Load Weight Based Energy Distribution and Dynamic Pricing using Fuzzy Logic in a Smart Grid Tree Network

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Abstract — The smart energy distribution according to the growing demand during peak hours at smart grid is very essential. The dynamic pricing per unit energy should depend on the demand and peak load hours of a day. In this paper, a new quantitative technique using Load Weight Based Energy Distribution (LWBED) is proposing to balance the dynamically varying loads at various levels and optimize the power distribution efficiency of the grid. Initially, LWBED Algorithm is applied at various junctions and the power is dynamically distributed to the sub junctions, connected to each junction which optimizes the power distribution efficiency of the grid. Later, a Dynamic Price per unit energy is charged based on the demand and time using Fuzzy logic. Incentives are provided during off peak hours to improve the user demand during non peak hours.

The proposed algorithms handle the demand on the grid very smoothly during peak and non peak hours and the users are charged based on their energy utilization in a day. From the simulation results it is clearly observed that the Fuzzy based pricing algorithm considers load variations, peak traffic hours, and leads to effective pricing charges.

Keywords — Dynamic pricing, Distribution, Fuzzy logic, Peak load and Smart grid.

I. INTRODUCTION

A smart grid is an advanced upcoming technology, which uses intelligent energy distribution algorithms and balances the energy demand during peak and non-peak hours in a day.

Smart grid brings smart electric power generation, transmission, and distribution from the substations to the end users to one common umbrella by integrating various advanced technologies [1-3], distribution management system [4], load balancing techniques and economic pricing strategies [5]. The Smart metering, advanced two way communication with intelligent algorithms provide flexibility to calculate the load using scheduling algorithms [6] and provides effective utilization of energy and increases the active participation of the user which reduces the price [7].

The demand side management system (DMS) handles the load demand and various demand management techniques are given in [8-19]. Scheduling, shifting, shedding, load curtailment etc., techniques are used to balance the load in a day [20-22]. Energy resources should be optimized to maximize the utility [23-27].

The power generated should be distributed according to the demand from the costumers and intelligent control algorithms should be applied for price reduction. The pricing per unit energy can be charged using various ways like real time, peak demand hour, time of use, action based, dynamic pricing and are given in [28-35].

For smart grid Fuzzy logic can be used for DSM and dynamic pricing strategies can be employed to meet the demand requirements during peak hours.

The objectives of this paper are listed below.

➢ An energy distribution based on load demand in a day.
➢ Shifting the load to other non-peak slots to balance the load during peak demand.
➢ Dynamic pricing per unit energy using a Fuzzy logic approach based on the demand and peak load.
The rest of the paper is arranged as follows. Section II describes the Smart Grid Tree Network system model. Section III explains Load Weight Based energy distribution. Dynamic Pricing per unit charge using Fuzzy Logic Based approach is discussed in Section IV. Results are discussed in Section V and conclusions are given in Section VI.

II. SYSTEM MODEL

The electrical energy is generated from renewable sources like solar, wind and non-renewable sources. This generated energy from the grid is transmitted to various Primary and Secondary substations. Then, the energy is distributed to the users. The energy flow paths are fixed and this entire energy supply chain can be modeled as a Smart Grid Tree Network.

Fig. 1 Energy Flow Tree model in Smart Grid

The energy supply chain using the tree network is shown in Fig. 1. The Primary substations are denoted as junctions and Secondary substations as sub junctions. Then, the energy is distributed to the users using distribution transformers.

In smart grid, the resources are limited and demand is more. The entire day is divided into different time slots. Based on the demand the day and time, 24 hour day time is categorized into 4 types. They are: (i) Day Peak (ii) Day Non Peak (iii) Night Peak (iv) Night Non-peak. The charging price to the customer varies with the demand and time. The unit energy charge is high during the peak demand. The main intention behind this is to decrease the demand during peak hours and brought the load to normal. During non-peak hours intensives are offered to the users to raise the demand during non-peak hours. This classification of time slots and price charges based on the demand and time can be done more clearly using Fuzzy Logic.

The communication among various sections of the tree network can be done by using Communication networking system [36-39] which uses existing networks in a geographical region like Wi-Fi, WLAN, WMAN, Cellular and Optical networks based on the distance between the sections and complexity of the network.

The users send the request to the substations and substations sends total load request to the grid. Computer control centers at various levels monitors the load request. The energy is distributed from the grid to various levels based on the demand and available energy on the grid. The available energy at the grid also varies with time, season and availability of resources in a geographic region and one such example is shown in Fig. 2.

Fig. 2 Energy available at the Grid in a day

During the peak demand, the loads of the users can be handled using weighted based energy distribution algorithm. The load in a day is scheduled properly ahead, and excess load during peak demand hours is shifted to non-peak hours of a day. Later, the users are charged based on the based dynamic pricing using Fuzzy logic.

The following section explains user demand and weighted based energy distribution in a smart grid tree network.

III. LOAD WEIGHT BASED ENERGY DISTRIBUTION

A three tier smart grid tree network with different category of users is shown in Fig. 1. Let the number of Primary substations connected to the grid are \( J \). The number of Secondary substations connected to each Primary substation is \( S \). Number of users connected to the Secondary substations are \( U \). Based on the energy consumption and incentives the users are classified into various categories \( \{ u_0, u_1, u_2, u_3, u_4, u_5 \} \) and are given below.
The load request at any level of the smart grid tree network is given by

\[ L_{i+1} = \sum_i L_i \]  

where \( L_i \) is the load of \( i^{th} \) section connected to \( i+1 \) stage of the smart grid tree network, ‘\( i \)’ represents the users connected to the Secondary substations at \( 1^{st} \) stage \( (i=1 \text{ to } U) \); Secondary substations connected to the Primary substation at \( 2^{nd} \) stage \( (i=1 \text{ to } S) \); Primary substations connected to the grid at \( 2^{nd} \) stage \( (j=1 \text{ to } S) \) in the smart grid tree model.

Let \( E_G \) is total energy on the grid, \( L_G \) is total load request at the grid, then the demand on the grid is given by

\[ D_G = \begin{cases} 
\text{High, if } E_G < L_G \\
\text{Low, if } E_G > L_G 
\end{cases} \]  

When demand is high, we apply Load Weight Based Energy Distribution (LWBED) Algorithm for energy distribution. Energy distributed to the \( i^{th} \) section from the \( i+1 \) stage (for stage 2 and 1) using LWBED is given by

\[ E_i = \frac{L_i}{\sum_i L_i} E_{i+1} \]  

The energy distributed to stage 2 (Secondary substation) is then allocated to various users according to their load request and distributed energy at stage 2 is given by

\[ E_{A_i} = \frac{L_{u_i}}{\sum_i L_{u_i}} E_s \]  

where \( E_s = \) Energy distributed to Secondary substation’s’,

\( L_{u_i} = \) Load requested from all the users of same category \( i=0, 1, 2, 3, 4, 5 \). After this allocation, the energy is distributed to the users of same category \( u_i \) starting from \( u_0 \) and the number of users got the energy distribution is given by

\[ N_u = \left[ \frac{E_{A_i}}{E_{c_i}} \right] \]  

The remaining unallocated users are shifted to nonpeak demand slots. The energy left by \( u_i \) users after allocation is \( E_{A_i} - N_u \times E_{c_i} \). The energy left at \( u_i \) users is added to energy allocated to \( u_{i-1} \) users category, \( i.e. \), \( E_{A_{i-1}} + (E_{A_i} - N_u \times E_{c_i}) \) and then distributed as explained above. This kind of distribution yields high fairness index as the energy left at high energy user is distributed to low energy users. This kind of approach increases the energy distributed to the number of users [40].

**IV. DYNAMIC PRICING WITH LOAD USING FUZZY LOGIC**

Based on the category, time period, time slot \( t_i \) the new pricing rates per unit energy of 1kWh are given in Table 1. The unit charging a price per 1kWh is \( R^h \). Based on the demand and the time slot, the charging price is adjusted and special incentives can be offered during non peak hours to increase the consumption. For example, from 7.00-11.00am during the time slot \( t_i = 0 \text{ to } 4 \) at day peak if the demand is high, new rate \( R^h_{new} = C_1 \times R^h \) for the customer \( (j,s,u) \) and if the demand is low price remains same. \( C_1, C_2 \) are scaling factors with \( C_1 > 1 \) and \( C_1 > C_2 \). \( C_1,C_2 \) depends on the market price. Fuzzy logic is applied to generate price categories of very high, high, low and very low based on the demand (High or low) during day or night time. The Dynamic Pricing with Load using Fuzzy Logic (DPWLFL) is explained in Algorithm 1. A Fuzzy logic based Triangular Membership Function (MTF) is used for the price classification and is given below.

**Table 1: Price based on the Time Zone and Demand**

<table>
<thead>
<tr>
<th>Time Zone Type</th>
<th>Time Zone (( t_i ) value)</th>
<th>( R^h_{new} ) at High Demand ( L_0 &gt; L_{GH} )</th>
<th>( R^h_{new} ) at Low Demand ( L_0 \leq L_{GH} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day peak</td>
<td>7.00-11.00am (0-4)</td>
<td>( C_1 R^h )</td>
<td>( R^h )</td>
</tr>
<tr>
<td>Day non peak</td>
<td>11.00am-5.00pm (4-10)</td>
<td>( C_2 R^h )</td>
<td>( R^h - R^h_{max} )</td>
</tr>
<tr>
<td>Night peak</td>
<td>5.00-9.00pm (10-14)</td>
<td>( C_1 R^h )</td>
<td>( R^h )</td>
</tr>
<tr>
<td>Night non peak</td>
<td>9.00pm-7.00am (14-24)</td>
<td>( C_2 R^h )</td>
<td>( R^h - R^h_{max} )</td>
</tr>
</tbody>
</table>
When demand is low, i.e., $L_G^l \leq L_G^{lH}$, the requested energy is distributed to the customers. When demand is high, the slots are allotted to primary substation, secondary substation using LWBEA method is distributed to the customer using EDTZLC Algorithm. Two cases are considered during high demand. They are: (i) Day/night non peak when $4 \leq t_i < 10 \parallel (14 \leq t_i < 24)$ and (ii) Day/night peak when $0 \leq t_i < 4 \parallel (10 \leq t_i < 14)$.

**Case-I:** $L_G^l > L_G^{lH}$, Demand is High

$$\text{triangle}[\{R_{new}^l(j,s,u):t_i\}] = \begin{cases} 
C_1 R_1^l & \text{for } 0 \leq t_i \leq 4 \\
C_2 R_1^l & \text{for } 4 < t_i \leq 10 \\
C_1 R_1^l & \text{for } 10 < t_i \leq 14 \\
C_2 R_1^l & \text{for } 14 < t_i \leq 24
\end{cases}$$

(10)

**Case-II:** $L_G^l > L_G^{lH}$, Demand is Low

$$\text{triangle}[\{R_{new}^l(j,s,u):t_i\}] = \begin{cases} 
R_1^l & \text{for } 0 \leq t_i \leq 4 \\
R_1^l - R_{lowest}^l & \text{for } 4 < t_i \leq 10 \\
R_1^l & \text{for } 10 < t_i \leq 14 \\
R_1^l - R_{lowest}^l & \text{for } 14 < t_i \leq 24
\end{cases}$$

(11)

The classification of price based on the inputs time and demand as given in Algorithm 2. Later defuzzification logic is applied to calculate the crisp values of new price rate as given in Algorithm 3.

After energy distribution, we charge the users based on the fuzzy logic as described above.

**Algorithm 1 Dynamic Pricing with Load using Fuzzy Logic**

1. for $i = 1$ to $I$ do
2. for $j = 1$ to $J$ do
3. for $k = 1$ to $K$ do
4. if $E_{AG}^i \geq E_{Ag}^i$ then
5. {if $(0 \leq t_i < 4) \parallel (10 \leq t_i < 14)$ then
6. $\text{Price}(i,j,k) \leftarrow \text{Very High}$
7. end if}
8. elseif $(0 \leq t_i < 4) \parallel (10 \leq t_i < 14)$ then
9. $\text{Price}(i,j,k) \leftarrow \text{Low}$
10. end if
11. end for
12. end for
13. end for

**Algorithm 2 Defuzzified output Pricing for Dynamic Load**

1. for $i = 1$ to $I$ do
2. for $j = 1$ to $J$ do
3. for $k = 1$ to $K$ do
4. if $\text{Price}(i,j,k) \leftarrow \text{Very High}$
5. then $R_{new}^l(j,s,u) \leftarrow C_1 \times R_1^l(j,s,u)$
6. elseif $\text{Price}(i,j,k) \leftarrow \text{High}$
7. then $R_{new}^l(j,s,u) \leftarrow C_2 \times R_1^l(j,s,u)$
8. else $\text{Price}(i,j,k) \leftarrow \text{Low}$
9. then $R_{new}^l(j,s,u) \leftarrow R_1^l(j,s,u) - R_{incentive}$
10. end if
11. end for
12. end for

**V. SIMULATION RESULTS**

A tree network with two primary substations, two secondary substations with five different categories of users are considered for implementation. MATLAB is used for simulation [41]. The energy request at various levels of a tree network is shown in the Fig. 3. GR - Requested energy on the grid, GA - allocated energy on the grid, J-Junction, $S_{ij}$ is the subjection connected to $i$-th junction. R indicates energy request, A is allocated energy. The energy is allocated to various levels of the tree network based on the load request using LWBEED scheme is shown in the Fig. 3. From the figure, it can be clearly observed that, if request energy is more, allocated energy also high when compared to less energy request.

![Fig. 3 Energy request at various levels of a tree network](image-url)
The excess and deficit energies at the grid during various time zones before distribution and after distribution are tabulated in Table 2. The excess energy is distributed to the deficit one after shifting and which time slots are shifted to which zones are clearly given. For example, the excess energy of 140kWh at $t_i = 4-10$ is distributed to $t_i = 0-4$ time slot (125kWh) and $t_i = 10-14$ time slot (15kWh).

The energy distribution to different category of users during the time slots $t_i = 0-4$, 4-10, 10-14, 14-16 and 16-24 are shown in Fig. 4-8. ELR is Energy requested, $E_A_B S$ is energy allocated before shift, and $E_A_A S$ is energy allocated after shift. From the figures 4-8, it can be observed that the requested energy is high during high demand, unallocated energy is shifted to lower demand slots. Therefore, the energy allocated before and after the shifting are same. For the time slots with low demand, the requested energy from the users is less compared to available energy, the energy allocated after the shifting is more and equal to available energy.

Table 2. Excess and deficit energies at the grid during various time zones

<table>
<thead>
<tr>
<th>Time Zone $t_i$</th>
<th>Load excess or deficit energy at grid before distribution (kWh)</th>
<th>Energy Deficit after energy distribution energy deficit (kWh)</th>
<th>Excess Energy Distribution to other time slots after shifting</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>123</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>4-10</td>
<td>-</td>
<td>140</td>
<td>125kWh to $t_i = 0-4$ time slot; 15kWh to $t_i = 10-14$</td>
</tr>
<tr>
<td>10-14</td>
<td>141.5</td>
<td>-</td>
<td>144</td>
</tr>
<tr>
<td>14-16</td>
<td>42.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>16-24</td>
<td>-</td>
<td>152.5</td>
<td>129kWh to $t_i = 10-14$; 23kWh to $t_i = 14-16$ time slot</td>
</tr>
</tbody>
</table>

Fig. 4 Energy distributed to different category of users during the time slots $t_i = 0-4$ (Demand high)

Fig. 5 Energy distributed to different category of users during the time slots $t_i = 4-10$ (Demand Low)

Fig. 6 Energy distributed to different category of users during the time slots $t_i = 10-14$ (Demand high)

Fig. 7 Energy distributed to different category of users during the time slots $t_i = 14-16$ (Demand high)

Fig. 8 Energy distributed to different category of users during the time slots $t_i = 16-24$ (Demand Low)
Total energy distributed to different category users in various time slots before and after shift and Pricing rates using Fuzzy algorithm is given in Table 3. For simulation, unit energy charging rates $R_i$ of user category $i$ are $R_1=1, R_2=1.5, R_3=2, R_4=3, R_5=4.5$ considered. The users energies $u_1=1\text{kWh}, u_3=1.5\text{kWh}, u_2=2\text{kWh}, u_4=5\text{kWh}, u_5=10\text{kWh}$ is considered. The energy available in the grid during $t=0-4$ is $550\text{kWh}$, $t=4-10$ is $420\text{kWh}$, $t=10-14$ is $700\text{kWh}$, $t=14-16$ is $450\text{kWh}$, $t=16-24$ is $400\text{kWh}$. Pricing rate is expressed in unit price ($\text{in unit price}$), $C_1=1.5, C_2=1.25, \ \ R^{\text{effective}}_i = 0.1R^i$ values are considered. Here, fixed incentives are considered, but they can be varied from one time zone to another, day to day or season. By regularly monitoring the real time price variations, the values of $C_1, C_2$ can be varied and they can be adjusted to get profits.

From the table it is clearly observed that, the pricing per unit energy is varying with the demand and time zone. The total energy cost in each time slot is clearly given in Table 3. It can be clearly observed that, during high demand in peak hours, the charging rate is high. During nonpeak hours, 10% incentives are offered for the time slots with low demand and when demand is high, normal rates $C_i R_i$ are charged. Hence, pricing with Fuzzy algorithm yields good results.

Table 3. Total energy distributed to different category users in various time slots before and after shift and Pricing rates using Fuzzy algorithm

<table>
<thead>
<tr>
<th>$t$</th>
<th>0-4</th>
<th>4-10</th>
<th>10-14</th>
<th>14-16</th>
<th>16-24</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>$R_5$</th>
</tr>
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<tbody>
<tr>
<td>U1</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td>U2</td>
<td>40</td>
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</table>

VI. CONCLUSION

In this paper, a dynamic weight based energy distribution in a smart grid tree network with fuzzy based pricing is proposed. During high demand, the energy is distributed based on the load. Unallocated slots are shifted to lower demand slots. Based on the demand and time zone, the unit energy charge changes and it controls the excess demand in peak hours and increases the load in non-peak hours.

From the simulation results, it is clearly observed that, the fuzzy based approach yields good results and the users are charged based on the load and time zone. The proposed approach based on dynamic real time pricing analysis with demand level prioritization based charging price provides further refinement in pricing.

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