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Real Time Energy Optimization Technique using Cyber Physical Controller for Micro-Smart Grid Applications

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Abstract : The recent development in Micro smart grid technology has improved energy efficiency and renewable energy utilization rate to serve local load with dispersed resources. We Propose a Hierarchical Household Load priority Load scheduling algorithm using cyber physical controller for Hybrid Energy Management in micro Smart Grids to maximize the utilization rate of the Renewable energy resources connected to the system. The Household appliances are connected to bundle with different priority according to the energy consumption pattern and the customer sophistications. The Scheduling of the appliance are done according the priority and the availability of the renewable resources such as Photovoltaic Cells and Wind energy added to the grid. The proposed scheduling algorithm used Minority Game Technique to improve the utilization factor of the renewable resources. The System further uses Non- Intrusive Load monitoring is essential to obtain specific power consumption by individual appliances which will be used to allocate priority during the load scheduling.

Keywords : Smart Grid, Load Scheduling, Non-Intrusive, Renewable Resources, Hybrid Energy Management, Cyber Physical System.

1. INTRODUCTION

Management in households have more gained more attention in recent years due to the continuous increase of energy demand and change in the consumption pattern of the users. A Smart Grid [1] is an evolved structure where the system manages the electric demand, in sustainable, economical and reliable manner. It uses two way communications between the generation and the consumer to dynamically respond to the demand and change in energy consumption pattern. Micro Grid is part of the Smart grid with low voltage network that is developed by interconnecting the renewable energy plants and storage network to govern the load in an apartments or dwellings. In modern micro grid technology renewable energy such as windfarms and solar cells are added to improve the efficiency of the system which increases the complexity and challenge to powergrid at various Levels [2]. In micro grid infrastructure uses demand side management technology to integrate the various renewable resources and schedule the load by maximizing the usage of the renewable sources. Demand side management technology can shift the workloads from consuming power during the peak time to off-peak time for load balancing and expense reduction [3] which is an essential property of smart homes in microgrids. Some of the common components in a smart home includes household appliances (Such as washing machines, refrigerators, personal computers,

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ovens, water heaters, air conditioners and juicers), energy storage components *i.e*. battery, renewable energy such as Photovoltaic (PV) array, Windmills (PMSG).

The main objective of the system is to reduce the electric charges paid to the power supplier by increasing the utilization of the renewable resources produced at the site and to reduce the Peak time demand. Scheduling algorithm is designed to forecast the demand and schedule the load according to the availability of the load. Automatic residential consumption scheduling algorithm [4] was designed by combining a real time tariff with inclining blocking rates. The three step control [5] methodology helps in effective managing the cooperation between energy production, consumption and storage. A swarm optimization technique is proposed [6] for effective coordination and optimal scheduling of residential resources to improve the advantages of smart home services.

The Paper focus on Cyber physical system (CPS) [7] it is tight integration of physical process and digital computing system. The major issue in the CPS are sensing and controlling the real time physical system. Other major applications of CPS are in medical system, traffic control and Smart Building etc. [8]

The proposed algorithm aims in reducing the peak to average ratio, total energy usage and electric charges by maximizing the usage of the renewable resources. The proposed model can control the all the major household components effectively in the real time environment by considering the comfort level of the user and the priority of the household components. The scheduling of the components is done by also considering the renewable resource available and the state of charge of battery. This Paper is organized as follows section 2 describes the setup of smart energy automation with renewable energy integration. The section 3 presents the system objective and section 4 explains NILM technique and section 5 describes the load scheduling feasibility. Section 6 explains the mathematical modelling of power calculation for each appliance and Section 7 describes the feasibility analysis of the proposed system. The reliability of the system is explained with case study in section 8 and conclusion is given in section 9.

2. SETUP OF SMART ENERGY AUTOMATION WITH RENEWABLE ENERGY INTEGRATION

Scheduling of appliances has proved to be efficient way of reducing house loads and energy usage. All the appliances in the household are not schedulable; the customer comfortless has to be taken before deciding the scheduling. The appliances such as HVAC and indoor lighting can be connected with the sensors to decide on the priory of the load and to make consumption more efficient. The grid must be customer oriented and has to operate on business principles where customer will have maximum information about the grid availability and gives the customer more choice to operate. This information's will help consumer to choose when to use electricity to save cost on electricity bills.

The Figure 1 shows the proposed system layout in that system the whole load is divided in to bundles where each bundle consists of various house hold equipment's. These bundles where connected to AC grid by using the Access point through a computer controlled switch. This enables the controller to power on or off the bundle. Major house hold equipment's such as Refrigerators, AC consume a large portion of the total energy utilized by the system; some of these can be scheduled without affecting the customer priority and reducing the energy utilization.

2.1. Primary Controller

The processor has three main objectives first, it communicates with other appliances to obtain the status and to coordinate them. Second processer serves as a gateway for the customers to control the appliances and cyber physical controller to get the status of the system. Third the Master controller has to execute the schedule the all the appliances based on the priority and Hierarchical algorithm.

2.2. Communication in between Notes

The system uses both wired and wireless modes of communication. The Primary controllers are connected with the cyber physical through Ethernet control and all the appliances inside the buildings are controlled by Using Wi-Fi. The main advantage of Wi-Fi is easy implementation and almost all the buildings are now covered with Wi-Fi signals, so it will reduce the installation cost and large data can be handled.

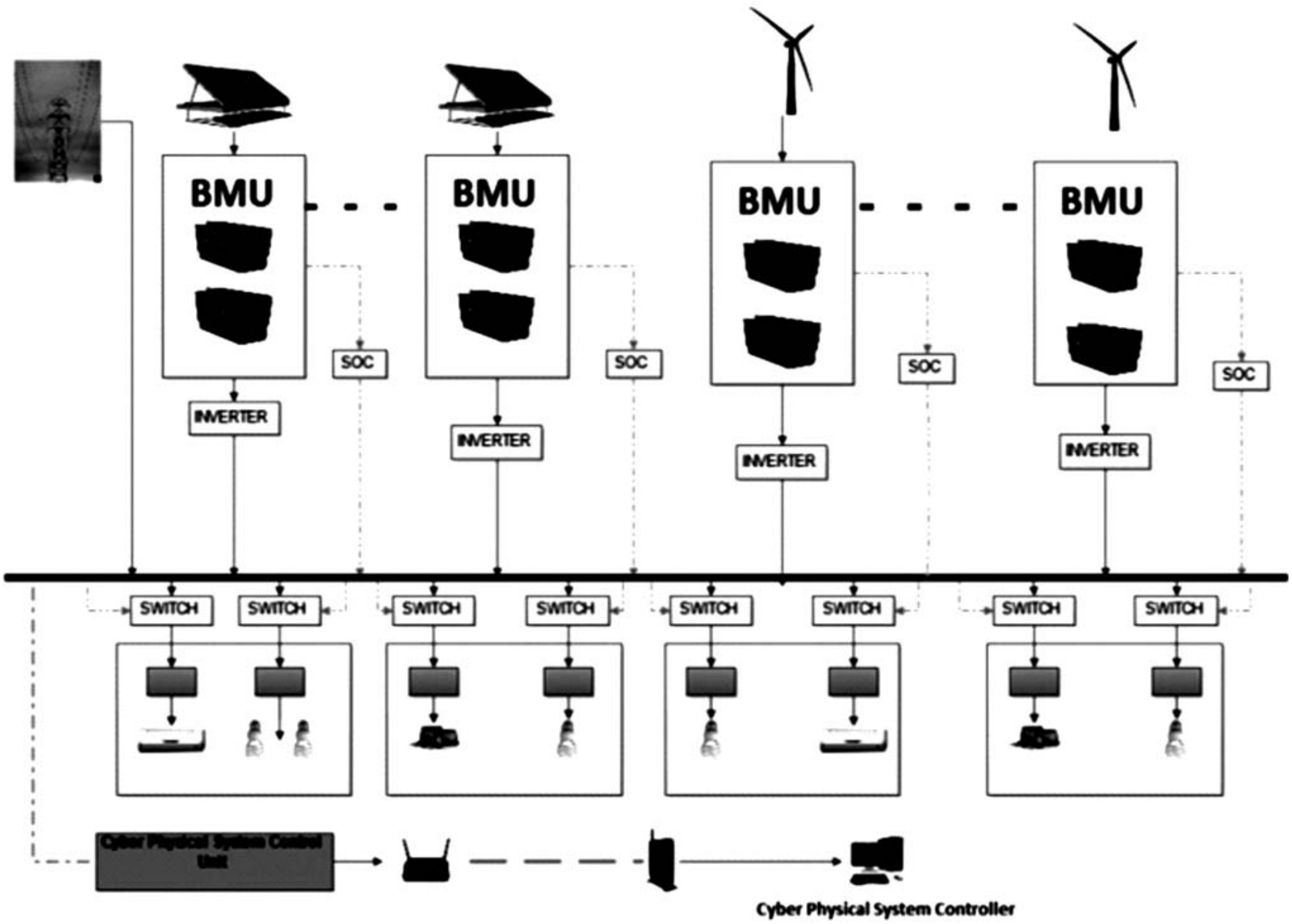

Figure 1: Setup of Home energy Automation with Renewable Integration

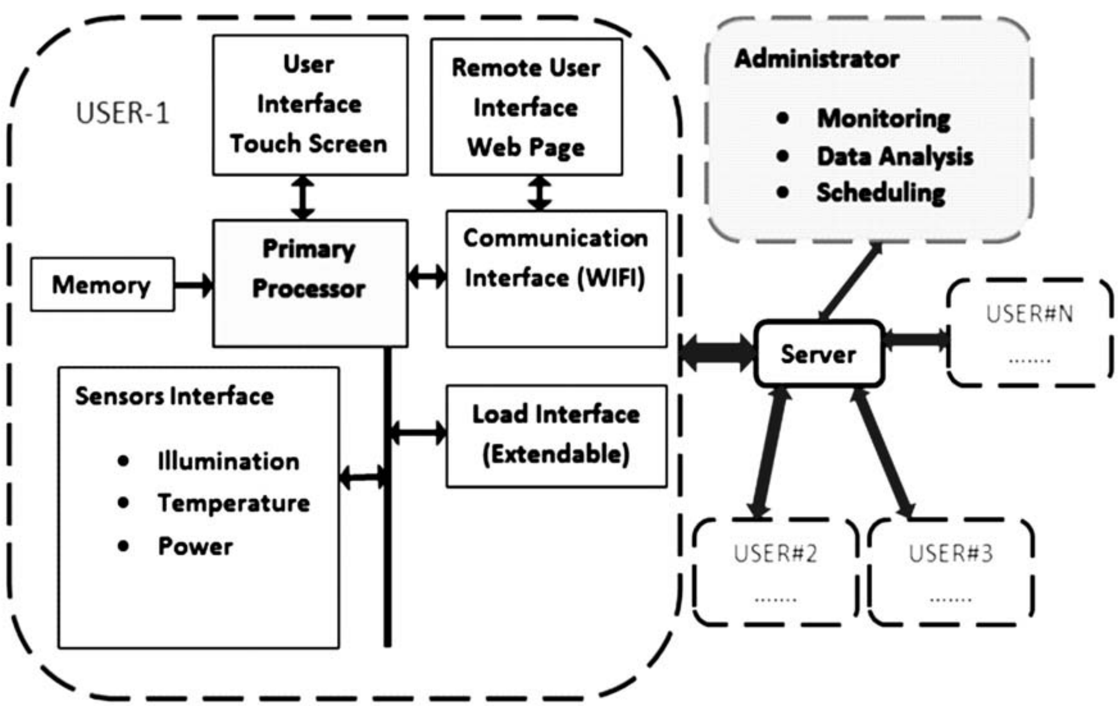

Figure 2: Wi-Fi control network at each bundle connected to the system

2.3. User Interface

Each Primary controller in the Building is connected with the PC of the customer for modifications in the priority of the appliances and for monitoring the system. Further master controller displays all the parameters to the customers by using a LCD display. Further the customer can also remote user interface in the web page to control the system.

2.4. Sensor Interface

The system has many sensors to collect real time data of power consumption by various appliances for finding the non-intrusive load monitoring. Further this system has temperature sensor in the buildings and to measure the state of charge of battery. The data collected by these sensors are passed to the master controller by using Wi-Fi.

2.5. Load Connection

All the Loads are connected with a computer controlled relay for scheduling according the availability of power in system and priority of the appliances.

A. PV and Battery Model

The PV and Battery model is developed to integrate with the existing homes to reduce the energy cost and carbon foot print. PV panels are arranged in larger units and interconnected in a series and parallel configuration to form PV arrays. Performance of Solar cells has complex relationship between solar radiations, temperature and total resistance that produces a nonlinear output efficiency graph known as I-V curve. The I-V characteristics of the equivalent electric cell circuit may be determined by following equations [10].

$$I = I_L - I_0\left[\exp q\left(\frac{V + IR_S}{KT}\right) - 1\right]\frac{(V + R_S)}{R_{Sh}} \tag{1}$$

$$I = I_L - I_0 - I_{sh} \tag{2}$$

When Diodes are connected in series the equation changes as,

$$I = N_P I_L - N_P I_0\left[\exp q\left(\left(\frac{V_{PV}}{N_S} + \frac{IR_S}{N_P}\right)AKT\right)1\right] - N_P\left(\frac{\frac{V_{PV}}{N_S} + I_{PV}RS}{R_{Sh}}\right) \tag{3}$$

Where, I = cell current (Amps), I_L = Light generated Current (Amps), I_0 = Diode saturating Current, q = Charge of electron, A = Diode ideality constant, K = Boltzman constant (j/k), T = Temperature in cell, R_s = solar cell in series (ohms), R_{sh} = Solar cell in Shunt resistance (Ohms), N_p = Number of cells in Parallel and Ns = Number of cells in series.

The lead acid battery used in this system is modelled [11] according to the battery type used in the smart home. The discharge characteristics

$$V_{batt} = E_0 - Ri - K\frac{Q}{Q - it}(it + i^*) \tag{4}$$

Where, V_{batt} = Battery voltage (V), Eo = Battery constant Voltage (V), Ri = Internal resistance (Ω), I = Battery Current (Amps), K = Polarization Constant (V/Ah), Q = Battery capacity (Ah), it = Actual battery charge, i^* = Filtered Current.

The state of charge (SOC) for the system can be calculated by using equation (5).

$$SOC = \frac{Q - it}{Q} \times 100 \tag{5}$$

When the state of charge becomes less than 10% the discharging of the battery is stopped and charging cycle is switched on.

B. PMSG Wind Mill Model

The proposed system uses apermanent magnet synchronous generator (PMSG) [12 which has advantages such as high reliable operation, low maintenance expenses and light weight with simple structure.

$$\frac{d}{dt}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_r i_q \tag{6}$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}p\omega_r i_d - \frac{\lambda p\omega_r}{L_q} \tag{7}$$

The torque equation of the PMSG is given by equation

$$T_e = 1.5\rho[\lambda i_q + (L_d - L_q)i_d i_q] \tag{8}$$

Where, L_q = q axis inductance, L_d = d axis inductance, R = resistance of the stator windings, i_q = q axis current, id = d axis current, vq = q axis voltage, vd = d axis voltage, ωr = angular velocity of the rotor, λ = amplitude of flux induced and p = the number of pole pairs.

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m) \tag{9}$$

$$\frac{d}{dt}\theta = \omega_r \tag{10}$$

Where, J = inertia of rotor, F = friction of rotor and θ = rotor angular.

$$V_B = \frac{1}{2\sqrt{2}}m_B V_{dc}\angle\delta_B \tag{11}$$

The PMSG consist of a rectifier, DC link and inverter to convert AC voltage output from PMSG based on Wind energy conversion system (WECS) to DC voltage. Inverter converts the DC voltage from DC Link capacitor to AC voltage at the rated frequency. Where, m_B = the modulation index, δ_B = the phase angle of control wave.

3. SYSTEM OBJECTIVES

Depending on the customers objectives such as energy consumption, utilization of renewable reouces,$C0_2$ emission and peak load scheduling are considered for optimized scheduling.

3.1. Renewable energy utilization

The main objective of the current model is to maximize the utilization rate of the renewable energy and reduce the consumption from the power grid which lowers the energy cost and CO_2 emission.

3.2. Energy Cost

The total energy cost represents the cost of electricity consumption, where the energy cost is reduced by optimized scheduling and using renewable resources.

3.3. $C0_2$ Emission Cost

Thermal and gas or diesel fired power plants are the main source of the $C0_2$ emission in the power industry, the proper furcating of the loads can reduce the carbon footprint. The cost includes the carbon footprint by the customer by utilizing power from the grid. The Emission cost can be reduced by utilizing renewable resources effectively. The cost includes carbon footprint of the customer

3.4. Peak load Factor

The demand for power is usually higher during the peak hours and scheduling of house hold appliances during such time is a great challenge since the algorithm must consider the customer priority and also the objective of the system. The scheduling of appliances during the hot afternoons of summer [9] is a great challenge.

3.5. Optimization

For the optimized scheduling all the objectives are considered simultaneously with different priority given by the customer.

$$O = AO_1 + BO_2 + CO_3 + DO_4 \tag{12}$$

Where O_1, O_2, O_3, O_4 are objectives and A, B, C, D are the priorities given to each objective respectively.

4. NON- INTRUSIVE LOAD MONITORING(NILM)

The Technique was proposed by Hart [15] in 1992 to disintegrate the total electrical load by monitoring the appliances specific power consumption pattern. The sensors are fixed in main electric panel to calculate the total power utilized by the building. The sensors are fixed at each bundle to calculate the power consumed at each bundle and sensors are further fixed across the major appliances such as Refrigerators, Air conditioners etc. This problem is formulated as

$$P(t) = p1(t) + p2(t) + ... + pn(t) \tag{13}$$

Where $P(t)$ is the total power consumption and pi is the power consumption of individual appliances where n is the total number of active appliances within the time period t.

5. LOAD SHEDULING FEASIBLITY

In our proposed method the priority is dynamically allocated so that the house hold equipment's can be scheduled according to the parameters such as customer priority, Activity Level, renewable resource availability and battery SOC. The whole household equipment's are classified in to three priority stages as High, low and medium. Different appliances have different time limits with dynamic priority where the time limit can be prescribed by the customer or manufacture of the products. The appliances are classified with priority according to the energy consumption and customer satisfaction.

A. Customer Priority

The scheduling pattern of the residential system first depends on the customer preferences and also depends on the energy saving aspects. In the dynamic priority scheduling technique the house hold equipment's are scheduled according to the renewable resource availability and the load demand the time period. The system also includes factor such as desired room temperature of the customer and maximum deviations that the customer will accept.

B. Activity Level

In the residential application the load curve for the load depends on the season and days such as weekdays and weekends. For a perfect scheduling of electrical appliances the activity level of the each bundle in the system must be monitored for every hour and plotted. The measured data for the weeks or months can be used to forecast the demand for each day. The load curve of the each house hold equipment's does not remain for e.g. the load curve of the refrigerator will not be same as the printer or microvan connected to the bundle.

C. Renewable resource availiablity

The energy production using the renewable resource like solar and wind are generally fluctuating and affects the reliability of the system. The output of the renewable resources depends on the weather forecast information's for E.g. If the wind speed for a day is obtained the windmill generated for day can be calculated so that the algorithm can schedule a part of load to the wind energy source.

D. State of Charge of Battery

SOC determination based on the open circuit voltage [13] is direct measurement method and efficient method for determining the performance and life of the battery. Table 1 explains the relation between the open circuit voltage and state of charge of battery for 12 V lead acid batteries. The proposed system uses the Li-ion battery where there will be voltage drop during the discharging in the linear or nonlinear way. The voltage is also affected by the current, temperature, discharge rate and age of cell.

Table 1

State of charge of 12 v Lead acid Battery

S.No	*Open Circuit Voltage*	*Charge*
1	12.73	100%
2	12.62	90%
3	12.50	80%
4	12.37	70%
5	12.24	60%
6	12.10	50%
7	11.96	40%
8	11.81	30%
9	11.66	20%
10	11.51	10%

6. MATHEMATICAL FORMULATION

Where Pa is the power consumed by appliances for 24 hour in the household calculated by,

$$P_a = \Sigma_{n=1}^{24} p_{h,n,a} \tag{12}$$

The total power consumed by each home is calcluated by

$$P_{TC} = \sum_{n=1}^{N}\sum_{a=1}^{A}\left[\left(\sum_{h=1}^{24} p_{h,n,a}\right)\right] \tag{13}$$

PG is the power genrated by using the wind and solar instllaed in each building. The power recived from the grid is calculated by the equation 14.

$$P_{grid} = \varnothing(P_{TC} - P_G) \tag{14}$$

The excess energy from each home is shared between the other homes and stored in battery for critical loads. The customer sets the priority to each load in system with positive integers from 0. Which helps during scheduling of loads.

7. FEASIBILITY ANALYSIS

The proposed algorithm initially schedules the appliances according to the priority status and forecasting of load demand. The sample house hold appliance priority is given in table 2. The figure 3 explains the flow of proposed algorithm.

The signal is sent to the master controller when the customer turns on the appliance. The controller checks the status of availability and turns on the appliance based on the availability of supply and priority of the load. When there is enough power is available under the limit the request is accepted if not the controller checks the priority of the appliance, if the priority is high the load is limitedly turned on. If power available for the home is already filled then the controller stops the other schedulable loads and satisfies the power limit. The power generated by Solar and wind are used as primary sources for the each home. When power generated by one home is not completely utilized the primary energy generated in other home will be share to other homes to compensate their demand. The system imports the excess power from the grid to compensate the demand of the system. This method will solve the peaking in the grid and increase the utilization factor of the primary source. The aim of the project is to flatten the demand curve of the customer for each time slots and to consume maximum power in the allotted time slots. The each home connected to the grid has maximum power that can be consumed.

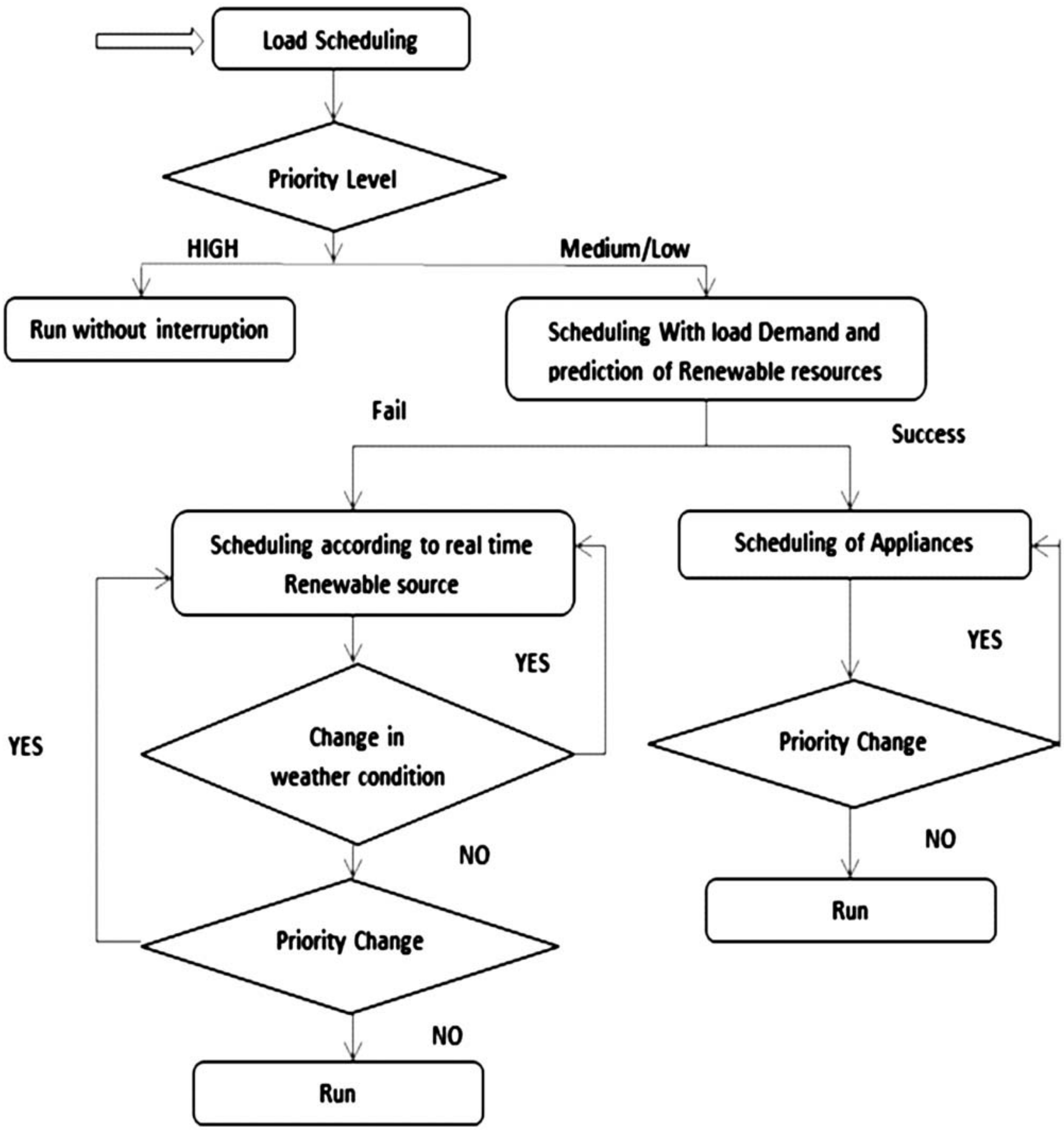

Figure 3: Flow Diagram of Proposed Scheduling algorithm

8. CASE STUDY

The real time prototype is being developed in the Hindustan university campus in Chennai, India which is funded by the MNRE, India. The system consist of 3 homes with solar panel capacity of 2KW,2KW and 1 KW respectively and each system has its MPPT controller , Inverter and Battery system separately. In this section simulation results are discussed by applying proposed model is discussed. A community of 5 homes is taken and power is generated by using installed solar and wind mills are added as primary sources for each homes. Connection are made such that when the generation is excess in one home can be shared with other home to reduce the power purchased from the grid and to reduce the peaking in the grid. In this no power is sold to the utility and excess power is saved in the battery.

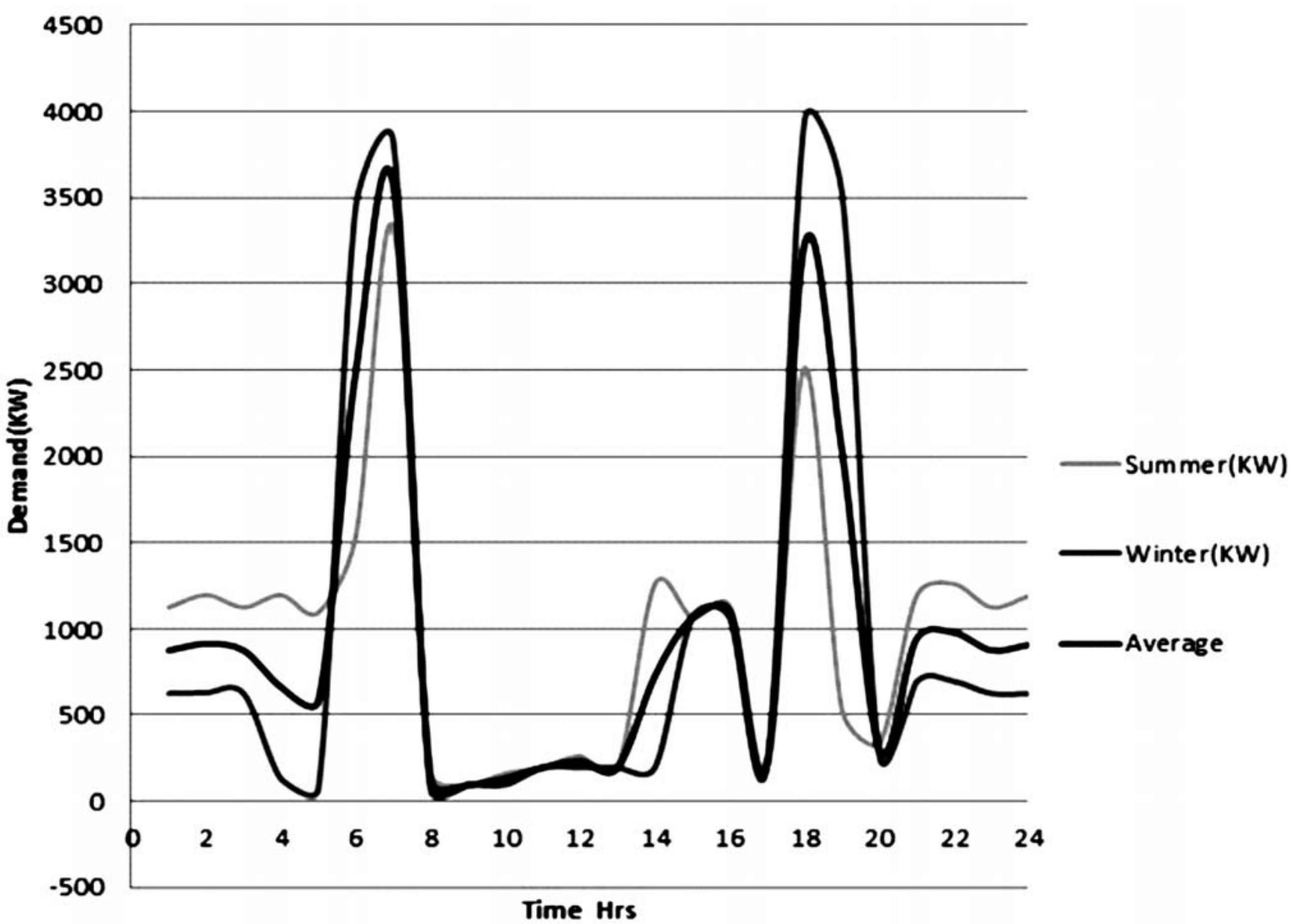

Figure 4: Energy demand in each home during summer and winter season

The power rating of various appliances is collected and averages of these appliances are used in this research. The household appliances are classified as schedulable and non-schedulable. The proposed algorithm is tested with a case of both priority scheduling and non-priority scheduling technique conditions. The sample house hold equipment is listed with user priority and load consumed by each load in a day is calculated using NILM technique for scheduling in Fig 6 and energy yield is calculated for the year by solar module for scheduling of load is shown in Table 3 and Fig 5. The shadow loss and other losses such as non-alignment of panels were taken in to account for energy yield calculation. The Chennai solar irradiation values were taken from NREL Website. For the case study the system Figure 8 explains the scheduling with priority and non-priority if the system in a graphical way.

Table 2

Sample house hold equipment's priority

Devices	*Energy Consumption Pattern*	*Energy Consumption (Watts)*	*Eligible For Scheduling*	*Priority*
AC	Continuous	2000	Yes	Medium
Water Heater	Periodic	3000	Yes	Medium
Fridge	Continuous	265	No	High
Washing Machine	Flexible and Periodic	330	Yes	Low
Fans	Continuous	75	Yes	Low
Light CFL	Periodic	11	No	High
Personal Computer	Instantaneous	75	No	High
Printer	Instantaneous	100	Yes	Low
LED Tv 40 inches	Instantaneous	110	No	Medium
Hair dryer	Periodic	1250	Yes	Low

Table 3

Solar energy yield

Month	*Days*	*Average Daily solar radiation (kW/m2/day)*	*Day time average temperature (deg C)*	*Cell Tempera-ture (deg C)*	*Energy Yield (kWh)*
January	31	4.93	28.8	54.00	574
February	28	5.89	30.5	55.70	615
March	31	6.64	32.5	57.70	768
April	30	6.72	34.3	59.50	746
May	31	6.12	36.8	62.00	695
June	30	5.24	36.9	62.10	575
July	31	4.73	35	60.20	541
August	31	4.8	34.3	59.50	551
September	30	5.01	33.9	59.10	558
October	31	4.42	31.8	57.00	508
November	30	4.06	29.6	54.80	456
December	31	4.24	28.5	53.70	494
Annual	365	5.23	32.8	58.00	7090

Table 4

Total energy demand

Appliances	*Power (Watt)*	*Qty*	*Winter*		*Summer*	
			Uses Time (h)	*Energy (Wh)*	*Uses Time (h)*	*Energy (Wh)*
CFL lights	10	4	14.5	580	13.0	520
Fans	30	3	23.0	2070	26.0	2340
TV	100	1	11.0	1100	11.0	1100
Mobile charger	10	2	3.0	60	3.0	60
Outdoor Lighting	40	2	6.0	480	6.0	480
Water Heater	3000	1	4.0	12000	1.0	3000
Fridge	265	1	6.0	1590	9.0	2385
Hair Dryer	1250	1	0.5	625	0.5	625
Water Pump	500	1	2.0	1000	2.0	1000
AC	2000	1	2.8	5500	7.0	14000

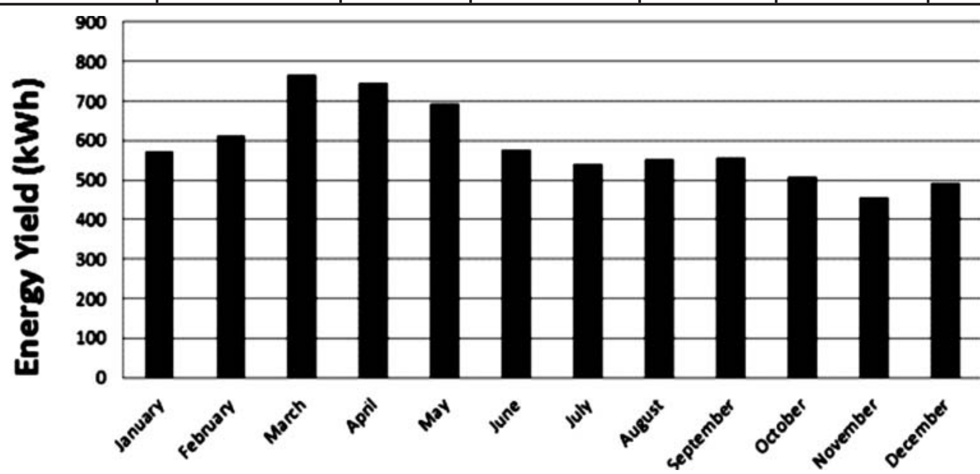

Figure 5: Solar Energy yeild for various Month

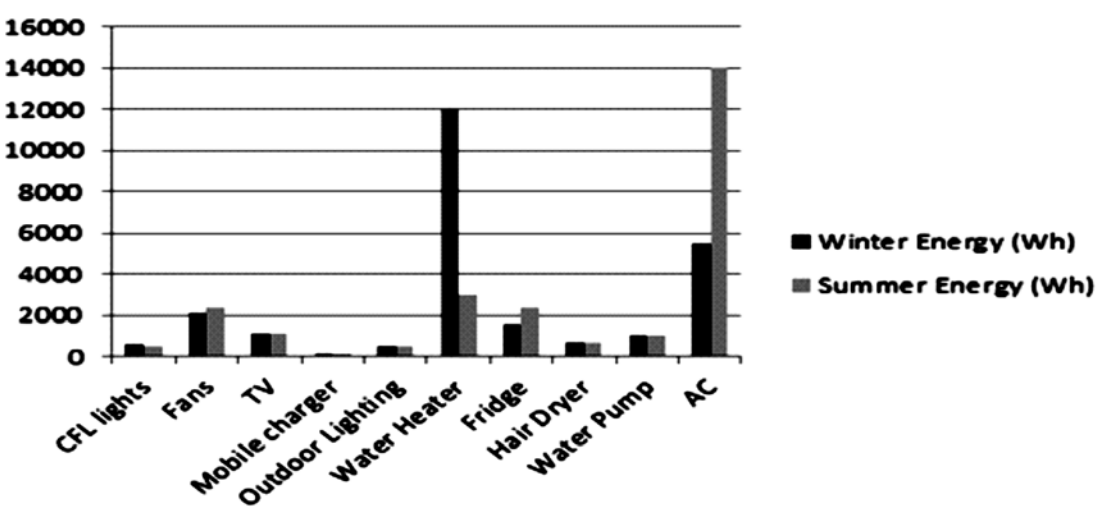

Figure 6: Energy utilization by each appliance estimated by using NILM Technique

Without priority scheduling the appliances switch on at random times according to the user needs so the total energy utilized increases. With the priority scheduling the usage of grid supply is reduced thereby increasing the utilization rate of renewable resources. The peak demand of the system is reduced by compensating the energy demand by using the renewable energy and scheduling of loads with their priority.

9. CONCLUSION

The paper presents controlling of load in smart grid using CPS. The hierarchical based Priority scheduling helps in controlling of peak demand in house hold equipment's effectively without disturbing the user comfort. The algorithm is simulated by using the case study where the appliances are switched on during the availability of renewable resources and only high priority load are switched on during the absence of renewable resources. Therefore, a scheduling scheme was proposed to residential households that would help consumers in saving money spent on electricity bill. The effective forecasting of availability of renewable resources and demand the efficiency of the algorithm can be improved.

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