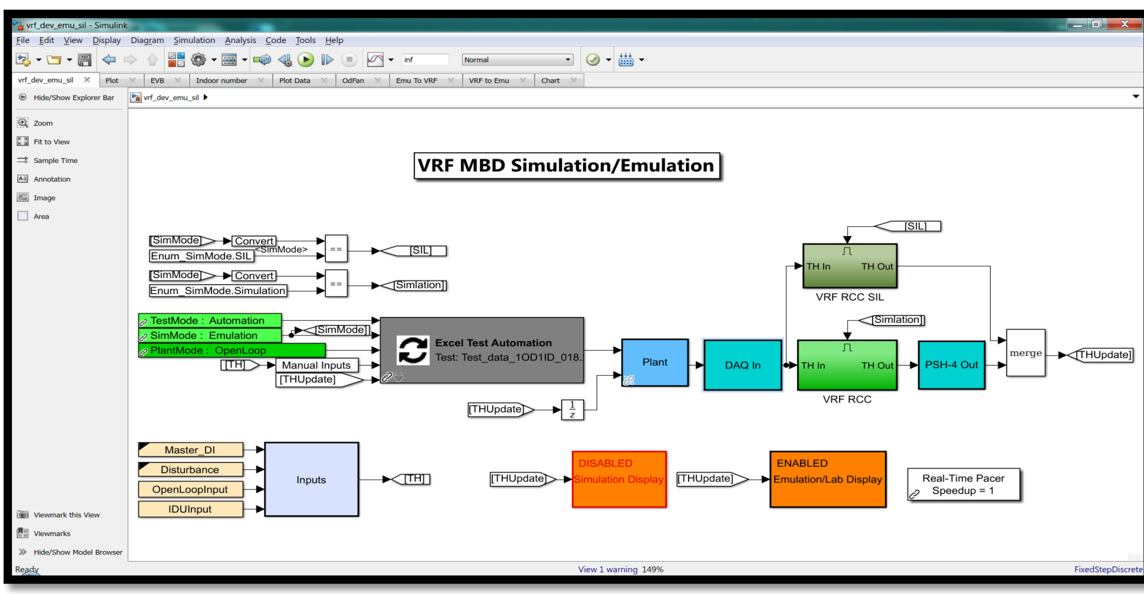

Figure 2. VRF Control Model Based Design Environment.

Fig. 3 shows major VRF RCC control function blocks. There are feedback and On/Off controls. The objectives of these feedback controls are to control certain variables to their setpoints.

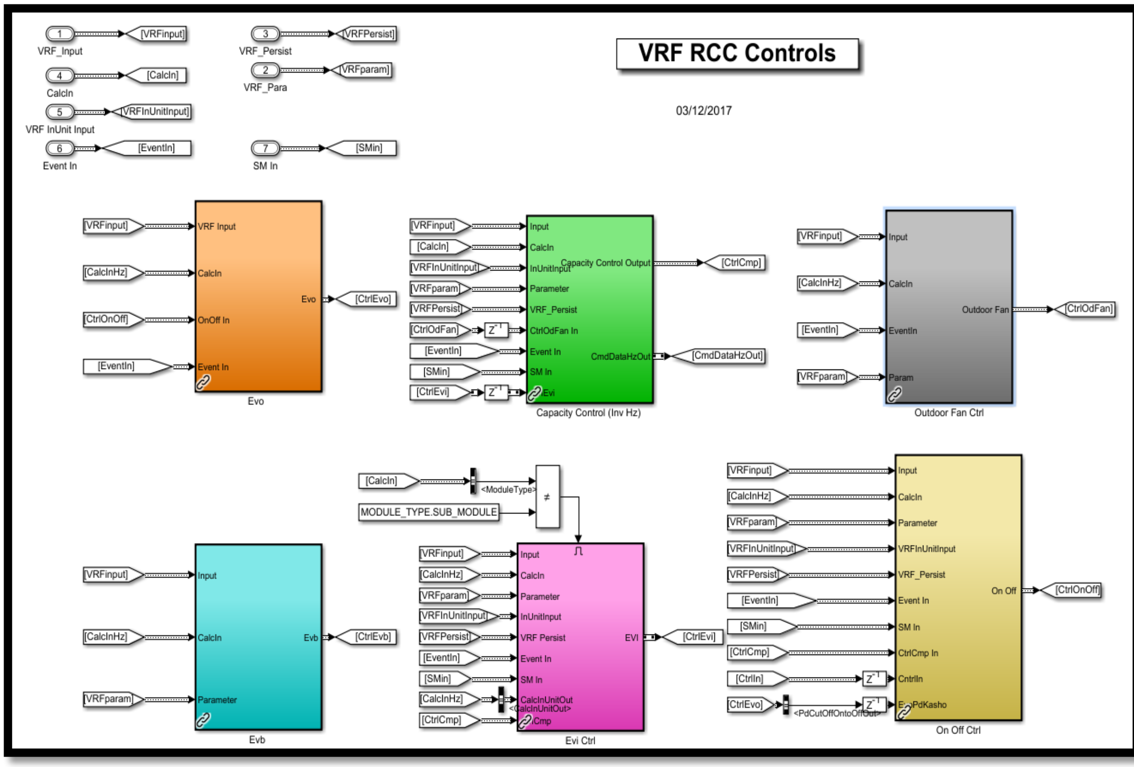

Figure 3. VRF Major Control System in MBD Environment.

Different from these feedback controls used in the VRF RCC, ESC used in VRF is an adaptive control that finds and drives the ODUs to the optimal operation point to save VRF energy consumption. Compared to other optimization methods, ESC requires less prior knowledge of the VRF system. One algorithm can be used across product lines. Though ESC needs to apply constant excitement signal to the system to find the optimal operation point, the disturbance caused by the excitement signal is acceptable in most HVAC systems, including VRF system.ESC and Economic MPC are two advanced control algorithm included in this project. ESC is embedded within other RCC control system and deployed to the ODU board. EMPC acts as a supervisor control, which can reside in a local workstation or up in the cloud controller.

2. Extremum-Seeking Control Algorithm

The ESC algorithm used in this paper work was previously developed and published [2]. The algorithm is based on sample statistics. The method uses the correlation between the measurement variable and the manipulated variable, in contrast to conventional ESC that use demodulation to calculate a gradient. This approach makes the ESC feedback variable scale-independent leading to easier configuration, which is attractive for low cost applications, such as VRF system.

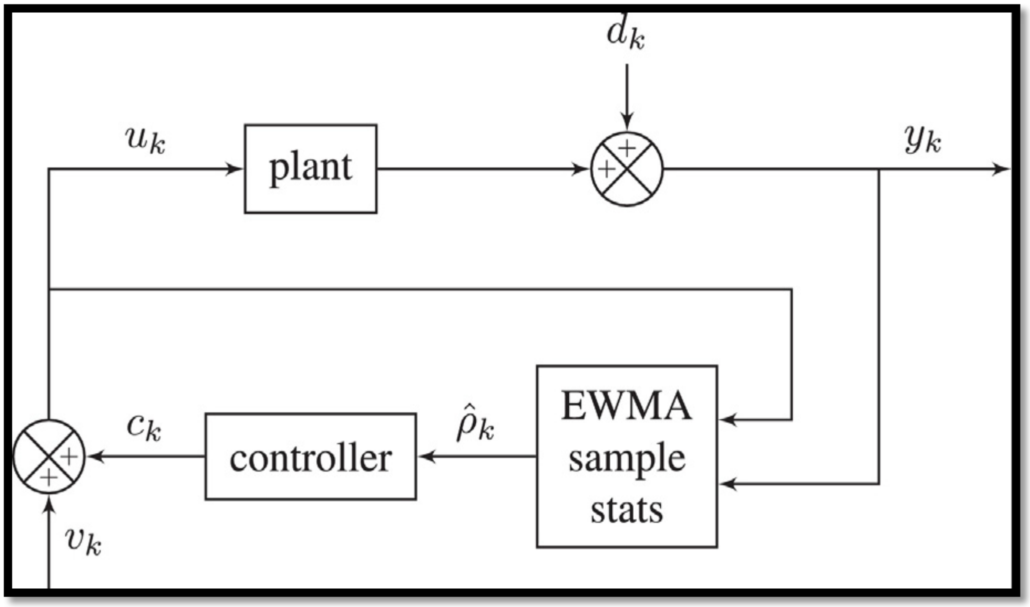

Figure 4. Block diagram of proposed ESC method [2]

The variables of interest are:

$$\bar{u}_k = \bar{u}_{k-1} + \frac{(u_k - \bar{u}_{k-1})}{min(k,W)} \quad (1)$$

$\bar{u}_k$ is an estimate of the mean of manipulated variable u

$$\bar{y}_k = \bar{y}_{k-1} + \frac{(y_k - \bar{y}_{k-1})}{min(k,W)} \quad (2)$$

$\bar{y}_k$ is the mean of measurement variable y

$$s_{u,k}^2 = s_{u,k-1}^2 + \frac{((u_k - \bar{u}_k)(u_k - \bar{u}_{k-1}) - s_{u,k-1}^2)}{min(k,W)-1} \quad (3)$$

$s_{u,k}^2$ is variance estimate of u

$$s_{y,k}^2 = s_{y,k-1}^2 + \frac{((y_k - \bar{y}_k)(y_k - \bar{y}_{k-1}) - s_{y,k-1}^2)}{min(k,W)-1} \quad (4)$$

$s_{y,k}^2$ is variance estimate of y

$$q_k = q_{k-1} + \frac{(s_{uy,k} - q_{k-1})}{min(k,W)-1} \quad (5)$$

q_k is the covariance of u and y, where $S_{uy,k}$ is given by:

$$S_{uy,k} = \frac{1}{2}((y_k - \bar{y}_{k-1})(u_k - \bar{u}_k) + \quad (y_k - \bar{y}_k)(u_k - \bar{u}_{k-1})) \quad (6)$$

$$\hat{\rho}_k = \frac{q_k}{\sqrt{s_{y,k}^2}} \quad (7)$$

$\hat{\rho}_k$ is the estimated correlation coefficient, which is used as the feedback signal in the feedback control loop shows in Fig. 4. The feedback loop is aimed to drive the $\hat{\rho}_k$ to zero by adjusting the plant input.

3. VRF ODU Power Consumption and Possible Energy Savings with ESC

Fig. 5 is a 10 HP VRF ODU units P&I Diagram. For an ODU unit, the power consumption comes from the power used by the compressor and outdoor fan. Variable speed compressor power can be obtained from the inverter and similarly the fan power can be obtained from Fan Motor. The compressor discharge pressure and suction pressure are measured continuously during operation.

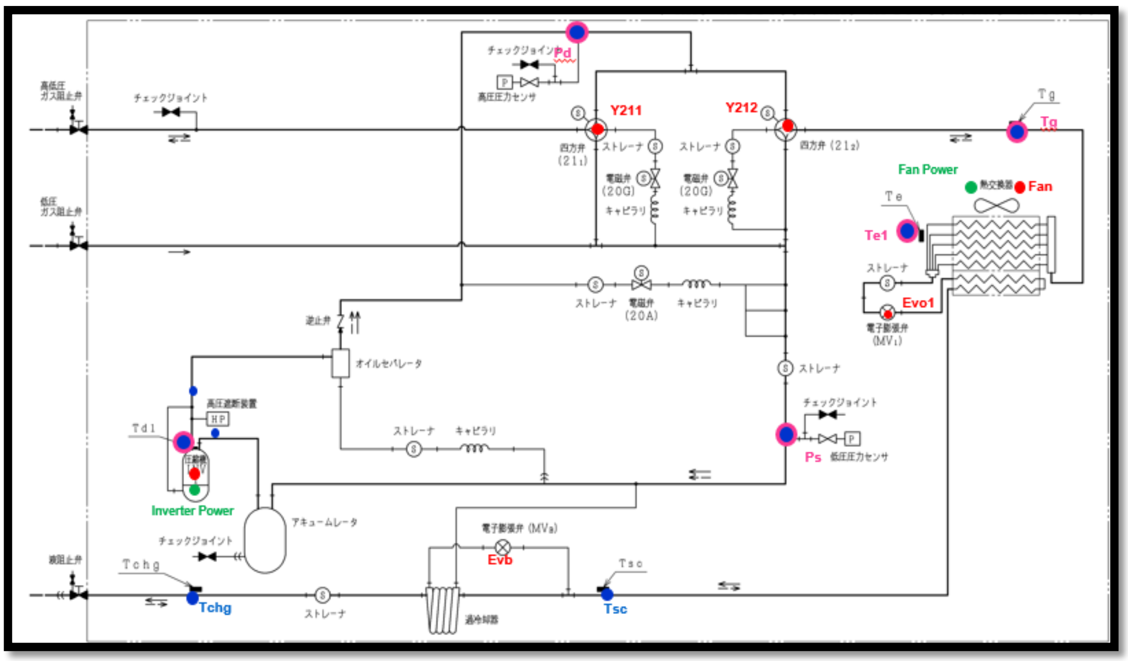

Figure 5. VRF Outdoor Unit P&I Diagram

Fig. 6 shows a 1 outdoor and 2 indoor VRF plant model in Dymola. Fig. 7 is the 10 HP outdoor unit model in Dymola, which is built on major ODU components. The model is based on first principles in Dymola/TLK tool suite. The inputs of the VRF model are from RCC control, such as inverter Hz, Fan speed and expansion valves position. VRF plant model outputs measurements to RCC control system, includes discharge/suction pressures, refrigerant side and air side temperatures and power consumptions of compressors and fans.

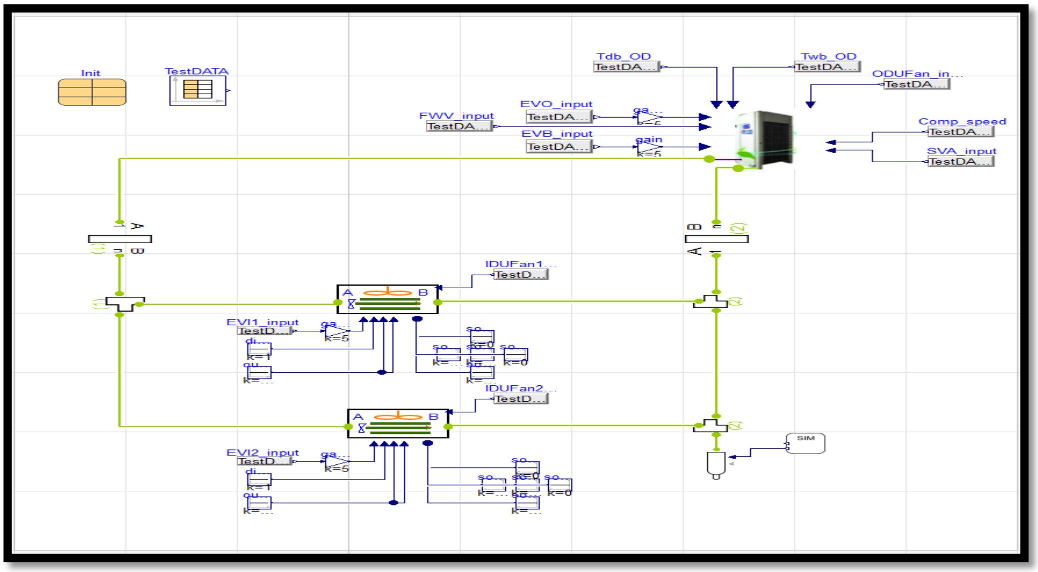

Figure 6. 1 ODU and 2 IDUs VRF Plant Model in Dymola

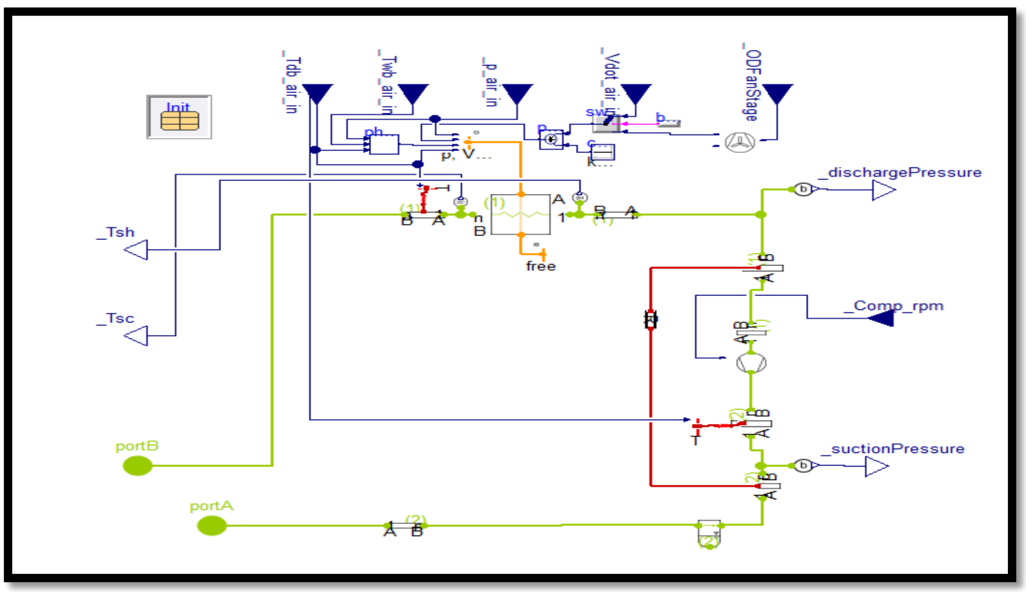

Figure 7. VRF Outdoor Unit Model in Dymola

Fig. 8 shows the simulation results of combined power consumption vs. discharge pressure over different load conditions. From the middle range load conditions, 50% and 75% capacity, there is V shape with optimal discharge pressure where ODU power consumption is at its minimum.

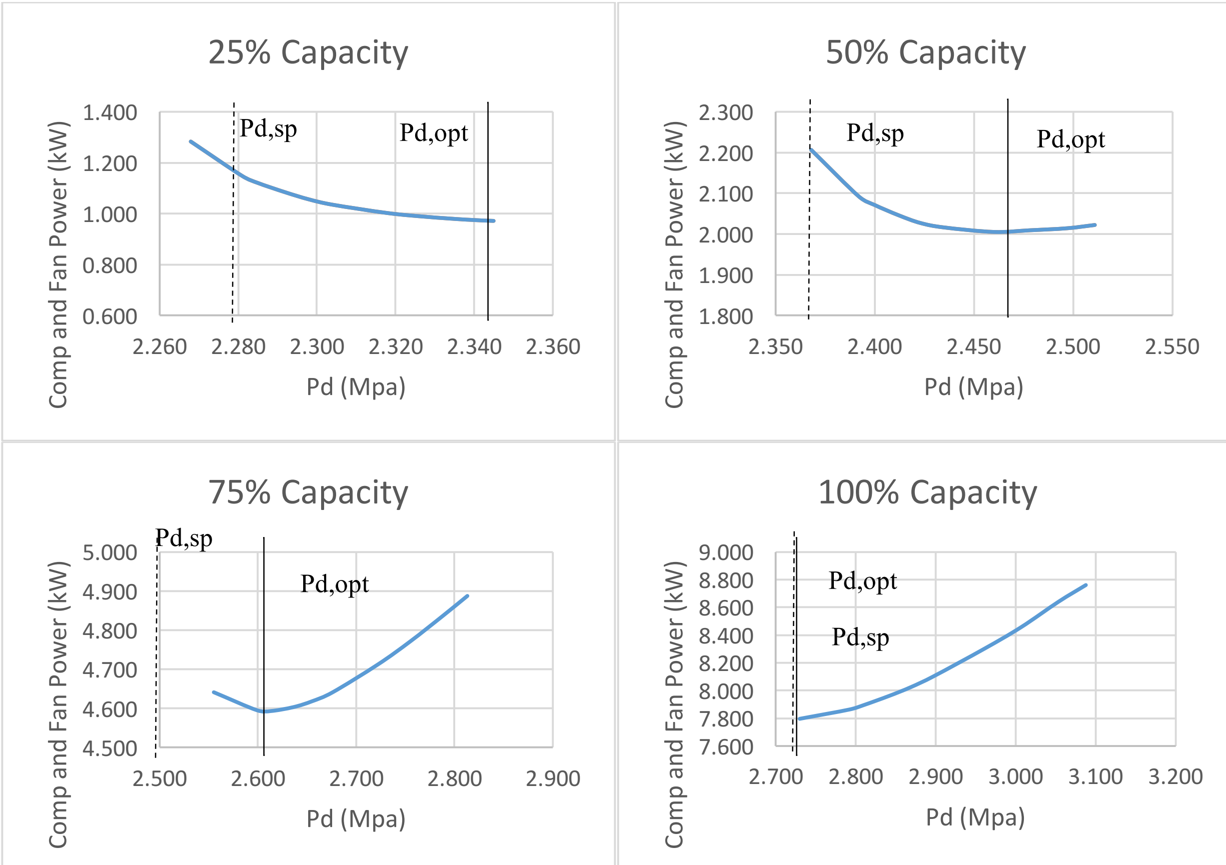

Figure 8. Simulation of Power Consumption and Discharge Pressure over Different Loads

Table 1 lists potential savings over different load conditions when compare the optimal setpoint from ESC and current setpoint. The potential savings range from 0% to 15%. When the unit is at the full or high capacity, there is very little savings. As unit load moves to low load conditions, the potential saving increases. Overall, 5% energy saving should be achievable when ESC is used in ODU discharge pressure control.

Table 1. Potential Savings with ESC Optimization

Capacity	25%	50%	75%	100%
Current Power Consumption	1.12	2.2	4.7	7.8
Optimal Power Consumption	0.97	2.05	4.59	7.8
Potential Savings (%)	15 %	7%	3%	0

4. Apply ESC Algorithm in VRF RCC control

In VRF RCC, discharge pressure is controlled by outdoor fan by adjust fan speed. Fig.7 shows the relation between the ESC and discharge pressure control. The input of ESC is the combined power consumption of Inverter and Fan power. ESC algorithm output discharge pressure setpoint, which includes the excitement signal. ESC will find the ODU optimal operation discharge pressure setpoint. The discharge feedback control drive the actual discharge pressure to the optimal point to save power consumption.

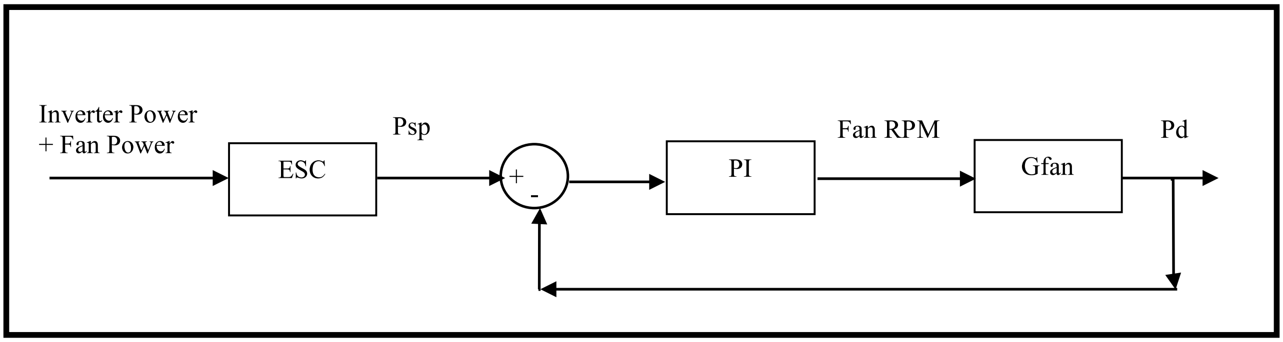

Figure 7. ESC in VRF ODU Fan Speed Control

Fig. 8 and Fig. 9 shows the implement action of ESC in the VRF Model Based Design. The ESC algorithm is implemented as pre-calculation control function block that calculates optimal discharge pressure. The optimal discharge pressure then is used in the discharge pressure control loop to control the discharge pressure.

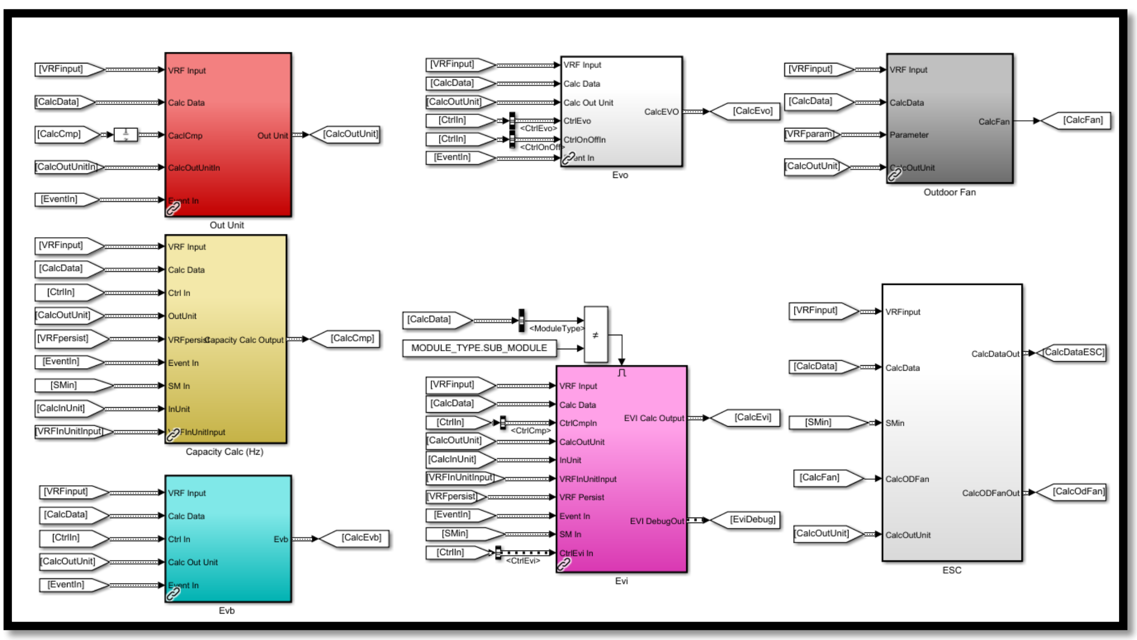

Figure 8. ESC as a Control function block in the MBD Controls

For the ESC block, minimal prior knowledge of system is required. This is a modeless approach.
High/low limits of the discharge pressure are hard constrains and are easy to be obtained from the RCC specification. The Tstimated Time Constant is the estimated response time (time constant) between the discharge pressure setpoint and the combined power consumption. It can be obtained by lab test.

Amplitude of the dither signal is what ESC applies to the discharge pressure setpoint. The Disable/Enable of ESC calculation is an input. When VRF system is in transit state, such as stopped, starting, defrosting or oil returning, ESC should be disabled. A steady state detector is appropriate for these cases. When VRF is in normal running state, ESC should be enabled. A state flow block is used in the MBD to Disable/Enable the ESC calculation.

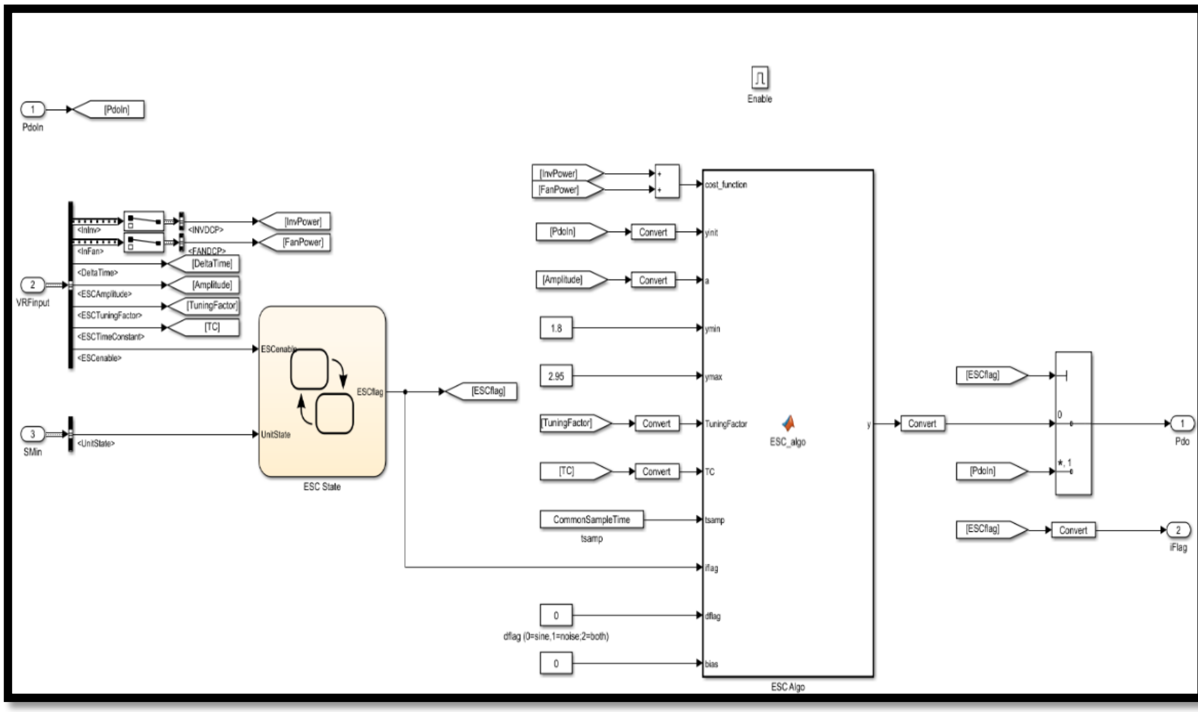

Figure 8. ESC as a Control function block in the MBD Controls

8. Conclusion and future work

The combined power consumption of compressors and fans in ODUs is changing with discharge pressure. The optimal point of the discharge pressure varies with load, outside temperature and other factors that makes it hard to calculate the optimal pressure from these factors. In the current approach, the optimal discharge pressure is calculated from inverter Hz and outdoor temperature. They are not optimal over the whole load range, especial in the low load operation condition.

ESC is an adaptive control that does not rely on these factors. ESC can find the optimal discharge pressure over entire VRF operation range, load conditions and outdoor temperature. The potential saving over all load condition should be more than 5%. The JCI ESC algorithm needs minimal system knowledge which makes it very suitable for VRF systems.

Future work is lab testing, such as frequency and amplitude of excitation signal. ESC lab tests will verify the ESC functionalities and fine tune the tunable parameters. Lab tests can also be used to checking the potential savings by compare the power consumption over the same condition without ESC optimization.

ACKNOWLEDGEMENT

The authors would like to thank Timothy Salsbury and John House for their research on JCI ESC control theory and algorithm. Their ESC work is used in this project and they helped with their time and knowledge during the design and implement of ESC in VRF.

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