STRONG COUPLING OF A BUILDING THERMAL MODEL WITH A CONTROLLED ELECTRICAL HEATER FOR AN HYBRID ENERGY SIMULATION

Sana GAALOUL[1], Benoît DELINCHANT[1], Frédéric WURTZ[1], Stéphane THIERS[2], Bruno PEUPORTIER[2]

1. G2Elab – Grenoble Electrical Engineering LABoratory, ENSE3, 961 rue de la Houille Blanche, 38402 Saint Martin d'Hères, France.
e-mail: sana.gaaloul@g2elab.grenoble-inp.fr, benoit.delinchant@g2elab.grenoble-inp.fr, frederic.wurtz@g2elab.grenoble-inp.fr

[2] ARMINES – Centre Energétique et Procédés
MINES ParisTech **:** 60, Boulevard Saint-Michel, 75272 Paris CEDEX 06.
e-mail: stephane.thiers@ mines-paristech.fr, bruno.peuportier@mines-paristech.fr

Abstract - The context of this study is the coupling of thermal and electrical models in order to efficiently simulate energy consumption in buildings, which requires managing interoperability problems between simulation environments. The coupling is accomplished in MATLAB™ tool between a thermal model of a building envelope using COMFIE software and an electrical heater model. Our purpose is to study and generalize the interoperability between these two domains governed by phenomena of different natures: continuous domain for thermal one and event driven for heating, both interacting in a strongly coupled way. A variable step solver is used to ensure an efficient hybridization offering faster simulation.

Keywords – Building, Coupling, Thermal, Regulation, Hybrid systems, Variable step simulation.

1. INTRODUCTION

In Europe, buildings exceed the third of the global energy consumption with an important proportion of electrical systems and essentially for heaters (87% for classical buildings and 30 % for ecological ones in France). That is why it is essential to ameliorate their performance by using, adapted regulators and choosing the optimized control strategies in addition to envelope isolation. To avoid expensive experimentations, several simulations for virtual prototyping should be realized in order to easily test and verify designed systems and control methods. A significant building simulation requires a complete modeling of coexisting systems and a coupling between the different areas that interact in this sector. In fact, building is a sector involving several areas: thermal, electrical, control-command, human behavior that interacts together in a weak or strong way. These areas are governed by various phenomena from different natures: they may be continuous, discrete or hybrid with event handling, and are characterized by different time constants. Therefore, the coupling between domains presents some difficulties and needs to take into consideration the differences between them and the specificities of each one.

This article proposes to study the difficulties encountered when coupling two different models (different nature) and to discuss the methodology proposed to ameliorate the performance of such a coupling. It consists on a coupling between a discretized thermal envelope model and an heater controlled by a thermostat generating events in order to switch the heater power. The variable step time methodology will be adopted as an efficient solution for this hybrid system simulation. We will show that the adoption of this solution will impose the modification of the two actors' models, without a special focus on models details.

In building simulation, several works have been done to offer more coupling possibilities by improving tools interoperability capabilities. Due to their modularity improvement, many building simulation environment such as EnergyPlus and TRNSYS [1], provide the opportunity to link envelope model to other equipments available in their libraries. But, the integration of new models stills a hard task and requires much development efforts. It may also be impossible in other cases like in COMFIE that didn't offer the possibility to develop new components. Other solution has also emerged to overcome this problem: the co-simulation. It could be a direct co simulation

between a master and a slave tools or based on a co-simulation environment like BCVTB [2]. The co-simulation is time consuming, which is an inhibiting factor for embedded simulation in centralized controls systems for prediction to efficiently reacting.

Few studies have been made regarding the difficulties of model coupling which are provided by various specialized environments. A first solution which is generally adopted is the use of reduced models all defined in the same environment. For example, in electrical engineering and control system design, a building is generally approximated to a simple equivalent electrical circuit (RC) [3] [4].

In this paper, a coupling solution is brought, using COMFIE software to establish a detailed building's envelope modeling which is imported in Matlab/Simulink in order to be easily connected to other equipments.

2. THERMAL MODEL

2.1. COMFIE BUILDING ENVELOPE THERMAL MODEL

COMFIE software [5] has been chosen to benefit from its capabilities in thermal building envelop modeling area:

- A graphical interface, Pleiades, reducing the time learning and offering easy data entry.

- A detailed envelope modeling taking into account several parameters: architectural structure, walls compositions and orientations, weather conditions…

- The simulation of the temperature evolution and energy requirements during a fixed period for predefined scenarii of occupancy and temperature set points.

- A speed simulation adapted for professional use due to a reduced meshing of the thermal zone but sufficient enough to reach a good accuracy.

However, Comfie presents some limits to introduce new equipments and does not offer any possibility to communicate with other tools. That's why we have chosen to externalize the resolution of COMFIE models.

Building model is firstly established for each thermal zone independently of others, using heat exchange equations at meshes level. For that, each zone is decomposed in finite meshes and according

to their localization (internal wall side, external wall side, intermediary mesh…) a corresponding equation is identified. The assembling of these equations leads to the linear matrix system formalized as below:

$$\begin{cases} \mathbf{C} \cdot \dot{T} &= \mathbf{A} \cdot T &+ \mathbf{E} \cdot U \\ Y &= \mathbf{J} \cdot T &+ \mathbf{G} \cdot U \end{cases} \quad (1)$$

T: discretized field of meshes temperatures
U: stresses vector
Y: output vector (area temperature, equivalent temperature)
C: diagonal matrix of thermal capacities
A: matrix of exchange terms between meshes
E: matrix of exchange terms between cells and stresses
J: matrix connecting the outputs meshes temperatures
G: matrix connecting the outputs to the stresses

Several mathematical manipulations leads to the simplification of this system: decomposition to steady state and a transient terms: $T = T_0 - A^{-1} \cdot E \cdot U$, base changing: $T = P \cdot X$ and order reducing by eliminating the smallest time constants [6]. This order reduction may visibly affect temperature evolution only when the excitation source time-constant is higher than reduced constants. This problem was not encountered when the model used in the illustration was not reduced.

After that, equations describing each area are coupled in a global system:

$$\begin{cases} \dot{X}_g &= \mathbf{F}_g \cdot X_g &+ \mathbf{B}_g^{\alpha} \cdot \dot{U}_g &+ \mathbf{B}_g^{\beta} \cdot \dot{Y}_g \\ Y_g &= \mathbf{H}_g \cdot X_g &+ \mathbf{S}_g^{\alpha} \cdot U_g &+ \mathbf{S}_g^{\beta} \cdot Y_g \end{cases} \quad (2)$$

Ug: vector of stresses
Xg: state vector
Yg: output vector containing the equivalent temperatures and the coupling variables
F_g, B_g^{α}, B_g^{β}, H_g, S_g^{α}, S_g^{β}: matrices resulting from the various mathematical manipulations.

System (2) can be integrated over a step time Δt to obtain the recursive system (3) (see the end of the paper).

The resolution of this recursive system, allows the internal temperatures evaluation at each iteration, for predefined scenarios of domestic inputs.

2.2. MODEL EXTRACTION FROM COMFIE

In order to take advantages from COMFIE capabilities and to go beyond its limits in terms of control systems simulation, we proceed to an externalization of the differential system (3) sequential resolution. The system is rebuilt, using generated matrix files, in Matlab/Simulink, which is

widely used for control systems modeling. This projection has been validated by comparing the temperature variation results obtained by COMFIE and those by MATLAB for the same simulation project (INCAs homes located in Chambéry, FRANCE).

3. THERMAL/ ELECTRICAL MODELS COUPLING

Thermal model is strongly coupled to a controlled heating model that manages the electrical power: the two models interact at each calculation step. The heater is commanded by an hysteretic loop depending on the inside temperature. His electrical power will influence the temperature evolution, which mathematically signifies the injection of power in thermal model stresses vector. In fact, stresses vector U is composed successively by: outside temperature, internal power dissipated in each zone (people and devices) and the incident solar flux. This operation will be repeated until the end of the simulation.

4. THERMAL/ELECTRICAL COUPLING SIMULATION: FIXED TIME-STEP SIMULATION

Initially, the simulation step has been imposed by the envelope thermal model: building time-constants τ_i are accessible via the matrix F_g whose diagonal elements represents terms $-1/\tau_i$. A step of one hour is sufficient to simulate the envelope behavior especially when available data (outdoor temperature and solar flux) are hourly data.

Temperature variation of each area can be visualized in order check the control strategy (**Error! Reference source not found.**).

After a transitional phase, the temperature becomes stabilized around the reference temperature imposed by the heating control.

The heating state is updated at each simulation step which corresponds in this case to one hour, meanwhile, the inside temperature follows his evolution and reaches the comfort limits. This does not reflect sufficiently the real behavior of the heating system and thus the thermal behavior of the house, which is not acceptable.

In order to improve the precision of the simulation, the time-step is reduced to 6 minutes (the minimum step in COMFIE). This step is more adapted to the heating system events detection. This operation improves performances of the simulation, smoothen the curves along with more precision because the overtaking of temperature limits is detected earlier as shown in Fig. 1.

However, a fixed step method gives an accuracy of about the calculation step[7], which imposes to reduce the simulation step to the minimum in order to obtain the best accuracy. But, this will slow the simulation. Indeed, simulation time became longer as the time-step is reduced which is not always necessary, especially when no event occurs for a long period. Therefore, it is important to carry out a variable step simulation allowing the adaptation of the simulation step according to the system dynamics.
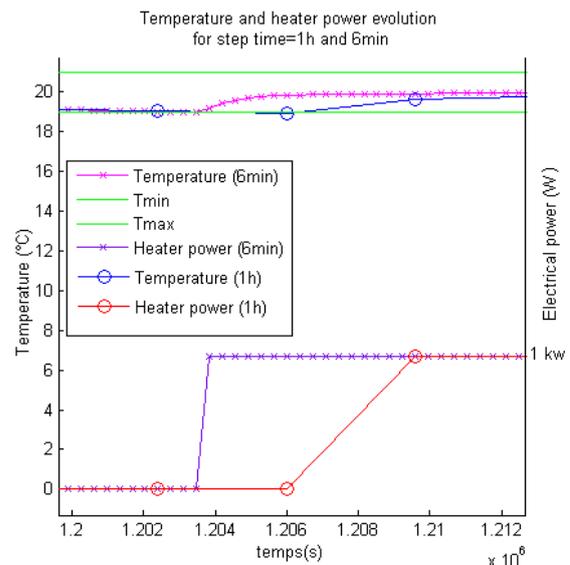

Fig. 1. Temperature and heater power evolution (step time: 1h and 6 min) in MATLAB

5. THERMAL/ELECTRICAL COUPLING SIMULATION: VARIABLE TIME-STEP SIMULATION

5.1. PRINCIPLE OF VARIABLE STEP SIMULATION

The system is an hybrid system containing both continuous state variables and discontinuous ones. So the simulation should be able to handle various discontinuities and ensure continuity of state variables for each state change and find a compromise between computation time and accuracy.

To improve the simulation performance without carrying many calculations, the adaptation of the calculation step is a relevant solution. As shown in Fig. 2, the simulation step is calculated by predicting the next important date: when discrete events will occur or when variables reach zeros crossings. The simulation step will be reduced to his minimal value when the next important date is near to calculation point [8].

Matlab/Simulink™ enables the simulation of models developed in its libraries with different types of solvers. It also offers the opportunity to implement dynamic models with an ordinary differential equations representation (ODE) thanks to the "S-function" blocks. It is a computer program (languages can be Matlab, C, C^{++}, Fortran, Ada) using a specific calling syntax to interact with the time integration solver. So, it allows the simulation of continuous, discrete or hybrid models.
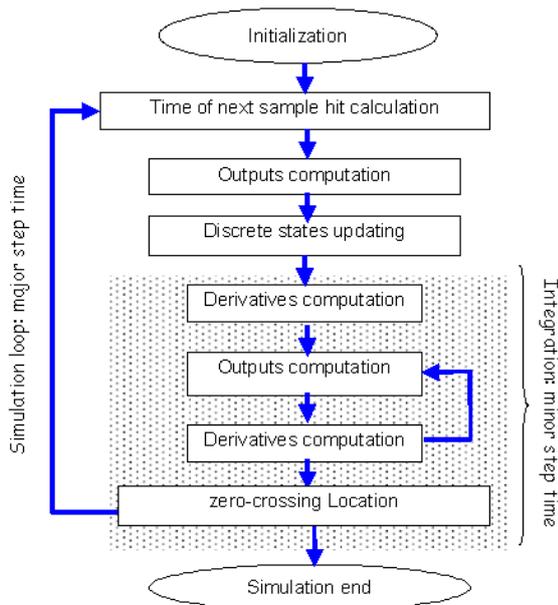

Fig. 2. The principle of variable step simulation in Simulink

In the other side, the model embedded in the S-function should implement functions (Fig. 3), that will be called by the solver at each step time in a sequential. These calls depends on the solver (integration order) and the model nature (continuous, discrete, hybrid) as indicated in the previous figure.
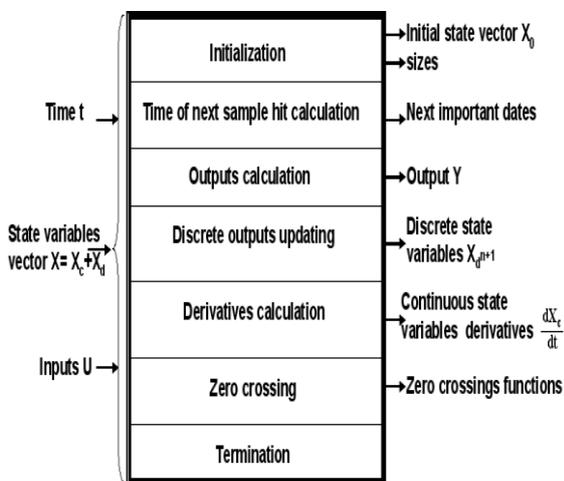

Fig. 3. Hybrid model and solver interactions

In our application, only the thermal model will be imported in a continuous "S-function" in order to be connected to other existing models in Simulink. The environment will manage the variable step by analyzing the different blocks used.

5.2. MODEL ADAPTATION: FROM SPECIFIC DIFFERENTIAL EQUATIONS TO CLASSICAL ODE

To take benefits from the capabilities of MATLAB/Simulink solvers, the building thermal model will be encapsulated in a continuous "S-Function". Therefore the model must be adapted to an ODE representation. The system (3) used previously is not a differential equation but a recursive model (already integrated in time). That is why; system (2) will be adopted in order to be implemented in Simulink S-function.

System (2) is not in the form of a classical states system as equation (1); indeed, it is expressed in function of outputs vector derivatives and stresses vector derivatives. It was necessary to process to a variable changing, $Z = X - B^{\beta}.Y$, leading to system (4) (at the end of thepaper).

The new system still not corresponds to standard state system of equation (1). The problem is now posed by $\dot{U}$ term persisting in the calculation of state variables derivatives. This term has been replaced by a finite backward difference which is ntroducing solver instabilities when important variations occur. In our case, between two consecutive steps when the temperature reaches fixed limits, the electrical power switched from 0 to the maximal heater power value (~ kilowatts). At each switching, $\dot{U}$ reaches infinite values perturbing the system solving, which will present many oscillations.

To improve the simulation and to stabilize the solving process, heater model has been refined by thermal constants introduction (Fig. 4). The heater behaves as a second order low pass filter to reduce ascent and decent slopes causing numerical oscillations. The model became so much closer to reality as the electrical power is not converted instantaneously into thermal power. Besides, these constants are negligible compared to the building ones and did not affect remarkably temperature evolution, but are essential for proper simulation.
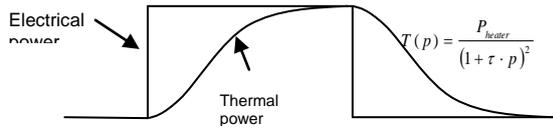So, the heater behavior is independent of the simulation step.

Fig. 4. The heater model

$$T(p) = \frac{P_{heater}}{(1 + \tau \cdot p)^2}$$

Scientists interested in the simulation of buildings electrical equipments are used to simplify thermal models by using equivalent electrical circuits. This can hide difficulties related to the coupling of different domains. It is shown here, that the use of detailed models for building's envelope needs the use of detailed equipments models. So, a better building simulation may require the coupling of models of a certain level of complexity.

5.3. *COMPARATIVE RESULTS*

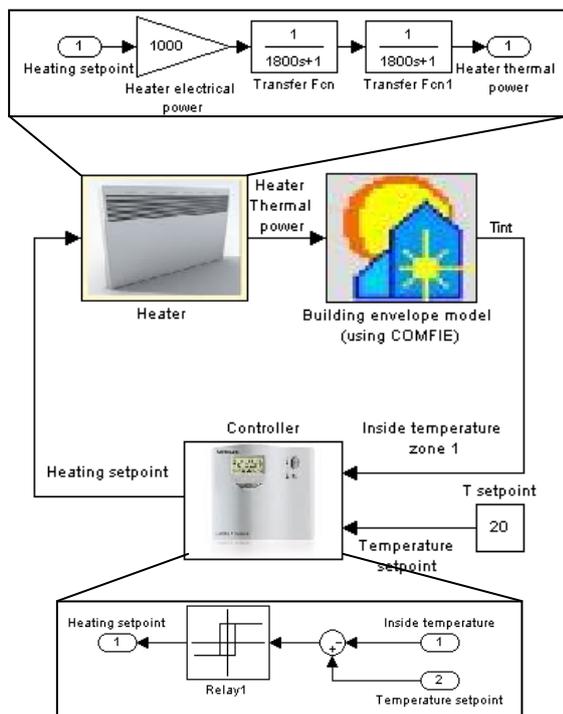The complete Simulink schema is shown in Fig. 5:

Fig. 5. Complete coupling schema in Simulink

To compare fixed and variable time-step simulations performances, a simulation with a fixed time-step of 6 min was performed. Firstly, the transformation was validated by comparison to recursive system (3) results coupled with a simple heater model. Secondly, the transformed system (4) was coupled with the second order heater model. The simulation time of about two weeks is about two seconds, which is quite good for classical studies of 1 year (~1 minute)...

After that, a simulation with a time step that varies between 6 min and 1 h has been performed. This operation improves the simulation time that is reduced to the half. This improvement is not very significant for a short simulation period (two weeks) and for our short system (two areas and one equipment) but becomes more significant for real case study (1 year, with many equipments and areas).

Fig. 6 shows that the solver adopts a time step higher than the minimal step on almost of the simulation and it is reduced when system dynamics changes are detected (when the heater switches).
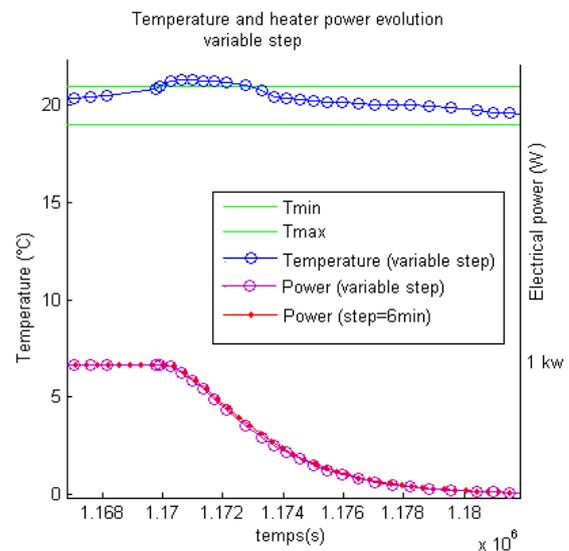

Fig. 6. Variable step time simulation

6. CONCLUSION AND PERSPECTIVES

This work shows the relevance to import models from existing and specialized modeling software like COMFIE in other environments to be coupled with other models. It has been shown the need to introduce thermal constants to electrical to thermal conversion to simulate their influence on temperature variations. This study also highlighted the difficulties associated with hybrid dynamic simulation problems. It is shown, in the one hand, the need to put the model in a standardized form such as explicit differential system, and in the other hand, the management of the time step when it is question of coupling systems with different dynamics or with events. This work will lead to the coupling of more complex electrical and thermal equipments. Other simulation environments will be addressed such as Modelica [9] and standardized coupling architecture using software components will be studied.

Other perspective of this work will consist on validating developed models and comparing simulation results with experimentation.

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$$\begin{cases} X_g^{n+1} = \exp(F_g \cdot \Delta t) \cdot X_g^n + W_g^\alpha \cdot (U_g^{n+1} - U_g^n) + W_g^\beta \cdot (Y_g^{n+1} - Y_g^n) \\ Y_g^{n+1} = MGIF \cdot X_g^n + MGIE \cdot U_g^{n+1} + MGID \cdot U_g^n - MGIC \cdot Y_g^n \end{cases} \quad (3)$$

Wgα, Wgβ , MGIF, MGIE, MGID, MGIC: different matrices resulting from the integration.
Xgn and Ygn: Xg and Yg values at time n.Δt
Xgn+1 and Ygn+1: Xg and Yg values at (n +1).Δt

$$\begin{cases} \dot{Z}_g = F_g \cdot Z_g + B_g^\alpha \cdot \dot{U}_g + F_g \cdot B_g^\beta \cdot Y_g \\ Y_g = (Id - S_g^\beta + H_g \cdot B_g^\beta)^{-1} \cdot (H_g \cdot Z_g + S_g^\alpha \cdot U_g) \end{cases} \quad (4)$$