Impact analysis of electricity pricing on the reliability of integrated Nepal power system

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\begin{abstract}
Time of Use of Electricity Pricing (TOU) strategy is adopted by many countries to reduce the peak load and minimize the cost of Electricity. In this research, the effect of the TOU tariff system on the reliability of the Integrated Nepal Power System (INPS) has been investigated. Implemented TOU is based on three time periods: Peak time, Flat time, and Valley time (PFV). The moving variable method is used to find the optimal PFV period in a day. Particle swarm optimization (PSO) is used to find optimal prices corresponding to the given periods, where two objective functions are converted to a single objective function. Prices are modeled with the demand response and a new load pattern of consumers after TOU has been obtained. Power plants of INPS are modeled into four states model and the Monte-Carlo simulation is used to find the generation adequacy indices like Loss of Load Probability (LOLP), Loss of Load Expected (LOLE), and Loss of Energy Expected (LOEE) before and after the implementation of the TOU. The risk level of INPS is reduced by 37\% and peak load is reduced by 4.2\% after the implementation of TOU. It is found that the reliability of INPS can be improved with the help of TOU.
\end{abstract}

\section{1. Introduction}

Time of Use of Electricity Pricing (TOU) is a tool of demand-side management. It helps to flatten the load curve and reduces the stress in the power system by shifting the load from Peak to Valley time. A properly designed TOU tariff system is beneficial to both - the utility, and the consumers; and increases the reliability of the system [1, 2]. Most of the powerhouses in Nepal are Run-Off-the-River (ROR) type with designed discharge exceedance of around 40\%. Because of the seasonal variation in a generation, and the dynamic nature of the load, Nepal’s power generation is insufficient for more than 60\% of the time in a year. It has resulted in huge power imports from India to fulfill the peak power demand [3]. After the end of load shedding in 2017, Nepal is striving towards the improvement of power system reliability and intends to reduce imports and increase revenue. Fixed TOU system has been adopted in Nepal for Industrial Consumers. Industrial consumers only make up 40\% of the total consumers, so, implementing TOU only for that small part of the total load doesn’t guarantee the peak load reduction and smoothening of the load curve. For other consumers, TOU is not implemented, instead, consumers are categorized in terms of the tariff; such tariffs cause leakages [4]. Developing proper fences to avoid leakages is both challenging, and costly. Various researchers have identified the economic advantages of TOU in specific electricity markets like Brazil [5], Switzerland [6], Taiwan [7], and Australia, etc., and have proposed two times/three time-period tariffs. Three time-period-based TOU tariff and its impact on the reliability of power system in Roy Billiton Test System (RBTS) has been addressed in [8].

This paper presents a new TOU tariff system for INPS over the existing tariff and compares the reliability of the system with the new tariff. Tariff is based on three periods: Peak period, Flat period, and Valley period tariff. Four state model of probability was built to evaluate the reliability of INPS before and after the TOU with the help of Monte Carlo simulation (MCS).
2. Optimal period and new load curve

The moving variables method is used to find the optimal PFV period. It assumes three variables: m1, m2, and m3 corresponding to the Peak period, Flat period, and Valley period between the intervals of [PL_{max}, PL_{min}]. Let PL_{t} (where t = 1, 2... 24) be the hourly load sequence for a day. PL_{min} denotes the minimum of the sequence and PL_{max} the maximum. The objective function is the Root Mean Square Distance (RMSD) between PL_{t} and PL_{max}PL_{min}. The movement of consumers from lower price to a higher price after TOU, and after considering Time-of-Use (TOU), respectively.

\[
R = \sqrt{\sum_{i=1}^{24} \frac{1}{24} (PL_{t} - \sum_{i=1}^{3} O_{ij}M_{ij}P_{L})^{2}} \quad \quad (1)
\]

Where \( j = 1, 2, 3 \) represent the Peak period, Flat period, and Valley period respectively; and \( G_{j} \) is the load set of the \( j \)-th period. If \( P_{L} \) is the element of \( G_{j} \), \( O_{j} = 1 \), otherwise \( O_{j} = 0 \). The set of \( G_{j} \) which has the minimum root mean square distance represents the optimal Peak period, Flat period, and Valley period.

When electricity prices changes, there is the movement of consumer between low price time and higher price time. The price elasticity of the Demand Matrix is used to describe the shift of electricity demand among the periods [9]. The new consumption pattern by the movement of consumers from lower price to a higher price after the TOU can be found from an apportionment technique and is given as:

\[
L_{i}^{before} = L_{i}^{before} \left( 1 + \frac{\Delta E_{M}}{E_{M}} \right) \quad \quad (2)
\]

\( E_{M} \) is the consumption of electricity in the \( m \)-th period before considering Time-of-Use (TOU), \( L_{i}^{before} \) is the load before TOU in the \( i \)-th hour of a day, \( \Delta E_{M} \) is the change in electricity consumption in the \( m \)-th period after TOU, and \( m \) represents different periods such that \( m \in \{ p, f, v \} \).

3. Optimal prices and reliability

Optimal prices for Peak Flat and valley period are obtained with the help of Particle swarm optimization (PSO). Following are the objective function and constraints used in the optimization process.

3.1. Objective function and constraints

Two objective functions are considered for the optimization[10] and they are:

- Minimization of peak period power
  \[
  F_{f1} = \min \{ P_{L_{t}}^{max} | t \in \{1, \ldots, 24\} \} \quad \quad (3)
  \]

- Minimization of difference between peak and valley power difference
  \[
  F_{f2} = \min \{ P_{L_{t}}^{max} | t \in \{1, \ldots, 24\} \} - \min \{ P_{L_{t}}^{max} | t \in \{1, \ldots, 24\} \} \quad \quad (4)
  \]

Here, \( p = (p_{1}, p_{2}, p_{3}) \) are the prices of peak, flat, and valley, respectively and constraints are:[11]

- The Customer Benefit Constraint
  \[
  g_{1}(p) = B(p_{u}) - B(p) \geq 0 \quad \quad (5)
  \]
  Where \( B(p_{u}) \) and \( B(p) \) represent the electricity paid by the customers before and after the Time-of-Use (TOU), respectively.

- The benefit of power supplier The total benefit of the power supplier is not reduced after TOU. i.e.
  \[
  g_{2}(p) = B^{\prime}(p) - (1 - \delta)B(p_{u}) \geq 0 \quad \quad (6)
  \]
  Where \( \delta \) be the benefit coefficient.

- Electricity Rate and constraint of valley period
  \[
  g_{3}(p) = p_{1} - p_{2} > 0 \quad \quad (7)
  \]
  \[
  g_{4}(p) = p_{2} - p_{3} > 0 \quad \quad (8)
  \]
  \[
  g_{5}(p) = p_{3} - p_{c} > 0 \quad \quad (9)
  \]
  \( p_{c} \) is the marginal cost per unit of energy for the utility.

- Load Inversion Constraint
  \[
  P_{p_{min}} - P_{v_{max}} > 0 \quad \quad (8)
  \]

3.2. Optimal prices for peak Flat and valley period

Two objective functions are converted to the single objective functions as:

\[
F(p) = \alpha F_{f1}(p) + \beta F_{f2}(p) + J(p) \quad \quad (9)
\]

Where \( \alpha \) and \( \beta \) are the ratio coefficients of \( F_{f1}(p) \) and \( F_{f2}(p) \). The penalty function \( J(p) \) can be represented as \( J(p) = \phi(k) \times H(p) \) [12]. The PSO algorithm is used to optimize the optimal peak, flat, and valley period prices. The generalized flow chart to calculate the optimal prices using the PSO algorithm is represented in Fig.1.
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![Flow chart of PSO to find Optimal Prices](image)

Figure 1: Flow chart of PSO to find Optimal Prices

4. Reliability evaluation

Monte-Carlo simulation method is used to evaluate the power system reliability. Four states model of the power plant is built with the help of the recursive method. Full Capacity, 67% of the Full Capacity, 33% of the Full Capacity, and Zero Power Available State for accuracy. Uniformly distributed Random number is generated between range [0,1] and it is compared as follows [13]:

- If \( U_1 < P_{\text{down}} \), the unit is deemed to be in a totally downstate.
- If \( P_{\text{down}} < U_1 < [P_{\text{down}} + P_{\text{derated}}] \), the unit is assumed to be in the de-rated state.
- Else, the unit is UP and the total cumulative capacity available in the given simulation is calculated.

The cumulative capacity is compared with the hourly load of the year and reliability indices like LOLE, LOLP, and LOLE were calculated.

5. Test system

The methodology described in the previous section is implemented in INPS. The annual peak load of Nepal was 1408 MW on August 22, 2018 at 7.05 PM. There are a total of ninety-one (91) generators present in INPS contributing 1156 MW of power. Power plants with less than a 1 MW rating have a total contribution of 12 MW in the system. The power that can be imported from India is 750 MW. Powerhouse trip data is collected to evaluate the four states model of probability. Six powerhouses have been taken as reference, and their four states model is built with the help of the recursive method. The four-state model of remaining powerhouses is considered as the average of evaluated powerhouses. According to the annual report published by Nepal Electricity Authority (NEA), the marginal cost for utility is NPR 9 per unit including demand charge, and the average flat-rate tariff price before TOUP is NPR 11 [14].

The Self-elasticity and cross-elasticity matrix coefficient used in this paper can be found in [15].

6. Case study

6.1. Period partitioning

Based on the moving variables method, the optimal Peak period, Flat period, and Valley period partitioning of the hourly sequential load has been obtained. Fig. 2 shows the peak that occurred in INPS from 7 pm to 9 pm in April. INPS followed the same pattern in May, June, July, August, September, October, and late March. Fig. 2 represents the period partition of April.

![Period Partition of April, 22](image)

From Fig. 3, it can be said that during winter, the peak period occurred in the morning from 7 am to 9 am, and in the night from 7 pm to 9 pm. Early March, February, November, December, and January have almost the same pattern as observed in December.

![Period Partition of December, 22](image)
6.2. Optimal prices for the PFV period

Optimal prices for 12 months are calculated by taking a reference of monthly peak load for each month. Optimal prices are given in Table 1. The peak price is higher than the previous price, and the Valley period price is lower than the previous Flat price. The maximum peak price calculated is NPR 16.97 for December because of the larger difference in Peak period power, and Valley period power.

Table 1: Optimal peak flat valley prices

<table>
<thead>
<tr>
<th>Month</th>
<th>Peak Period</th>
<th>Flat Period</th>
<th>Valley Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 15 to May 14</td>
<td>14.29886</td>
<td>12.00604</td>
<td>9.800439</td>
</tr>
<tr>
<td>May 15 to Jun 15</td>
<td>14.84264</td>
<td>10.97393</td>
<td>10.35192</td>
</tr>
<tr>
<td>Jun 16 to Jul 16</td>
<td>14.05584</td>
<td>11.81112</td>
<td>9.068148</td>
</tr>
<tr>
<td>Jul 17 to Aug 17</td>
<td>13.30186</td>
<td>11.23712</td>
<td>9.906389</td>
</tr>
<tr>
<td>Aug 18 to Sep 17</td>
<td>13.22546</td>
<td>11.15368</td>
<td>10.04887</td>
</tr>
<tr>
<td>Sep 17 to Oct 17</td>
<td>14.20161</td>
<td>10.50438</td>
<td>10.06721</td>
</tr>
<tr>
<td>Oct 18 to Nov 16</td>
<td>14.57746</td>
<td>11.60086</td>
<td>9.826976</td>
</tr>
<tr>
<td>Nov 17 to Dec 16</td>
<td>13.30186</td>
<td>11.23712</td>
<td>9.906389</td>
</tr>
<tr>
<td>Dec 17 to Jan 14</td>
<td>13.93853</td>
<td>11.6224</td>
<td>9.296857</td>
</tr>
<tr>
<td>Jan 15 to Feb 14</td>
<td>14.20161</td>
<td>10.50438</td>
<td>10.06721</td>
</tr>
<tr>
<td>Feb 15 to Mar 13</td>
<td>14.57746</td>
<td>11.60086</td>
<td>9.826976</td>
</tr>
<tr>
<td>Mar 13 to Apr 14</td>
<td>16.97902</td>
<td>11.17794</td>
<td>10.04616</td>
</tr>
</tbody>
</table>

7. Daily Load Variation After TOU

Fig. 4 and Fig. 5 represent the load curve after TOU for December 22 and April 22. It is found that by implementing the TOU, the peak load is reduced. The decrease in energy consumption due to reduction of the peak is shifted from peak period to flat and valley period. On December 22 daily peak load before TOU is 1230 MW and it is reduced to 1105 MW after TOU. Similarly, the daily peak of August 22 is 1246 MW before TOU and it is reduced to 1151 MW after TOU.

Fig. 6 represents the load curve August 22 after TOU.

The annual peak load of 1408 MW occurred on this day. After the implementation of TOU the annual peak load is reduced to 1348 MW.

Similarly, a new load pattern for each day of the year was calculated. Monthly peak load variation after the TOU throughout the year is shown in Fig. 7. Daily Peak load after TOU is given in Table 2.
7.1. Reliability evaluation
Most of the power plants of INPS are run off river type with designed discharge around 40%. So, power plants are modeled with two de-rated states of 67% of the Full capacity, and 33% of the Full capacity including Up and Downstate. Table 3 represents the four states model of the probability of the major six power plants of INPS. State 1 represents Full capacity state, State 2 represents 67% of Full capacity state, State 3 represents 33% of Full capacity state, and State 4 represents Zero output state. Six major power plants have taken, and the average is taken for remaining power plants. According to the report of Power Grid of India 2018/2019, transmission line availability is 0.9982. Availability of power import from India is assumed to be equal to transmission line availability. Monte-Carlo simulation has been used to find the reliability indices before and after the TOU with a non-chronological load curve, as shown in Table 4.

8. Conclusion And Discussion
In this paper, TOU based on three time periods has been implemented in INPS. Annual peak demand of INPS reduced to 1335 MW from 1408 MW, risk in the system reduced to 0.000525 from 0.000827, energy not served to the consumer reduced to 530 MWhr/Yr from 1338 MWhr/Yr, and expected outage in an hour per year reduced to 4.59hr from 7.24hr after the TOU is implemented. This indicates that we can improve the reliability of INPS by implementing TOU without
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Table 3: FOUR STATE MODEL OF POWER PLANT

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>State 1</th>
<th>State 2</th>
<th>State 3</th>
<th>State 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>U. Marshy angdi</td>
<td>0.619</td>
<td>0.2688</td>
<td>0.0995</td>
<td>0.0127</td>
</tr>
<tr>
<td>Chilime</td>
<td>0.5427</td>
<td>0.2426</td>
<td>0.1928</td>
<td>0.0219</td>
</tr>
<tr>
<td>Khimiti</td>
<td>0.4695</td>
<td>0.3354</td>
<td>0.1918</td>
<td>0.0033</td>
</tr>
<tr>
<td>Kali gandaki</td>
<td>0.4523</td>
<td>0.2919</td>
<td>0.2557</td>
<td>0.0331</td>
</tr>
<tr>
<td>M. Marshy angdi</td>
<td>0.5199</td>
<td>0.3233</td>
<td>0.1423</td>
<td>0.0144</td>
</tr>
<tr>
<td>L. Marshy angdi</td>
<td>0.5301</td>
<td>0.2865</td>
<td>0.135</td>
<td>0.0484</td>
</tr>
<tr>
<td>Average</td>
<td>0.5223</td>
<td>0.2914</td>
<td>0.1695</td>
<td>0.0223</td>
</tr>
</tbody>
</table>

Figure 8: (a) EENS, (b) LOLE of INPS before TOU from MCS

Figure 9: (a) EENS, (b) LOLE of INPS after TOU from MCS

Table 4: RELIABILITY OF INPS

<table>
<thead>
<tr>
<th>Description</th>
<th>LOLE (Hr/yr)</th>
<th>EENS (MWhr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before TOU</td>
<td>0.0000827</td>
<td>1372.057</td>
</tr>
<tr>
<td>After TOU</td>
<td>0.000525</td>
<td>539.8</td>
</tr>
<tr>
<td>% change</td>
<td>-37</td>
<td>-60</td>
</tr>
</tbody>
</table>

Reducing the benefit to consumers and the utility.

References