Applied Thermal Engineering 111 (2017) 647–659

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Development and calibration of a model for the dynamic simulation of fans with induction motors

Massimo Vaccarini [a], Alessandro Carbonari [a,*], Miquel Casals [b]

[a] Universitá Politecnica delle Marche, Department of Civil and Building Engineering and Architecture, via Brecce Bianche 12, 60131 Ancona, Italy
[b] Universitat Politecnica de Catalunya, Department of Project and Construction Engineering, Group of Construction Research and Innovation, C/Colom 11, 08222 Terrassa, Spain

HIGHLIGHTS

- A model for dynamic simulation of fans with induction motors was developed.
- The performances of control logics applied to air supply systems can be simulated.
- The model was validated against empirical data.
- The model was compared with both dynamic time domain and non-transient models.

ARTICLE INFO

Article history:
Received 6 June 2016
Revised 1 September 2016
Accepted 14 September 2016
Available online 21 September 2016

Keywords:
Facility operation and control
Fans
Induction motors
VFD
Dynamic simulation

ABSTRACT

In this paper a model for the dynamic simulation of fans used in mechanical air supply systems is described. Thanks to this model, the behavior of fans subject to control by variable frequency drives (VFD) can be predicted, which includes power absorbed by the fan and expected ventilation rates. Hence, it can help design energy control systems for buildings. The proposed model was based on the Modelica language and was developed from the dynamic phasor domain representation, because this representation is a trade-off between the basic non transient representation, that is computationally efficient but cannot describe fan dynamics, and the dynamic time domain model, that is the most representative one but computationally very demanding. A comparison among these models showed that, within fan frequency variations typical of ventilation systems in buildings, the phasor domain model is as representative as the more complex dynamic time domain model in terms of prediction of the dynamic behavior, that is neglected by the basic non transient model. Moreover, the new phasor domain model was validated against measured data relative to a fan installed in a subway station in Barcelona. Thanks to this model, energy consumption of dynamically driven fans can be estimated at the simulation stage, at the expense of a reasonable computational effort.

1. Introduction

Due to the huge amount of energy consumption determined by buildings, HVAC renovation of the existing building stock can provide a rather high contribution to the overall energy saving. Renovation often consists in the partial replacement of aged components and in the definition of new control strategies. However, the design and development of advanced control strategies, whose performances are usually affected by several parameters, requires testing of alternative strategies, either in the field or through simulation, prior to implementation [7]. Indeed, the availability of reliable models would allow designers to compare and evaluate control strategies at the design phase. The models should be used first to establish the baseline and then to predict expected performances by candidate control strategies, as a result of enhanced regulation and control of HVAC, in order to select the best one. Moreover, simulation models should be used not only to select the best control strategy, but also to accurately estimate expected savings and include such figures in cost-benefit analyses.

Several reasons are produced in literature to stress the importance of user friendly simulators. First, designers should be allowed to easily change parameters and immediately evaluate results, as explained in Tomažič et al. [21]. Even Nagano et al. [15] showed at what extent user-friendly design and performance prediction tools can help in the execution of quick feasibility studies. Several authors highlighted that simulators should be able to carry out reliable simulations in short times, e.g. in Park and Krarti [16].

* Corresponding author.
E-mail address: alessandro.carbonari@staff.univpm.it (A. Carbonari).

http://dx.doi.org/10.1016/j.applthermaleng.2016.09.080
1359-4311/

Otherwise, designers would be hindered in the process of evaluating candidate control solutions, before making a final decision, due to the rather high computational effort. In addition, the availability of fast and reliable simulation models is critical when they are integrated in real-time control systems. In this case, a controller exploits a simulation unit in order to evaluate how the system would evolve within each of any candidate and alternative control strategies. Considering that the controller must accomplish each control step in short time (usually in the order of minutes) and that a huge number of iterations are performed in each control step, the simulation effort required to run the model is bound to be very limited. Basically, dynamic models enable researchers to test new control concepts and to optimize the simulated system's behavior under unsteady boundary conditions, that would not be feasible with the use of just a steady state approach [20]. Dynamic models were critical even in the process of evaluating potential faults in advance, such as in preventive maintenance of rooftop units: a baseline model of variable frequency driven compressors installed on rooftop units was setup, then deviations from expected behavior could be assessed to implement automated fault diagnosis [13].

The work reported in this paper was targeted to find a trade-off for modeling induction motor fans, so as it could be both accurate enough for energy saving estimation and computationally efficient at the same time.

Induction motor fans are typically used in air supply systems of buildings and they are responsible for relevant power consumption. For example, in the test-case considered in this paper, that is relative to the ventilation system of a metro station, two fans are in operation for fifteen hours per day in weekdays and twenty-one hours per day in weekends. Hence, there is a great potential for energy savings, but an accurate evaluation of achievable results can be attained just in case a dynamic model is set up for simulations. The model described in this paper was based on the Modelica language, because Modelica was specifically developed for the simulation of control systems integrated in multiphysics domains, as explained in Wetter [26]. Modelica based models can take into account several physical phenomena, such as heat and mass transfer and fluid-dynamics. For that reason, the model developed in this paper was expanded from the Modelica `Buildings` library and was developed in the Dymola programming environment, and it was made compliant with models relative to building components and HVAC systems. In fact, the current version of the Modelica `Buildings` library used for the application described in this paper offers components that can be used to develop two different types of induction motor models: the first one exploits the basic stationary representation, whereas the second one exploits the time domain representation. The former is computationally very efficient but is not able to simulate the dynamics of fan induction motors; the latter is very accurate and exposes every parameter of fan induction motors, but is computationally very demanding.

Considering the premises described above, the main contributions provided by this paper are:

- a component extended from the Modelica `Buildings` library was built, which was based on the phasor representation of induction motors, so as to be able to account for the dynamic behavior of induction motor fans, while requiring limited computational effort for simulation;
- calibration and validation of the aforementioned component against measured energy consumption;
- a comparison between the power consumption figures estimated under transient conditions by a fan model based on the phasor representation and the figures estimated by both the basic stationary and time domain representations, that are already available in the current Modelica library.

The validation took advantage of data measured during the operation of a real fan equipped with induction motors and installed in the "Passeig de Gràcia" metro station in Barcelona, which is a fan driven by Variable Frequency Drives (VFD), hence its rate can be adjusted according to actual ventilation needs in the station. The comparison between the model developed in this paper and the other two models was targeted to two main goals:

- assessing at what extent the phasor representation model is more accurate than the basic stationary one and less accurate than the domain representation;
- estimating how much more accurate the phasor representation model is than the basic stationary representation, while the fan is dynamically driven (i.e. transient behavior) over a typical day it is in operation.

In the next Section 2 the relevant state of the art is analyzed, along with some further remarks about the steps ahead provided by the work described in this paper. The following Section 3 is split into two more subsections: Section 3.1 describes the proposed Modelica component as it was developed by means of the Dymola environment, whereas Section 3.2 reports on the related analytics. Section 4 was split into two sub-sections. The first one (Section 4.1) includes a description of the fan with induction motor used for calibration and of the metro station where the fan was installed. The second one (Section 4.2) includes a description of the experimental dataset collected while the fan was in operation, in order to calibrate the simulation model, and shows that an opportune tuning of some parameters made available by the model gives back a very good matching between simulation results and measured power plots. Then, the performances of the model were compared with the basic stationary and the time domain representation models, whose development is the subject of Section 5.1 and whose dynamic behavior was assessed in Section 5.2. Finally, conclusions are discussed in Section 6.

2. Scientific background

2.1. Simulation of integrated systems

As stated by Kral et al. [11], partial load efficiency of induction motors should be computed for the determination of the nominal operating point when subjected to electric drives. Although fans and pumps are designed to perform during peak loads, these loads occur rarely during the operating year. Therefore, in order to control flow during off-max load conditions, VFDs are often used to deliver only the required flow while reducing energy consumption. A good estimation of energy saving deriving from such a control policy is well described by the so called affinity laws [29]: when the air flow rate generated by fans is reduced by means of a rotational speed reduction, the corresponding decrease in absorbed power will follow a cubic mathematical relationship. However, the dynamic behavior of induction motors cannot be represented by means of affinity laws, and more refined simulation tools and mathematical models are needed. Once those models are available, they can be exploited for prediction of potential savings that can derive from energy improvement actions to be implemented in buildings.

Designers of integrated control systems for existing buildings usually develop a model relating to the current scenario of the buildings as a first step; then, a calibration methodology is applied to assure accuracy; finally, several opportunities for energy saving supplied by renovation actions and enhanced control systems are assessed based on the same calibrated model [18]. In conclusion, whenever enhanced control systems integrated in existing large