Control of Aggregate Air-Conditioning Load using Packetized Energy Concepts

Oluwagbemileke Oyefeso
Gregory Ledva
Johanna L. Mathieu
Ian Hiskens
Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI, USA
{ooyefeso, gsledv, jlmath, hiskens}@umich.edu

Mads Almassalkhi
Electrical and Biomedical Engineering
University of Vermont, Burlington, VT, USA
{malmassa}@uvm.edu

***Abstract*—This paper extends the packetized energy management (PEM) control strategy to enable coordination of compressor-based thermostatically controlled loads (TCLs), such as air conditioners, thus providing a new method to harness the flexibility of this ubiquitous resource. This flexibility can be used to provide a variety of grid services such as frequency regulation. While in traditional PEM, resources request energy packets and turn on if their request is approved, here we modify the PEM scheme by introducing the concept of turn-off requests. We find that this increases flexibility and improves load tracking performance. Through a case study, we evaluate the performance of a population of air conditioners providing frequency regulation under PEM, highlighting both the capabilities and performance limitations. Simulations indicate our controller extensions increase resource availability by at least 150% and improve tracking performance by up to 61%. Specifically, we show that it is possible for a population of about 1000 TCLs to achieve power tracking RMS errors below 1% when providing more than 0.2 MW of frequency regulation.**

***Index Terms*—Air conditioners, Demand dispatch, Frequency regulation, Packetized energy management, Thermostatically controlled loads.**

I. INTRODUCTION

Environmental concerns and the drive to decarbonize the power sector have resulted in traditional generators, such as coal fired power plants, being phased out and replaced with the renewable energy alternatives. Continual growth in renewable generation requires an increase in the amount of balancing services needed to compensate for the inherently intermittent nature of renewable energy generation to maintain the stability and reliability of the power grid [1]. Traditionally, balancing services have been provided by synchronous generators, but new sources of flexibility are needed. Aggregations of distributed energy resources (DERs) such as thermostatically controlled loads (TCLs) can offer such flexibility [2]–[8].

The Michigan team was supported by the U.S. Department of Energy's Advanced Research Project Agency - Energy (ARPA-E), Award DE-AR0001061. M. Almassalkhi was supported by ARPA-E award DE-AR0000694 and is co-founder of startup Packetized Energy, which seeks to bring to market a commercially viable version of Packetized Energy Management.

A TCL of interest is the air conditioner (AC). Houses have thermal energy storage which gives ACs the flexibility to shift its energy consumption in time. Furthermore, ACs are ubiquitous resulting in a large resource potential; almost 90% of US homes utilize air conditioning equipment [9]. The large adoption level and usage of ACs is not only a US phenomenon but a global one [3], [10], [11]. The abundant and distributed geographic location of ACs, make them a prime and valuable candidate for providing flexibility to the grid especially when aggregated. Leveraging these AC resources for grid services requires coordination and control that is non-disruptive to occupants, robust, dynamic, and efficient, whilst satisfying privacy and autonomy concerns. There are AC coordination and control techniques that achieve some of these requirements to varying degrees and with varying capabilities; some are centralized, others decentralized, some are model free, others model based, some are suitable for fast time scale dynamic signals, others can only work on slower time scales. However, the most efficient and practical strategy for controlling and coordinating ACs remains an open research question.

The goal of this paper is to develop a packetized energy management (PEM) approach to effectively control ACs to provide frequency regulation. PEM [12] is a device-focused scheme that has been shown in real-world application to achieve non-disruptive, asynchronous, and anonymous load coordination using electric resistance water heaters for load following, i.e., tracking a reference signal over a period of 4 hours. However, the existing PEM scheme does not explicitly consider the capabilities and constraints of compressor-based TCLs like ACs, heat pumps, and refrigerators. Moreover, resistance-based TCLs (water and space heaters) are gradually being replaced by compressor-based TCLs because they are more efficient. Hence, there is a need to extend the PEM scheme for compressor-based TCLs, as their dynamics differ from resistance-based TCLs.

There has been a significant amount of work on PEM. Ref. [13] developed a macro-model for a homogeneous population of electric water heaters under PEM. Ref. [14] extended the macro-model to a diverse group consisting of electric water heaters and energy storage systems operating under

PEM. Ref. [15] shows a system analysis of the diverse group, providing a discrete-time control law that maximizes requests accepted whilst tracking a regulation signal. Refs. [16], [17] further extends analysis of the macro-model for and control architectures of the PEM scheme with diverse device types (batteries, EVs, and resistance-based water heaters). Finally, [18] develops a decentralized frequency-responsive control scheme for electric water heaters, using local frequency-dependent control policies based on an adaptation of PEM. However, none of this prior work has considered ACs.

In this paper, we develop a non-disruptive control approach to coordinate ACs under PEM. The approach could be used by an aggregator to provide frequency regulation. Our approach accounts for compressor lock-out, i.e., compressors can not be switched on immediately after switch off or switched off immediately after switch on, which has been considered in other load control work, e.g., [19], but not PEM. We also increase the flexibility of the PEM scheme by incorporating turn-off mechanisms, i.e., TCLs not only request to turn on but can also request to turn off.

The main contributions of this paper are the following. First, we adapt the PEM control strategy to compressor-based cooling TCLs and we introduce the idea of a flexible epoch (the duration of time for which the TCL is turned on), which mitigates the negative effect of lock-out on resource availability. Second, we extend the PEM control strategy to incorporate a mechanism for turning off TCLs mid epoch, which increases flexibility and improves tracking performance. Third, we demonstrate PEM for compressor-based TCLs under realistic conditions; showing improvements in the fleet's performance score of up to a factor of 61%.

The remaining parts of this paper are thus structured. Section II describes AC operation, our AC model, and how ACs could used within PEM. Section III details the controller extension. Section IV presents case study results and analysis. Section V concludes and discusses future directions.

II. Air Conditioner Control with PEM

In this section, we first describe typical AC operational dynamics and present the AC model we use. We then describe the PEM scheme and explain how it can be modified to incorporate ACs.

A. AC Overview and Model

ACs usually have their power consumption and ON/OFF state governed by a thermostat, utilizing a temperature dead-band to achieve hysteretic control that regulates temperature around a setpoint T^{set}. The dead-band is the narrow comfort region around the AC's temperature setpoint $[T^{\max}, T^{\min}]$, within which the house temperature is confined. For fixed power ACs, i.e., ACs that consume rated power when cooling and minimal power when not, a dead-band is necessary to prevent the AC from frequently cycling, which leads to wear-and-tear and shortens its lifespan. The AC turns on (cools) when the temperature goes above $T^{\max}$, remains on until the temperature falls and hits $T^{\min}$, and then switches off until the temperature rises again to the upper dead-band. This cycle gives rise to alternating periods of power draw and no power draw. Fixed power ACs are dominant in the US.

We model ACs using the equivalent thermal parameter (ETP) model of [20]–[25] with indoor air temperature T_{a} and inner mass temperature T_{m} dynamics

$$\begin{aligned}\dot{T}_{\text{a}}(t) &= \frac{1}{C_{\text{a}}}(T_{\text{m}}(t)H_{\text{m}} - (U_{\text{a}} + H_{\text{m}})T_{\text{a}}(t) + Q_{\text{a}}(m(t)) \\ &\quad + T_{\text{o}}(t)U_{\text{a}}), \\ \dot{T}_{\text{m}}(t) &= \frac{1}{C_{\text{m}}}\left(H_{\text{m}}(T_{\text{a}}(t) - T_{\text{m}}(t)) + Q_{\text{m}}\right),\end{aligned}$$

where C_{a} is the air thermal mass, H_{m} is the conductance between inner air and solid mass, U_{a} is the conductance of the building envelope, T_{o} is the outdoor air temperature, C_{m} is the building thermal mass, and Q_{m} the heat flux to interior solid mass. Function Q_{a} is the heat flux into the interior mass, which includes the internal and ambient heat gains and cooling from the AC, which in turn is a function of the AC's discrete on/off mode m. These dynamics can be expressed as a linear time-invariant system

$$\dot{x}(t) = Ax(t) + Bu(t),$$

where

$$\begin{aligned}x(t) &= \begin{bmatrix} T_{\text{a}}(t) & T_{\text{m}}(t)\end{bmatrix}^T, \\ u(t) &= \begin{bmatrix} Q_{\text{a}}(m(t)) & T_{\text{o}}(t) & Q_{\text{m}}\end{bmatrix}^T, \\ A &= \begin{bmatrix} -(U_{\text{a}} + H_{\text{m}})/C_{\text{a}} & H_{\text{m}}/C_{\text{a}} \\ H_{\text{m}}/C_{\text{m}} & -H_{\text{m}}/C_{\text{m}}\end{bmatrix}, \\ B &= \begin{bmatrix} 1/C_{\text{a}} & U_{\text{a}}/C_{\text{a}} & 0 \\ 0 & 0 & 1/C_{\text{m}}\end{bmatrix}.\end{aligned}$$

Using a timestep of τ, the above continuous-time state space model can be discretized as

$$x[k+1] = A_d x[k] + B_d u[k],$$

where

$$A_d = e^{A\tau},$$

$$B_d = A^{-1}(A_d - I)B.$$

In discrete time, the switching dynamics are

$$m(k+1) = \begin{cases} 1, & \text{if } m(k) = 0 \ \wedge \ T_{\text{a}}(k) \geq T^{\max} \\ 0, & \text{if } m(k) = 1 \ \wedge \ T_{\text{a}}(k) \leq T^{\min} \\ m(k), & \text{otherwise} \end{cases}.$$

ACs also include compressor lock-out restrictions meaning after an AC has turned on it cannot turn off for a duration of $t^{\text{on}}_{\text{locked}}$ and after it has turned off it cannot turn on for a duration of $t^{\text{off}}_{\text{locked}}$. The lock-out times restrict the compressor from changing states rapidly, protecting the compressor from short cycling, and prolonging the compressor lifespan.

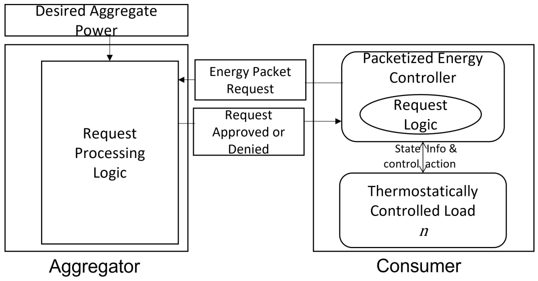

Fig. 1. PEM Scheme for TCLs.

B. Packetized Energy Management Overview

In PEM, TCLs request to turn on for fixed-duration periods to consume a fixed amount of energy. This has the effect of splitting and shifting their consumption in time such that they are on for shorter durations and switched more often. The concept is based on how large data packets are broken and transmitted in smaller packets, in digital communications. The fixed-duration energy consumption is referred to as an *energy packet*. The fixed duration is called the *epoch*, t^{on}. TCLs choose whether to request an energy packet based on their local dynamic states. The load aggregator coordinating these TCLs approves or denies the energy packet requests to achieve some overarching objective, such as using the aggregate power consumption of the TCLs to track a reference signal [12], [16], [17].

Fig. 1 shows the PEM scheme for TCLs. In this diagram, we see that the *Packetized Energy Controller* at the device in the consumer's home contains *Request Logic* that determines when the TCL should request an energy packet. This request logic utilizes local state information from TCLs to decide whether to make an *Energy Packet Request* or not. The aggregator processes the requests along with the *Desired Aggregate Power* of the fleet and uses its *Request Processing Logic* to decide whether to approve or deny each packet request. Since energy requests are initiated by the consumers, the aggregator sees asynchronous requests. The requests are anonymous and arrive stochastically at the Aggregator, which accepts/denies requests based on system needs. This ensures fair resource deployment. The scheme also does not require the exchange of private household data, thus preserving customer privacy.

TCLs participating in PEM make energy requests probabilistically. Specifically, we adopt the approach from [12], where the probability that AC n makes an energy packet request R_n^{on} during the kth time-step (of duration Δt) is computed with the cumulative exponential distribution function

$$P(R_n^{\text{on}}|T_{\text{a},n}[k]) := 1 - e^{-\mu(T_{\text{a},n}[k])\Delta t}, \tag{1}$$

where $T_{\text{a},n}$ is the indoor air temperature of the house conditioned by AC n and $\mu(T_{\text{a},n}[k])$ is a rate parameter based on the indoor air temperature (and defined below). We also take into account the AC's temperature dead-band to force an energy packet request if the house temperature is above the dead-band and ensure there is no request if the temperature is below the dead-band, i.e.,

$$P(R_n^{\text{on}} \mid T_{\text{a},n}[k] \le T_n^{\min}[k]) = 0, \tag{2}$$
$$P(R_n^{\text{on}} \mid T_{\text{a},n}[k] \ge T_n^{\max}[k]) = 1. \tag{3}$$

The rate parameter is defined as

$$\mu(T_{\text{a},n}[k]) = \begin{cases} 0, & \text{if } T_{\text{a},n}[k] \le T_n^{\min}[k] \\ f(T_{\text{a},n}[k]), & \text{if } T_{\text{a},n}[k] \in \left(T_n^{\min}[k], T_n^{\max}[k] \right) \\ \infty, & \text{if } T_{\text{a},n}[k] \ge T_n^{\max}[k] \end{cases} \tag{4}$$

where

$$f(T_{\text{a},n}[k]) = \left(\frac{T_{\text{a},n}[k]-T_n^{\min}[k]}{T_n^{\max}[k]-T_{\text{a},n}[k]}\right) M_{\text{on}} \left(\frac{T_n^{\max}[k]-T_n^{\text{set}}[k]}{T_n^{\text{set}}[k]-T_n^{\min}[k]}\right) \tag{5}$$

and M_{on} is the mean on-request frequency, which is a design parameter. A mean time to on-request of 10 min implies $M_{\text{on}} = \frac{1}{600}$ Hz [12]. To ensure non-disruptive control, the dead-band limits used within (2)–(5) are slightly constricted help prevent violation of the dead-band constraint even if TCLs change states close to the dead-band limits and must remain in the new state for a given duration [12]. The choice of constriction is a design choice based on the thermal dynamics and epoch duration.

C. Air Conditioner as a Packetized Load

The PEM scheme presented in the previous subsection does not address compressor lock-out. We next describe how PEM can be modified to handle compressor-based loads. We equip the controller with a timer t_{comp}, which begins recording time elapsed whenever the compressor is locked, and resets to zero after the lock-out time. Specifically, when the AC turns on, $t_{\text{comp}} \in (0, t_{\text{locked}}^{\text{on}}]$ and resets after $t_{\text{locked}}^{\text{on}}$, and when the AC turns off, $t_{\text{comp}} \in (0, t_{\text{locked}}^{\text{off}}]$ and resets after $t_{\text{locked}}^{\text{off}}$ passes. We refer to the set of timesteps when the AC is off and locked as $\mathcal{K}_{\text{lock}}^{\text{off}}$ and when the AC is on and locked as $\mathcal{K}_{\text{lock}}^{\text{on}}$. Then, (2)–(3) are replaced by

$$P(R_n^{\text{on}}|T_{\text{a},n}[k] \le T_n^{\min}[k] \vee k \in \mathcal{K}_{\text{lock}}^{\text{off}}) = 0, \tag{6}$$
$$P(R_n^{\text{on}}|T_{\text{a},n}[k] \ge T_n^{\max}[k] \vee k \in \mathcal{K}_{\text{lock}}^{\text{on}}) = 1. \tag{7}$$

Note that the epoch must be chosen to be larger than the on lock-out time, $t^{\text{on}} > t_{\text{locked}}^{\text{on}}$.

ACs that are able to make PEM requests (i.e., operating within their dead-band and not locked) are considered available, and so compressor lock-out significantly reduces TCL availability as we will demonstrate through case studies in Section IV-B. This, in turn, impacts control performance, which motivates the controller extensions in the following section.

III. Controller Extensions

In the PEM scheme presented in the previous section, the aggregator has the ability to turn on TCLs (by approving energy packet requests) but can not turn off TCLs should the need arise. This makes it hard to closely track downward trajectories as the aggregator relies on solely rejecting all new

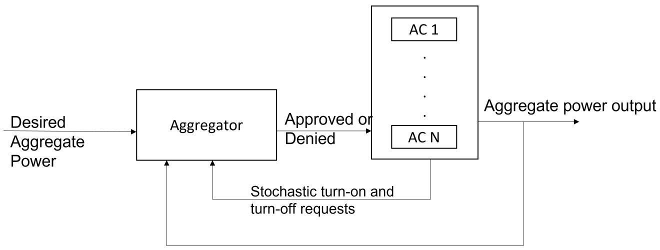

Fig. 2. Extended PEM for closed-loop control of an AC aggregation.

energy packet requests and the decrease in aggregate power consumption as AC epochs expire. This issue is compounded by compressor lock-out, which reduces TCL availability since TCLs are locked and unavailable as soon as they switch off at the end of an epoch. Reduced availability makes it harder to track in general. We will show the impact of these through case studies in Section IV-B.

To address these issues, we introduce a flexible epoch and a turn-off mechanism that increase flexibility and TCL availability. The epoch length t^{on} now becomes a range $[t^{\text{on}}_{\text{min}}, t^{\text{on}}_{\text{max}}]$ where $0 < t^{\text{on}}_{\text{locked}} \leq t^{\text{on}}_{\text{min}} \leq t^{\text{on}}_{\text{max}}$. The controller is equipped with a timer that records the elapsed epoch duration of an energy packet, $t \in (0, t^{\text{on}}_{\text{max}}]$. An AC with a successful energy packet request will turn on for a minimum epoch length of $t^{\text{on}}_{\text{min}}$ and maximum epoch length of $t^{\text{on}}_{\text{max}}$.

The turn-off mechanisms enables turn-off requests R^{off}_n during the epoch period $[t^{\text{on}}_{\text{min}}\ ,\ t^{\text{on}}_{\text{max}}]$. The probability that AC n in the ON state, operating in the PEM scheme, having an elapsed epoch time of $t_n \in (0,\ t^{\text{on}}_{\text{max}}]$, makes a turn off request R^{off}_n during the kth time-step is

$$P\left(R^{\text{off}}_n | T_{\text{a},n}[k] \wedge t_n[k]\right) := \left(1 - e^{-\mu(T_{\text{a},n}[k])\Delta t}\right)\left(1 - e^{-\gamma(t_n[k])\Delta t}\right), \tag{8}$$

where rate parameter $\gamma\left(t_n[k]\right)$ is

$$\gamma(t_n[k]) = \begin{cases} 0, & \text{if } t_n[k] < t^{\text{on}}_{\text{min}} \\ \left(\frac{t_n[k] - t^{\text{on}}_{\text{min}}}{t^{\text{on}}_{\text{max}} - t_n[k]}\right) M_{\text{off}}, & \text{if } t_n[k] \ \in [t^{\text{on}}_{\text{min}},\ t^{\text{on}}_{\text{max}}] \\ \infty, & \text{if } t_n[k] > t^{\text{on}}_{\text{max}} \end{cases} \tag{9}$$

and M_{off} is the mean off-request frequency, a design parameter. Then the turn-off request is constrained as

$$P\left(R^{\text{off}}_n \mid T_{\text{a},n}[k] \leq T^{\text{min}}_n \vee t_n[k] \leq t^{\text{on}}_{\text{min}}\right) = 1, \tag{10}$$
$$P\left(R^{\text{off}}_n \mid T_{\text{a},n}[k] \geq T^{\text{max}}_n \vee t_n[k] \geq t^{\text{on}}_{\text{max}}\right) = 0. \tag{11}$$

The turn-off mechanism follows the distributed nature of the PEM algorithm with request probabilities computed locally.

Fig. 2 shows the closed loop feedback system for a load aggregator with ACs under PEM control. The load aggregator receives tracking signals from the grid operator and must then coordinate the available resources to match this signal. The load aggregator sees a collection of anonymous energy packet requests (henceforth referred to as turn-on requests) and turn-off requests from ACs under its control. When the aggregate power consumption falls short or goes over the tracking signal, the aggregator determines the number of turn-on or turn-off requests to approve to correct the tracking error, and randomly selects ACs to approve.

The fixed epoch design of traditional PEM scheme means devices with approved packet request are considered unavailable as they do not make PEM requests for the epoch duration. The flexible epoch and turn-off mechanism allows these devices to become available beyond the minimum epoch time and start making PEM requests, increasing TCL availability. This in turn improves flexibility and tracking performance as the aggregator sees more requests since there are more available devices making requests. Also, the turn-off requests provide the aggregator with the ability to actively track downward requests. Specifically, in addition to rejecting new on-packet requests and the overall decrease in aggregate power consumption from epochs expiring, the aggregator can now turn off ACs mid packet. The benefits of this new approach are demonstrated through case studies in Section IV-B.

TABLE I
CASE STUDY SCENARIOS

Case	Regulation Capacity	Flexible Epoch and Turn-off Capability	Compressor Lock-Out
0	0.25 MW	No	No
1	0.25 MW	No	Yes
2	0.25 MW	Yes	Yes
3	0.5 MW	No	Yes
4	0.5 MW	Yes	Yes
5	1 MW	No	Yes
6	1 MW	Yes	Yes

TABLE II
SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
Δt	2 s	t^{on}	10 min
$t^{\text{on}}_{\text{locked}}$	3 min	$t^{\text{off}}_{\text{locked}}$	5 min
$t^{\text{on}}_{\text{min}}$	3 min	$t^{\text{on}}_{\text{max}}$	10 min
T^{set}_n	$[20, 24]$°C	$T^{\text{max}}_n - T^{\text{min}}_n$	$[1, 2]$°C
T_{o}	32.22°C	M_{off}	1 s
M_{on}	5 min	Simulation Period	1 h

IV. Case Studies

A. Simulation Scenarios and Parameters

We simulate the response of $N = 1103$ ACs (using parameters generated by GridLAB-D [20] with ±10% random variation around each parameter; each AC consumes 2.5 kW on average) under the PEM scheme controlled to provide frequency regulation. The PJM RegD signal [26] is used as the reference tracking signal. We assess the AC population's tracking performance under a variety of conditions.

Table I defines the seven cases explored in this paper. They include cases with varying amounts of regulation capacity, with and without the controller extensions (i.e., flexible epoch and turn-off capability) described in the last section, and with and without compressor lock out. Table II lists the simulation parameters used. As explained in Section II-B, we constrict the dead-band the PEM controller uses (referred to as the PEM dead-band). Here we use dead-bands of $0.8(T^{\text{max}}_n - T^{\text{min}}_n) \forall n$.

TABLE III
CONTROLLER PERFORMANCE RESULTS ACROSS ALL CASES

Metric	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
NRMSE (%)	5.45	5.59	1.62	15.11	12.5	36.01	35.29
PJM Accuracy Score (0-1)	0.70	0.62	0.88	0.52	0.77	0.43	0.53
PJM Delay Score (0-1)	0.89	0.89	0.91	0.85	0.90	0.84	0.86
PJM Precision Score (0-1)	0.74	0.69	0.94	0.55	0.80	0.39	0.63
PJM Composite Score (0-1)	0.78	0.73	0.91	0.64	0.82	0.55	0.67
Mean Availability (%)	44.17	18.88	74.18	19.03	61.14	18.87	47.68

B. Simulation Results

Table III and Fig. 3 summarize all of the controller performance results across all of the cases. Specifically, in Table III, we show the normalized root mean square error (NRMSE) between the aggregate power and the power reference, normalized by the baseline power consumption of the aggregation. We also show an industry performance metric, i.e. PJM performance scores [27], and the mean availability, which is calculated as the average percentage of available devices over the simulation period. An AC is considered available when it is unlocked and within the PEM temperature deadband, and hence available to participate and make turn-on or turn-off requests in the PEM scheme. The top set of plots in Fig. 3 show the reference tracking signal, the aggregate power of the ACs, and the baseline power consumption. The bottom set of plots show the percentage of available ACs, the ramp-up flexibility, and the ramp-down flexibility. The ramp-up/down flexibility is the fraction of available ACs making turn-on/off requests. It defines the flexibility the aggregator has in increasing/decreasing aggregate power consumption by approving turn-on/off requests.

Fig. 4 shows the fraction of the population that is ON/OFF and what portion of these are available/unavailable for Cases 0–2. Table IV presents these values averaged over the simulation period. By comparing the results of Cases 0 and 1, we can see the impact of compressor lock-out on availability, which in turn affects performance. We see in Case 0 that an average of 55.83% ACs are ON while the remaining 44.17% are OFF and available because lock-out is ignored in Case 0. In Case 1, an average of 54.31% of ACs are ON, but, of the 45.69% that are OFF, only 18.88% are available because of compressor lock-out. Hence, lock-out reduces the mean AC availability by a factor of 134%. This disparity in availability accounts for the noticeable difference in the ramp-up flexibility between both cases (shown in Fig. 3) as there are fewer available ACs making requests. Due to the reduced flexibility, we see from Table III that performance scores decrease by up to a factor of 13% and the NRMSE increases by a factor of 2.5%. This effect becomes more pronounced when regulation capacity increases.

By comparing the results of Cases 1 and 2, we can see how the extended controller mitigates the lock-out effect on availability. From Table IV, we see this results in an improvement of the mean device availability by a factor of 293%, which in turn affects the ramp-up/down flexibility, as seen in Fig. 3. The improved flexibility yields an increase in PJM performance scores by up to a factor of 42% and decrease

TABLE IV
AVERAGE AC AVAILABILITY

	Case 0	Case1	Case2
ACs ON (%)	55.83	54.31	54.18
ACs OFF (%)	44.17	45.69	45.82
ON & Unavailable (%)	55.83	54.31	9.97
ON & Available (%)	0	0	44.21
OFF & Unavailable (%)	0	26.81	15.86
OFF & Available (%)	44.17	18.88	29.96

in NRMSE by a factor of 71%. Fig. 5 zooms in on a 15 min window of the tracking results shown in Fig. 3 for Cases 1 and 2, clearly showing the impact of the controller extension on tracking performance.

Comparing the results of Cases 1 to 2, Cases 3 to 4, and Cases 5 to 6, we see that the controller extensions greatly increase device availability and flexibility. In Fig. 3, we see instances when the standard PEM controller is unable to track an upward trajectory as its limited by the available ACs and ramp-up flexibility, and also unable to actively track downward trajectories without the turn-off mechanism. For example, comparing Cases 3 and 4, we see from Table III that the NRMSE decreases by a factor of 17.3%, mean device availability increases by a factor of 221.3%, and performance scores increase by up to a factor of 48%. Comparing Cases 5 and 6, we see a decrease in NRMSE by a factor of 2%, an increase in mean device availability by a factor of 152.7%, and an increase in performance scores by up to a factor of 61%.

PJM requires composite scores greater than 0.75 [27] and we see that the extended PEM controller qualifies for market participation with 0.25 and 0.5 MW regulation capacity. It falls a little short in the 1 MW scenario (Case 6) because of the limited number of ACs. From Fig. 3 we see the tracking is often hampered by the available ramp-up and ramp-down capacity; there are simply not enough devices.

To improve the performance in the 1 MW frequency regulation capacity case, we adjusted M_{on} (holding all other parameters constant). Fig. 6 shows the new tracking performance, which almost meets the 0.75 requirement. Nevertheless performance is still limited and constrained by the available number of ACs. Hence, it is important to be able to ascertain the number of ACs needed to offer a given regulation capacity or the maximum capacity attainable by a given population of ACs to satisfy a performance objective. Estimating this heuristically via multiple simulations is cumbersome and inefficient due to large parameter space [28], which is why developing

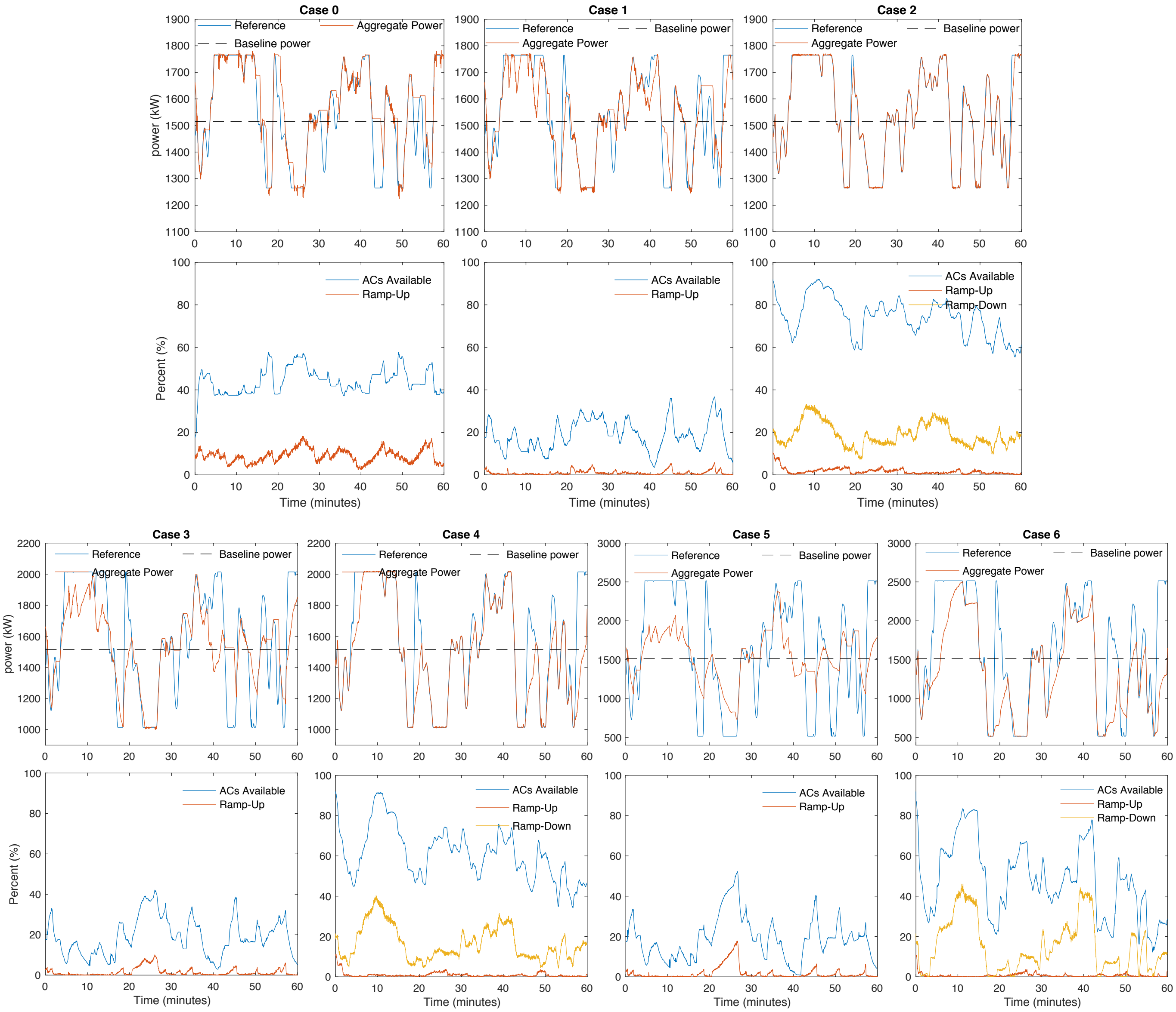

Fig. 3. Reference tracking, resource availability, and flexibility for all cases.

an aggregate model that accurately approximates the dynamics of compressor-based TCLs is a future research direction.

V. Conclusion

In this paper, we extended the PEM approach to incorporate compressor-based TCLs. Specifically, we included compressor lock-out constraints and developed both flexible epochs and a turn-off mechanism. We showed that these extensions improve device availability, flexibility, and controller performance. We find that it is possible to satisfactorily offer up to 1 MW of frequency regulation capacity with around 1000 ACs.

An aggregate model that accurately approximates the dynamics of compressor-based TCLs under PEM is yet to be developed. The existing macro-models described in the introduction do not account for compressor-based loads like ACs under PEM control. Such a model is important to analytically ascertain the flexibility limits of a fleet of compressor-based TCLs under PEM. An aggregate model would also be useful for analytically obtaining steady-state parameter distributions and analyzing dynamic behaviors seen in simulation. Additionally, it would allow us to do sensitivity analysis and compute optimal design parameters such as epoch and mean request frequencies.

In the future, we intend to further enhance the PEM controller with distribution-network awareness. We will also explore controller behavior and performance in the presence of communication latency and drop-outs, and will develop strategies to mitigate issues associated with these real-world challenges. Furthermore, we plan to benchmark and compare PEM against other state-of-the-art control strategies in an effort to understand the trade-offs between the centralized methods and more distributed schemes like model-free PEM.

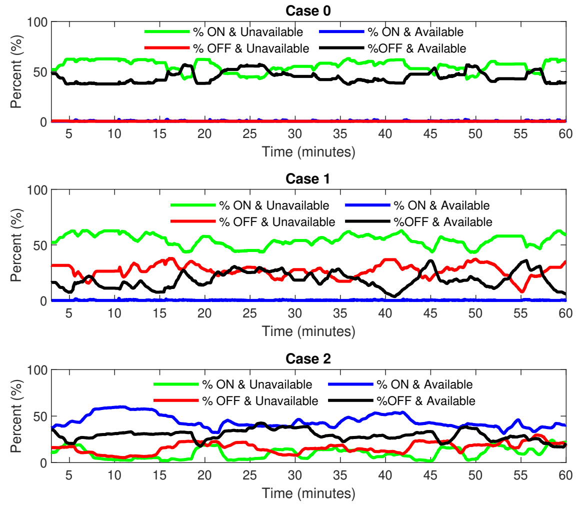

Fig. 4. Effect of lock-out and controller extensions on AC availability.

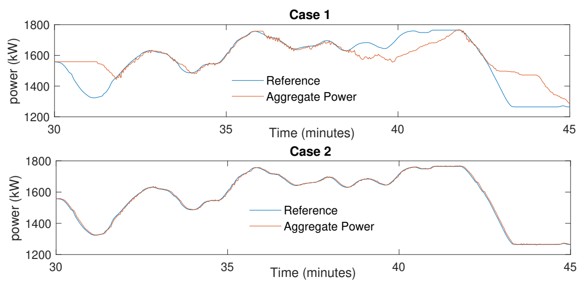

Fig. 5. Close-up of the tracking results for Cases 1 and 2.

Acknowledgment

We thank Duncan Callaway, Phillippe Phanivong, Ioannis Granitsas, Adil Khurram, and the teams at Pecan Street and Packetized Energy for stimulating conversations.

References

[1] J. A. Taylor, S. V. Dhople, and D. S. Callaway, "Power systems without fuel," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1322–1336, 2016.

[2] F. Schweppe, R. Tabors, J. Kirtley, H. Outhred, F. Pickel, and A. Cox, "Homeostatic utility control," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-99, pp. 1151–1163, May 1980.

[3] Y. Ding, Y. Song, H. Hui, and C. Shao, *Integration of Air Conditioning and Heating into Modern Power Systems*. Springer, 2019.

[4] D. S. Callaway, "Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy," *Energy Conversion and Management*, vol. 50, no. 5, pp. 1389–1400, 2009.

[5] D. S. Callaway and I. A. Hiskens, "Achieving controllability of electric loads," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 184–199, 2011.

[6] J. L. Mathieu, S. Koch, and D. S. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 430–440, 2013.

[7] A. Nayyar, J. Taylor, A. Subramanian, K. Poolla, and P. Varaiya, "Aggregate flexibility of a collection of loads," *Proceedings of the IEEE Conference on Decision and Control*, pp. 5600–5607, 2013.

[8] H. Hao, B. M. Sanandaji, K. Poolla, and T. L. Vincent, "Aggregate flexibility of thermostatically controlled loads," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 189–198, 2015.

[9] U.S. Energy Information Administration, "Table CE3.1 Annual household site end-use consumption in the U.S. 2015." https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce3.1.pdf, 2015.

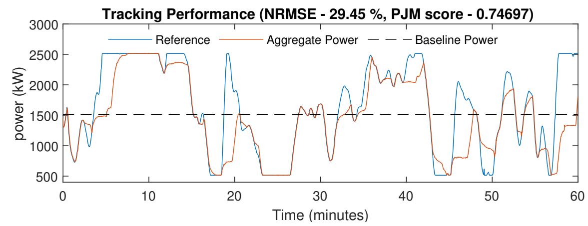

Fig. 6. Extended PEM providing 1 MW frequency regulation, with new M_{on}.

[10] L. W. Davis and P. J. Gertler, "Contribution of air conditioning adoption to future energy use under global warming," *Proceedings of the National Academy of Sciences*, vol. 112, no. 19, pp. 5962–5967, 2015.

[11] M. Izquierdo, A. Moreno-Rodríguez, A. González-Gil, and N. García-Hernando, "Air conditioning in the region of Madrid, Spain: An approach to electricity consumption, economics and CO2 emissions," *Energy*, vol. 36, no. 3, pp. 1630–1639, 2011.

[12] M. Almassalkhi, J. Frolik, and P. Hines, "Packetized energy management: Asynchronous and anonymous coordination of thermostatically controlled loads," *American Control Conference*, pp. 1431–1437, 2017.

[13] M. Almassalkhi, L. Duffaut-Espinosa, P. Hines, J. Frolik, S. Paudyal, and M. Amini, "Asynchronous coordination of distributed energy resources with packetized energy management," in *Energy Markets and Responsive Grids* (J. Stoustrup and S. Meyn, eds.), Springer, 2018.

[14] L. A. Espinosa, M. Almassalkhi, P. Hines, and J. Frolik, "Aggregate modeling and coordination of diverse energy resources under packetized energy management," *IEEE Conference on Decision and Control*, pp. 1394–1400, 2018.

[15] L. A. Espinosa, M. Almassalkhi, P. Hines, and J. Frolik, "System properties of packetized energy management for aggregated diverse resources," *Power Systems Computation Conference*, 2018.

[16] L. A. D. Espinosa and M. Almassalkhi, "A Packetized Energy Management Macromodel With Quality of Service Guarantees for Demand-Side Resources," *IEEE Transactions on Power Systems*, vol. 35, no. 5, pp. 3660–3670, 2020.

[17] L. A. Espinosa, A. Khurram, and M. Almassalkhi, "Reference-Tracking Control Policies for Packetized Coordination of Heterogeneous DER Populations," *IEEE Transactions on Control Systems Technology*, 2020.

[18] H. Mavalizadeh, L. A. Duffaut Espinosa, and M. R. Almassalkhi, "Decentralized frequency control using packet-based energy coordination," *IEEE SmartGridComm*, 2020.

[19] C. Y. Chang, W. Zhang, J. Lian, and K. Kalsi, "Modeling and control of aggregated air conditioning loads under realistic conditions," *Innovative Smart Grid Technologies Conference*, 2013.

[20] "Tech:Residential - GridLAB-D Wiki." http://gridlab-d.shoutwiki.com/wiki/Tech:Residential.

[21] R. Pratt and Z. Taylor, "Development and testing of an equivalent thermal parameter model of commercial buildings from time-series end-use data." Pacific Northwest National Laboratory, 1994.

[22] R. Sonderegger, "Dynamic models of house heating based on equivalent thermal parameters." Princeton University, 1978.

[23] K. Subbarao, "Thermal parameters for single and multizone buildings and their determination from performance data." Solar Energy Research Institute, 1981.

[24] N. Wilson, B. Wagner, and W. Colborne, "Equivalent thermal parameters for an occupied gas-heated house," *ASHRAE Transactions*, vol. 91, p. 2, 1985.

[25] W. Zhang, K. Kalsi, J. Fuller, M. Elizondo, and D. Chassin, "Aggregate model for heterogeneous thermostatically controlled loads with demand response," *IEEE Power and Energy Society General Meeting*, 2012.

[26] PJM Interconnection, "PJM - Ancillary Services." https://pjm.com/markets-and-operations/ancillary-services.

[27] CPowerEnergyManagement, "How the PJM interconnection frequency regulation program works." https://cpowerenergymanagement.com/wp-content/uploads/2019/03/PJM_FR_Snapshot_3-1-2019.pdf, 2019.

[28] A. Khurram, L. Duffaut Espinosa, and M. Almassalkhi, "A Methodology for Quantifying Flexibility in a fleet of Diverse DERs," in *IEEE PES PowerTech*, 2021.