Incorporating Dynamic Building Load Model into Interconnected Power Systems

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***Abstract*—A driving force behind improving the information embedded power system is the ever growing need to enhance the controllability of electrical demand. The smart grid initiative approaches this problem by enhancing the communication between power system components. Bi-directional communication and increased data acquisition/transmission speeds help to portray system dynamics as was not widely available in the past. With enhanced metering/actuating infrastructures building dynamics can be incorporated into the grid with an appropriate dynamic model. The presented work proposes to utilize a dynamic building load model to integrate a building and/or a group of buildings to the electric grid and thereby evaluate its dynamic performance. The model leverages the electro thermal coupling of the building and thereby also evaluates the demand response capability of the building. This work further enhances the scope of the "smart building" classification by providing a simple tool for a network operator or planner. The model can be used to investigate the dynamic behavior of grid connected buildings under load variations or demand response actions.**

***Index Terms*—Buildings, dynamic response, load modeling**

I. Introduction

Recent advances in technology have greatly influenced the power system structure. The advent of advanced metering infrastructure (AMI) and bi-directional communication therein [1] has shifted more control to the demand side. Dynamic pricing from AMI has increased the scope of demand response resources (DRR). DRRs are increasingly used to mitigate the effects of load growth where insufficient investment in transmission and generation facilities exists [1, 3]. Electric water heaters and air conditioners used to be the primary candidates for demand response control [2]. This has expanded into a class of thermostatically controlled loads (TCL) including buildings, appliances and even to plug-in electric vehicles (PEV) [1]. The PNNL Olympic Peninsula trial during 2006-2007 with grid friendly appliances showed a 15% peak load reduction using smart appliances [1]. PEVs depend on battery technology and further advances in battery lifespan are needed [1].

With increased load diversity, however, comes more complicated power system equilibrium operating conditions [3]. The authors of [3] show how subtle changes in the consumer behavior can have dramatic impacts on load diversity. This in turn reiterates the necessity for effectively capturing the causality of load dynamics. Although dynamic load models have received renewed interest with AMI and demand response (DR) programs, the field of dynamic load modeling is by no means new. Chong and Debbs [4] first introduced power system functional load models in 1979. Their hybrid state model incorporated consumer input on/off states as well as continuous states such as voltage and frequency. Bergen and Hill [5] introduced energy function analysis for power system in the form of structure preserving models (SPM) in 1981. The work in [7, 8, 9] further enhanced the SPM effort with transient stability analysis and nonlinear load modeling and model identification. In 1993 the IEEE task force on load representation for dynamic performance produced [6], a guide for power system engineers in their modeling efforts. The reviewed work is by no means a comprehensive list on load modeling. The mentioned works, however, do form a foundation for the modeling effort pursued by the authors of this paper.

The assigned task for this paper is to present a methodology for building integration into the electric grid. To this end an appropriate building model needs to be introduced. Such a dynamic model was first introduced by the authors in [10]. The circuit equivalent building model in [10] is a measurement based model where the circuit parameters are evaluated in steps similarly to [11]. The authors of [12] also present circuit based building models. However, these do not leverage the electro-thermal coupling inherent in buildings and are not easily integrated into the electric grid. [13] describes the effect of precooling in buildings and associated peak load shifting but offers no grid connection. Building energy simulation software such as DOE-2 [14] sponsored by the department of energy are designed as standalone programs for planning purposes. Such software packages are not easily integrated into electric power system analysis. The building model incorporated in this paper is an improved version of [10]. Further details regarding the model will be discussed in the following section.

II. The Building Load Model

A circuit based building model is easily integrated into power flow studies as shown in Fig. 1. The underlying building model is shown in Fig. 2. The notation $\dot{E}_{B1} \ldots \dot{E}_{BN}$ represents the complex power requirements of N buildings connected to a single load bus through an electrical to mechanical energy

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transformation, E2MT. E2MT is assumed lossless in the scope of the presented work. In the ensuing discussion the equivalent building model capturing the dynamics of all attached buildings will be discussed. To this end the equivalent circuit model, Fig. 2, is used to capture both temperature dynamics, through ψ, as well as equivalent load dynamics through P_S. Equation (1) describes a functional relationship that exists between the equivalent building load and temperature in Fig. 2. Further discussion of this relationship is provided in sub sections A, B, C.

$$P(\psi) = P_n\left(\frac{\psi}{\psi_n}\right)^{\alpha} \tag{1}$$

Equation (2) describes the equivalent building temperature dynamics while (3) and (4) are basic definitions used to clarify (2). These equations are derived from the equivalent building circuit model in Fig. 2.

$$\frac{d\psi}{dt} = \frac{1}{\left(R^{Th}+R_S\right)C^{Th}}\left(-\psi+\psi_S-R_S P_n\left(\frac{\psi}{\psi_n}\right)^{\alpha}\right) \tag{2}$$

$$P_S = \frac{R^{Th}}{\left(R^{Th}+R_S\right)}P_n\left(\frac{\psi}{\psi_n}\right)^{\alpha}+\frac{1}{\left(R^{Th}+R_S\right)}\left(\psi_S-\psi\right) \tag{3}$$

$$\psi_S = \psi + R^{Th}C^{Th}\frac{d\psi}{dt}+P_S R_S \tag{4}$$

ψ – Building envelope temperature (°F)

R^{Th} – Building envelope thermal resistance (°F/kW)

C^{Th} – Building envelope thermal capacitance (kWh/°F)

R_S – Building envelope source resistance (°F/kW)

P_S – Building load (kW)

$P(\psi)$ – Building P-ψ functional relationship

P_n – Building nominal load (kW)

ψ_n – Building nominal temperature (°F)

α – Building P-ψ sensitivity

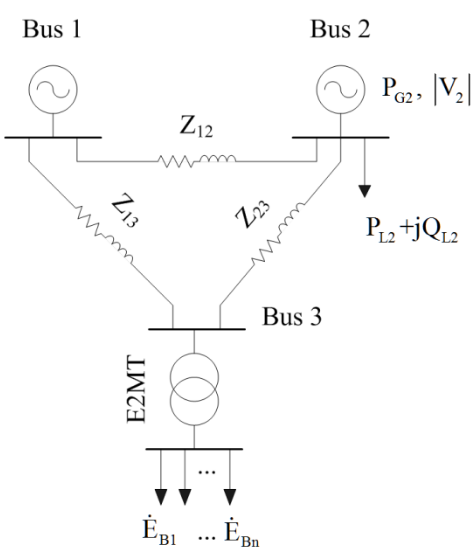

Fig. 1. 3-bus power system with attached buildings

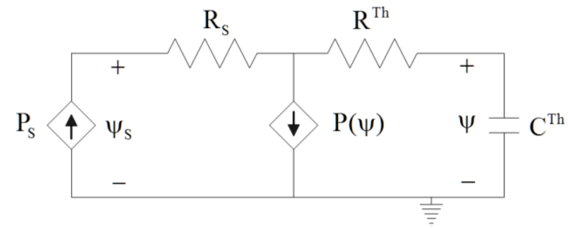

Fig. 2. Circuit equivalent building load model

The flows in the circuit represent energy flux or power, P, and have units of (kW). The potential energy in the circuit is stored as temperature, ψ, and has units of (°F). The building electrical load to be supplied by the utility grid, P_S (3), is modeled as a function of the temperature and the building temperature gradient, $d\psi/dt$.

The circuit parameters R^{Th} and C^{Th} are the equivalent building thermal resistance (°F/kW) and thermal capacitance (kWh/°F) respectively. The estimation of these parameters is done by quantitative analysis on the responses to temperature setpoint changes from the set of buildings similarly to the single building approach described in [10]. The product $R^{Th}C^{Th}$ forms the equivalent building thermal time constant.

$P(\psi)$ is modeled as an exponent load model. The exponent form has been extensively studied for the voltage power relationship in power systems [9], also discussed in [8, 11]. The application in temperature – load dynamics is justified by making crucial observations. When the building is operating at nominal temperature, ψ_n, $P_S=P(\psi)=P_n$. This satisfies the steady state load conditions. The exponent, α, can be adjusted to match the direction of load variation with temperature. More importantly P_n, ψ_n and α provide three degrees of freedom in modeling the equivalent building temperature-load dynamics. These parameters describe the equivalent building operating point and could also be considered functional parameters sensitive to occupancy, weather, human interaction etc. The discussion of the parameters in the following sub sections treats the equivalent building as a single building load.

A. *Nominal building load, P_n*

The nominal building load, P_n, is predominantly a factor describing the energy flux of the building. Larger P_n values correspond to physically larger buildings with greater DR potential. P_n can also be used as a functional parameter for occupancy. A rise in occupancy for example will result in an increase in thermal mass; hence the building draws more power to maintain temperature resulting in a new operating point with a higher P_n. Fig. 3 shows some operating curves for P_n. The designation (α,ψ_n,P_n) is used in Fig. 3,4,5 to indicate the values of the parameters on each plot.

B. *Nominal building temperature, ψ_n*

The nominal building temperature, ψ_n, describes the type of building load. This is usually due to the comfort requirement. A building housing laboratories or data servers for example would have a lower ψ_n than a residential building. ψ_n can be related to humidity as a functional model. Higher humidity will require lower ψ_n to maintain comfort. Fig. 4 shows some operating curves for ψ_n.

C. *P-ψ sensitivity, α*

The parameter α governs the temperature gradient. A negative value for α indicates cooling loads while α>0 indicates heating loads. The magnitude of α describes the sensitivity of the load to temperature. Lower magnitudes of α indicate larger thermal inertia and characterize buildings better suited for DR programs. Fig. 5 presents some operating curves for α in (1).

The operating curves in Fig. 3, 4, 5 offer valuable insight as to how the parameters (α, ψ_n, P_n) should be varied to reach a new operating point. These parameters can be adjusted to reflect occupancy, weather, etc. as they have a major impact on the building load [15]. Operating curves for multi-parameter variation are not presented here but can be interpolated from the presented curves.

III. Incorporate Building Into Grid

Integration of the building model into the electrical grid is done through the use of structure preserving models first introduced by Bergen and Hill [5]. The published work uses differential-algebraic equation (DAE) sets to preserve machine dynamics when connected to the electric network. With DR programs buildings seek to maintain different load levels and act somewhat like distributed generators. This behavior affects the voltage profile of the grid [16] and warrants investigation. The presented work uses DAEs to incorporate building dynamics into the power system equations. The power system state vector is augmented with the equivalent building temperature, ψ. The functional relationship between the temperature and demand of the equivalent building, described by (3) strongly drives the resulting power system dynamics.

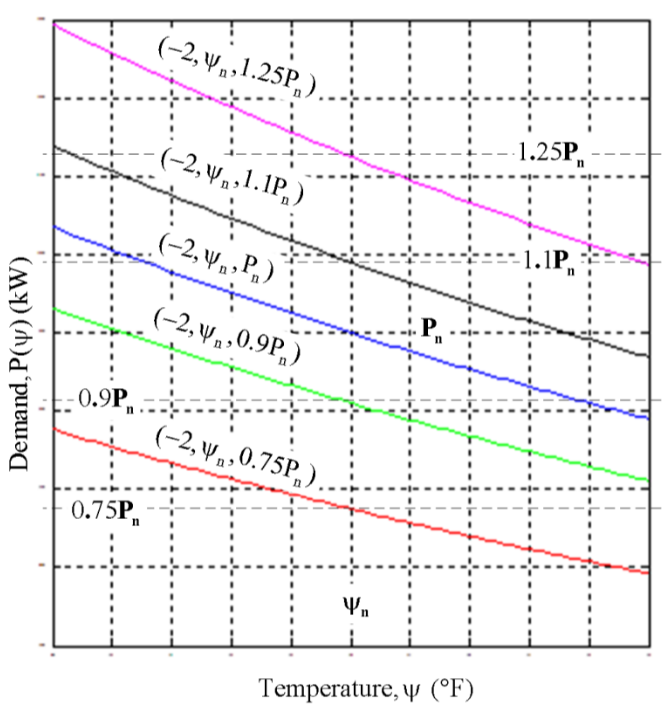

Fig. 3. P_n operating curves for (1)

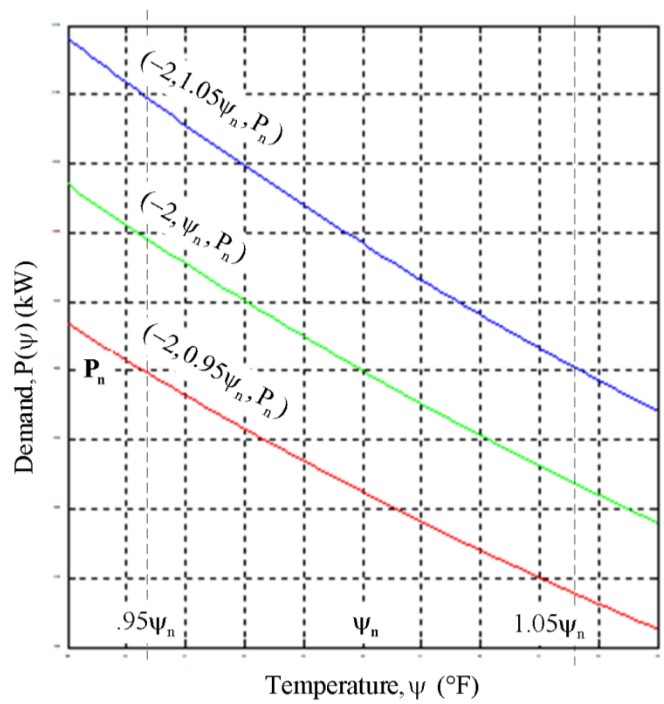

Fig. 4. ψ_n operating curves for (1)

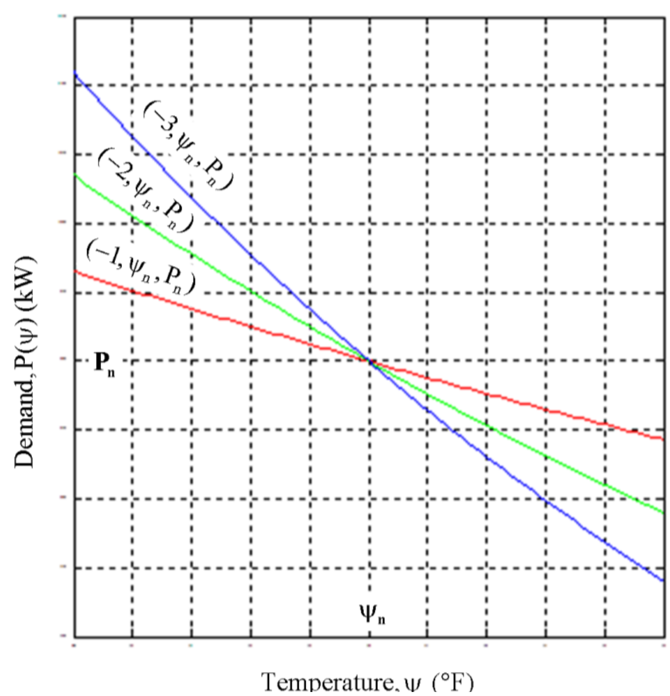

Fig. 5. α operating curves for (1)

Equations (2), (5), (6), (7) describe the DAE system for the building connected electric grid. The equations are derived for the 3-bus power system in Fig.1 with the equivalent building model as shown in Fig. 6. The equivalent building parameters are estimated such that the aggregate characteristics of all connected buildings are captured. The circuit model that describes (2) is shown in Fig. 2. Equations (5), (6), (7) are derived from load flow equations as presented in [17]. The reactive load for the building bus is assumed to be held at a constant power factor with P_S. This is done in (7) by using the

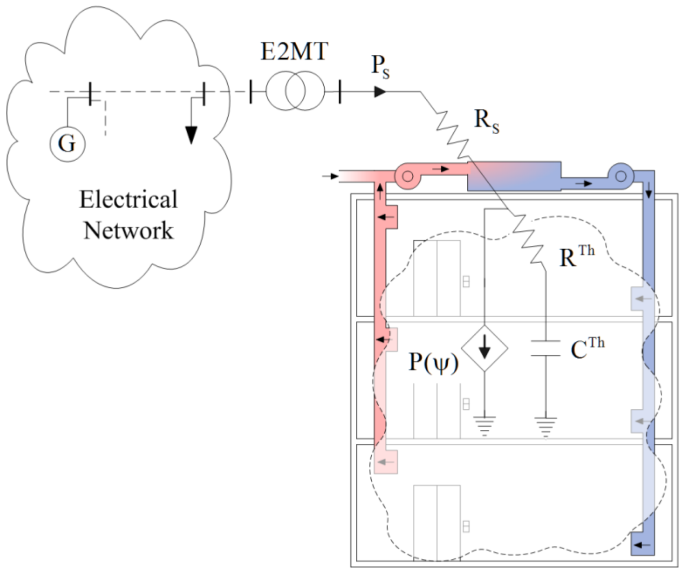

Fig. 6. Equivalent building connection to electric network

constant k_B (8). The authors acknowledge that this assumption must be relaxed in future studies.

$$\frac{d\psi}{dt} = \frac{1}{\left(R^{Th} + R_S\right)C^{Th}}\left(-\psi + \psi_S - R_S P_n \left(\frac{\psi}{\psi_n}\right)^{\alpha}\right) \qquad (2)$$

$$0 = -\left(P_{G2} - P_{L2}\right) + \sum_{k=1}^{N}\left|V_2 V_k Y_{2k}\right|\cos\left(\theta_{2k} + \delta_k - \delta_2\right) \qquad (5)$$

$$0 = -\left(0 - P_S\right) + \sum_{k=1}^{N}\left|V_3 V_k Y_{3k}\right|\cos\left(\theta_{3k} + \delta_k - \delta_3\right) \qquad (6)$$

$$0 = -\left(0 - k_B P_S\right) - \sum_{k=1}^{N}\left|V_3 V_k Y_{3k}\right|\sin\left(\theta_{3k} + \delta_k - \delta_3\right) \qquad (7)$$

Where, $\left|Y_{3k}\right|\angle\theta_{3k}$ is the admittance from bus 3 to bus k and $\left|V_3\right|\angle\delta_3$ is the voltage at bus 3.

$$k_B = \tan\left(\cos^{-1} PF\right) \qquad (8)$$

Capturing the collective dynamics of multiple buildings through an equivalent model reduces the computational effort and complexity of the problem. There are also other advantages such as dispatching a group of buildings for a price based DR program similar to [18]. The work in [18] utilizes building data obtained through [19] for grouping purposes. In a different approach [20] and [21] look at aggregate behavior of appliances and TCL respectively. These papers focus on the thermostatic control of devices to meet an aggregate load profile. The following section examines the performance of the building-grid integration. The building management system (BMS) of each building is assumed to perform component control within the building envelope to maintain comfort using schemes such as presented in [20, 21].

IV. Building-Grid Dynamics

The driving force underlying this modeling effort is the necessity to capture the grid dynamics under demand response actions. In an attempt to evaluate this dynamic performance, the nominal building load was driven from its operating point P_n^0 to a desired value P_n^* through the parameter P_n in (1). A ramp load variation with parameter β was used as in Fig. 7. β accounts for the physical limitations in load shedding in the building. The actual load variations are controlled by the BMS and/or building operator. This method of parameter variation was also performed in [11]. The load variation could also be performed using the parameters ψ_n and α. However, the

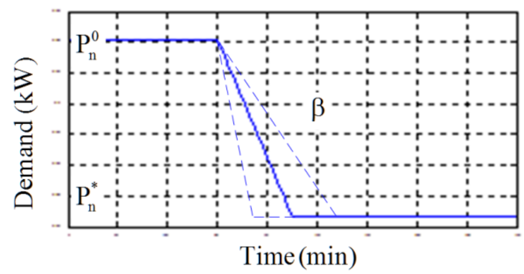

Fig. 7. Reference load shedding

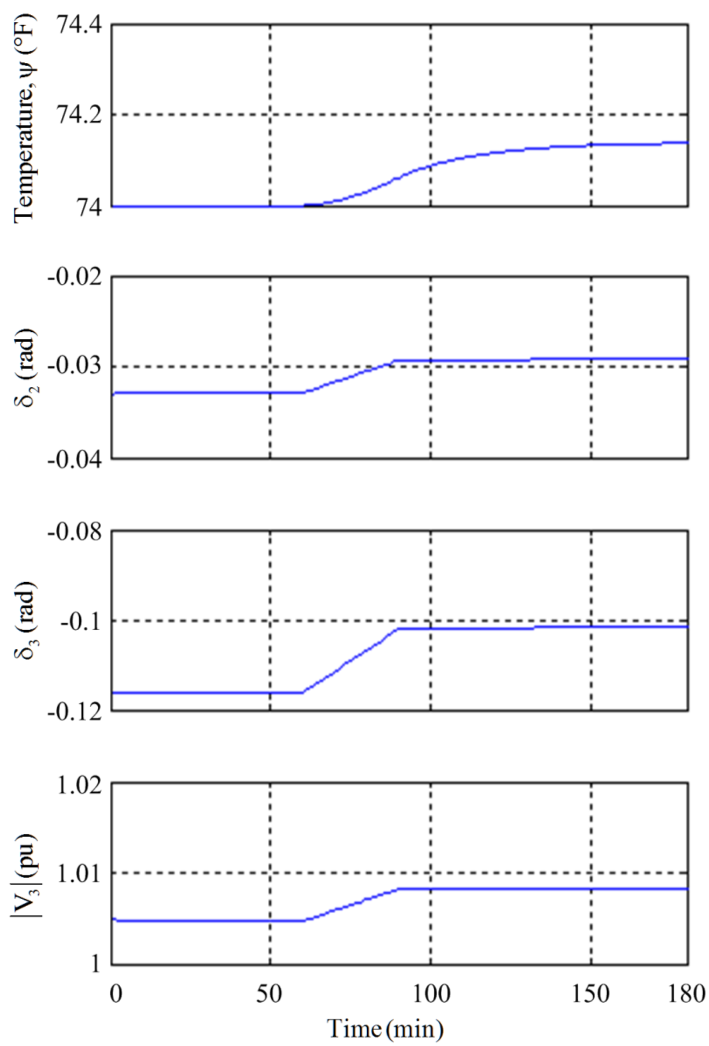

Fig. 8. Power system state dynamics

operating curves Fig. 4 and Fig. 5 should be consulted for the direction and magnitude of the variation. To reduce load using ψ_n control, for example, the new value ψ_n^* needs to be less than ψ_n^0. This is somewhat counter intuitive since higher temperature corresponds to lower demand for a cooling load.

The dynamics of the power system states including temperature due to the load variation are shown in Fig. 8. The error between building load and desired load using P_n control is given in Fig. 9. The error between building load and desired load using ψ_n control is given in Fig. 10. The traditional power system states $\{\delta_2, \delta_3, |V_3|\}$ in Fig. 8 reflect the power system response to a demand response action. The DR action performed is the load reduction in Fig. 9, 10. This relationship between voltage and power is the same result as the traditional power system solution. The novel inference displayed here is the temperature-voltage relationship. The temperature response in Fig. 8 is also a function of the type of load and BMS control performed. The presented results show approximately 10% load reduction with less than 0.2 degree temperature change. The error plots of Fig. 9,10 indicate that even though the building nominal load is forced to a desired point, the actual building load has a delay in responding, which is expected. The magnitude of the error is also related the thermal resistance of supply, R_S. If R_S is much larger than R^{Th} then the error is larger. This indicates that R_S is also an important parameter in formulating the control problem for building load control.

V. Conclusions

Grid integration of a dynamic building load model such as presented here has some major advantages. Evaluation of DR capabilities of a building or group of buildings is one such advantage. With correctly estimated parameters the building model can be used to evaluate how much the building load can vary from its nominal values before violating constraints. This becomes a simple comparison since both temperature and voltage are states of the grid DAE system. Temperature constraints are important since maintaining comfort is a major task for building managers and BMSs. An advantage for the utility side appears in voltage regulation. If, for instance, a system operator were aware of DR actions being taken, they could pre-adjust transformer tap settings accordingly to prevent voltage constraint violations.

The building load and load error curves in Fig. 9 and Fig. 10 indicate that building load control is necessary. However, load control is not examined in this work. What this work has successfully done is integrate a dynamic building load into the power system equations. This effort provides important inferences on the causality of building dynamics on the electric grid. Since DR actions directly influence building dynamics, incorporating building dynamics into the grid is essential.

The logical progression of this work cries out for the inclusion of uncertainty into the model. The authors hope to utilize the plethora of research in this area to improve the presented building model. A key component of the work that needs exploration is the energy transformation E2MT from electrical to mechanical in the building. With a greater understanding of E2MT the dynamic reactive power consumption of the building can be evaluated. This will allow for the constant power factor assumption to be relaxed.

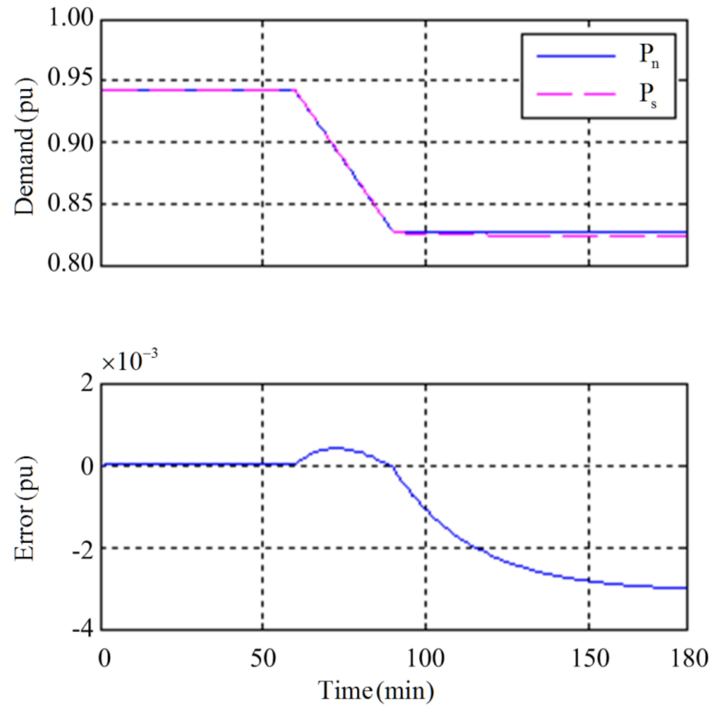

Fig. 9. Error between desired and actual load with P_n control

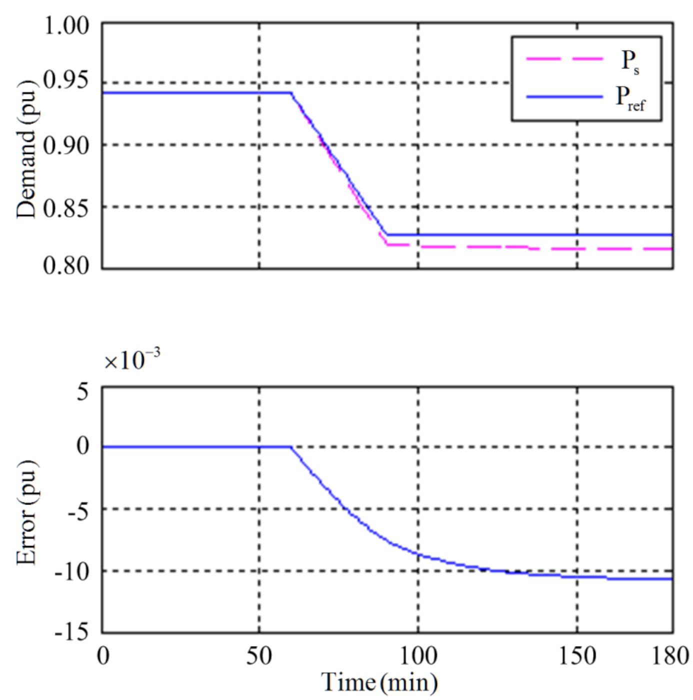

Fig. 10. Error between desired and actual load with ψ_n control

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