Single-site and multi-site reference controller designs

ARENA Virtual Power Station 2 Project
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The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.
Summary

This report presents the reference controller designs for the coordination of air conditioner load, solar photovoltaic (PV) generation and battery storage in a virtual power station electric network. The approach is a model-based predictive control (MPC) strategy that optimises the balance between loads and generation to achieve control objectives defined in an optimisation cost function, which may be customised. The present report illustrates the application of the proposed MPC strategy by controlling air conditioners load to follow PV generation assuming a short-term PV generation forecast is available. The proposed MPC strategy manipulates the demand of air conditioners using control commands consistent with the demand response capabilities specified by the AS/NZS 4755 standard. Namely, the MPC commands can control air conditioners to reduce their energy demand to 75% (DRM3), 50% (DRM2), or to switch off their compressor (DRM1). The performance of the proposed MPC strategy is illustrated in balancing fluctuations in aggregate PV generation by controlling the demand of ACs. The proposed MPC strategy may be applied through a single DRM signal channel to control demand of ACs in a single site, or at multiple sites. When more DRM signal channels are available, the proposed MPC strategy can control the population of ACs subdivided in clusters, each of which is associated with one DRM signal channel. Simulation results illustrate substantial improvements in tracking performance achieved for a heterogeneous population of 60 ACs.
1 Introduction

This report presents reference controller designs to manage coordination of distributed controllable loads, rooftop solar PV generation, and battery storage systems connected to a low-voltage electricity distribution network. These controllers may be used to manage the balance of controllable loads and generation and support power quality at either a single site, or at multiple sites with distributed resources connected to the same local network.

1.1 Controllable devices and the AS/NZS 4755 and AS/NZS 4777 Standards

We consider controllable loads that respond to demand response commands compliant with the AS/NZS 4755 Standard and able to respond to demand response commands as specified in the standard. The present report focuses on air conditioners, which are assumed to implement demand response modes DRM1, DRM2 and DRM3 as described in Table 1. Other types of controllable loads compliant with the AS/NZS 4755 Standard, such as pool pumps, electric-boosted storage water heaters, and charge/discharge devices for electric vehicles, could be managed in the similar way with the appropriate models.

Table 1 Demand response modes for air conditioners as specified in AS/NZS 4755.3.1:2014

<table>
<thead>
<tr>
<th>DRM</th>
<th>OPERATION IN THIS MODE</th>
<th>MANDATORY FOR COMPLIANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRM1</td>
<td>Compressor Off</td>
<td>Yes</td>
</tr>
<tr>
<td>DRM2</td>
<td>The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.</td>
<td>No</td>
</tr>
<tr>
<td>DRM3</td>
<td>The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.</td>
<td>No</td>
</tr>
</tbody>
</table>

We further consider solar PV generators that are connected to the grid by means of an inverter compliant with the AS/NZS 4777 Standard [1], as described in Table 2. Inverters connecting batteries are specified in the AS/NZS 4755.3.5:2016 [2], with a similar DRM description as that in Table 2, but with limit rates applied to import/export reference values rather than to rated capacity. For PV inverters only DRM0 is mandatory, while for energy storage systems (ESS) DRM0, DRM1 and DRM5 are mandatory for the systems to be compliant.
### Table 2 Demand response modes for inverters (generators and batteries) as specified in AS/NZS 4777.2

<table>
<thead>
<tr>
<th>DRM</th>
<th>OPERATION IN THIS MODE</th>
<th>MANDATORY FOR COMPLIANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRM0</td>
<td>Operate the disconnection device</td>
<td>Yes</td>
</tr>
<tr>
<td>DRM1</td>
<td>Do not consume power</td>
<td>No</td>
</tr>
<tr>
<td>DRM2</td>
<td>Do not consume at more than 50% of rated power</td>
<td>No</td>
</tr>
<tr>
<td>DRM3</td>
<td>Do not consume at more than 75% of rated power and source reactive power if capable</td>
<td>No</td>
</tr>
<tr>
<td>DRM4</td>
<td>Increase power consumption (subject to constraints from other active DRMs)</td>
<td>No</td>
</tr>
<tr>
<td>DRM5</td>
<td>Do not generate power</td>
<td>No</td>
</tr>
<tr>
<td>DRM6</td>
<td>Do not generate at more than 50% of rated power</td>
<td>No</td>
</tr>
<tr>
<td>DRM7</td>
<td>Do not generate at more than 75% of rated power and sink reactive power if capable</td>
<td>No</td>
</tr>
<tr>
<td>DRM8</td>
<td>Increase power generation (subject to constraints from other active DRMs)</td>
<td>No</td>
</tr>
</tbody>
</table>

#### 1.2 Location of control intelligence and communications support

The proposed reference controller designs may be implemented locally or remotely:

- Locally, whereby the controller intelligence is located at the building site, and uses local measurements of power consumed and generated on site.

- Remotely, whereby the controller intelligence is located at a substation or load control centre managed by the electricity distribution utility or an aggregator. The remote controller implementation requires either:
  - Two-way communication channels with each individual site to gather data and assert control commands, or
  - One-way communication channels to gather measured data of power consumed and generated by multiple sites, aggregated at distribution transformer or substation level, and one-way data communication channels to assert control commands.

For a single site the proposed controllers can be implemented locally or remotely. For multiple sites, the proposed controllers are implemented remotely. Both local and remote controller implementations assume the availability of forecasts of local solar irradiance and temperature as a broadcast data stream (one-way communications).

The pilot demonstration in Yarrabilba currently implements the following communications structure (see Figure 1) with centralised (remote) control of resources from CSIRO:

- One-way single-channel (broadcast) communications to assert DRM commands to all air conditioners via audio frequency load control (AFLC) signals transmitted from Energy Queensland’s Load Control System (LCS)
- One-way multiple-channel communications to gather power data at each household (by EMS – Energy Monitoring Solutions)
- Two-way multiple-channel communications to assert DRM commands and gather power data of PV and battery inverters at each household.
1.3 Supported services

The proposed controllers can coordinate controllable loads, generation and battery storage to locally support the local balance of electricity demand and generation by:

- controlling local loads to minimise power swings in local generation (regulation)
- controlling local loads to reduce peaks in demand (peak control)
- controlling local generation to minimise power and voltage swings (power quality support)

1.4 Control strategy

The proposed controllers adopt a model-based predictive control (MPC) strategy. MPC is an optimisation-based control strategy that has been widely applied in the process control industry since the 1970s, due to its ability to cope with constrained inputs and states [5]. The application of
MPC has since been extended to many other areas, and in recent years has attracted increasing interest in the control of electrical networks [6]–[8]. MPC has great potential to handle complex problems involving large numbers of controllable resources, while explicitly considering system constraints and disturbances to compute optimal control actions in real time.

In recently published work [8], the authors describe the implementation of an MPC strategy to control the demand of a distributed population of air conditioners to compensate rapid fluctuations in PV generation aggregated at a substation or distribution transformer level. The MPC design proposed in the work of [8] controls the aggregate demand of a population of air conditioners by broadcasting small offset changes to the air conditioners thermostat set-points. These offset changes are computed using feedback from aggregate demand measurements. Distributed and centralised MPC implementations are proposed to drive aggregate AC demand to track fluctuations in local PV power generation over sustained periods of time based on short-term solar forecasts. The present report extends the work reported in [8] to an MPC implementation that drives DRM commands as specified in AS/NZS 4755 and AS/NZS 4777.
2 The model-based predictive control strategy

2.1 What is predictive control?

Predictive control is intuitive and used in our daily activities like walking, driving, studying and so on. Think about managing a project. Basically, one has to do a set of things:

- **Predict**: When one sets a target for a “desired” output, one has to plan and work towards the target. It may be too early to consider the final target at beginning of the project. Instead, one should think a few weeks ahead and predict what performance may be achieved over this shorter time window. The target within the shorter time period can be, for example, certain “desired” milestone products.

- **Plan**: Compare the predicted performance with the shorter time target. If a difference is to be expected, for example, lower than the target, then additional efforts should be considered, subject to constraints, such as finance or weather conditions.

- **Act**: If it is expected that the additional efforts likely make one meet the target, then the additional efforts will be put into action. Although a set of the additional efforts, for today, tomorrow, and so on, has been planned days or weeks ahead, only the effort planned for today can actually be materialized today. In the next day, the procedure of prediction and planning is repeated, and a new set of efforts is determined. Thus, the next day’s action will be taken according to the new planning. This process proceeds continuously until the end of the project.

Model predictive control (MPC) includes a class of model-based control schemes that utilize a process model for two central tasks:

1. To generate a prediction of the system future behaviour, and
2. To compute appropriate corrective control actions required to drive the predicted output of the system as close as possible to the desired target values.

MPC strategies are typically used to [5]

- Prevent violations of input and output constraints.
- Drive some output variables to their optimal set-points, while maintaining other outputs within specified ranges.
- Prevent excessive movement of the input variables.
- Control as many process variables as possible when a sensor or actuator is not available.

Playing chess is a well-known analogy for MPC: a good chess player is able to predict the game a few steps ahead based on the potential moves of the opponent, and plans a few sequences of potential response moves. However, only one move is actually applied at each time, following which, and based on the follow-up move of the opponent, a new set of predictions is made, and a new set of future moves is determined as a result. This is called the *receding time-horizon* technique in MPC literature (see Feature Box 1). The procedure is repeated throughout the game.
Initialisation – Predict future trajectories and select the best control action sequence forward based on current knowledge: At time $t$ solve the optimisation problem over an $N$-step prediction horizon. The solution produces the optimal predicted control policy over the future starting at time $t$ to the horizon $t + N$, using the system model and constraints, current measurements available at time $t$ and previous data.

Step 1 – Apply the first control action of the sequence: Apply only the first value of the computed control sequence, $u(t)$, and discard the rest of the sequence.

Step 2 – Re-evaluate predictions and control action sequence forward using new knowledge: At time $t + 1$, shift the horizon one step forward, and solve the optimisation problem over the shifted $N$-step prediction horizon, update by re-computing the control sequence from $t + 1$ to $t + N + 1$. The solution produces the optimal predicted control policy starting at time $t + 1$ over to the shifted horizon $t + N + 1$ using the system model and constraints, current measurements available at time $t + 1$ and previous data.

Next step – Repeat the process from Step 1: Apply only the first computed control value, $u(t + 1)$, discard the rest of the sequence, and so on.
How does MPC works?

GPS navigation is another example of an MPC strategy: a prediction model describes how the vehicle moves on a map. Typical constraints are driving on roads and respecting one-way roads. A disturbance could be a distraction to the driver, or an unmapped detour. The set-point is a desired destination, and the cost function could be, for example, to get there in minimum travel time or with the minimum travelled distance. The receding horizon mechanism in this case is event-based, where optimal route re-planning is performed when the original path is lost.

Analogously, the methodology of all the controllers belonging to the MPC family can be characterised by the following steps [5]:

1. The future outputs for a predetermined horizon N, called the prediction horizon, are predicted at each instant t using the process model. These predicted outputs \( \hat{y}(t + i|t) \) for \( i = 1, \ldots, N \) depend on the known values up to instant t (past inputs and outputs) and on the future control signals \( u_{t+i}, i = 0, 1, \ldots, N - 1 \), which are those to be sent to the process and to be calculated.

2. The set of future control signals is calculated by optimizing a determined criterion in order to keep the process as close as possible to the reference trajectory, subject to constraints. The criterion usually takes the form of a quadratic function of the errors between the predicted output signal and the reference trajectory. The control effort is included in the objective function in most cases. An explicit solution can be obtained if the criterion is quadratic, the model is linear and there are no hard constraints; otherwise an iterative optimization method has to be used.

3. The control signal \( u_t \), i.e., the control action calculated for the current time, is sent to the process whilst the calculated future control actions are discarded because in the next sampling instant \( y_{t+1} \) is already known; step 1 is repeated with the new value and all the sequences are brought up to date. Thus \( u_{t+1} \) is calculated at time instant \( t + 1 \) (which in principle will be different from \( u_{t+1} \) calculated at time instant \( t \) because of the new information available).

2.2 Proposed MPC implementations

The MPC strategy proposed in present report adapts the centralised MPC strategy proposed in [8] to the control air conditioners via DRM commands compliant with the AS/NZS 4755 standard, rather than by offsetting their temperature set-points.

As in [8], the proposed MPC controller utilises a reference signal for aggregate air conditioner load, which may be a feed of short-term forecasts of solar PV generation (in the case of balancing generation by load control), or a reference for maximum demand (in the case of peak demand shaving).

Figure 2 illustrates a general control structure compatible with the Pilot instrumentation map in Figure 1 but showing multiple control channels. The controlled population of ACs may then be subdivided in independent clusters of ACs, the number of which is defined by the number of independent control channels available.
Figure 2 Centralised (remote) MPC control structure with multiple control channels

The case of one common control channel (as in Yarrabilba) applies to either the control of ACs in a single house or the control of ACs in multiple sites sharing a common control channel, as shown in Figure 3.

Figure 3 Control structure for a single site, and multiple-sites sharing a common control channel
3  Simplified air conditioner models for estimation and control

A central piece of MPC strategies is a model of the system to be controlled. This section presents the mathematical models used to formulate the proposed MPC strategy. The first model characterises the electric demand of a single variable-output compressor air conditioner (VOCAC). VOCACs are also known as inverter air conditioners, or variable-speed compressor air conditioners, as opposed to the older single-speed, or on-off type, where the compressor is switched between maximum output and zero using a hysteresis-based thermostat controller. VOCACs allow a finer control of their operating regime, which can make them significantly more efficient than single-speed ACs. Variable-output compressor technology is adopted also in fridges in recent years.

The demand of an air conditioner depends on a number of factors that include the desired temperature set-point specified by the user, their rated cooling or heating capacity, the thermal characteristics of the space to be conditioned (size and thermal insulation), and the ambient temperature and humidity conditions.

Mathematical models describing the dynamic behaviour of ACs facilitate analysis and simulation of one or many devices under normal or abnormal circumstances, such as a power outage or a load control (LC) event.

The AS/NZS 4755.3.1 (2014) Standard [9] specifies demand response capabilities for single phase and three phase vapour compression ACs. The standard describes three demand response modes (DRMs) (see Table 1. Note the only mandatory demand response mode is DRM1 (compressor off). Energy capacity limits are implemented in DRM2 and DRM3 with respect to the energy that would be used by the unit during 30 minutes of normal operation at the same set-points, and temperature and humidity conditions [9].

Note that field tests in Yarrabilba indicate that most air conditioners in the trial appear not to implement DRM2 and DRM3, or implement the 2012 version of the standard, where energy limits are specified as a fraction of the unit rated capacity – and thus if the unit loading is below 50% of its rated capacity, it will not respond to DRM2 or DRM3 commands. See the test report [10] for details.

3.1  On/off versus variable output compressor ACs

Traditionally, ACs had a compressor that could only operate at constant speed and would typically operate switching between on and off modes, driven by a thermostat controller with hysteresis. The compressor is switched off once the conditioned room temperature reaches the lower end of the temperature regulation band, centred around the temperature set-point, and is switched on again once the room temperature reaches the higher end of the regulation band. A well-known model that describes these dynamics is defined by the set of equations [11]
\[
\frac{dT}{dt} = \frac{1}{CR} [T_a(t) - T(t) + R Q_{AC}(t)]
\]

\[
Q_{AC}(t^+) = \begin{cases} 
0 & \text{if } T(t) \leq T_- \\
-\eta P & \text{if } T(t) \geq T_+ \\
Q_{AC}(t) & \text{otherwise},
\end{cases}
\]

where \( T_a \) represents the ambient temperature, the state \( T(t) \) is the regulated room temperature, and \( Q_{AC}(t) \) is the cooling power output of the AC, which switches between 0 and the maximum rated power \( \eta P \) according to the state of a thermostat regulating temperature within the hysteresis band \([T_-, T_+]\). Here, the desired temperature is the centre point of the band, i.e., \( T_d = (T_+ + T_-)/2 \). Other key model parameters are the thermal capacitance \( C \) \((W/°C)\), thermal loss coefficient of the room \( R \) \( (°C/kW) \), the rated electrical power \( P \) \((kW)\) and the cooling coefficient of performance \( \eta \). As it is apparent, this type of AC can easily implement DRM1, but would be limited to implement DRM2 or DRM3 due to potential excessive switching in short periods of time, which would impact the device life.

In recent years, air conditioners with variable speed compressors have become predominant in the market as inverter technology matured. These devices, referred to as variable output compressor air conditioners (VOCACs), are capable of implementing all DRMs in the AS/NZS 4755.3.1 standard without detriment to the unit. By modulating compressor speed via an inverter, the refrigerant flow may be continuously regulated, thus smoothly adjusting the cooling output of a VOCAC to maintain a constant room temperature under varying conditions.

Mathematical models exist to describe the operation of VOCACs (eg Yang, Wu, & Chang, 2014). A Simulink model for a VOCAC implementing DRM as specified by AS/NZS 4755 was developed in [13] based on experimental data collected at the CSIRO National HVAC Performance Testing Facility. The Simulink model developed in [13] was redeveloped as a state-space model suitable for analysis and MPC design in [14]. This model (in cooling mode) may be simplified by reducing room thermal dynamics to the first order equation

\[
\frac{dT}{dt} = \frac{1}{CR} [T_a(t) - T(t) + R Q_{AC}(t)],
\]

where \( Q_{AC} \) is the air conditioner’s cooling power output defined as a saturation function of the reference (desired) cooling power \( Q_d \) as

\[
Q_{AC}(t) = \begin{cases} 
Q_i^+ & \text{if } Q_d \geq Q_i^+ \\
Q_i^- & \text{if } Q_d \leq Q_i^- \\
Q_d(t) & \text{otherwise},
\end{cases}
\]

The upper and lower saturation limits to cooling capacity \( Q_i^+ \) and \( Q_i^- \) are a function of the device operation mode \( i \), where \( i = 1,2,3 \) correspond to operation under demand response modes DRM1, DRM2, and DRM3, and \( i = 4 \) represents unrestricted (normal) operation. The reference (desired) cooling power \( Q_d \) is computed as the output of a PI controller with anti-windup compensation (eg Goodwin, Graebe, & Salgado, 2000) to regulate room temperature to the set-point \( T_d \), defined by

\[
\frac{dl_c(t)}{dt} = -K_i (T_d - T(t)) + K_b (Q_{AC}(t) - Q_d(t))
\]

\[
Q_d(t) = l_c(t) - K_p (T_d - T(t)).
\]
With minor modifications, the above model structure can also be used to represent a VOCAC in heating mode. For a more complete and detailed model description refer to [14].

From the above equations, the output power $P_{AC}$ of a VOCAC during normal operation (no DRM, and not at capacity) may be approximated by the linear time invariant second-order transfer function model

$$P_{AC}(s) = \frac{K_p s + K_i}{\eta (RC s^2 + (K_p R + 1)s + K_i R)} T_d(s) - \frac{K_p R C s^2 + (K_p + K_i R C) s + K_i}{\eta (RC s^2 + (K_p R + 1)s + K_i R)} T_d(s).$$

Assuming a constant temperature set-point $T_d$ and time-varying ambient temperature, the model in Equation (1) reduces to

$$P_{AC}(s) = \frac{K_p s + K_i}{\eta (RC s^2 + (K_p R + 1)s + K_i R)} T_d(s) - \frac{T_d}{\eta R}. $$

The model structure in Equation (2) may be calibrated by estimating its parameters $K_p, K_i, \eta, R, C, T_d$ from measured temperature and demand data using standard system identification techniques, as done in [8].

### 3.2 Aggregate demand model

A key finding drawn from the analysis of the VOCAC model formulated in [14], and expressed in simplified form in the previous section, is that the aggregate demand of an ensemble of VOCACs may be approximated by the model of a single ‘mean-field’ VOCAC. This is in stark contrast with the case of on/off ACs, where the dynamics of a single unit is very different to the aggregate dynamics of an ensemble, which is closely approximated by a linear time invariant second-order transfer function as above (see [16]). This may be observed in Figure 4, which shows in the top plot the response to a step change in temperature set-point of a single on/off AC together with that of the ensemble of on/off ACs.
For VOCACs, on the other hand, simulation results [14] reveal that the response of a single VOCAC is similar to that of an ensemble of VOCACs, as seen in the bottom plot in Figure 4.

The aggregate power response of a population of TCLs to an external event, such as a power outage or a broadcast LC control signal, constitutes a particular phenomenon. For example, when electricity is restored to a population of ACs after an outage on a hot day, a large proportion of the devices turn back on at the same time. This is likely to cause a peak in demand known in the industry as cold load pickup [17], [18]. We can characterise this response to simulate the effect of such external events, and to identify parameters or design algorithms for aggregate LC.

The power demand of a population of ACs can be modelled using two main approaches:

- modelling each device individually, and then computing the aggregated power as the sum of the individual powers; or
- describing the whole population as one system.

The first approach has been used extensively for simulation analyses, and is used here to represent the plant to be controlled (an ensemble of VOCACs). However, for the purpose of control, it may be complicated and time-consuming for large populations. Therefore, a simple model that represent the whole population is of interest.

A simplified model for the aggregate demand response of a population of ACs has the following advantages:
• The aggregate model enables the analysis and prediction of aggregate demand behaviour of a specific class of loads.
  – It aims to characterise the dynamic response of aggregate power demand of populations of TCLs to changes in temperature set points and in ambient temperature.
• The aggregate model keeps a low-complexity aggregate model structure with physically meaningful parameters.
  – A model structure based on both insight into the real system and measured input-output data is postulated.
  – The structure is that of a second-order differential equation, with parameters that are explicit functions of the means, and variances of key thermal parameters of the loads that are distributed in the population.
• The aggregate model enables the application of efficient numerical methods to estimate and validate model parameters.
  – It can be numerically fit and validated to specific populations based on measured demand data using maximum likelihood estimation methods.
• The aggregate model can be used to manage loads using state-of-the-art prediction and control techniques.
  – It can precisely quantify potential impacts to end users, and energy savings and available resources for demand-side grid services.
  – It can systematically design and deploy feedback controllers for peak-shaving, load following, arbitrage, solar capacity firming, power quality support and so on.

The authors developed such a low-order model for the aggregate demand response of a population of on/off ACs, which is well-suited to parameter calibration and control [1].

The proposed MPC design uses a single VOCAC model as described in Section 2 to also represent a population of VOCACs. The parameters of this heuristic ‘mean-field’ model may be calibrated using observed aggregate demand of such population, as described in the following section.

### 3.3 Model calibration (parameter identification)

As argued in the previous section, Equation (2) may be used as a heuristic ‘mean-field’ model structure for the aggregate demand response of an ensemble of VOCACs to time-varying ambient temperature under normal operation. The parameters of this model may be calibrated to represent the aggregate demand response of a specific ensemble under consideration from historical records of temperature and electricity consumption. The model uses the following (assumed time-invariant) parameters:

- **Thermal loss coefficient** $R$ (should not be confused with $R$-value) is a lumped parameter that represents building drop in temperature per unit of heat flow due to thermal losses, and relates to how well thermally insulated is the air-conditioned space.
- **Thermal capacity** $C$ also known as thermal mass, is an indicator of the ability of a material to store heat per unit volume. The greater the thermal capacity of a material, the more heat it can store in a given volume per degree of temperature increase.
– Higher thermal capacity can (but will not always) reduce heat flow from the outside to the inside environment by storing the heat within the material. For example, heat entering a wall during the daytime can be stored within the wall for several hours until it flows back out to the cool night air. This parameter is mainly affected by the dwelling size.

• **Thermal power** (in cooling mode) is the amount of heat removed from the building by consuming electrical energy. It is obtained by multiplying AC electrical power and the coefficient of performance.

• **Temperature set-points** $T_d$. Each AC potentially has a different temperature set point to maintain. Our model uses the mean of all of these set points in the population.

• **PI controller gains** $K_i, K_p$, specify the rate of the response towards the desired cooling power due to the changes in ambient temperature and/or desired temperature set-point.

Note the output of the model is the aggregate power demand of ACs only. We calibrate the parameters under normal operation of VOCACs, no DRM, and only due to the changes in ambient temperature. The simplified second-order model in Section 3.1 along with temperature and aggregate demand data of several days, lead to the estimated values given in Table 3.

**Table 3 calibrated parameters of a VOCAC model**

<table>
<thead>
<tr>
<th>$R$ (°C/kW)</th>
<th>$C$ (kWh/°C)</th>
<th>$K_i$</th>
<th>$K_p$</th>
<th>$K_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.29 \cdot 10^{-3}$</td>
<td>1</td>
<td>$6.6 \cdot 10^{-5}$</td>
<td>1.14</td>
<td>$5.79 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

The VOCAC model with calibrated according to Table 3 now represents a population of VOCACs, and hence, can be used in the MPC design.
4 Single-site coordination strategies

This section presents simulation results illustrating the performance of the proposed MPC controller when there is a single control channel to send DRM commands to either all ACs in a single site. This strategy also applies to control ACs over multiple sites sharing a common control signal (broadcast).

MPC controller design [8], [19] encompasses:

1. A state observer that estimates the states of the mean field model representing the aggregation of ACs in the site/cluster, using available measurements of demand. A linear quadratic observer is used
2. A prediction model for the aggregate AC demand in the site/cluster
3. Calibration parameters for the prediction model, taken from the identified set in Table 3
4. A cost function for the receding horizon optimisation. As in [19], the main objective considered here is the balance of fluctuations in PV generation by controlling AC demand. Thus, the optimisation is formulated to minimise a cost function takes the form

\[
J = \sum_{\tau=0}^{N-1} (z_{k+\tau} - \hat{y}_{k+\tau|k})^2
\]

where \(z_k\) represents the sequence of reference signals for the aggregate demand (e.g., a forecast of PV generation) and \(\hat{y}_{k+\tau|k}\) represents the predicted aggregate demand at time \(\tau + k\) computed based on information available at time \(k\).

5. Constraints: the control signals are limited to take values in the set \{1,2,3,4\} corresponding to DRM1, DRM2, DRM3 \{1,2,3\}, and normal operation (no DRM is asserted), represented by \{4\}.

Figure 5 shows the results of a simulation implementing the MPC using a single channel to optimise the tracking performance of the aggregate demand response of a population of 60 VOCACs to follow fluctuations in PV generation due to clouds, which is assumed to be forecast 1 minute ahead. The bottom plot in Figure 5 shows the sequence of DRM signals generated by MPC, which fluctuate between DRM2 (control signal 2), DRM3 (control signal 3) and normal operation (control signal 4).

As it can be seen from the top plot of Figure 5, the fact that there is a single control channel imposes a limitation to follow the reference PV signal, especially when there is a significant drop in generation. This limitation is simply due to the coarse nature of the DRM control signals, where only 50% or 25% reductions are admissible. For example, in the time between 2700 and 3500 seconds, the MPC asserts DRM2, but the demand produced it is still well above the desired reference PV. Note DRM2 is the closest lowest possible value in this case, since DRM1 would turn off all the ACs and the demand will then drop to zero, which would worsen the tracking error.

This limitation may be circumvented by adding additional control channels and dividing the population into several clusters, each of which associated with a DRM input channel. Such
arrangement may be exploited to increase controllability of the aggregate VOCAC demand. For example, if two clusters with the same peak demand were available, then by asserting DRM2 to one and DRM1 to the other, the total demand would be able to attain 25% capacity. The following sections present simulation results that illustrate improved balancing performance when two and three DRM control channels are available.

Figure 5 simulated aggregate demand of a centralised MPC with one DRM channel versus solar PV generation. Control signal 4 means no DRM.
5 Multiple-site coordination strategy

5.1 Two control channels

When more control channels are available, each channel can activate a different DRM signal at any given time, which allows controlling aggregate AC demand with a finer resolution, which results in more accurate tracking of reference signals.

For illustration, consider the population of 60 VOCACs analysed in the previous section is now randomly divided into two clusters, each encompassing 30 VOCACs. We implement the MPC structure illustrated in Figure 2 using two DRM control channels, one for each cluster. In this case, the aggregate demand of the whole population can be controlled to a higher resolution in 16 different levels, which arise from all possible permutations of four levels of demand in each cluster, as illustrated in Table 4.

Table 4 AS/NZS 4755 demand response mode control applied via two independent control channels

<table>
<thead>
<tr>
<th>Cluster 2</th>
<th>DRM1</th>
<th>DMR2</th>
<th>DRM3</th>
<th>No DRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 1</td>
<td>DRM1</td>
<td>{1,1}</td>
<td>{1,2}</td>
<td>{1,3}</td>
</tr>
<tr>
<td>DRM2</td>
<td>{2,1}</td>
<td>{2,2}</td>
<td>{2,3}</td>
<td>{2,4}</td>
</tr>
<tr>
<td>DRM3</td>
<td>{3,1}</td>
<td>{3,2}</td>
<td>{3,3}</td>
<td>{3,4}</td>
</tr>
<tr>
<td>No DRM</td>
<td>{4,1}</td>
<td>{4,2}</td>
<td>{4,3}</td>
<td>{4,4}</td>
</tr>
</tbody>
</table>

Note that unless the two clusters have identical distributions of AC load, these permutations will generally lead to 16 different levels of aggregate AC demand for the whole ensemble (namely, activating a control pair {2,3} will generally produce a different response to that of activating {3,2}). Therefore, grouping the ACs in diverse clusters increases controllability resolution for the demand response of the whole population.

The top of Figure 6 shows the improved tracking performance of the aggregate demand of all the VOCACs in the population. The bottom of Figure 6 shows the 16-level control sequence produced by the MPC.
Figure 6 simulated aggregate demand of a centralised MPC with two DRM channels. Look at the finer steps with 16 different DRM possibilities (bottom).

Error! Reference source not found. shows the decoded DRM commands corresponding to each of the two clusters in this example. Note in Error! Reference source not found. at the times between 3000 and 4000 seconds, where the VOCACs in the first cluster momentarily turn off (DRM1) to allow aggregate demand to track drops in PV generation. However, the total off-time
during the 2 hours of simulation is only about a couple of minutes, which is arguably of minor impact to AC end-users.

Figure 7 DRM input for each of two clusters in the population; decoded from the bottom plot of Figure 6

5.2 Three control channels

Increasing the number of independent control channels further increases controllability resolution. Figure 8 shows the results obtained when applying MPC to the population randomly divided into three clusters, each composed of 20 VOCACs. As seen in the plots, having more DRM channels provides finer control resolution (64 levels) which enables very close tracking of the fluctuations in PV generation, comparable to that achievable with non-quantised MPC [8].
Figure 8 simulated aggregate demand of a centralised MPC with three DRM channels. Look at the finer steps with 64 different DRM possibilities (bottom).

Figure 9 shows the DRM control signals for each of the three clusters decoded from the MPC sequence shown at the bottom of Figure 8. It may be observed that the improved tracking performance in this case may come at the expense of somewhat higher AC off-times (DRM1).

These simulations indicate that the achievable tracking performance of an MPC strategy implementing AS/NZS 4755 for AC load control with three independent control channels is already comparable to that achievable by continuous (non-quantised) MPC. The latter is shown in [8] to achieve a 94% reduction in the rapid variability of PV output arising from clouds.
6  Conclusions

The results in Sections 4 and 5 show that the proposed MPC strategies are able to coordinate air conditioning loads with PV generation and hence can be effective in managing LV network power quality and constraints. In particular, it has been illustrated how air conditioning demand may be effectively controlled based on AS/NZS 4755 demand response modes to compensate rapid PV output variability due to clouds by dividing the population of ACs into clusters, each controlled using a separate control channel. It was shown in numerical simulations that three independent control channels can already achieve a performance comparable to continuous MPC.

The simulations show that AC load control can be very effective in providing fast power balancing and reduce energy storage system requirements to firm collocated PV generation capacity.

Diversity is an important factor in forming the AC clusters for control. Grouping ACs in diverse clusters (for example, with different maximum aggregate AC load) increases the achievable resolution of aggregate load control via AS/NZS 4755 DRMs.
7 Bibliography


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