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Partially decentralized control of large-scale variable-refrigerant-flow systems in buildings

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ABSTRACT

We consider the problem of designing a scalable control architecture for large-scale variable-refrigerant-flow (VRF) systems. Using a gray-box modeling approach, and by exploiting the one-way coupling between the fluid dynamics and thermal dynamics, we derive individual linearized models for each class of dynamics. This sufficiently reduces the complexity of the problem so that a scalable analysis is possible. Based on the natural dynamics and coupling of the VRF system, which become apparent through the structure of the derived models, a partially decentralized control architecture is proposed. Communication is limited to one-way sensor information flow from the individual decentralized controllers to a global controller, leading to a simple yet highly effective control architecture which easily scales for systems with a large number of evaporators. The ability of the proposed control architecture and design to provide both high performance and reduced energy consumption is demonstrated through a simulated case study.

1. Introduction

In an effort to reduce energy use in buildings, there is a growing interest in the performance and efficiency of large-scale heating and cooling systems. In particular, variable-refrigerant-flow (VRF) systems, also termed multi-evaporator vapor-compression systems, are gaining significant market attention in the U.S. because of the benefits they offer with respect to energy efficiency and flexibility for architects [1,2]. VRF systems consist of a single condenser (heat rejection unit) and compressor which are then connected to n evaporators (heat absorbing units) (Fig. 1).

For practical acceptance, both in design and installation, it is critical to have a control architecture that is scalable ($n \gg 2$) as well as accessible to the building HVAC installation practitioner. It is common to have more than 30 evaporators interacting with the single condenser and compressor in a VRF system [1]. Each zone in a building typically has a dedicated evaporator, electronic expansion valve (EEV), and evaporator fan which are used to deliver a desired amount of cooling to that zone, so a decentralized control architecture is more practical for scalability as the number of evaporators increases. However, because all n evaporators are interacting with a single compressor and condenser, a decentralized approach must be robust to the coupling which exists between evaporators in the overall network. In this paper we present and validate a partially decentralized control architecture which is scalable to arbitrarily large VRF systems.

The first challenge in controlling VRF systems is deriving an appropriate model of the system dynamics. Black-box models obtained from traditional data-driven system identification techniques suffer from various disadvantages: (1) they cannot be developed during the system design phase since the use of black-box model identification techniques requires that the system already exists and (2) they are not scalable (with respect to the number of evaporators in the system) since an identified model will be specific to the system configuration at the time data is gathered. *Therefore, our first objective is to develop a generalized model for an n-evaporator VRF system which overcomes these disadvantages of black-box modeling approaches but is still suitable for model-based control design*. We will do this using a gray-box modeling approach and by exploiting the one-way coupling between the VRF system fluid and thermal dynamics to derive separate models for each class of dynamics.

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Nomenclature

Symbols

a	aperture
C	capacitance
$\dot{m}$	mass flow rate
P	pressure
$\dot{Q}$	heat transfer rate
R	resistance
T	temperature
$K, \alpha, \beta, \eta, \lambda, \mu$	coefficient of linearization
ω	rotational speed

Subscripts

a	air
c	condenser
e	evaporators
f	fan
F	fluid dynamics
k	compressor
L	load
q	junction
r	refrigerant
T	thermal dynamics
v	valve
w	coil wall

The second challenge is to design an appropriate control architecture for large-scale VRF systems. Various control schemes have been proposed in the literature for dual- and triple-evaporator VRF systems. In [4] a cascaded control structure is proposed for a dual-evaporator VRF system which takes advantage of the time scale separation between the refrigerant thermal dynamics and the zone air thermal dynamics. The paper [5] introduces a fuzzy algorithm used with PID controllers to regulate zone air temperatures for a triple-evaporator VRF system. However, neither of these approaches is shown to be scalable to systems larger than $n = 2$ or $n = 3$, respectively. In [6] a dual-evaporator VRF system with discharge pressure regulating (DPR) valves at the outlet of each evaporator is analyzed and then controlled using a decentralized approach which achieves a desired cooling capacity and evaporator superheat in each evaporator. The presence of DPR valves decouples evaporator pressures in the system thereby significantly reducing the dynamic coupling and enabling a decentralized control architecture. However, while effective for a dual-evaporator VRF system, [6] does not offer additional analysis to understand how their approach might scale to larger VRF systems. What is clearly lacking in the literature is a scalable dynamical analysis of *arbitrarily large* VRF systems, particularly those *without* DPR valves (which are often omitted due to the variable cost they add from the manufacturer's perspective). *Therefore, our second objective is to propose and implement a scalable control architecture for VRF systems which is guided by an analysis of the VRF system dynamics and is amenable to industrial implementation.*

This paper is organized as follows. In Section 2, the dynamic models for the fluid dynamics and thermal dynamics are derived using electrical circuit analogies. In Section 3, a partially decentralized control architecture is proposed which uses separate controllers to meet

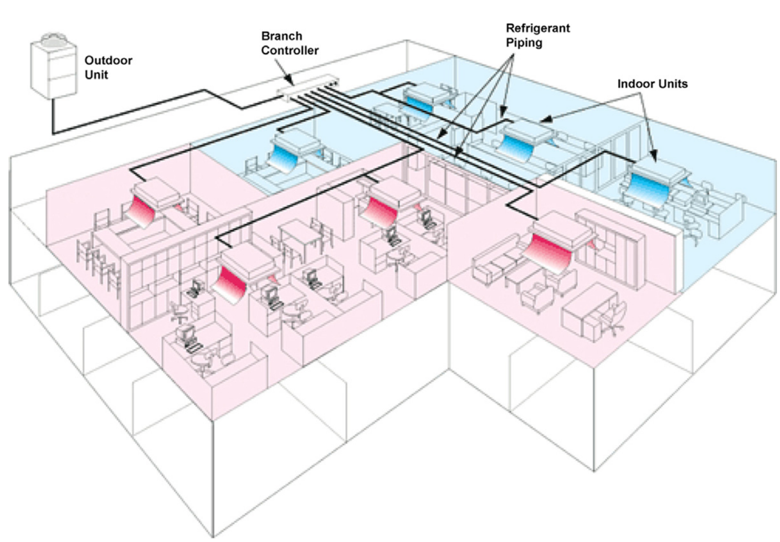

Fig. 1. Schematic of a Mitsubishi Electric VRF system [3].