Abstract – Demand response of building loads is often considered a building manager operated task on an as-needed basis. With fast developing advances in the communication network of interconnected power systems, buildings have arrived at a crucial point where their autonomous grid connected operation is feasible. In order to effectively participate in demand response programs, building operating limits and effect on the interconnected power system need to be evaluated. This work presents an appropriate building model and evaluates its limits of operation. The goal is to facilitate an improved understanding of grid connected building operation. Building demand response capability will be evaluated under varying ambient conditions and other applicable system parameters. The presented investigation also elucidates conditions under which buildings can be effectively utilized as controllable loads for the electric power system.

Keywords: Buildings, power system modeling, demand response, load modeling

1 INTRODUCTION

Widespread advancement in technology has facilitated the foundation of the information embedded power system. Commonly referred to as the Smart Grid initiative, improvements are chiefly focused around the implementation of an advanced metering infrastructure (AMI). A significant improvement of AMI over its predecessor AMR (automated meter reading) is the embedded bi-directional communication. Consequently, consumer loads have been provided with real-time pricing information that permits them to actively participate in energy markets. Loads can either directly respond to price signals or participate in distributed energy conservation strategies [1]. In the light of these improvements, demand response (DR) programs have received increased interest. DR resources are increasingly used to mitigate the effects of load growth where insufficient investment in transmission and generation facilities exists [1,2]. DR resource operators are also using economic DR as a means to obtain significant cost savings. A recent publication by PJM Interconnection [3] reports that, economic DR for the seven month period from April through October of 2012 generated $8.7 million of revenue from 133,466 MWh.

A significant consequence of increased interest in DR has been a rapid growth of grid connected controllable load resources. Building loads in particular have readily embraced DR programs and made the transformation from being static to controllable loads. This has inadvertently increased the complexity of the power system equilibrium operating conditions. The authors of [2] use the example of on-off cycling electrical heating devices in buildings and show how subtle changes in consumer behavior can have dramatic impacts on system wide load profiles. The underlying outcome of these developments is the necessity of models that are able to effectively describe the behavior of buildings under control actions, which is the primary investigation of this paper.

Traditional models for thermostatically controlled building loads primarily concern electric heating equipment with on/off states [4,5,6,7]. Although these models are discussed in great detail, they overlook the fact that HVAC equipment is not cycled too often for reliability, maintenance and efficiency reasons [8]. They also forgo the electrical power required to maintain air movement and ventilation. Another approach employed in building load modeling is through the quadratic voltage-power approximation presented in ZIP models [9,10]. While the traditional approach for ZIP models does not include thermostatic control, the work in [10] incorporates this into the constant power component. Yet another building load modeling approach is via the use of stand-alone software tools such as DOE-2 [11] sponsored by the Department of Energy. Such software tools are, however, intended for building design purposes and are not easily integrated into electric power system analysis.

The equivalent building model discussed herein has been designed to chiefly address the limitations of the existing models discussed above. Additionally, the presented model is shown to be capable of describing the coupling that exists between building temperature, building bus voltage, and ambient temperature. The main contribution of this work will be the exploration of building operating limits under DR programs given ambient temperature and regulatory schemes such as conservation voltage reduction (CVR). The ensuing discussion emphasizes the necessity for (or advantage in) considering building thermal behavior within the optimization step for regulatory action such as CVR.

The organization of material in the remainder of the paper is as follows. Section 2 will introduce the building model with the above discussed characteristics. The building-grid interconnection where the energy conversion will be accounted for will be presented in Sections 2.1 and 2.2; the remainder of the section will discuss the limiting behavior of building operation. Section 3 will elaborate on the electric grid operation with controllable building loads. Section 4 will present a discussion of results and Section 5 will conclude the paper.
2 BUILDING-GRID INTERCONNECT

An adequate representation of the load bus at which a building connects to the grid is essential for demand response purposes. Any action taken on the building side is reflected to the grid through this junction. Since buildings can have multiple energy loads (electrical, thermal, gas, etc.), multiple energy sources, and energy storage, the concept of energy hubs [12] is employed. Considering the electrical energy input alone, energy hubs allow for multiple types of output connections.

- Direct connections: lighting, equipment loads, etc.
- Conversion: electrical to thermal energy conversion in cooling/ heating coil, electrical to (mass) flow energy conversion in air movers, etc.
- Storage: Thermal energy storage (ice), compressed air systems, etc.

The building-grid energy hub discussed herein will be used to represent the electrical to mechanical to thermal conversion, termed E2MT. The hub will concern only the electrical energy input from the grid to the building and will assume to have no external storage capability. E2MT is graphically described in Figure 1 and mathematically in (1).

\[ P_{B} = P_{\text{elec}} + \eta_{\text{eq}} P_{\text{th}} \]

**Figure 1:** Building-grid energy transfer point E2MT.

- \( P_{\text{elec}} \) – Building uncontrollable electric load
- \( P_{\text{th}} \) – Net controllable thermal building load
- \( \eta_{\text{eq}} \) – Equivalent efficiency of conversion

A significant advantage of E2MT lies in its ability to facilitate additional components such as storage and alternate energy sources, with minimal effort. Additionally the equivalent conversion efficiency could be further decomposed, for m components, as in (2) or even considered to be a thermal load dependent value. Further discussion about the temperature (internal and ambient) and load dependent performance of chillers can be found in [13]. This information is also included in machine specification sheets.

\[ \eta_{\text{eq}} = \frac{P_{\text{th}} + \ldots + P_{\text{th}}}{P_{\text{elec}} - P_{\text{elec}}} = \frac{\eta_{\text{elec}} + \ldots + \eta_{\text{elec}}}{\eta_{\text{elec}} - \eta_{\text{elec}}} \]

It should be noted that the key assumptions that pertain to the energy hub formulation [12] are also upheld here. Some of which are that, all electrical transient dynamics have died out, losses occur only in conversion within the hub, power conversion is characterized through power and efficiency only, and that power flow direction is as indicated. These assumptions outline some limits of the presented analysis. Chiefly, inrush currents due to internal switching processes and thermal characteristics of distributed sources are both ignored.

The two outputs of E2MT will be elaborated upon in the proceeding sections.

2.1 Uncontrollable load portion

The uncontrollable portion of the building load refers to the portion of the overall building load that is independent of temperature variations. These are lighting loads, appliance loads, etc. These loads are approximate to vary with building bus voltage in a quadratic manner, commonly known as the ZIP model [5,9,10]. The parameters in (3,4) can be experimentally obtained as has been done in [9,10]. The ZIP coefficient evaluation has seen new enthusiasm in recent times due to the effect of power electronic devices. As an example, loads such as lighting equipment that used to be characterized as constant impedance are now outfitted with electronic dimmers, ballasts, etc, and consequently display constant power load characteristics [9].

\[ P_{\text{elec}} = P_{0} \left[ Z_{0} \left( \frac{V}{V_{0}} \right)^{2} + \left( \frac{V}{V_{0}} \right) + P_{f} \right] \]

\[ Z_{0} + I_{0} + P_{f} = 1 \]

2.2 Controllable load portion

The controllable portion of the building load is described as that part of the building load which can be thermostatically controlled. This load portion is characterized by the net thermal load, \( p_{th} \), as well as the efficiency of conversion discussed previously. The net thermal load is obtained from the equivalent circuit model shown in Figure 2. Since the analysis presented will focus on steady state conditions, the corresponding circuit in Figure 3 will be used.

**Figure 2:** Dynamic equivalent circuit model for a building connected to the electric grid.

**Figure 3:** Steady state equivalent circuit model for a building connected to the electric grid.
Thermostatically controlled loads (TCLs) of buildings are governed by two main parameters. The temperature setpoint, $\psi_{set}$, which is a control input to the HVAC system and the ambient temperature, $\psi_a$, which can determine how much power is consumed to maintain $\psi_{set}$. The equivalent thermal parameter model presented is a variation on the model presented in [14].

The new model described by (5) is sensitive to variations in both $\psi_{set}$ and $\psi_a$ which was not the primary focus of [14]. The model captures the energy exchange between the building exterior and the conditioned space, in the same fashion as models used by the HVAC community [15]. The model parameters have been obtained through a least squares estimation with measured building performance data similar to the discussion in [16]. A brief description of the parameters in (5) and their purpose follows.

- The conversion (liquid to air) and distribution losses (pipe, duct) are lumped into the thermal resistance $R^th$.
- The space load dynamics are characterized by thermal capacitance $C^th$ and thermal resistance $R_a$.
- The net total thermal load is captured through the flows in the equivalent circuit as indicated in (5b); which are also component loads in (2).

The temperature-load relationship, $P(\psi)$, in (5b) is a functional description of the equipment load discussed in [17]. The thermostatic control of the building is assigned to a control parameter “u”, which is an equivalent setpoint assigned by the building management system (BMS) so as to drive the building internal temperature to the desired value $\psi_{set}$. This exact description of “u” can vary depending on BMS design and can be difficult to ascertain from measured data. Furthermore, the building setpoint can be effectively controlled only within certain operating limits. These limits are discussed next.

### 2.3 Building limiting operation

The illustrations in Figure 4 depict the nonlinear operation of buildings. This is due to the nonlinear relationship that exists between temperature and power (5b) as well as the existence of operational limits of the HVAC equipment. The ambient temperature, $\psi_a$, coupled with equipment limits can force a given building to operate in one of two saturation regions; a $P^{max}$ saturation region or a $P^{min}$ saturation region. Although the present discussion is related to a building cooling load, the extension of the analysis to a building heating load is quite easily achieved.

#### 2.3.1 $P^{max}$ saturation

Figure 4(a) describes the limiting behavior when maximum equipment load, $P^{max}$, is reached due to very hot ambient conditions. At this operating point the building zone can be effectively cooled to a minimum temperature $\psi_{min}$, obtained by solving (6). As this operating point is also a function of the ambient temperature, $\psi_{min}$ is not a fixed value and varies in the same direction as $\psi_a$.

$$\eta_{eq}P_{elec,max} = P_{th,max} = P_{th} \left( \psi_{min} \left/ \psi_a \right. \right)^{\alpha} + \psi_a - \psi_{min} \frac{R_a}{R_{th}}$$  \hspace{1cm} (6)

In the region where $\psi_{min} > L$ (or correspondingly $\psi_{act} < \psi_{min}$), the building temperature is unaffected by $\psi_{act}$ and varies in the same direction as $\psi_a$.

#### 2.3.2 $P^{min}$ saturation

Figure 4(b) describes the limiting behavior when minimum equipment load, $P^{min}$, is reached corresponding to low ambient temperature. As the model is derived for a cooling load, when $\psi_{set} > \psi_a$, the cooling system has no affect and $P^{min}$ is consumed in air circulation and maintaining $\psi_{act} = \psi_a$. The minimum thermal load thus consumed (7) can be found by the substitution of $\psi = \psi_a$ in (5b).

$$\eta_{eq}P_{elec,min} = P_{th,min} = P_{th} \left( \psi_{a} \left/ \psi_a \right. \right)^{\alpha}$$  \hspace{1cm} (7)

In the region where $\psi_{a} < H$ (or correspondingly $\psi_{act} > \psi_{a}$), the building temperature is unaffected by $\psi_{act}$ and varies in the same direction as $\psi_a$.

Since steady state analysis of building loads has to consider these limits, (5) is used to present the building temperature – load equation in a switched form (8), for a building connected to a bus i.

$$F_{\psi,i} = \left\{ \begin{array}{ll}
\left( R_{th} + R_a \right) \psi_i + R_{th} \psi_a + \psi_{set} < \psi_a < \psi_{a} \\
- \left( R_{th, min} + R_{th} \right) \psi_i + \psi_{set} < \psi_{min,i} \\
- \left( R_{th, min} + R_{th} \right) \psi_i + \psi_{set} < \psi_{min,i}
\end{array} \right.$$  \hspace{1cm} (8)
At any given time a building will only satisfy one of the presented inequalities and \( F_{pi,j} = 0 \). This form of the building equation will be used when incorporating the buildings into the interconnected power system, discussed in the following section.

3 BUILDING-GRID OPERATION

There exists another important limit of building operation: the building bus voltage limit. Since buildings participating in DR programs typically shed load and consequently the bus voltage increases, the voltage limit is somewhat overlooked. However, given the preceding discussion, it is apparent that the building load – temperature interaction is quite complicated. Hence, to better understand the bus voltage behavior the complete system needs to be studied.

The power flow equations for the network can be written as (9) in accordance with [18]. \( P_{pi} \) denotes the generation at bus \( i \), \( P_{Di} \) denotes the load at bus \( i \), and \( \psi_{ik} = g_{ik} + j b_{ik} \) is the complex admittance of the network branch between buses \( i \) and \( k \). Bus 1 is assumed to be the slack bus in this formulation.

\[
F_{pi,j} = -P_{pi} + P_{Di} + \left| \sum_{k=1}^{n} Y_{ik} \left( g_{i} \frac{\sin \theta_{k}}{\tan \theta_{k}} + b_{ik} \frac{\cos \theta_{k}}{\tan \theta_{k}} \right) \right|
\]

\[
F_{Qi,j} = -Q_{pi} + Q_{Di} + \left| \sum_{k=1}^{n} Y_{ik} \left( g_{i} \frac{\cos \theta_{k}}{\tan \theta_{k}} - b_{ik} \frac{\sin \theta_{k}}{\tan \theta_{k}} \right) \right|
\]

\[
P_{Di} = p_{i} \left( Z_{pi} \left( \frac{V_{i}}{V_{h,i}} \right)^{2} + I_{pi} \left( \frac{V_{i}}{V_{h,i}} \right) + P_{pi} \right) + \frac{1}{\eta_{i}} \left[ p_{i}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n} + \frac{\psi_{i} - \psi_{s,i}}{R_{a,i}} \right]
\]

\[
Q_{Di} = k_{load,i} P_{di} \left[ Z_{ji} \left( \frac{V_{j}}{V_{h,j}} \right)^{2} + I_{ji} \left( \frac{V_{j}}{V_{h,j}} \right) + P_{ji} \right] + \frac{k_{load,i}}{\eta_{i}} \left[ p_{j}^{b} \left( \frac{\psi_{j}}{\psi_{s,j}} \right)^{n} + \frac{\psi_{j} - \psi_{s,j}}{R_{a,j}} \right]
\]

The active portion of the building load is given in (10) and is constructed from the preceding discussion using (1), (3), and (5b). The reactive portion of the building load is assumed to vary with the active portion according to a constant power factor (PF) assumption (12). Although this assumption is made as a simplification of the model, it is partly due to there being no data collection relating to reactive power consumption of HVAC equipment. Also, from building electrical load data, it can be seen that buildings operate at somewhat constant power factors, where the parameter \( k_{load} \) is defined as (12).

\[
k_{load,i} = \tan^{-1} (\cos^{-1} (PF))
\]

The ZIP coefficients for the reactive portion of the uncontrollable load are also experimentally obtained as in [9,10] and the equations are formulated similarly to (3) and (4). The resulting reactive building load is given in (11). For buses that are not building buses the loads \( P_{Di} \) and \( Q_{Di} \) are as traditionally described.

The power system operating point can now be obtained by solving (13) with state vector (14). The corresponding power system Jacobian is given in (15) with entries as described in (16) - (23). The dimensions of the Jacobian are determined by the total number of buses, \( n \), the number of building buses, \( n_{b} \), and the number of generators in the system \( m \).

\[
F(x) = 0
\]

\[
x = [\psi, \theta, |V|^T]
\]

\[
J = \begin{bmatrix}
\frac{\partial F_{vi}}{\partial \psi}, & \frac{\partial F_{vi}}{\partial \theta}, & \frac{\partial F_{vi}}{\partial |V|} \\
\frac{\partial F_{vi}}{\partial \psi}, & \frac{\partial F_{vi}}{\partial \theta}, & \frac{\partial F_{vi}}{\partial |V|} \\
\frac{\partial F_{vi}}{\partial \psi}, & \frac{\partial F_{vi}}{\partial \theta}, & \frac{\partial F_{vi}}{\partial |V|}
\end{bmatrix}
\]

\[
z = n_{b} + 2n - m - 1
\]

\[
\frac{\partial F_{pi,j}}{\partial \psi_{i}} = \left( -R_{a,i} \right)
\]

\[
\frac{\partial F_{pi,j}}{\partial \psi_{j}} = 1 + \alpha_{i} p_{pi}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n-1}
\]

\[
\frac{\partial F_{pi,j}}{\partial \theta_{i}} = 0, \forall i \neq j \in B
\]

\[
\frac{\partial F_{pi,j}}{\partial \theta_{j}} = \left( -1 - \alpha_{i} p_{pi}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n-1} \right)
\]

\[
\frac{\partial F_{pi,j}}{\partial |V|} = \left[ 2 \sum_{k=1}^{n} Y_{ik} \left( g_{ik} \frac{\cos \theta_{k}}{\tan \theta_{k}} + b_{ik} \frac{\sin \theta_{k}}{\tan \theta_{k}} \right) + \frac{1}{\eta_{i}} \left( p_{i}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n} + \frac{\psi_{i} - \psi_{s,i}}{R_{a,i}} \right) \right]
\]

\[
\frac{\partial F_{pi,j}}{\partial \psi_{i}} = \left[ 2 Z_{pi} \left( \frac{V_{i}}{V_{h,i}} \right)^{2} + I_{pi} \left( \frac{V_{i}}{V_{h,i}} \right) + P_{pi} \right]
\]

\[
\frac{\partial F_{pi,j}}{\partial \psi_{j}} = \left[ 2 Z_{ji} \left( \frac{V_{j}}{V_{h,j}} \right)^{2} + I_{ji} \left( \frac{V_{j}}{V_{h,j}} \right) + P_{ji} \right]
\]

\[
\frac{\partial F_{pi,j}}{\partial \theta_{i}} = \left[ 2 \sum_{k=1}^{n} Y_{ik} \left( g_{ik} \frac{\cos \theta_{k}}{\tan \theta_{k}} + b_{ik} \frac{\sin \theta_{k}}{\tan \theta_{k}} \right) + \frac{1}{\eta_{i}} \left( p_{i}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n} + \frac{\psi_{i} - \psi_{s,i}}{R_{a,i}} \right) \right]
\]

\[
\frac{\partial F_{pi,j}}{\partial \theta_{j}} = \left[ 2 \sum_{k=1}^{n} Y_{ik} \left( g_{ik} \frac{\cos \theta_{k}}{\tan \theta_{k}} + b_{ik} \frac{\sin \theta_{k}}{\tan \theta_{k}} \right) + \frac{1}{\eta_{i}} \left( p_{i}^{b} \left( \frac{\psi_{i}}{\psi_{s,i}} \right)^{n} + \frac{\psi_{i} - \psi_{s,i}}{R_{a,i}} \right) \right]
\]
The relationship between bus voltage and building temperature can now be somewhat brought to light by considering (8), (9), (10) and (11); still more information regarding the load–temperature–voltage sensitivities can be obtained from the Jacobian entries. To further investigate the coupled behavior, a simulation example and results will be presented.

### 4 RESULTS

The analysis performed in this section will be on the example network shown in Figure 5. The network and connected buildings have been modeled to replicate a portion of an existing network from non-intrusively collected operational data. The model parameters pertaining to the buildings are given in Tables 1 and 2. The nominal bus voltage magnitudes, \(|V_i|\), were determined from the power flow solutions with temperature setpoint \(\psi_{set} = \psi_n = 73°F\) and \(\psi_a = 90°F\). The equivalent efficiencies \(\eta_{eq}\) have been set to 80% which is a rather high value. As was discussed earlier, the efficiency is load dependent and can vary greatly with equipment type. The nominal controllable load is given in electrical quantities and can be converted to their corresponding thermal values using the efficiencies, \(\eta_{eq, elec} = \eta_{eq}\). Electrically speaking, the building loads are represented as complex quantities where \(S_{Di} = P_{Di} + j Q_{Di}\) with active and reactive building loads as represented in (10) and (11).

![Diagram of 5-bus distribution network with buildings on buses 2, 4 and 5.](image)

**Figure 5:** 5-bus distribution network with buildings on buses 2, 4 and 5.

<table>
<thead>
<tr>
<th>Bus</th>
<th>(Z_{p,i})</th>
<th>(I_{p,i})</th>
<th>(P_{p,i})</th>
<th>(Z_{q,i})</th>
<th>(I_{q,i})</th>
<th>(P_{q,i})</th>
<th>(V_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.21</td>
<td>-1.61</td>
<td>1.41</td>
<td>4.35</td>
<td>-7.08</td>
<td>3.72</td>
<td>0.983</td>
</tr>
<tr>
<td>4</td>
<td>0.40</td>
<td>-0.41</td>
<td>1.01</td>
<td>4.43</td>
<td>-7.98</td>
<td>4.56</td>
<td>0.975</td>
</tr>
<tr>
<td>5</td>
<td>0.76</td>
<td>-0.52</td>
<td>0.76</td>
<td>6.92</td>
<td>-11.75</td>
<td>5.38</td>
<td>0.982</td>
</tr>
</tbody>
</table>

**Table 2:** Building uncontrollable load parameters

The approximation for the equivalent building setpoint “\(u\)” was obtained from solving for the steady state solution of (5a). Hence, \(u\) was approximated by (24) which varies linearly with the setpoint \(\psi_{set}\).

\[
u_i = \left(\frac{R_{a,i} + R_{s,i}}{R_{s,i}}\right)\psi_{set} - \frac{R_{a,i}}{R_{s,i}}\psi_s\]  

(24)

Three types of analysis were performed and will be discussed. These are i) \(\psi_{set}\) variation holding \(\psi_a\) constant, ii) \(\psi_a\) variation holding \(\psi_{set}\) constant, and iii) substation tap variation.

The results of \(\psi_{set}\) variation are given in Figure 6. The most apparent observation is that the building at bus 5 has the smallest range of temperature control while the building at bus 2 has the largest. This is quite interesting as both buildings have similar nominal loads and equipment ratings. The difference lies in the load–temperature sensitivities \(\alpha_i\) and building insulation quantified through \(R_{a,i}\). The results of \(\psi_a\) variation shown in Figure 7 further accentuate this. Following the temperature trajectory of the building at bus 5 it can be seen that for \(\psi_a = 100°F\) the building cannot maintain a temperature cooler than 78°F which would be towards the upper limit of a comfort region.

![Graphs showing results of temperature setpoint variation (60°F ≤ \(\psi_{set}\) ≤ 95°F) with ambient temperature \(\psi_a = 90°F\).](image)

**Figure 6:** Results of temperature setpoint variation (60°F ≤ \(\psi_{set}\) ≤ 95°F) with ambient temperature \(\psi_a = 90°F\).

Thus the building at bus 5 can not affectively participate in DR without sacrificing occupant comfort on a day that \(\psi_a = 100°F\). Similarly, the other two buildings are able to maintain an internal temperature as low as
74°F on the same day, yielding them the better candidates for DR.

From the results in Figure 6 and the discussion in Section 2, it can be seen that the load-temperature limits occur in pairs \((P_{\text{max}}, \psi_{\text{min}}), (P_{\text{min}}, \psi_{a})\). Table 3 shows an index of the building load variation rates as ambient temperature changes. The index for each building is calculated as in (25) and is a straight line approximation of a building operating within load-temperature limits. The results indicate that a larger amount of load can be shed per temperature variation at lower ambient temperatures. According to these results, building at bus 5 offers the greatest benefit from DR actions, which is contradictory to the conclusion previously reached. These results indicate that the DR potential for buildings should be done by considering the limiting behavior of all concerned buildings. An appropriate optimal scheduling of DR for multiple buildings can thus be obtained.

\[
\Lambda_i = \frac{P_{\text{elec, max}} - P_{\text{elec, min}}}{\psi_{\text{min},i} - \psi_{a}} \quad \text{(kW/°F)}
\]

<table>
<thead>
<tr>
<th>Ambient temperature, (\psi_{a})</th>
<th>(\Lambda_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bus 80 85 90 95 100 105</td>
<td>2 -34.1 -30.6 -27.9 -25.8 -24.2 -22.8 4 -25.8 -21.8 -19.0 -16.9 -15.2 -13.9 5 -62.9 -47.4 -38.1 -32.0 -27.7 -24.6</td>
</tr>
</tbody>
</table>

The presented results also describe the bus voltage behavior as \(\psi_{\text{set}}\) and \(\psi_{a}\) are varied. The limiting behavior of building loads also ensures a corresponding limiting behavior of bus voltages. It can be seen, however, that buildings at buses 4 and 5 affect the voltages at each other. This is as expected since buses 4 and 5 are directly connected. Thus DR actions taken on a building will affect the adjoining building loads. More interesting results are presented in Figures 8 and 9. These are the results of substation transformer tap changes, which simulate the effect CVR. Figure 8 depicts the results when the uncontrollable load portion in (3) is modeled with ZIP coefficients in Table 2 while Figure 9 assumes a constant impedance load \((Z_{p} = Z_{q} = 1)\).

It can be seen that CVR is ineffective for buildings with ZIP loads while marginally effective for buildings with a majority of constant impedance loads. What’s more, under the effects of CVR, even at a tap setting of 0.97, which would yield a substation voltage of 116.4 V for a 120V base, the lowest bus voltage will drop below the low voltage limit of 0.95pu. This also gives a limit of operation for the corresponding building with regard to the entire grid. From Figure 8, the lowest temperature at which the building at bus 4 and all directly connected buildings can operate at when \(\psi_{a} = 85°F\) and \(t = 0.97\) so as to not violate voltage limits is 77°F. The same limit from the results in Figure 9 is 78°F. These results clearly indicate the necessity for coordination between utility driven programs such as CVR and customer driven programs such as DR.
5 CONCLUSION

The grid connected operation of buildings is discussed in this paper. A suitable building model that can effectively describe electrical and thermal behavior of utility driven programs such as CVR. This results point the potential disharmony that can exist if utility driven programs such as CVR and customer driven programs such as DR are not coordinated. Conversely, the results also indicate that, if coordinated, the different programs can alleviate the burden on each other. A possible direction is to incorporate appropriate building load models, such as the one presented, into the optimization step within CVR.

The building specific limits describe the effective operational region for a building under DR. For multiple buildings, it was shown how the limiting behavior of a single building can affect all other adjoining buildings. The results indicated that the process of evaluating the DR potential of buildings is a complicated process and can greatly benefit from identifying the limiting behavior of all buildings concerned.

The network limit for bus voltages outlined the effect that DR can have on networks already under other energy conservation programs such as CVR. These results point to the potential disharmony that can exist if utility driven programs such as CVR and customer driven programs such as DR are not coordinated. Conversely, the results also indicate that, if coordinated, the different programs can alleviate the burden on each other. A possible direction is to incorporate appropriate building load models, such as the one presented, into the optimization step within CVR.

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