A Multidisciplinary Model to Couple Power System Dynamics and Building Dynamics to Enable Building-to-Grid Integration

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Abstract

Interactions between power systems and buildings are usually ignored or over-simplified by existing modeling and simulation tools. This limits how system modeling can support Building-to-Grid integration activities. In this paper, we developed a multidisciplinary model for motor-driven building devices to consider the interactions. This multidisciplinary model considers both mechanical dynamics and electrical dynamics of the motor-driven building devices. It characterizes the motor behavior, in response to disturbances from both power systems and buildings. We validated this model by comparing its simulation results, in terms of the response to a varying voltage signal, to those from a commonly-used power modeling tool. To demonstrate the usage of the developed model, we integrated the developed model into a simulated building cooling system. We then studied how this simulated system responses to changes in the supply voltage and the thermal load.

Introduction

Power systems and buildings interact in a dynamic and coupled manner. For example, the supply voltage was found to dramatically affect the instantaneous energy efficiency of the building systems. (Hood (2004); Bichik et al. (2015); Lee (2014)). The operation of building systems, on the other hand, influences the transient performance of the power system, such as the voltage stability (Wu et al. (2006); He et al. (2012); Li et al. (2017)). Therefore, it is necessary to consider those interactions when designing and operating power systems or buildings in order to avoid undesirable side effects. When it comes to the Building-to-Grid (B2G) activities, this necessity becomes even more urgent since more interactions are expected to be introduced by the B2G activities.

Modeling and simulation is an effective way to investigate the interactions. However, when simulating power systems or buildings, the interdependent influences tend to be ignored. One major reason is that existing models and simulation tools were developed from a single disciplinary perspective and thus have difficulties in capturing the multidisciplinary interactions. For example, in the power system modeling, it is quite common that power factors of the building system are assumed to be constant (Chassin et al. (2008a)). In the building system modeling, usually the influence from power systems is ignored by implicitly assuming the supply voltage to be constant (Crawley et al. (2001)).

There were efforts to consider the interactions between buildings and power systems (Chassin et al. (2008b); Bokhari et al. (2014); Clarke (2015)). For example, a ZIP coefficient model (Bokhari et al. (2014)) was proposed to approximate the influences of the voltage on the building device using a polynomial function. However, they over-simplify those interactions, and thus may not be able to support lager-scale applications. The ZIP coefficient model, for instance, is a static model and ignores the transient dynamics. Thus, it may not be used for the dynamic analysis purposes.

Under specific circumstances, we remark that, ignoring or simplifying those interaction may be acceptable. For example, when resistive devices (such as the electric heater) dominate the power usage in buildings, we can assume the power factor is constant without sacrificing the accuracy too much (Gilbert (1965)). Furthermore, for the static or semi-dynamic analysis on the power system, the ZIP coefficient model can still provide reasonably good approximation on the response from the load side (Hatipoglu et al. (2012)). Nevertheless, ignoring or simplifying those interactions would generate significant errors in some applications, especially the B2G activities, such as optimizing the supply voltage to maximize power saving in a building (Arriffin et al. (2017)). In those applications,obviously, ignoring the interaction or only considering the one-directional impacts from power system to buildings may lead to unrealistic or even incorrect conclusions.

To support broader applications, we discussed how to consider those interactions in the building system modeling (Fu et al. (2019)). We also performed a proof-of-concept by developing models for motor-driven building devices. Those models, however, were designed primarily to support qualitative analysis and based on simplified mathematical descriptions of the motor operation. Therefore, they may not be able to be used directly in a real application.

In this paper, we developed a new multidisciplinary model for motor-driven building devices to better represent the interactions between power systems and buildings. This multidisciplinary model considers both mechanical dynamics and electrical dynamics in the motor-driven building devices. It characterizes the motor behavior, in response to disturbances both from power systems and buildings. We validated this model by comparing its simulation results, in terms of the response to a varying voltage signal, to those from a commonly-used power modeling tool. To demonstrate the usage of the developed model, we integrated the developed model into a simulated building cooling system. We then studied how this simulated system responses to the changes in the supply voltage and the thermal load.

The rest of the paper is organized as below: we first describe the studied motor-driven building devices, and then elaborate how their dynamic behaviors are modeled. After that, we validate the model by comparing its simulation results with that from a commonly-used power analysis tool. We then perform a case study to demonstrate the usage of the developed model. At last, we discuss the simulation results and future works.

Motor-driven Building Devices

Typical motor-driven building devices include fan, pump, chiller, etc. They are the major consumers of the electricity in buildings (Webster et al. (2000)). As shown in Figure 1, a typical motor-driven building device consists of three major components:

- **Variable frequency drive (VFD)**
  The VFD is used to adjust the input frequency and voltage for the motor. It is connected with the components (such as transformers) in power systems and transports the electricity power to the motor. It is noted that VFDs are generally optional. In absence of VFDs, the input frequency and voltage of the motor depends on the power system operation directly.
- **Motor**
  Induction motors are the commonly used type of motors in buildings. A typical induction motor consists of several sub-components: coil, magnet, stator, and rotor. The coil and stator are connected with the electric circuit from the VFD and generates induced magnetic field. The generated magnetic field from the coil and the stator interact with the rotor, and produces an electromagnetic torque around the rotor's axis. The torque forces the rotor to rotate at a constant or varying speed.
- **Transitional device**
  The transitional device links the shaft in the rotor with that in a mechanical counterpart. It transfers the torque from the rotor to the mechanical device. A commonly used transitional device is belt.
- **Mechanical devices** The mechanical device converts the torque into mechanical works. In buildings, they usually interact with other systems indirectly via different fluid loops. For example, for supply air fans, the mechanical device circulates the air between the air conditioning system and the room, so that the cooling and heating energy can be delivered from the former to the latter. Usually feedback controls are utilized to guarantee that the mechanical system can deliver a desired amount of mechanical works. Those feedback controls monitor the controlled variable and send the frequency signal to the VFD in order to modulate the input frequency of the motor.

The operation of the motor-driven building devices are affected by both power systems and other systems in buildings. In that sense, motor-driven building devices act as an interface to connect power systems and buildings. Specifically, the impact of power systems to the buildings is reflected by the supply voltage and the frequency, which affects the amount of electromagnetic torque that motors can generate. The electromagnetic torque determines the amount of mechanical works that motor-driven building devices can provide. In addition, the impact of the buildings on the power systems is reflected in the current of the power flow through the buildings,which influences the actual voltage of the power system. Therefore, modeling the motor-driven building devices is the key to consider the interactions between power systems and the buildings.

System models

In this section, we elaborate how the motor-driven building device are modeled at the component level.

- **Variable frequency drive (VFD)**
  The VFD model basically has three inputs: input voltage,$V_{in,i}$, input frequency,f_{in}, and frequency signal, f_{sig}, and two outputs: output voltage, $V_{vfd,out,i}$, and output frequency, $f_{vfd,out}$. In this study, the VFD is assumed to be ideal, in other words,

$$f_{vfd,out} = f_{sig} \tag{1}$$

$$V_{vfd,out,i} = V_{in,i} \tag{2}$$

  where the subscript i denotes the phases of the power system.
- **Motor**
  We considered a three-phase induction motor with unbalanced supply. It has two major inputs: the input frequency, $f_{motor,input}$, the input voltage for each phase, $V_{motor,input,i}$, calculated

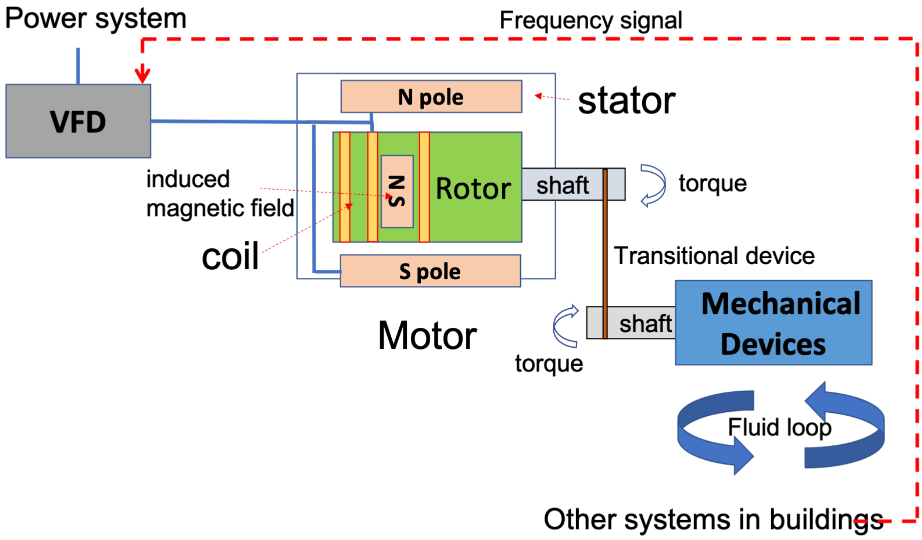

Figure 1: Motor-driven Building Devices

by:

$$f_{motor,input} = f_{vfd,out} \tag{3}$$

$$V_{motor,input,i} = V_{vfd,out,i} \tag{4}$$

The outputs include the apparent power of the motor and the generated electromagnetic torque, τ_e, obtained by solving a series of differential equations that represent the electrical dynamics and magnetic dynamics of motors (Stankovic et al. (2002)).

- **Transitional device**
  Regarding the transitional device, the inputs include the τ_e and the load shaft power, P_{shaft} while the outputs include the load speed, ω_r and the load torque, τ_L. One major parameter for the transitional device is the load moment inertia J_L. The τ_L is calculated by solving the following equations:

$$\tau_L = \frac{P_{shaft}}{\omega_r} \tag{5}$$

$$\frac{d\omega_r}{dt} = \frac{\tau_e - \tau_L}{J_L} \tag{6}$$

- **Mechanical device**
  The major input of the mechanical devices is the mechanical work they provide, w. For the device such as fans or pumps, the mechanical work is calculated by:

$$w = \Delta p Q \tag{7}$$

where Δp and Q are the head and the volume of the fluid, respectively. The output of the mechanical device is P_{shaft}, calculated by

$$P_{shaft} = \frac{w}{\eta_{shaft}} \tag{8}$$

where η_{shaft} are the shaft efficiency. For fan or pumps, η_{shaft} can be expressed as a quadratic equation as

$$\eta_{shaft} = (b_0 + b_1(\frac{Q}{r}) + b_2(\frac{Q}{r})^2)r^2 \tag{9}$$

where the normalized speed r can be calculated based on the rotation speed ω_r and the nominal rotation speed $\omega_{r,0}$, and is shown as

$$r = \frac{\omega_r}{\omega_{r,0}} \tag{10}$$

It is noted that all the above formulas, including both algebraic equations and deferential equations, shall be solved simultaneously since some of them are coupled. To simplify the implementation process, we use Modelica (Fritzson and Engelson (1998)) as the modeling tool. Modelica is an equation-based modeling language which allows describing the systems with implicit equations. Therefore, differential equations can be directly implemented in Modelica without any modification. Figure 2 is the diagram of the generated Modelica model for one type of motor-driven device: fan/pump.

Validation

In this section, we validate the developed Modelica model against *PSCAD* (Woodford (2003)), a widely used power modeling tool. In this validation, we considered a scenario where there are sudden changes in the supply voltage of a motor-driven device, due to a fault occurs in the power grid. We then modeled the above scenario with both the developed Modelica model and the PSCAD. For the Modelica models, we simulate it with a solver called DASSL, provided by a commercial software Dymola (Brück et al. (2002)). The solver DASSL supports variable time steps, and

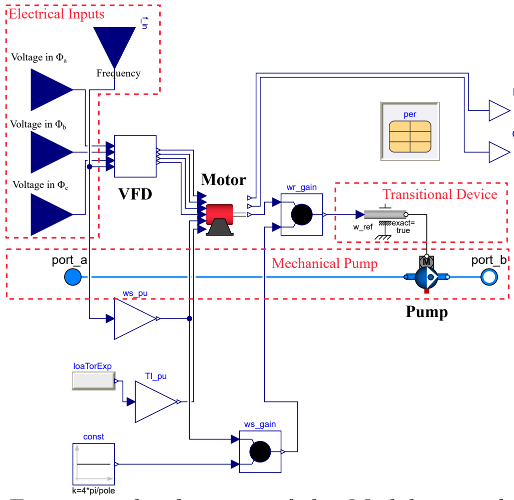

Figure 2: the diagram of the Modelica model

the minimum and the maximum time step in the Modelica model during the simulation are 0.0154 μs and 0.282 s, respectively. For the *PSCAD* model, we select a fixed time step as 50 μs and use the trapezoidal algorithm for integration.

Figure 3 illustrates the simulation results. We can see that, at the 5 s, the voltage ramps down to 0.3 $p.u.$, i.e., decreasing by 70%, in 0.02 s, then stays at 0.3 $p.u.$ for 0.3 s. At t=5.32s, the voltage ramps up to 1 $p.u.$ in 0.02 s, and finally keeps at 1 $p.u.$ till the 8 s. The two models can generate approximately close results in general.

The simulated rotor speed, real power, and reactive power from the two models, in response to the voltage change, are close in terms of general patterns. There are some relative large differences, however, in the period from the 0 s to the 3 s, this is because the initial values for state variables are different for the two models. Due to the limitations of the simulation environment, we are not able to force the two models to have the same initial values. Based on the above results, we believe that the developed model provides reasonable representation on the system dynamic behaviors, in response to the voltage change, for the studied motor-driven device.

Case Study

To demonstrate how the developed Modelica models can help to capture the interactions between power systems and buildings, we conducted a case study. In this case study, we integrated the developed model with a simulated building cooling system. We then investigated how the model responses to the disturbances in both power systems and buildings.

This section starts with a brief description on the studied building cooling system; It then elaborates the simulation scenarios and simulation results.

Studied system

We considered a simplified building cooling system in this study. As shown in Figure 4, this simplified system contains a water loop and a air loop. The water loop consists of an ideal cooling source, a pump, an air handler, and a two-way valve and the air loop contains an air handler and a load. In the water loop, the ideal cooling source maintains the temperature of the leaving water to be 7 ^oC and the pump circulates cold water between the cooling source and the air handler. In the air loop, the cold supply air from the air handler then removes the heat from the load with a constant air flow rate. In addition, there are some interactions between the water loop and the air loop. The water flow rate is modulated by adjusting the opening position of a two-way valve to maintain the cold air leaving the air handler to be around 16 ^oC. In addition, the frequency of the pump is adjusted to maintain a constant pressure difference in the pipe across the air handler when the water flow rate varies.

We then modeled the studied system with Modelica Buildings library When generating the system models, we considered two options as well. In the first option (named as "proposed"), the pump is modeled with the developed model while in the second option ("conventional"), the pump is modeled with a module called "Buildings.Fluid.Movers.SpeedControlled_y" from Modelica Buildings library (Wetter et al. (2014)). "Buildings.Fluid.Movers.SpeedControlled_y" doesn't consider the interactions between the power system and pumps, and thus is used as a reference to better understand the performance of the proposed model. For both options, the rest components of system besides the pump were modeled with components from the Modelica Standard library (Fritzson and Engelson (1998)) and the Modelica Buildings library.

Testing scenarios

In this case study, we considered two scenarios. In the first scenario, we studied how disturbances in power systems affect the studied system by introducing a step change in the supply voltage from the grid and assuming that the thermal load keeps constant. In the second scenario, we studied how disturbances in buildings affect the studied system. Similar to the first scenario, we introduced a sudden increase of the thermal load and keep the voltage unchanged.

In both scenarios, the simulations are conducted from 0 s to 1600 s, and the signal changes are implemented at the 800s. We use the above simulation time settings to make sure the system has sufficient time to become steady before and after the signal changes. This can allow us to study both the dynamic and the steady state responses of the system to the changing signals.

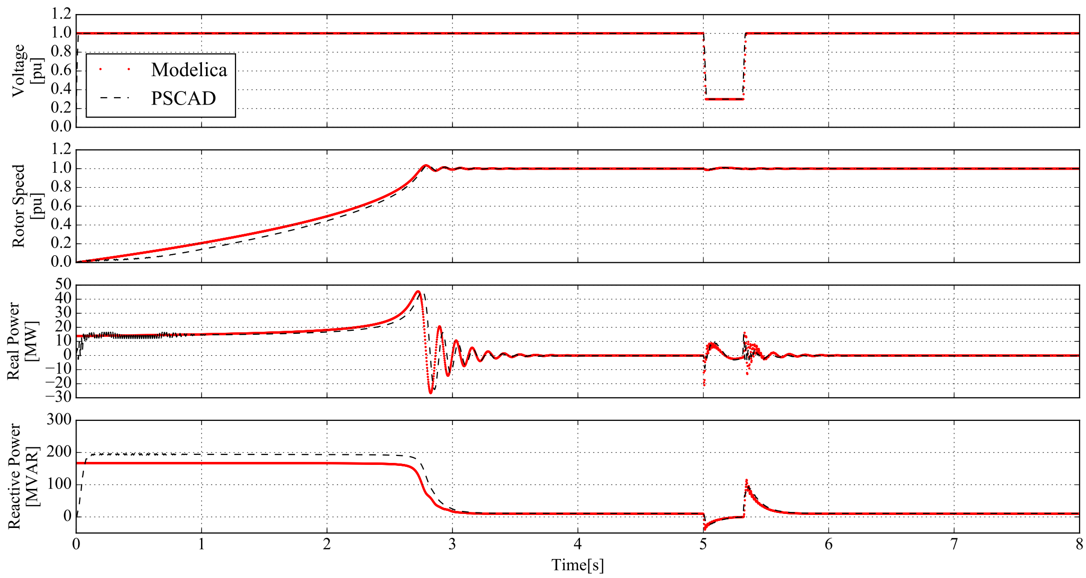

Figure 3: the validation results of the Modelica model

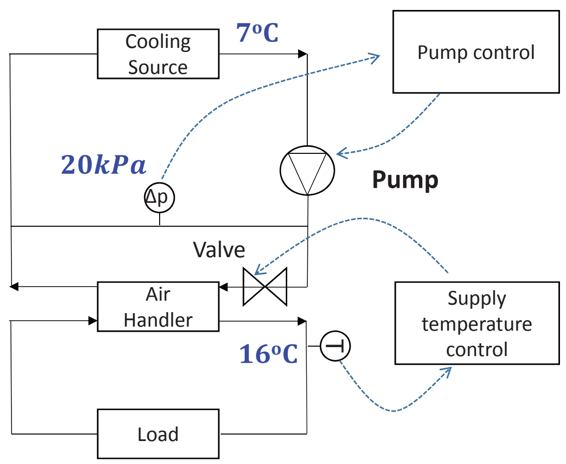

Figure 4: The studied cooling system

Results

Figure 5 illustrates the simulation result for scenario 1. The step change in the voltage from 1.0 $p.u.$ to 0.5 $p.u.$ is introduced at 800 s. In response to the sudden change of the voltage, in the "proposed" option, the real power oscillates dramatically between -10 kW and 15kW in a very short time (less than 0.2 s). The real power becomes negative because this rapid voltage change could force the motor to be in a generator mode and generates some real power during the contingency. After that, the real power become relatively steady at around the 801 s. The steady state values of the real power changes slightly before and after the voltage dip: from 4.15 kW to 4.29 kW. However, in the "conventional" option, there is no change in the real power as the voltage is not considered as a input for the pump operation. In addition, the "proposed" option shows that the reactive power of the pump experiences an oscillation as well: from around -17.00 $kVar$ to around 3.00 $kVar$ in 0.2 s. The steady value of the reactive power also changes slightly, from 2.94 $kVar$ to 2.83 $kVar$.

As shown in Figure 6, the primary reason for the oscillations is that the speed controller of the pump tries to maintain a constant pressure difference. When the voltage decreases, the electromagnetic torque produced by the motor drops. As a result, the motor speed, driven by the electromagnetic torque, also decreases, leading to a lower head pressure. To maintain a constant pressure difference in the pipe across the air handle, the speed controller of the pump generates a higher frequency signal to increase the motor speed. The increased motor speed then generates a higher head pressure and forces the speed controller to reduce the frequency signal. The above process repeats until the frequency signal becomes steady.

The oscillations influence significantly the power consumption by the pump . Before the dip, the pump consumes 4.15 kW. During the rebalancing process, the pump can consume as much as 13.5 kW, which increase the demand by about 2.25 $p.u.$. However, those oscillations don't dramatically affect the building operation performance. For example, as shown in, the change of the static pressure is less than 0.03 kPa. This is because the mechanical inertial prevents the load torque changes as the same pattern as the electromagnetic torque.

Figure 7 illustrates the simulation results for scenario 2. At t=800 s, its thermal load increases by 0.5 $p.u.$. As a consequence, more chilled water need to pass through the air handler, which then decreases the pressure difference. The frequency of the pump is then increased by the pump controller to maintain a constant pressure difference.

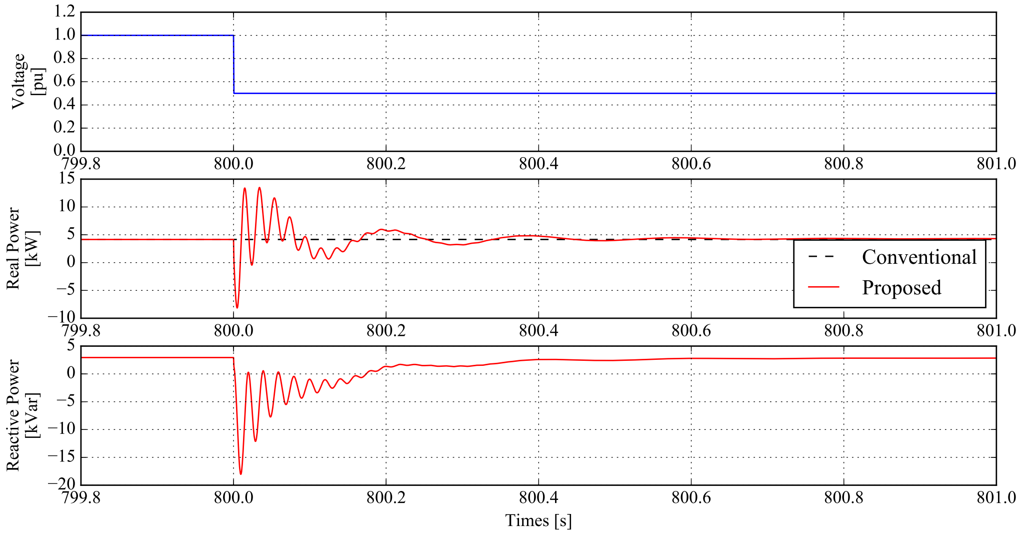

Figure 5: Simulation results of the scenario 1

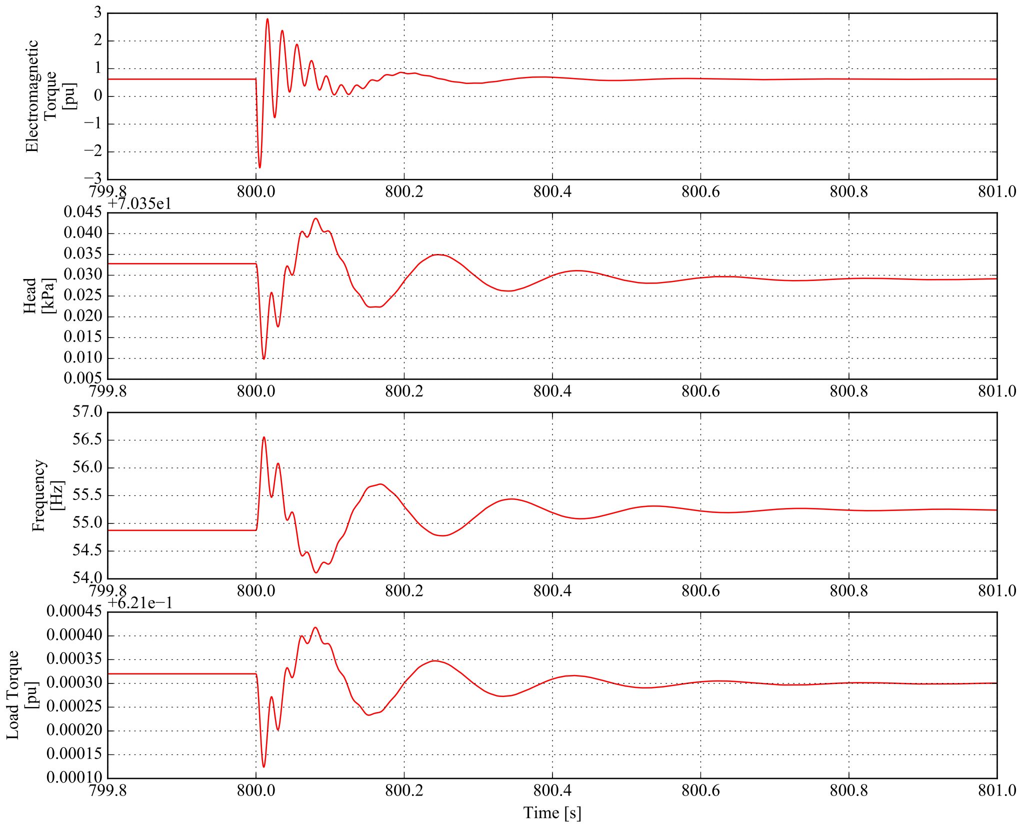

Figure 6: Detailed simulation results of the scenario 1

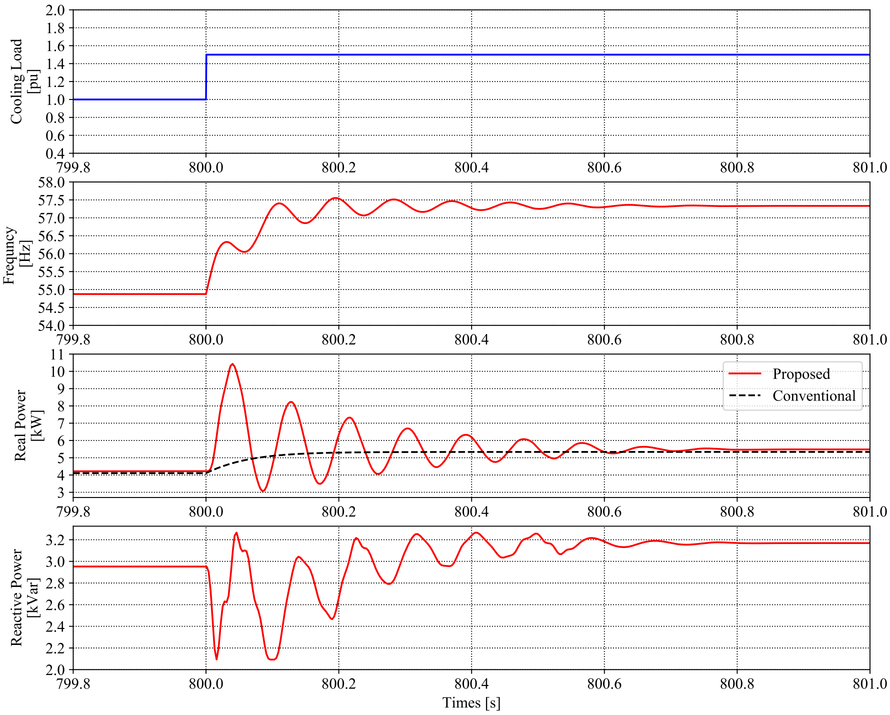

Figure 7: Simulation results of the scenario 2

In the "proposed" option, similar to scenario 2, the pump control contributes mostly to the significantly oscillations in the real power. We can see that the real power changes from around 4 kW to around 10 kW in just 0.1 s. In addition, there is a significant oscillation in the reactive power as well.

However, in the "conventional" option, we observe no oscillations since "Buildings.Fluid.Movers.SpeedControlled_y" doesn't consider the mechanical inertia in the motor and the transitional device. Therefore, the change of the frequency signal is much smoother than that in the "proposed" option.

Conclusion

In this paper, we developed a Modelica models to allow considering the interactions between buildings and the power system. We validated the developed model by comparing its simulation outputs to those from a power modeling tool. The validation results suggested that the developed models can predict reasonable responses of the motor-driven devices to the studied changing voltage. To demonstrate the usage of the developed model, we conducted a case study with a simplified building cooling system. The case study results suggest that the proposed model provides more realistic representation on how the studied system responses to the disturbances from the supply voltage and the thermal load, compared with the existing models.

In the future study, we will perform a more realistic case study by including power systems into the simulation scope rather than treating it as a boundary condition. By doing that, we can better understand how the buildings and power grids interact in a coupled manner. In addition, we will also apply the proposed model in the B2G activities to support the design or the evaluation of the relevant controls.

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