Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 05, May-2016

A Novel Algorithm for Intelligent Home Energy Management System

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***Abstract*— Home energy management (HEM) is a system which analyzes, manages and controls the energy requirement for household appliances. This paper presents an algorithm which allows operation of large power consuming household appliances and ensuring that total household consumption is within preset limit. The proposed algorithm manages the power consumption of controllable loads. The algorithm built in simulink platform with 10 houses and validated the algorithm performance by doing real time hardware in loop simulation for one house using OP5600 simulator. The existing HEM systems are with load shedding algorithm. The proposed algorithm controls the power consumption of loads instead of cut out it completely. The major advantage of this work is that there is no violation of consumer comfort level. This paper demonstrates a tool with which the utility can interact with its customers and vice versa. This work serves as an essential stepping stone towards smart grid.**

I. INTRODUCTION

Ever increasing energy demand increases the demand supply gap. As the demand supply gap of electrical energy is increasing, it induces more frequent stress in power system elements [1]. Especially transformer failure and transmission line outages are two important effects of power system stress condition. It results in power outages and may lead to blackout. Demand response can play an important role to avoid such conditions [2]. According to the federal energy commission, demand response is defined as, changes in energy usage pattern by the consumers from their normal consumption patterns. This is an intentional modification to consumer’s energy usage pattern to reduce the overall electricity demand. Three main types of demand response programs are there [3]. Emergency demand response, economic demand response and ancillary service demand response. Demand response is in its nascent stages in India. To reduce the demand supply gap, one option is to cut down electricity supply to certain area. Tata power had launched a demand side management (DSM) programs for its customers in Mumbai to encourage energy efficiency in 2012. It is necessary to identify the appropriate consumers to be roped in demand response for the success of the program.

This paper proposes an algorithm, which act as a tool for residential consumers to perform demand response programs. The demand response programs existing for residential consumers are either manually controlled or automated [4]. Both the methods will results in peak shaving of demand. Among these, automated demand response programs are mostly accepted by consumers. HEM system is a tool to implement the fully automated demand response program for residential consumers. For automation of demand response program, there will be a central system which is individually connected to each controllable load. The existing programs cut off the lower priority loads during the violation of preset demand limit [5]. This is the drawback of the existing HEM systems.

In this paper, four different household appliances are considered with varying power demand in a range of 2 – 4 kW. The appliances considered here are space cooling/ heating load, water heater, clothes dryer and electric vehicle. Among these, clothes dryer and electric vehicle are considered as critical loads and algorithm is to control the space cooling/ heating load and water heater. The proposed algorithm allow all the household appliances to work together without violating the preset limit.

II. LOAD MODELING

The simulation did for 10 houses with similar loads. Each house has a HEM system which will be connected to all the loads. Utility give the demand limit for each house. The HEM system with proposed algorithm keeps the total household demand within the limit, without cutting down any of the loads.

A. *Space cooling/ heating load* [6]

Inputs to the load model are the demand response control signal ($C_{AC,i}$), outdoor temperature data (T_{out}t), thermostat set point (T_s), allowable temperature deviation or dead band (ΔT), room temperature data (T_i) and control signal to adjust thermostat setting (C_s).

Model output are electric power consumption ($p_{AC,\ i}$) in kilowatts of space cooling /space heating unit, and room temperature (T_{i+1}) at next time step.

The power consumption of space cooling/ heating load model depends on thermostat setting. This model is able to represent this variation in power consumption also.

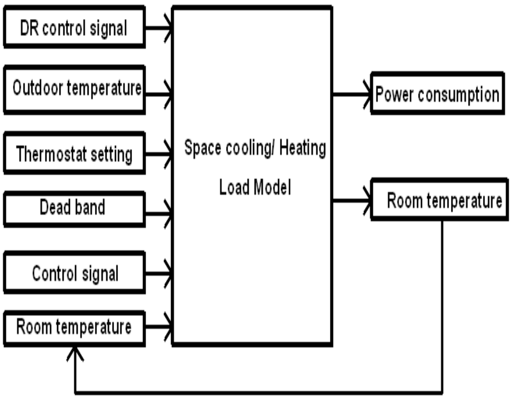

Fig 2. Block diagram for space cooling/ heating load model

A central space cooling/ heating unit with a thermostat works in an “on-off” mode and by changing thermostat setting, it is possible to vary the power consumption of this unit. The equation for power demand is

$$P_{AC,i} = \frac{C_{HVAC}}{\Delta C}[T_S - T_C][P][\omega_{AC}][C_S] \qquad (1)$$

where
$P_{AC,i}$ = electric power consumption, (kW)
P = rated power of the space cooling/ heating system (kW), 2.352 kW
ω_{AC} = status of space cooling/ heating unit in time slot i, 0 = OFF, 1 = ON
T_s = thermostat set point (^{0}F), 78^{0}F
T_i = room temperature data (^{0}F)
C_s = control signal to adjust thermostat setting
C_{HVAC} = cooling/ heating capacity (Btu/h), 1200 Btu/h
ΔC = energy needed to change the temperature of the air in the room by 1^{0}F (Btu/^{0}F), 487.5 Btu/^{0}F
ΔT = allowable temperature deviation or dead band, 2^{0}F

$$\Delta C = C_{air} \times V_{house} \qquad (2)$$

where
C_{air} = specific heat capacity of air for a typical room condition (1,202 J/gk or 0.0195 Btu/ft$^{3\,0}$F)
V_{house} = volume of house, 25000 ft^3

For space cooling, the unit is ON when the room temperature increases above the set point. The unit is OFF when the room temperature decreases below a certain value. For space heating, the unit is ON when the room temperature decreases below the set point. The unit is OFF when the room temperature increases above a certain value.

B. Water Heater Load

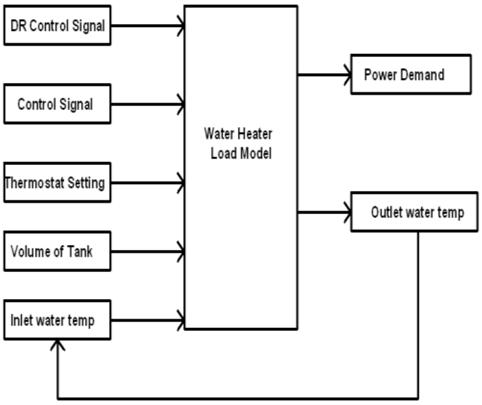

Fig 3. Block diagram for Water heater load

The inputs to model are inlet water temperature (T_i) , demand response control signal($C_{WH,i}$),status of water heater in time slot i,0($\omega_{WH,i}$), difference in thermostat setting and inlet water temperature ($T_s - T_i$), control signal to adjust thermostat setting (C_W) [7] [8].

1 litre of water needs 4.2kW power to increase its temperature to 1^{0}c in 1 hour.

So power demand can be calculated as below

‘g’ gallon = g×3.8 litre

1 hour = 3600 seconds

$$P = \frac{g \times 3.8 \times \Delta t \times 4.2}{3600} \qquad (3)$$

Where Δt is the difference between thermostat setting and inlet water temperature. The outputs of model are the demand for electricity of the water heating unit ($p_{WH,i}$) and water temperature in the tank ($T_{outlet,i+1}$).

C. Clothes Dryer

The power consumption of typical clothes dryer is from the motor and heating coil. The power demand of the motor part is usually in the range of several hundred watts, but that of the heating coils can be several kilo watts [6].

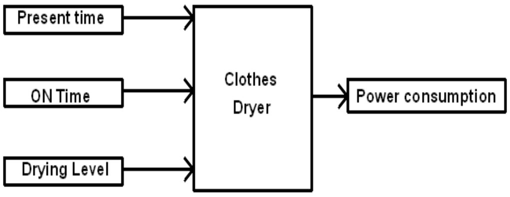

Fig 4. Block diagram for Clothes Dryer Load

For each time interval i, the power demand for the model can be ($p_{CD,i}$) calculated as,

$$P_{CD,i} = k \times P_h \times \omega_{CD,i} \times C_{CD,i} + [P_m \times \omega_{CD,i}] \quad (4)$$

Where
P_h = rated power of clothes dryer heating coil (kW)
k = drying level (k = 1/M, 2/M… M/M)
M = total number of drying levels
P_m = power consumption of the dryer's motor (kW)
$\omega_{CD,I}$ = status of the clothes dryer's heating coils in time slot i , 0 = OFF, 1 = ON
$C_{CD,I}$ = DR control signal for clothes dryer in time slot I , 0 = OFF, 1=ON

The electric power demand also depends on the DR control signal ($C_{CD,i}$) received from an external source, such as an in-home controller

or a utility. For the clothes dryer load, when a DR control signal is received, only the heating coil will be controlled (ON/OFF) but the motor part will not be controlled .This implies that the clothes dryer will be spinning during the control period, thus consuming only a fraction of the overall load (several Kw).
For this model the values assumed are,
P_h = 3.7 kW
K = 1, expecting zero moisture content in clothes
M = 3, in 3 different level it is possible to do the drying process
P_m = 0.3 kW

The maximum ON time set as 4 hours to show the performance of algorithm.

D. Electric Vehicle

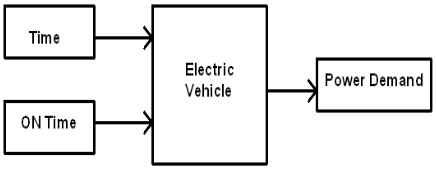

Fig 5. Block diagram for Electric Vehicle Load

To model EV charging profile three parameters are essential: the rated charging power, the plug-in time and the battery state of charge (SOC). The calculation of EV charging profile [6]

$$P_{EV,i} = P_{EV} \times S_{EV,i} \times \omega_{EV,i} \times C_{EV,i} \quad (5)$$

Where
$P_{EV,I}$ = EV charge power in time slot i (kW)
P_{EV} = EV rated power (kW)
$S_{EV,I}$= EV connectivity status in time slot i , 0 if EV is not physically connected to the outlet and 1 if EV is connected
$\omega_{EV,I}$ = uncontrolled EV charging status in time slot i ,which depends on the battery SOC: 0 if EV is not being charged and 1 if EV is being charged
$c_{EV,I}$ = DR control signal for EV in time slot i , 0 = OFF, 1 = ON
Here we are considering full charging, so SOC_{max} = 100

$$\omega_{EV,i} = \begin{cases} 0, SOC_i \geq SOC_{max} \\ 1, SOC_i < SOC_{max} \end{cases} \quad (6)$$

The battery SOC at time slot i is a function of the SOC at the previous time slot, the energy used for driving and the battery rated capacity, which is determined by

$$SOC_0 = 1 - \frac{E_{dr}}{C_{batt}} \quad (7)$$

$$SOC_i = SOC_0 + \left(P_{EV} \times \frac{\Delta t}{C_{batt}}\right) \quad (8)$$

Where
SOC_0 = battery SOC when EV is plugged in
Δt = length of time slot i (minute)
E_{dr} = energy used for driving (kWh)
C_{batt} = battery rated capacity (kWh)

The EV demand depends on the DR control signal ($c_{EV,i}$) received from an external source, such as an in-home controller, or a utility. The DR control signal of 0 will stop the charging of EV while the DR control signal of 1 will allow the EV to start charging.

III. PROPOSED ALGORITHM

Home energy management system is a tool to perform fully automated demand response program for residential consumers. Consumers are not interested to perform demand response manually. So an efficient home energy management system will do the necessary control operations to reduce total household demand during peak hours.
The proposed algorithm gathers information in each interval. The inputs to the algorithm are from different sources. From load controller, the current appliance status and its power consumption is given as input to algorithm. Consumer set the comfort level for each appliance. Utility decides the demand limit for each time interval. And temperature sensors will give the room temperature and water temperature as algorithm inputs.

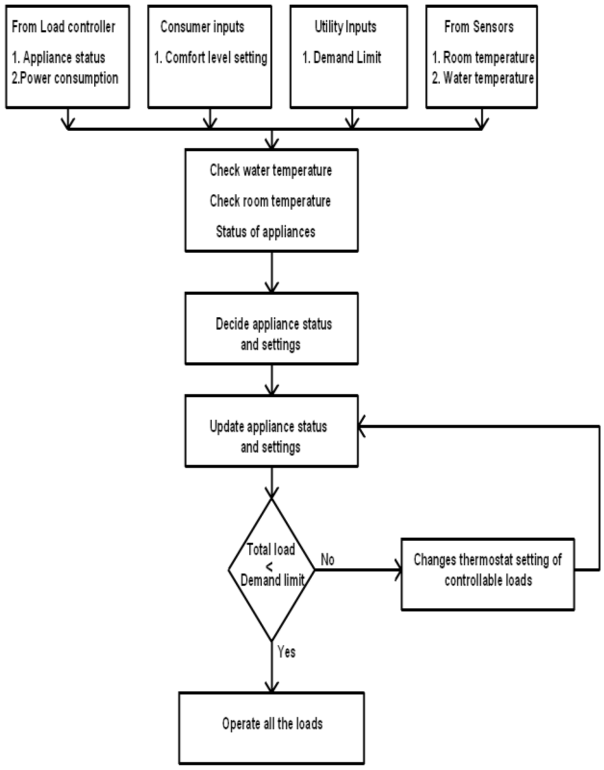

Fig 6. Flow chart showing Proposed Algorithm

Then, the algorithm checks for comfort level violations. This includes water temperature for the water heater model, room temperature for the space cooling/ heating load and status of all the appliances. Then it decides and updates the status. After this, the algorithm compare the total load demand with the demand limit set by the utility for that particular time period. If total demand is within the demand limit, algorithm allows all the appliances to work by consuming the rated power. If the total demand exceeds the demand limit, then algorithm control the thermostat setting of water heater and space cooling/ heating load. This reduces its power consumption and allows all the appliances to operate without violating the preset demand limit. The proposed algorithm uses the advantage of thermostat settings in appliances. So during peak hours, by setting thermostat setting of such appliances in to a proper temperature, it is possible to keep total house hold demand within the demand limit and there is no need of turning off any load.

IV. HIL SIMULATION

Simulation results obtained from simulink is validated with HIL simulation. HIL simulation is done by using OP5600 real time simulator. The most effective way to develop an embedded system is to connect the embedded system to the real plant. This is done by Hardware In Loop (HIL) simulation. Real time simulators will help to interact embedded system with real plant. The simulator is developed by OPAL-RT. HIL simulation did for one house and demand limit kept at the lowest possible limit. Then the results are verified. For doing the HIL simulation, the algorithm of home energy management system programmed on F28335 control card. The loads were kept at one core of simulator. The signals between four loads and controller send through analog channels.

V.HIL SIMULATION SETUP

For this project hardware-in-loop simulation is to realize the applicability of novel algorithm in real world. The hardware setup is as shown in figure 7.

Figure 7: Hardware setup for hardware-in-loop simulation

For the simulation, OP5600 is used as real time simulator and F28335 control card is used as hardware. Connection is as shown in figure 4.2.

OP5600 carries the plant model and f28335 control card programmed with novel algorithm. There are four analog output channels from plant model. It is taken through 2, 3, 4, 5 analog output channels of simulator to control board. These signals are received to control board through input analog input channels A0, A1, A2, and A3.

The output from control card is an analog signal to control thermostat setting of space cooling/ heating load and water heater load. It is taken out through PWM out from 01 channel and ground. The signal is connected to second analog in of simulator. And the plant model receives the control signal.

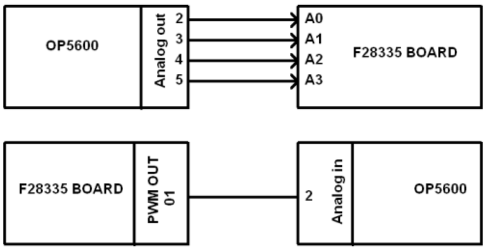

Figure 8: Schematic diagram of connection

VI. HIL SIMULATION RESULT

All the load models and algorithm are first implemented in simulink environment. Consider a utility supplying power to 10 houses. The loads are ON as shown in the table 1.

Water Heater	Always ON
Space cooling/ heating load	Always ON
Clothes Dryer	12pm- 2pm
Electric Vehicle	4pm -6pm

Table 1. Status of Appliances

The room temperature and water temperature inputs set at 65^0F. The thermostat setting of space cooling/ heating load is set at 78^0F. For the water heater load, thermostat set at 200^0F. Electrical vehicle and clothes dryer are considered as critical loads. So thermostat control is applicable only for water heater and clothes dryer loads.

From 12-2pm all the 10 houses uses the clothes dryer load. Also from 4-6pm all the houses using electric vehicle load. So there is a peak demand of power during these time. It is almost 150Kw. The base load is an average of 110kW and peak load is 150 kW. The maximum individual demand for each load will be around 15kW.

Consider one house for hardware-in-loop simulation. Plant model consist of four loads and algorithm works in real microcontroller F28335. It is possible to check the real time compatibility of proposed algorithm by hardware-in-loop simulation. Considering two cases here, one with demand limit set as 5.5kW and 6kW. The results obtained as shown below.

First total demand set as 5.5 Kw. According to the objective of project, under this situation all the four loads should work all the time without violating total demand limit. During software simulation, it is possible to set minimum demand limit as 5kW and all the loads are working for 24 hours. But this may not be the actual case. In real case, it may not be possible to achieve the objective for this minimum limit.

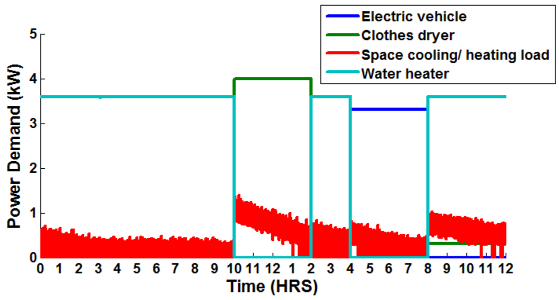

Figure 9: Individual load response for 5.5Kw demand limi

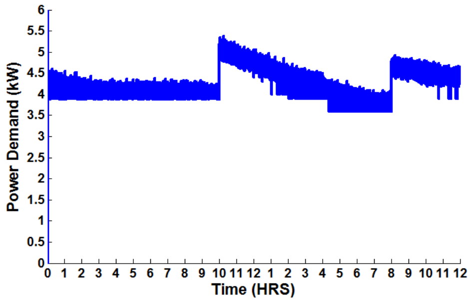

Figure 10: Total demand of house for demand limit set as 5.5kW

Figure 9 and 10 shows the result of hardware-in-loop simulation for demand limit set as 5.5kW. Figure 9 shows individual load responses for particular demand limit setting. Here algorithm keeps total demand of house as below 5.5kW. But during peak hours, water heater load is not active. Algorithm cut down water heater load to keep total demand within required limit.

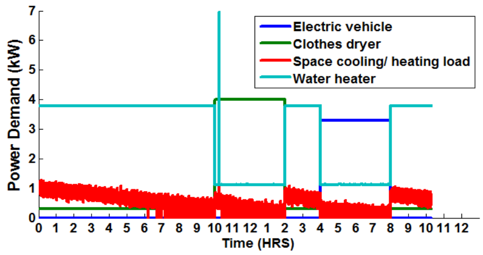

Figure 11: Individual load responses for demand limit 6Kw

As the next case, total demand limit set as 6kW. Figure 11 and 12 shows the result for this particular demand limit.

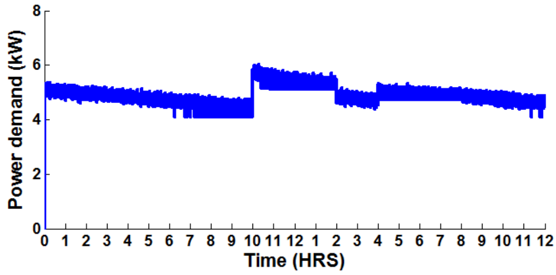

Figure 12: Total demand of house for demand limit set as 6Kw

From figure 12, it is clear that algorithm keeps total demand of house within preset demand limit. Also from figure 11, it is clear that all loads are working all the time. So for this particular load set up, possible lowest demand limit is 6kW.

VI. CONCLUSION

This paper presents a novel home energy management system which can be used for demand response applications. The simulation results show that the HEM system can control the total power demand of a house with the proposed algorithm. The proposed algorithm always ensures that the total consumption of a house is always within the preset limit. The proposed HEM algorithm considers inputs from utility and consumer. Thus make a two way communication between utility and individual consumer.

Hardware-in-loop simulation will do realization of electrical model. Here HIL simulation done by using OP5600 real time simulator and F28335 control card. Signals are transferred via analog channels. These channels introduce delay in data transfer in reality. While doing software simulation in Matlab, same model gave good response for 5kW as demand limit. But with HIL simulation algorithm can work perfectly with 6kW only. If we set demand limit below this value, one of the load get cut off. The response for 6kW is same for both the cases. Variation from software result is that, the minimum possible demand limit in software simulation is 5kW and in HIL it is 6kW. So in actual implementation we can keep lowest demand limit for this setup as 6kW.

In this HEM system, consumers need not sacrifice their comfort level fully. Thus, the utility can control individual consumer demand without violating their comfort level. This paper illustrates an intelligent home energy management system with a novel algorithm. This enables the residential consumers to perform demand response program in a large scale. As a future work, we will try to implement the algorithm in a microcontroller and test the algorithm with real loads.

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