AIR-CONDITIONER GROUP POWER CONTROL
OPTIMIZATION FOR PV INTEGRATED MICRO-GRID
PEAK-SHAVING

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ABSTRACT. Heating, Ventilation, and Air-Condition (HVAC) systems are considered to be one of the essential applications for modern human life comfort. Due to global warming and population growth, the demand for such HVAC applications will continue to increase, especially in arid areas countries like the Arabian Gulf region. HVAC systems' energy consumption is very high and accounts for up to 70% of the total load consumption in some rapidly growing GCC countries such as Qatar. Additionally, the local extremely hot weather conditions usually lead to typical power demand peak issues that require adequate mitigation measures to ensure grid stability. In this paper, a novel control scheme for a combined group of Air-Conditioners is proposed as a peak-shaving strategy to address high power demand issues for Photovoltaic (PV)-integrated micro-grid applications. Using the local daily ambient temperature as input, the AC group control optimization is formulated as a Mixed-Integer Quadratic Programming (MIQP) problem. Under an acceptable range of indoor temperatures, the units in the same AC group are coordinately controlled to generate desired power consumption performance that is capable of shaving load peaks for both power consumption and PV generation. Finally, various simulations are performed that demonstrate the effectiveness of the proposed control strategy.

1. Introduction. Heat, Ventilation, and Air-Condition (HVAC) systems help maintain good indoor air quality through adequate ventilation with filtration and provide thermal comfort. They are mandatory for comfortable and healthy living conditions, particularly in areas with hot climate environments such as the Arabian Gulf region. However, among the largest consumers of grid electricity, HVAC systems are not grid-friendly and usually lack of cost-effectiveness, especially under harsh climatic conditions. Unlike other electricity consumption loads in utility grids, the HVAC systems profile presents a diversity of time-variant characteristics because it changes with building ambient temperature and weather conditions. This variation of power demand is not favorable -or maybe even harmful- for utility grid load-side demand response. This is mainly due to the uncertainty of HVAC power consumption, which
can cause irregular power peaks and fluctuations. To address the irregular peaks caused by HVAC systems, utility providers need to deploy large enough and extra capacity margin of power generation sources, such as reserve power plants, as well as to upgrade existing facilities with additional distribution and protection resources. For smoothing the irregular fluctuations caused by HVAC, the grid needs to employ additional storage capacity. Thus, it is not a cost-effective solution for conventional grid regulators to respond to HVAC load in practical operations.

Additionally, renewable power sources are currently being integrated into utility grids with the advancement of renewable energy technologies. Higher deployment of renewable energy sources such as Photo-Voltaic(PV) and wind means that grid power suppliers also present a diversity of time-variant characteristics. This fact makes the grid’s demand response more complex and very challenging. To address this complexity, effective HVAC load management solutions are highly essential. Fortunately, an HVAC system is a type of large-inertia dynamical system because building slow thermal dynamic characteristics. Accordingly, the temperature control of HVAC is a time-delayed process. The large inertia of thermal dynamics could provide benefit for storage applications. For example, grid voltage and frequency fluctuations can be regulated by effective HVAC control because large-inertia systems (such as flywheels) can absorb ultra-fast changes of grid power fluctuations. Moreover, the indoor temperature range by HVAC control has some flexibility to provide acceptable levels of comfort. For example, indoor temperature can vary from 20 degree$^\circ$C to 25$^\circ$C as a comfortable level. This flexibility can allow the group controlled HVAC cluster to work as a virtual storage system through advanced communication, sensing, and control technologies. With the help of modern ICT technologies, the grouped HVAC systems can generate the required profile under different demand response scenarios. Therefore, it is promising to employ a group of HVAC units for optimal demand response by effective group control strategies, especially under smart micro-grid control applications.

Currently, some research work has been reported for HVAC-based energy efficiency optimization and grid regulation applications. For individual AC control optimizations, most of the studies focus on one or two of the performance metrics to evaluate the performance of their proposed controllers. In [9, 10, 8, 16], energy-saving optimization of individual air-conditioners are studied. In the work presented in [14], the Peak load shifting capability by HVAC control was studied. The transient response improvement studies (decrease in rise time, settling time, and peak time) were presented in [13, 11, 7, 19], and steady-state response improvement (decrease in offset error) were studied in [19, 15]. For studies related to grouped AC control, several research work have recently been reported. [3, 6, 4, 5] have studied model predictive control, and augmented optimal control for buildings to compensate fluctuations in solar power generation. The demand-response-oriented HVAC control solutions are discussed in [17], which include concentrated control, distribution control, and load aggregator-based control. However, only few studies of group AC control were conducted with real case application scenarios under hot climate conditions.

The motivation of this paper is to propose an advanced air-conditioners group power control solution based on high-performance computational intelligence and optimization tool. This can be achieved via the capability of large-scale data processing, daily-based HVAC Group control Optimization under various time-scale levels. In addition, the ACs in one group can be coordinately controlled to generate
the desired power consumption profile, which can eventually shave the power peaks during both load consumption and PV generation.

2. AC thermal model and baseline control strategy.

2.1. House thermal model. To mimic the real-world house/building thermal dynamics, a thermal dynamic model of Air-conditioned room, is built based on physics’ first principle. In this model, the Air-Conditioner is simplified as a unit for transferring heat flow. Thus, the Air-Conditioned room is modeled as a first-order system, which can be represented as follows [12, 1]:

\[
\frac{dT_{\text{indoor}}}{dt} = \frac{\dot{Q}_d - \dot{Q}_e}{C_pm} \\
\dot{Q}_d = \frac{T_{\text{outdoor}} - T_{\text{indoor}}}{R} 
\]

By substituting (2) into (1), the room model can be represented as follows:

\[
\frac{dT_{\text{indoor}}}{dt} = -\frac{1}{C_pmR} T_{\text{indoor}} + \frac{1}{C_pm} \dot{Q}_e + \frac{1}{C_pmR} T_{\text{amb}} 
\]

Where the variables in the above formulations are shown in the table below (Table 1):

| Parameter | Definition                  |
|-----------|------------------------------|
| T_{\text{indoor}} | Indoor temperature of the house |
| T_{\text{outdoor}} | Outdoor temperature of the house |
| Q_d       | Heat flow from outdoor to the house |
| Q_e       | Cooling Energy by AC system |
| R         | Thermal resistance from outdoor to the house |
| m         | Mass of the indoor air |
| C_p       | Heat capacities of the room air |

For controller design, the thermal model of the house can be represented as a state-space model format as follows:

\[
\dot{x}(t) = Ax(t) + Bu(t) + E
\]

\[
y(t) = Cx(t)
\]

where \( x \) represents the state \( T_{\text{indoor}} \), and it is measurable so that \( C = 1 \). \( u \) represents the binary on-off control input \( u = \dot{Q}_e = P_{AC} \), which can be denoted as follows:

\[
u = \begin{cases} 
P_{AC} & t \in T_{\text{on}} \\
0 & t \in T_{\text{off}} 
\end{cases}
\]

The coefficient \( A,B,E \) have the following expressions:

\[
A = -\frac{1}{C_pmR} \\
B = -\frac{1}{C_pm} \\
E = \frac{1}{C_pmR} T_{\text{amb}}
\]
To be noted, the variables in (1) include the state variable $T_{\text{indoor}}$, and the input variable $\dot{Q}_e$. $T_{\text{outdoor}}$ is not constant due to the large variations of the outdoor temperature. So, in this study it is considered to be changing with time.

2.2. **Baseline AC control strategy.** The compressor is the most important component of an AC system. Due to different compressor working principles, air-conditioners in the market can be classified as Inverter Compressor based and On-Off Compressor based air-conditioners. The On-Off type of compressor used to be popular in the past and still dominates in practical home applications, while DC Inverter type of compressor is the latest technology in the market [20, 18, 21, 2]. The On-Off AC operates by being either totally turned ON or totally turned OFF depending on the set-point temperature and the outdoor temperature. Usually there is a dead band of about 1.5 °C to 2.0 °C to prevent too frequent ON-OFF switching of compressor that will reduce its lifespan. In the GCC region, ACs mainly work in cooling mode due to the special desert climatic weather conditions. For example, in cooling mode, the AC compressor will be turned ON when the indoor temperature is higher than the set-point temperature by 2 °C (may vary at different scenarios). It will only go off when the room temperature drops below the set-point temperature. To describe the control philosophy and logic mentioned above, the baseline AC control can be represented as follows:

1) If $T_{\text{indoor}} \geq T_{\text{set}} + \Delta T_c$, AC compressor is switched on;
2) If $T_{\text{indoor}} < T_{\text{set}}$, AC is switched off;

Here, $T_{\text{set}}$ is the set point temperature, and $\Delta T_c$ is the temperature dead band.

For illustrations, an AC On-Off control temperature profile is shown in Figure 1. As shown in this figure, when ON-OFF control enters a stable stage, the temperature oscillates with time between $[T_{\text{set}}, T_{\text{set}} + \Delta T_c]$. In practice, the oscillation frequencies and ranges can vary under different climatic conditions. Thus, this means the On-Off AC control has some flexibility. Also, the temperature profile shows a slow response dynamics. Both of these characteristics bring a great potential for a group of ACs to work as time-shifting storage units.

![Baseline on-off AC control temperature profile](image)

**Figure 1.** Baseline on-off AC control temperature profile

3. **AC group control optimization problem formulation.** An AC within a group of other ACs can be considered as a single unit with individual thermal dynamics and temperature control process. To achieve the role of time-shift applications like a storage system, a number of AC units need to be coordinately controlled...
to participate in achieving the desired power profiles. In addition, the AC unit control need to follow some constraints such as required temperature-control range, and time-correlation. To implement this coordinated control, it is feasible to monitor and control all AC units based on existing industrial control technologies such as telecommunication, sensing and Internet of Things (IoT). For the sake of simplicity, this paper focuses on elaboration of the proposed AC group control optimization methodology.

3.1. **Discretized AC group model.** Due to the fact that On-Off AC control is the dominant method in current AC units, we consider the problem where the Air-Conditioned rooms are controlled within certain bounds of a fixed dead-band by baseline On-Ogg control. Thus, discretized On-Off control is implemented as a sampled-data based controller employing the continuous house thermal model (see equation (4)) discretized with sampling period $\Delta T$, and $t_i = i\Delta T$. For the convenience of state-space model discretization, we denote $x = x - T_{amb}$. Thus, equation (4) can be represented as a standard state-space model as follows:

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

Therefore, it can yield the discrete-time group AC model as follows:

$$\tilde{x}_{k+1,j} = A_j \tilde{x}_{k,j} + B_j u_{k,j}$$

$$j \in [1, N_{AC}], k \in [0, N_T - 1]$$

where the parameters $A_j$ and $B_j$ are expressed by:

$$A_j = e^{A\Delta T}$$

$$B_j = \left( \int_0^T e^{A \sigma} d\sigma \right) B$$

The parameter $N_{AC}$ denotes the AC unit number involved in a group control, $N_T$ denotes the time step number during a control optimization window period. For example, if we consider the time interval as $\Delta T = 2h$, the time-step number $N_T = 24/2 = 12$. The main group control objective is to generate On-Off control signals to make the AC group total power consumption follow the demand of time-shift scenarios without violating indoor temperature comfort constrains. For load-side peak-shaving scenarios, the group control target is to make the total power consumption be constant or follow slow or steep changes by demand. Thus, the control target can be represented as follows:

$$P(k) = \sum_{j=1}^{N_{AC}} u_j(k) \approx \text{cons}$$

For generation-side peak-shaving scenarios, the group control target is to make the total power consumption be almost the same as the power generation. Thus, the control target can be represented as follows:

$$P(k) = \sum_{j=1}^{N_{AC}} u_j(k) \approx P_G(k)$$
3.2. Constraints. Because each AC unit temperature control is a slow thermal dynamics process, both the state and control input have constraints in this group control problem. For indoor temperature state constraint, it holds:

\[ x_{k,j} \in [20^\circ C, 25^\circ C] \]

\[ j \in [1, N_{AC}], k \in [0, N_T - 1] \] (12)

For the discrete On-Off control input, it should be a binary variable, and it holds:

\[ u_{k,j} \in \{0, 1\} \]

\[ j \in [1, N_{AC}], k \in [0, N_T - 1] \] (13)

where \( u_{k,j} \) has only two values. If the AC unit is commanded to be turned ON, the value of \( u_{k,j} \) is \( P_{AC} \). Else if the AC unit is commanded to be turned OFF, the value of \( u_{k,j} \) is 0.

3.3. Cost function. The cost function is a tool to evaluate the target of optimization. The group control target is peak-shaving, which essentially means the minimization of power profile spikes. If we denote the difference between total control signal and constant power signal for each time step \( k \), the cost function for each step can be denoted as follows:

\[ J_u(k) = \left( \sum_{j=1}^{N_{AC}} u_j(k) - P_C(k) \right)^T R \left( \sum_{j=1}^{N_{AC}} u_j(k) - P_C(k) \right) \] (14)

Here \( P_C(k) \) denotes the objective power consumption at the time step \( k \). If it is for load-side peak-shaving, \( P_C(k) \) should be constant or piece-wise linear. However, if it is for generation-side peak-shaving, \( P_C(k) \) should have the following form:

\[ P_C(k) = a \times P_{PV}(k) + b \] (15)

where coefficients \( a \) and \( b \) denote the scaler factor and offset factor respectively.

If we also consider the indoor temperature variations as the performance target, the total cost function can be represented as follows:

\[ J = \sum_{k=1}^{N_T} \left\{ (x(k) - x_{ref})^T Q (x(k) - x_{ref}) + J_u(k) \right\} \] (16)

As can be seen from (14) and (16), the control input values are binary variables in the optimization. Thus, Mixed Integer Quadratic Programming (MIQP) is applicable for this problem. Once the cost function and constraints are defined, it can be solved using advanced optimization solvers.

4. AC group control implementation. To implement the group control, AC units need to be equipped with sensors for power consumption information, indoor temperature, and open Application Programing Interface (API) for remote control interface. More importantly, a remote high-performance control workstation is needed to perform data consolidation and optimization computation. To illustrate this network structure, a diagram of the AC group control ICT hardware infrastructure topology is shown in Figure 2.

As can be seen from Figure 2, an air-conditioned building is additionally equipped with smart meters to monitor the power consumption, and the power metering data is sent to remote control center in real-time. The control center will concentrate all the power metering data, and make decisions on individual On-Off control logic
based on real-time outdoor measurement and optimization solvers such as Gurobi or CPLEX. Conventionally, the optimization is a time-consuming task depending on optimization unit and variable numbers, sparsity of solution space. However, with the aid of the high-performance computation and large data-processing by super-computers, the control center can manage the data processing efficiently with fast response. These advantages can make AC group control become more feasible.

To implement the AC group control in a real-time control response manner, a flowchart for the control program is designed and shown in Figure 3. As can be seen from Figure 3, once the group control is started, one-day ahead outdoor temperature prediction will be calculated. This is considerably feasible based on current weather prediction technologies. Once done, initial individual room temperatures for each AC room are recorded and set in the program. Based on the load peak-shaving regulation criteria, the desired profile is generated. With the constraints, all these settings are sent as inputs to the optimization process, which depends on the solver being used, such as Gurobi/Cplex, to reach the optimal solution. Once the solution is found, the corresponding On-Off Control signals can be generated and sent to individual thermostat units for cooling action. This will be repeated until one day time frame is elapsed.

Remarks: To test the optimized group control under different outdoor profiles and constraint conditions, simulations are necessary and useful for lab demonstrations. To build the simulation environment for AC group control, the open-source UI tool for general optimization problems- Yalmip is recommended to modeling the Air-conditioning thermal dynamics problems and it is compatible with Matlab simulation environment. Also, through Yalmip, Conventional commercial solvers such as Gurobi and Cplex can be integrated into matlab environment, and work together in the uniform programming language by Yalmip.
5. Key results. To demonstrate the proposed AC group control methodology for micro-grid peak-shaving applications, typical ambient weather conditions in Qatar are considered for AC cooling cases. A real-time measurement of one-day outdoor temperature is shown in Fig. 4. As can be seen from Fig. 4, the outdoor temperature profile shows that the outdoor temperature is still very high during daytime and over 30 °C, even in November in the Arabian Gulf region. Also, the temperature variation range is large and it means that the cooling energy needed for AC units will be diverse.

To investigate how communication delay affects the unit AC control performance, a simulation scenario is designed to verify AC unit ON-OFF control with 3 levels of delay time-1-min, 5-min, and 10-min. The On-OFF control power profile is shown in Fig.5 and the temperature profile comparison is shown in Fig.6. From Fig.5 we can see that the control delay has a direct impact on the control power pulse width, this means that the delay will be shorter for shorter control pulse width. Also, the control power pulse becomes wider with the outdoor temperature becomes lower. From Fig.6 we can see that 1-min and 5-min delay has no obvious impact on the control performance, which means the indoor temperature oscillate among the target range between 24 °C and 26 °C. However, the 10-min delay has an impact on the control performance, which means the indoor temperature could
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Figure 4. Outdoor Temperature in One day measured in Qatar

be out of the target temperature range due to control time delay. Also, the control stability still persists because of the feedback mechanism (On-Off control).

Figure 5. On-Off Control Power profile subjected to different time delay

In this paper, both load-side and generation-side peak-shaving scenarios are considered to demonstrate the AC group control methodology. The load side peak
shaving aims to regulate and smoothen the consumption profile by controlling AC units as a group. The generation peak shaving aims to absorb the power generated from PV arrays by managing the power of all AC units, which is constrained by acceptable comfort level of the indoor temperature. Comparing with the load-side peak shaving, PV generation peak-shaving has a direct effect on energy demand-supply balance.

With an acceptable comfort level, the target room indoor temperature range is set to be from \(20^\circ C\) to \(25^\circ C\). A total of 40 AC units are considered as an AC group load, and work together to generate a constant power consumption profile against the variation of local ambient temperature. The thermal parameters of the thermal model is shown in Table 2.

**Table 2. Parameters values of the thermal model and optimization.**

| Parameter | Value 1 | Parameter | Value 2 |
|-----------|---------|-----------|---------|
| \(A\)     | \(-2.00123e-4\) | \(J_{SW}\) | 2       |
| \(B\)     | \(4.4028e-6\) | \(C_p (J/Kg^\circ C)\) | 1005  |
| \(E\)     | \(0.002^4T_{ref}\) | \(m (kg)\) | 222    |
| \(R (^\circ C/W)\) | 0.022 | \(Q\) | 300    |

5.1. **Load demand Peak-Shaving.** In order to simplify the optimization process, the AC On-Off control step interval is set to 2 hours. One day AC group control are performed for the 40 AC units. With the coordinated control by the proposed method, indoor temperature profiles of 40 air-conditioned rooms are shown in Figure 7. from this figure it can be concluded that the room temperature profile presents the same peaks during the noon time with the outdoor temperature. However, the range of the indoor temperature is constrained within the required range.

The On-Off control logics for the considered 40 AC units are shown in Figure 8. To differentiate the profile for each AC units, the individual AC unit profiles were shifted to different y-axis levels, which denote different AC ID labels. From
the control logic profile, we can see the AC units show a diversity of On-Off logic, while it is coordinately controlled by the proposed group control strategy.

**Figure 7.** Indoor temperature profiles of load-side peak shaving (The different curves are for the considered 40 AC units)

**Figure 8.** Individual AC power control logic of load-side peak shaving
The total power consumption of the 40 AC units is shown in Figure 9. By comparing to desired constant power curves, the group control profile is almost identical, and the difference during all the duration of peak-shaving is small. From this result, it can be concluded that the ACs of the considered group are well organized, harmonized and coordinately controlled in the desired manner regardless of the ambient temperature change and the inconsistency of individual AC unit power consumption.

5.2. PV generation peak-shaving. Compared with load peak-shaving, PV generation peak-shaving needs to generate a more time-variant power profile to balance the PV generation and AC consumption. In doing this, the AC group control needs more control units and flexibility to satisfy the diversity of time-variant characteristics. In this section, not only the binary on-off mode are considered for AC unit control mode (Case 1), but also the ternary modes (Case 2) which include ON(2), half ON(1), OFF(0), that are analyzed for better peak-shaving.

5.2.1. Case 1- group AC control for PV peak-shaving with binary on-off modes (0-1). The indoor temperature profiles for PV peak shaving scenario under binary mode are shown in Figure 10. From the profiles of the 40 air-conditioned rooms, we can see that all the indoor temperatures drop within the target indoor temperature range, and the curves present time-variant characteristics similar to the load peak shaving scenario. This similarity is due to the impact by the outdoor temperature profile. Also, it demonstrates that the AC group control can, not only achieve the same comfort level of room temperance, but also absorb the PV power and shave the peaks from PV generation sources.

Figure 11 shows the individual AC unit power control logic for PV peak shaving scenario under binary mode, and Figure 12 shows the power profile comparison for both AC group consumption and PV power generation. By comparing Figure 11 with Figure 8, the individual AC power control logic is similar, while the control logic profile is changing less frequently, which results in less fluctuations that minimizing AC wearing issues. From Figure 12 we can see that the PV power profile is similar.
Figure 10. Indoor temperature profiles under binary Mode

to the AC group consumption profile, which demonstrates that AC group control works efficiently for PV peak shaving.

Figure 11. Individual AC power control logic for PV peak shaving scenario under binary mode
5.2.2. Case 2- group AC control for PV peak-shaving with ternary modes (0-1-2). As some AC products in the market have different working states such as fully ON, fully OFF, partially ON, it is beneficial to control AC units under different working states and not only ON-OFF switching states. For simplification, Ternary Modes (0-1-2) are considered in the AC unit work mode applied in the scenario of PV peak-shaving. Figure 13 shows the indoor temperature profiles for PV peak shaving scenario under the ternary mode. Apart from the binary mode in Figure 10, the profile shows that each AC unit presents a more diverse temperature profile, which means the AC unit has more work states and the group control has more flexibility to accommodate the complex characteristics of PV power generation profiles.

Figure 12. PV side Peak-shaving by AC group control under binary Mode

Figure 13. Indoor temperature profiles under Ternary Mode (0-1-2)
Figure 14 shows the ternary control logic for PV peak shaving scenario under the ternary mode. As can be seen from the profile, the AC working states alternate among ON (2), OFF (0), Half ON(1) based on the criteria of AC group control. Also, the control profile between AC units is not identical and the variations in 2 hours interval are minimal.

Figure 15 shows the comparison of power profiles between AC group total consumption and PV generation. The two curves exhibit a good fitting, which means the PV generation power can be fully absorbed by the 40 AC units under the proposed AC group control strategy. Also, by comparing Figure 15 with Figure 12, the ternary mode has a better fitting than the binary mode because of more control flexibilities.

It is to be noted that AC group control flexibility depends on the diversity of AC work states. With the potential penetration of new variant-frequency Air-Conditioning technologies, the AC working state switching will become a continuous state change for power rather than discrete change like conventional ON-OFF AC. Theoretically, the group control for variant-frequency has better peak-shaving capability than On-Off control. In addition, the proposed AC group control can be applied to regions with similar climate conditions, which has both peaking-shaving demand and existed solar PV farm facilities. For other regions with different climate conditions, because local conditions such as outdoor temperature and solar irradiance are different, load peak-shaving group control can be applied, while the PV
peak-shaving group control may be not applicable if it is not customized. That is mainly due to different PV technologies and cooling/heating demand. However, the AC group control can be applied in a generic manner but with specific constraints and criteria related to weather conditions.

6. Conclusions. An AC Group control scheme for micro-grid peak-shaving is proposed in this paper. The optimization problem for daily based AC load control is studied and addressed as a MIQP problem. Based on the powerful optimization solvers such as Gurobi, a group of AC units can be coordinately controlled to generate the desired power consumption profile with acceptable comfort level regardless of the ambient temperature changes. Finally, simulations under a typical ambient weather condition in Qatar successfully demonstrates the concept and effectiveness of AC load management. Future work will focus on more thermal electric loads such as water heaters, refrigerators and its demonstration for applications under various seasonal desert weather conditions.

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