Frequency-Based Time-of-Use Pricing with Multiple Battery-buffered Smart Loads

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\textbf{Abstract.} This work discusses a new time-of-use energy pricing structure based on grid frequency. Under the proposed pricing structure, energy cost depends on the time of frequency deviation and the period during which energy is used. This pricing mechanism is intended for use with multiple behind-the-meter home batteries as part of a frequency-controlled smart load strategy known as a battery buffered smart load. The load energy consumption from the grid and energy storage rates thus depend on the frequency deviation and hours of use, which means that the proposed pricing encourages battery-using customers to not only utilise energy arbitrage, shifting peak demand but also to contribute to demand-side primary frequency control. The second contribution of this paper is the presentation of an operation strategy for multiple buffered battery smart load units in which charge and discharge decisions are made according to off- and on-peak period information to ensure continuous provision of primary frequency control under the proposed time of frequency division pricing. A MATLAB simulation of the proposed pricing and operation modes of the BBSL was conducted with multiple battery-buffered smart load to assess feasibility.

\textbf{List of Abbreviations}

| Abbreviation | Description |
|--------------|-------------|
| ToU          | Time-of-use |
| ToFD         | Time of frequency deviation |
| SOC          | State of charging |
| BBSL         | Battery buffered smart load |
| U.S. EIA     | United States energy information administration |

1. Introduction
Electricity prices for the residential sector have been continually increasing according to data provided by the U.S. EIA. Figure 1 shows annual residential kWh prices (in cents) over the last 17 years in the U.S., highlighting that prices have increased by 21% in the last decade. These are expected to increase further, according to the EIA’s projection at least to 2040 [1], due to various factors such as increases in fuel cost, increased demand, additional expenses imposed by compulsory regulations that require utilities to invest in clean energy, increases in maintenance costs, and climate change influences. These factors are differ from state to state, and currently, 13 states in the U.S. still have no renewable energy requirements, while the remaining states require companies to either already fulfil certain standards or be working to meet specific future goals [2]. This means that electricity prices differ by state. Figure 2 shows residential electricity prices in c/kWh by state for July 2016; Arkansas is among the ten lowest priced states, while prices are considerably higher in the northeast states; however, the highest prices are seen in the non-contagious states.

![Figure 1. Annual average electricity prices for the residential sector in the U.S.](image1)

Figure 1. Annual average electricity prices for the residential sector in the U.S.

![Figure 2. Residential electricity prices for each state July 2016](image2)

Figure 2. Residential electricity prices for each state July 2016 [2].

In the face of increasing electricity prices, end user-oriented services based on time-of-use (ToU) energy arbitrage can be provided by battery energy storage systems being positioned behind users’ energy meters that may offer considerable economic benefits. With time-of-use energy rate plans, utilities charge different electricity prices based on the time of the day during which users consume energy. This incentivises users participating in ToU plans to alter their patterns of their energy consumption to shift away from use during more expensive peak hours, which both enables users to achieve savings in their electricity bills and reduces peaks in demand. Energy storage allows such shifts to be attained more seamlessly and conveniently based on storing energy when the rate is low and using it later as required, in a similar manner to filling up a water tank or recording a movie or a television show to watch later. In this paper, section 2 introduces frequency-based time-of-use pricing more comprehensively, while section 3 offers an outline time of frequency deviation with multiple battery buffered smart loads, with several numerical results and their validations discussed in section four. Finally, a conclusion and a list of references are attached as sections five and six, respectively.

2. Frequency Based Time-of-Use Pricing

Time-of-use energy pricing consists of two or three levels of constant off-peak and on-peak rates as set by the utility company. The primary aim of such time-of-use rates is to shift demand to even out peak and off-peak demand [3 - 4]. Primary frequency control can be applied at any time required by the system, regardless of the time of the day or time-of-use of energy pricing, however [5-6], and thus constant off-peak and on-peak rates are not ideal for the regulation of energy achieved by battery buffered smart loads. A more practical system of BBSL, as well as
the relevant experimental setup, block diagrams, and schematic diagrams, were discussed and presented in the authors’ previous publications [7-8].

During an off-peak period, where the energy price is low, battery buffered smart load BBSL users might not be willing to provide under frequency regulation or to discharge the BBSL battery to reduce their load consumption. The same applies to on-peak periods, where BBSL users might find it unreasonable to charge batteries to provide over-frequency regulation due to the higher prices at such a time. Under-frequency and over-frequency regulation in off-peak and on-peak periods, respectively, interfere with enticements from a monetary perspective. This suggests that utility companies should offer more enticing pricing to motivate BBSL customers to contribute to primary frequency control.

In this work, a new time-of-use energy pricing structure is thus proposed based on the grid frequency. Under this proposal, energy costs depend on Time of Frequency Deviation (ToFD) and the daily time during which energy is used. Compared to other frequency-based real-time pricing structures for distributed energy prosumers [9] and other real-time pricing presentations [10-11], this ToFD pricing encourages BBSL customers to not only use energy arbitrage to shift peak demand but also to contribute to primary frequency control. The structure of the proposed frequency-based pricing is described in the flowchart in Figure 3 and its characteristics are outlined in Figure 4, which shows how the rate is selected according to the frequency condition and the time of the day.

When the frequency deviation is positive and stretches beyond the dead-band, the rate is set at a low level; in contrast, the rate is set to a high level when the frequency deviation is negative in a way that stretches beyond the dead-band. Within the dead-band, the rate is decided solely according to the time of the day. The high and low rates in this work are based on the Arkansas time-of-use plan as of April 2020, as shown in Table 1.

A time of frequency deviation with multiple battery buffered smart loads is thus introduced with two modes of operation for multiple BBSL systems.
**Figure 3.** The structure of the proposed frequency-based time-of-use pricing.

**Figure 4.** Price-frequency deviation characteristics.
Table 1. Arkansas energy (time-of-use) rate plans [5].

| Time Period   | Price       | 1:00 AM | 2:00 AM | 3:00 AM | 4:00 AM | 5:00 AM | 6:00 AM | 7:00 AM | 8:00 AM | 9:00 AM | 10:00 AM | 11:00 AM | 12:00 PM | 1:00 PM | 2:00 PM | 3:00 PM | 4:00 PM | 5:00 PM | 6:00 PM | 7:00 PM | 8:00 PM | 9:00 PM | 10:00 PM | 11:00 PM | 12:00 AM |
|---------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Jan-to-May    | 0.17655 $/kWh | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jun-to-Sep    | 0.05254 $/kWh | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Oct-to-Dec    |             | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

Within frequency regulation mechanisms as used in the power system currently, the frequency is strongly tied to the active power balance in the system. The effect of change in the active power of the power system can thus be translated into a frequency deviation, and regulation of the frequency can be performed by adjusting the active power. The power-frequency relationship is governed by the dynamic behaviour of a synchronous generator, described by the swing equation, which is one of the power system fundamentals. The BBSL is primarily part of the demand-side primary frequency control, acting as a frequency-responsive load with the aid of battery energy storage. The established droop control strategy as employed on the governors of the generation units is thus used for the proposed smart load to modulate the energy flow among the battery, the load, and grid based on frequency conditions [7].

Full details on the battery model used with the BBSL are offered in the authors’ previous work. The battery model here is used to mainly portray the state of charge, as the battery voltage remained relatively constant (variation not exceeding ±0.25V) in the conducted experiments, as the state of charge (SOC) was maintained within the range 20 to 80%. This SOC was estimated using conventional coulomb counting, i.e., the current integration method, in both the experimental setup and simulation [8].

3. Time of Frequency Deviation with Multiple BBSLs

The proposed pricing structure can be used in conjunction with multiple BBSL units; here, the case of two units is considered. The first unit was controlled to provide only over-frequency unidirectional regulation within a daily window. The battery state of charge began at the minimum level and in the period where energy use is encouraged by the time-of-use strategy, the battery buffer of the smart load operates to provide over-frequency regulation with offset power. In the on-peak period where reduced energy consumption is encouraged, the BBSL operation was switched to over-frequency regulation without offset power. At the end of the on-peak period, the SOC reached its maximum level. This mode of operation, applied over a 24-hour operation window, is referred to as mode 1. The second unit is simultaneously controlled with a different mechanism, referred to as mode 2, in which the battery provided under-frequency regulation (discharge only).

This battery began in the maximum state of charge, being discharged following the frequency deviation without any offset power in the off-peak period where discharge is not encouraged. In the on-peak period, the offset discharge power was thus applied to bring the
battery state of charge to the minimum level at the end of the on-peak period. At the end of the 24-hour operation window, the two units then switch modes to achieve energy arbitrage. The two modes of operation are shown in Figure 5.

![Figure 5. The two modes of operation for multiple BBSL systems.](image)

4. Simulation Results and Verifications

In this section, the proposed scenario was verified using MATLAB simulation resources. The time response was checked using the simulation values provided within the scheme design parameters, with the structure of the proposed frequency-based time of the simulated case study as mentioned in Figure 3. The simulation results can be classified into a frequency-based time-of-use pricing and time of frequency deviation with multiple battery buffered smart loads.

4.1. Simulation results of Frequency-Based Time-of-use Pricing

The daily window of the frequency-based time-of-use plan at different dead-bands, based on Arkansas time-of-use structure, is shown in Figure 6. It is notable that when no dead-band is used, the rate mainly depends on the frequency deviation; the time of the day has little to no effect on the price. The wider the dead-band applied, the more the rate depends on the time of the day. This makes it necessary to sift through the number of hours for each price level in the generated pricing signal and to compare these to the conventional Arkansas time-of-use plan, which contains 13 hours of low pricing and 11 hours of high pricing.

The generated frequency-based pricing does not necessarily provide the same number of hours, however, as the low price and high price hours vary from day to day based on the applied dead-band and frequency conditions.
4.2. Simulation Results for Time of Frequency Deviation with Multiple BBSLs

The offset power and droop settings were selected to achieve the state of charge targets using the lowest required offset power and highest achievable regulation. The developed frequency-based time-of-use pricing method was thus structured to coordinate with the operation modes of multiple BBSL units to always attain the best price for energy arbitrage and to offer compensation for any regulation provided.

Charge energy from the over frequency regulation in on-peak hours is purchased at a low price, while the price must be high in the on-peak period. Similar commentary can be offered for off-peak hours based on under frequency regulation. The simulation results for the first and second operation modes for the daily operation window are thus presented in Figure 7 and Figure 8, respectively.
Figure 7. The first mode of operation based on time of frequency deviation with multiple BBSLs
Figure 8. The second mode of operation based on time of frequency deviation with multiple BBSLs.
5. Conclusion and Remarks

In this study, energy arbitrage combined with primary frequency control was found to increase the value and utilisation of batteries under a battery-buffered smart load strategy. The proposed frequency division pricing can thus be used by utility companies to incentivise customers with battery buffered smart loads to participate in primary frequency control regulation. The energy rate is derived from the correlation between the time of the day and the grid frequency condition. This energy pricing scheme is designed to be applied with multiple battery buffered smart load systems to permit continuous compensation of the primary frequency control energy transactions made by the smart loads while delivering energy arbitrage savings. The effectiveness of the proposed approach was shown through numerical simulations, which also confirm the applicability of the new time-of-use energy pricing structure based on the grid frequency.

6. References

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