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Home Energy Management System for Demand-Based Tariff Towards Smart Applicances in Smart Grids

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***Abstract*— The peak demand placed on an electricity network can be reduced using a demand-based tariff, in which part of a customer's electricity bill is dependent on their maximum demand reached over a period of time. This paper reviews the state of the associated technologies, and it offers a smart grid hardware and software solution to achieve a home energy management system to assist electricity users to reduce their maximum demand. The method uses the application of the standards for demand response capabilities of electrical products, in combination with plug-in switching modules placed between any mains-powered appliance and the power point. The software system uses a heuristic algorithm that takes actions to achieve the target limit while causing the least inconvenience possible to the user. A prototype system has been developed and demonstrated using a simulated data that the maximum demand in a simulated household can be reduced significantly.**

***Index Terms*— Expert systems, heuristic algorithms, load management, smart grids, smart homes, energy management, demand based tariff**

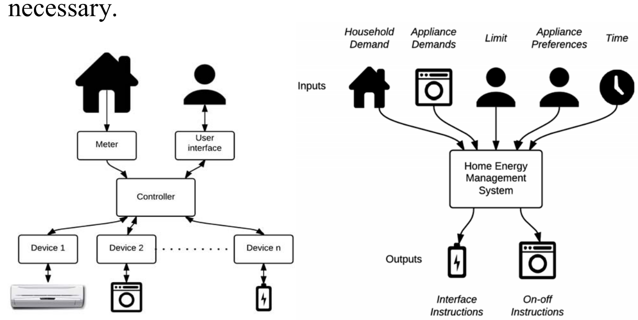
I. Introduction

The peak demand placed on an electricity network drives costs such as maintenance, operation, and investment [1]. Reduction of load is also highly critical in weak power systems where the wide area distributed generation systems includes significant level of intermittent (wind and PV) energy sources which can jeopardize grid stability.

This has led to the introduction of cost-reflective tariffs: pricing schemes which encourage electricity users to reduce their impact on peak demand [2]. A demand-based tariff is one example of a cost-reflective tariff (among real-time pricing, critical-peak pricing and time-of-use tariffs), in which users can lower their electricity costs by evenly distributing their electricity usage throughout the day, thus reducing their peak demand.

In practice, however, price signals can have limited impacts on peak demand [4]. For many households, the indirect costs of the time, effort and knowledge required to change their electricity usage habits can outweigh potential savings [5]. Providing technology to assist these users often improves their responsiveness to the price signals. As reported in [6], with technological assistance can reduce the peak demand on customer side 27-44%, which can provide users with information, decision-making assistance, automation and communication with the utility.

Home Energy Management Systems (HEMS) (Fig.1a) with demand based tariff (Fig.1b) is the technology considered in this paper to reduce the time, effort and knowledge aiming to adapt a cost-reflective charge, which can shift and/or curtail the demand of a household in order to meet various objectives [8]. Typically, a meter is used to measure the household's demand, and the system communicates with the user over a user interface. The system monitors and controls two types of devices: appropriate devices for the standard interfaces of compatible appliances, and on-off modules used to measure the demand of other appliances and switch them off when necessary.



a b

Figure 1: Structure of a Home Energy Management System (a) and inputs and outputs for demand tariff (b).

Table 1 compares and summarizes existing HEMS reported in the literature, which can be designed to meet various objectives. Some of previous studies incorporated smart appliances, and others used external switching modules. For example the system described in [17] assumes the existence of various interfaces to affect the operation of appliances, such as controlling an air-conditioner set point. However, no system was found that describes and implements such interfaces.

One major objective of a HEMS is to reduce electricity costs for the user, or keep them under a certain budget, which depends on the tariff for which the system is designed. The system described in [13] included a setting to limit household demand, but did not consider a demand-based tariff. In addition, no system considered on-off modules.

TABLE I. EXISTING HOME ENERGY MANAGEMENT SYSTEMS (HEMS) RESEARCH

HEMS Reported	Control Method	Objectives	Tariff	Algorithm	User Preferences	Cost Reduction
H. Kim et. al. [9]	Smart appliances	Cost reduction	Real-time variable pricing	Heuristics	Appliance priorities	5-17%
Y-S. Son et. al. [14]	Smart appliances, On-off modules	Cost reduction, energy saving	Any	Optimisation with learning	Appliance settings	10%
P. Siano et. al. [13]	N/A	Cost reduction, energy saving, demand limit	Real-time variable pricing, time-of-use tariff	Heuristics in Finite State Machine	Choice of modes	13-20%
B. A-Bediako et. al. [10]	N/A	Cost reduction, energy saving, demand response	Real-time variable pricing	Agent-based optimisation	N/A	N/A
A. Devidas et. al. [12]	On-off modules	Cost limit	Time-of-use tariff	Heuristics with learning	Choice of bill amount	N/A
S. Hussain et. al. [11]	On-off modules	Cost limit	Real-time variable pricing	Optimisation	Choice of bill amount	N/A
N. Dlodlo et. al. [15]	On-off modules	Energy saving	N/A	User control	N/A	N/A
Q. Hu and F. Li [17]	Load interfaces	Cost reduction	Any	Optimisation with learning	Choice of modes	N/A

The system's objectives must also be balanced with user well-being. This can be a difficult task, as the value users place on their appliances varies from person to person [8]. This can be modeled through user preferences and settings, set through the user interface. Some systems give users a choice of modes capturing various user priorities. For example, in [13], users could choose between "comfort", "economy", "energy limit" and "power limit" modes.

The organization of this paper is as follows. Section II discusses the unique features of a demand-based tariff and household demand. Section III describes principles of monitoring demand. Section IV describes appliance models, while the performance of the system in example households is given in Section V together with the hardware description. Section VI is the conclusion.

II. FEATURES OF THE DEMAND-BASED TARIFF AND HOUSEHOLD DEMAND

The demand-based tariff described in this paper, part of the user's electricity bill is dependent on their maximum demand over one billing period. Although various systems are described in Table 1 for real-time variable pricing or time-of-use tariffs, a demand-based tariff requires a different control strategy that is not sensitive to all changes in usage. Instead, they are sensitive to once-off, abnormal events. The user's cost under a demand-based tariff is solely dependent on a single demand measurement at a single time during the billing period: the maximum demand. Up until this maximum demand is reached, the user can use electricity at any time without receiving any additional financial benefit or cost. This means that to reduce costs under a demand-based tariff, a different approach is needed that reduces unusual, costly maximum demand events, while avoiding as much unnecessary inconvenience as possible outside of these events.

As the HEMS focuses on reducing rare and costly events, it requires a variety of control methods. During periods of low to medium demand, it will have little to no effect on the appliances within the household. However, during rare periods of extremely high demand, the system may need to curtail a large number of appliances within the household. Because of this, the system is designed for a combination of standard interfaces and on-off modules, in order to control as many appliances within the household as possible.

Where a control interface is available, the appliance is controlled using this interface. Other appliances are controlled using an on-off module placed between the power-point and the appliance, through which the power supply to the appliance can be remotely interrupted. These modules are also used to remotely monitor appliance demands.

A heuristic algorithm is used in this study. An optimization algorithm was not used due to the formulation of the problem as minimising inconvenience subject to a demand limit. Inconvenience cannot be measured exactly, and is easier to capture in a series of rules reflecting human preferences and choices. User preferences are incorporated in the limit chosen by the user. They are also used to develop a model for the importance of each appliance to the user. These design choices are summarised in Table II.

FEATURES OF HOUSEHOLD DEMAND

To control household appliances, a HEMS must build up a model of each appliance's capacity to respond to external control. In addition, a classification of household loads and their inherent ability to respond to external control is required. This can be achieved using typical household demand data, which is shown in Fig. 2.

TABLE II. DESIGN CHOICES FOR THE PROPOSED HEMS

	Choice	Rationale
Control Method	Standard interfaces, on-off modules	Control as many appliances as possible
Objectives	Demand limit	Predictable costs for user under demand-based tariff
Tariff	Demand-based tariff	
Algorithm	Heuristic	Minimise inconvenience through rules reflecting human preferences and choices
User preferences	Limit, appliance preferences	Users can choose their own cost, user minimises inconvenience

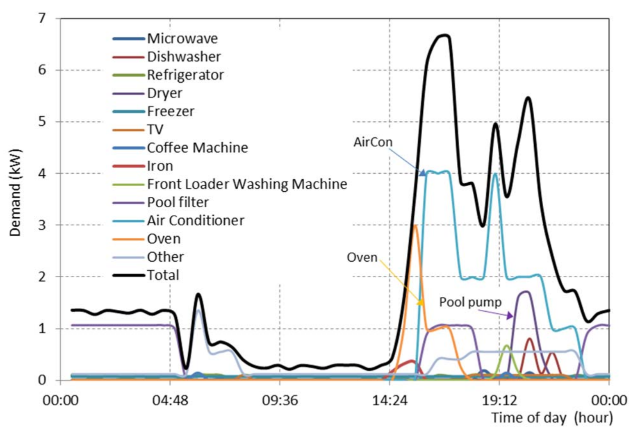


Figure 2 A typical household demand data in a day.

As stated previously, the system consists of two types of loads: loads controlled via standard interfaces, and loads controlled via on-off modules. Two kinds of standard interfaces are implemented in the system, with the ability to extend to additional interfaces.

The first is a simple interface to an energy storage unit, by which the Home Energy Management System can instruct the unit to charge or discharge. The unit is assumed to have sufficient charge available to discharge at any time.

The second interface uses a novel application of the AS/NZS 4755 Standard for demand response. This Standard defines operating instructions which, when received by compatible appliances through a defined interface, cause the appliance to alter its normal mode of operation in order to temporarily reduce its demand. An appliance may have one or more "demand response modes" in which they can function with reduced demand [7]. These modes can be activated without affecting the user, as long as the appliance is not left in a demand response mode for an excessive length of time.

Where standard interfaces are not available, on-off modules are used. The information provided by these on-off modules is limited to their demand patterns. Unlike smart appliances, the on-off modules provide no functionality for checking the appliance's future power needs, or whether switching its power supply off at any given time would lead to a malfunction. The system hence needed the ability to develop, from the demand measurements provided by the switch and information provided by the user, a model of the appliance's behaviour. This included the appliance's load characteristics, response to the interruption of its power supply, and its importance to the user.

The system needed to reliably stay below the limit in an unpredictable household environment, in which it is not feasible or desirable to control and/or monitor all loads. The household's demand on the grid may also be affected by energy sources within the household, such as varying solar PV output. Therefore the algorithm chosen should be able to adapt in real-time to changes in household conditions over a wide range of scenarios.

Demand-based tariffs do not charge users based on their instantaneous maximum demand, as this would require a smart meter capable of storing demand measurements over infinitely small time intervals. In practice, users are charged based on the maximum demand measured by their smart meter, which measures the average demand over some time interval. In Australia, this time interval is 30 minutes [18]. The system hence needs to keep track of these intervals, known hereafter in this paper as *Metering Intervals*. Instead of keeping the instantaneous demand of the household below the limit at all times, the system only needs to keep the average demand over each metering interval below the limit.

Household Demand gives the total demand of the household as measured by the meter, and the consumption so far over the current metering interval. *Appliance Demands* represent the demand measurements taken from the on-off modules, and any demand measurements provided by the standard interfaces. Two inputs are provided by the user through the user interface: *Limit* and *Appliance Preferences*. As the system needs to keep track of each metering interval, *Time* is also an input to the system. The system takes these inputs and produces two outputs: *Interface Instructions* provided to standard interfaces, and *On-off Instructions* provided to on-off modules which switch the power supply to the associated appliance on or off.

III. PRINCIPLES OF MONITORING DEMAND

This paper proposes a system that keeps the demand of the household below a user-set limit, while minimising the inconvenience to the user. The system is designed to adapt in real time to a household environment. To do this, it can take a variety of control actions. Some of these may be immediate, such as switching a battery bank from charge to discharge. Others may be pre-emptive, such as delaying the operation of a dishwasher before it starts its cycle. Hence the system requires a heuristic for determining when it needs to take action to reduce demand, and the magnitude of the demand reduction it needs to achieve. It requires a heuristic that calculates this for the current time, so that the system can take immediate actions. It also requires a heuristic to calculate this for future time periods, so that the system can take pre-emptive actions.

The system calculates whether it needs to reduce demand at regular intervals, known hereafter in this paper as *Scheduling Intervals*. All demand measurements are averaged over this interval. This interval should be small enough to adjust to medium-term changes in demand, but long enough to avoid the system reacting to transient spikes in demand such as boiling a kettle which will have a very small effect on the average demand over the *Metering Interval*. In this paper, the *Scheduling Interval* was chosen to be 5 minutes.

Every *Scheduling Interval*, the heuristic described in Fig. 3 (top) is undertaken. This heuristic decides how much immediate demand reduction the system needs to undertake. In addition, the system checks if the limit is likely to be exceeded in the current *Metering Interval* of time *T*. Measurements of demand *D* and consumption C_0 in the current *Metering Interval* so far are taken from the meter. The current demand is adjusted to find what the demand would be if no appliances were modifying their demand due to the HEMS,

$$D' = D + \sum \Delta d_i \qquad (1)$$

where the Δd_i are the current reductions in demand of each appliance due to the HEMS. This is used to find the available consumption C_a for the remaining duration *t* of the current *Metering Interval*. This is the difference between how much electricity will be consumed in this *Metering Interval* if the current demand pattern continues with no reductions, and how much electricity can be consumed in this *Metering Interval* without exceeding the limit.

$$C_a = L \cdot M \cdot T - C_o - D't \qquad (2)$$

The limit is multiplied by a margin *M* to account for any changes in demand that the system cannot react fast enough to. In this paper, this margin was set to 10%.

If $C_a \geq 0$, the system is not on track to exceed the limit. Hence the system returns all appliances to normal operation. If $C_a < 0$, the system is on track to exceed the limit, and demand needs to be reduced. The system iterates through all appliances which can respond immediately and finds the maximum reduction in consumption $\Delta c_{max,i}$ they can achieve over the rest of the *Metering Interval*. It then requests reductions in consumption Δc_i such that

$$\sum \Delta c_i \geq - C_a \qquad (3)$$

$\Delta c_i \leq \Delta c_{max,i}$ for all appliances *i*, and inconvenience is minimised. If these conditions cannot be achieved because

$$\sum \Delta c_{max,i} < - C_a \qquad (4)$$

then the limit may be exceeded. This results in a practical limit on the reduction in demand that can be achieved with this system.

Some appliances may not be able to reduce their demand immediately, but may be able to do so pre-emptively. For example, some appliances can be delayed in their operation, but cannot be interrupted once they are operating.

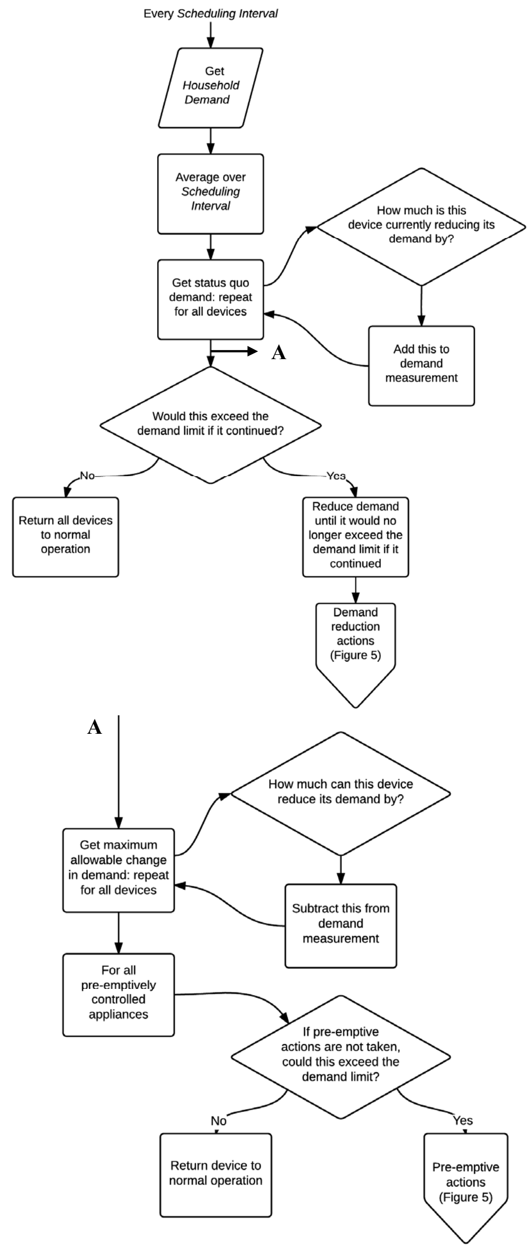


Figure 3: Heuristic for Immediate Demand Reduction (top), and Heuristic for Pre-emptive Demand Reduction (bottom)

Hence another heuristic is used to determine whether demand is likely to exceed the limit in future time periods. This heuristic is shown in Fig. 3 (bottom). Note that the initial steps of this heuristic are the same as in Fig. 3 (top). The system then finds the biggest new demand that could be added to the system at this point without exceeding the limit. It does so by calculating the maximum reduction in consumption that each appliance could achieve immediately:

$$\Delta c_{max,n} = \sum \Delta c_{max,i,n} \qquad (5)$$

This quantity is calculated for all metering intervals n until the end of the tariff period. It is then added to C_a to find the biggest new demand $C_{new,0}$ that could be added to the system in this metering interval

$$C_{new,o} = L \cdot M \cdot T - C_o - D't + \Delta c_{max,o} \quad (6)$$

and the biggest new demand $C_{new,n}$ that could be added in subsequent intervals n:

$$C_{new,n} = L \cdot M \cdot T - D'T + \Delta c_{max,n} \quad (7)$$

For each device which can respond pre-emptively, the system compares its possible load pattern without pre-emptive actions to $C_{new,n}$. If the device has a possible demand pattern which exceeds $C_{new,n}$, then it could place a demand on the system too great for it to adapt to, and the limit may be exceeded. Pre-emptive actions are then taken to avoid this. This reduces the likelihood that the condition in equation (4) will occur ($\sum \Delta c_{max,i} < - C_a$), hence increasing the ability of the system to reduce demand.

IV. Modelling Appliances

The above described heuristic requires the following information about each appliance in a household:

- Δd_i, the appliance's current reduction in demand due to the HEMS
- $\Delta c_{max,i,n}$, the maximum reduction the appliance can achieve immediately in this metering interval and each subsequent one
- Whether it can respond pre-emptively, and if so, its possible load pattern(s) with and without pre-emptive actions
- The inconvenience caused to the user if the appliance's operation is modified

Separate models are used to model appliances with a standard interface, and appliances controlled by on-off modules. For those appliances with a standard interface, the information above is provided by a model of that interface.

In this system, two interfaces are modeled: a switch between charging and discharging for an energy storage unit, and an AS/NZS 4755 Standard interface for an air-conditioner. Additional models can be incorporated into the system, as long as they can provide the information above. This could include various types of smart appliances.

The energy storage unit is assumed to have sufficient capacity to discharge for the entire demand-based tariff period. This model may not reflect a real energy storage system, but illustrates the principle of using an energy storage unit to manage demand. The energy storage unit's default state is to charge itself. When discharging, it is able to provide a demand reduction equal to the sum of the power drawn when charging and the power provided when discharging:

$$\Delta d_{storage} = P_{charge} + P_{discharge} \quad (8)$$

It is assumed that this demand reduction can be sustained for an infinite time period. Hence the consumption reduction the energy storage unit can achieve in a given time period is given by the demand reduction multiplied by the length of the time period:

$$\Delta c_{max,storage,0} = \Delta d_{storage}\, t \quad (9)$$

$$\Delta c_{max,storage,n} = \Delta d_{storage}\, T \quad \text{for } n>0 \quad (10)$$

The energy storage unit cannot respond pre-emptively and causes no inconvenience to the user if its operation is modified.

For the air-conditioner, Δd_{ac} is defined in AS/NZS 4755 for each demand response mode the air-conditioner is able to operate in. It is determined in terms of the usual demand of the air-conditioner, and hence requires the air-conditioner's demand to be metered [7]. For the demand response mode implemented in this system, it is assumed that there is no limit on the time which the air-conditioner can operate in this mode without inconveniencing the user. For other modes, such a limit may exist, and is incorporated by reducing $\Delta c_{max,i,n}$ by the appropriate factor. If these limits are kept to, the air-conditioner causes no inconvenience to the user if its operation is modified. The air-conditioner cannot respond pre-emptively.

For those appliances controlled by on-off modules, only two instructions are available: on and off. Some appliances can be interrupted at any time, irrespective of whether they are currently operating or not. Other appliances have a high value to the user, and should not be interrupted. This information is obtained through a simple priority system, set through the user interface.

Appliances which the user set as "low priority" could be interrupted at any time. These were able to respond immediately, with a $\Delta c_{max,i}$ equal to their current demand multiplied by the time remaining in the current metering interval. Once switched off, they were considered to remain off, so their Δd_i while switched off was taken to be zero. Pre-emptive actions were not considered for these appliances. Switching these appliances off was considered to cause greater inconvenience than modifying the operation of the air-conditioner or battery storage system.

Appliances which the user set as "high priority" were only switched off pre-emptively. While these appliances were not operating, the system would check whether or not the limit may be exceeded if they were to be switched on right now. This was done using a method for predicting appliance load profiles based on the max power data it receives from the on-off modules. A more accurate load prediction can be done by taking a series of demand measurements during the operation of an appliance, or incorporating machine learning methods over a long period of time.

Large changes in uncontrolled load can affect the system's predictions of whether or not it can accommodate high-priority appliances. This effect is important if the system were to be used in conjunction with household solar PV, which causes the household's total demand from the grid to vary according to PV output. In this case, the system could be made more effective by incorporating predictions of PV output based on the time of day and weather forecasts.

V. Performance Studies in Example Households

The simulated loads in three different household are shown in Table III. The algorithm described above was first simulated in MATLAB using data from a study which measured electrical load profiles of large appliances in two US households [20]. For each household, various load profiles were randomly generated. In the third household, the system was implemented in hardware and tested using a load bank. The data for this test was provided by SA Power Networks (SAPN).

Table III. The simulated loads in three different household.

	Household A	**Household B**	**Household C**
Data source	Small House [20]	Large House [20]	Provided by SAPN
Simulation method	MATLAB	MATLAB	Load bank with hardware
Loads with interfaces	Air-conditioner	Air-conditioner	Air-conditioner, battery storage
High priority loads	WM, dryer	WM, dryer, DW	WM, DW
Low priority loads		Hot water service	Pool pump
Uncontrolled loads	Refrigerator	Refrigerator, electric oven	Other loads
Peak demand without EM	4.8 kW	8.1 kW	8.03 kW
Peak demand with EM	2.5 kW	5.38 kW	4.17 kW
Peak demand reduction	48%	34%	48%

EM: Energy management, WM: Washing machine, DW: Dish washer

Note that the peak demand of Household C was reduced from 8.03 kW to 4.17 kW under a 4 kW limit, with no high-priority appliances being shifted. Instead, these reductions were achieved by appropriate use of the battery storage system and air-conditioner, while switching off the low-priority pool pump as a last resort. The lower limits were slightly exceeded, indicating that a 20% margin for changes in uncontrolled loads may be more appropriate than the 10% margin used. For this household, a large peak demand reduction of 48% was achieved with very little inconvenience to the user. This indicates that this system is a very effective way to co-ordinate multiple appliances within a home to achieve large reductions in peak demand. Larger demand reductions could be possible if other appliance interfaces become available, or as part of a system of smart appliances.

Fig.4 shows an example scenario over a given time, in which the system is operating with a 5 kW limit. The household consists of a demand response-compatible air-conditioner, a low-priority pool pump, a high-priority dishwasher and some uncontrolled loads. To simplify the example, each load is assumed to change only every half-hour, and the margin for changes in uncontrolled loads is neglected.

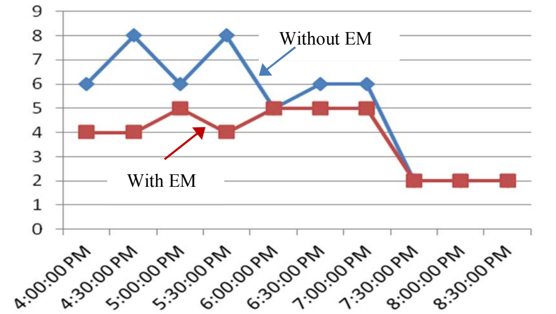


Figure 4: Total demand of example household with and without energy management (EM)

<u>Hardware description</u>

The HEMS was implemented in hardware using components communicating over Z-Wave. These components included a home energy meter used to meter the total household demand, plug-in smart switches used as on-off modules, and relay switches connected to appliance interfaces (Fig.5).

Figure 5. Demonstration frame circuit and load bank.

The controller was built around a Raspberry Pi, with a Z-Wave transceiver from the RaZberry platform. This platform consists of hardware and software specifically designed for adding Z-Wave functionality to a Raspberry Pi. The algorithm and Z-Wave interfaces were implemented on the Raspberry Pi, with a multithreaded design used to handle asynchronous communication between the controller and system components. A WiFi modem was used to enable the controller to communicate with the user interface over the Internet. The user interface was implemented as an Android application and cloud server (Fig.6).

Figure 6 Overviews of the controller's software (top) and smartphone application screen shoots (bottom)

VI. CONCLUSIONS

A HEMS was developed for a demand-based tariff. It reduces the peak demand of a household by keeping the total demand of the household below a user-set limit. The system makes use of the AS/NZS 4755 Standard for demand response-compatible appliances. It combines this with plug-in modules attached to any mains-powered appliances, and a simple battery energy storage system. The system uses a heuristic algorithm that keeps track of the total household demand at all times. If the limit is likely to be exceeded, it controls various household appliances in order to keep the household below the limit while minimising the inconvenience to the user.

The system was able to reduce the peak demand of a sample household with an air-conditioner and energy storage by 48% with little inconvenience to the user. Greater reductions in peak demand, or reductions in inconvenience, could be achieved if additional or improved models for loads were available. The model used for appliances controlled by plug-in modules could be improved through a system of user priorities developed through user feedback. The method for predicting the load profiles of appliances could make use of large sets of data gathered over months and even years to make more accurate predictions. The system could be extended to any demand response-compatible loads, and additional models could be added for any other method of controlling loads, including smart appliances.

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