A Frequency Based Real-time Electricity Rate for Residential Prosumers

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***Abstract*—The emergence of distributed generation has made a case for a deregulated, competitive, transactive energy market, operating at the level of the traditional residential consumer. These new energy players, prosumers, will interact as the larger energy generators do under the supervision of Independent System Operators (ISOs), but with their own Distributed System Operators (DSOs). This work proposes a prosumer energy management scheme, broken into a day-ahead schedule and a real-time adjustment, mirroring the ISO market structure. Within this framework, a dynamic rate can be designed and tested for the prosumer. A time-of-use (TOU) rate was combined with a frequency based, real-time dynamic rate to produce a hybrid rate that the prosumer can optimize for during its day-ahead and real-time dispatch. This hybrid rate can be calculated every one minute and applied autonomously from the grid frequency, providing secondary frequency regulation and an incentive for better solar management and use of energy storage. Such a real-time rate is the first designed for price-reactive control. In simulation, the real-time hybrid rate is compared to conventional TOU and flat rates and the final daily energy costs are calculated for a variety of residential load types with a realistic distributed solar generation curve gathered from Pecan Street Inc. Dataport. Under the one minute hybrid rate, the results indicate a near zero energy bill can be achieved for a prosumer with day-time load and smart use of energy storage.**

***Index Terms*—Economic Dispatch, Microgrid, Autonomous, Distributed, and Transactive Control, Energy Router, Energy Cell**

I. Introduction

Increased penetration of renewables, especially distributed generation (DG) onto the grid creates challenges in terms of stability, reliability, and control. The California Independent System Operator (CAISO) explains these challenges in terms of its anticipated "Duck Curve" [1]. As the capacity of grid connected solar increases in California, the predicted load minus the expected renewable generation (net load), ramps down during the mid-day and then sharply up in the late afternoon as solar generation decreases and load reaches one of its daily peaks. To maintain demand, more and more ramping flexibility will be needed. Oversupply during the day is also a concern.

Dynamic pricing has been proposed as a control mechanism, [2][3] giving the prosumers agency to participate in the market rather than solely respond as customers in the one-directional legacy system. Integrating demand and supply flexibility into the operation of the electricity system allows for a more efficient market, predictable dynamic price response, and optimal utilization of distributed energy resources (DERs) [2]. Current schemes for residential prosumers include flat rates, time-of-use (TOU) rates, net metering, critical peak pricing, etc., [4] while researchers have begun to explore real-time price reaction and transactive control [5][6]. Transactive control is a mechanism for the Internet of Things or the Energy Internet, enabling prosumers to compete with each other in a deregulated market via a consumer-to-consumer commerce model, similar to eBay [7][8].

On the power systems' side, Distribution System Operators (DSOs) have been proposed to be the facilitators of energy transactions at the substation or even microgrid level, acting as an interface between the existing Independent Service Operator (ISO) or balancing authority and the owners and operators of demand side assets (prosumers) [4]. At the power electronics level, technologies such as the solid-state transformer (SST) have been touted as an essential device for the smart grid [9]. As a smart transformer, the SST operates as the energy router of the smart grid, regulating power flow to and from its microgrid at its point of common coupling to the main grid. It provides isolation, islanding, voltage and frequency control, and can measure the grid frequency [10].

An electricity rate that fluctuates in real-time is based on supply and demand, is the product of a competitive market, and reflects additional services provided to or purchased from the grid, in effect reducing the anticipated duck curve. In such a market, there will be a stronger business case to store or curtail renewable generation when supply is high and demand is low. Additionally, energy storage can be used to smooth expensive load peaks. This paper explores the concept of using a one minute, real-time frequency based rate on top of a baseline TOU rate. While a true prosumer-to-prosumer transactive market is still on the horizon, this real-time rate reflects an intermediate or alternate step, allowing the grid frequency to act as a price signal, autonomously determining the rate from the utility or local distribution coordinator to the prosumer. The

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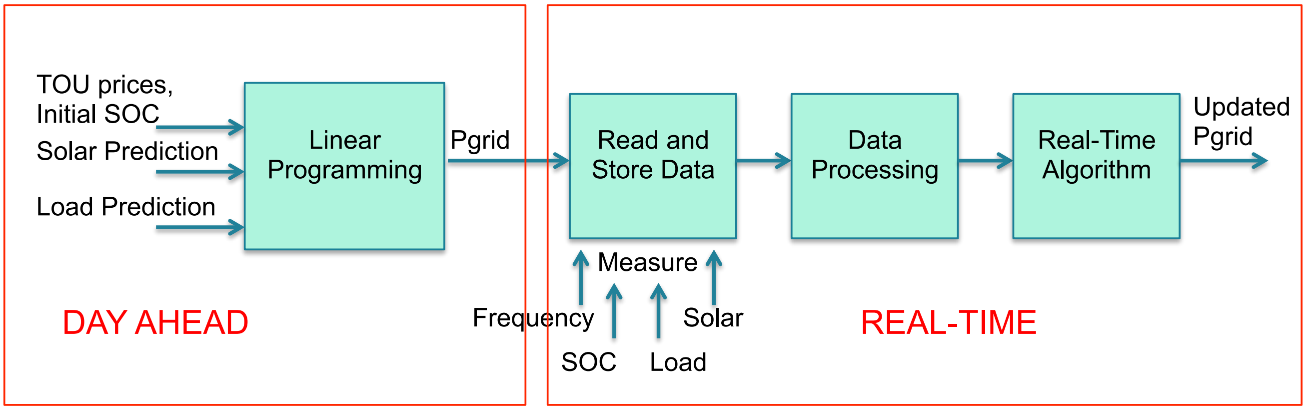

Fig. 1. Prosumer Energy Management Framework

prosumer's response to such a variable rate (whether from a deregulated market, a frequency based price, or a price signal from a utility) has yet to be fully analyzed [11][12]. However, there has been energy scheduling for day-ahead and TOU rates [13][14]. This paper will consider a prosumer's residential load and solar curve patterns in determining the most economic rate.

Using the grid frequency as a droop control has been explored for microgrids [15]. As DERs increase, frequency regulation will become an important grid service. As contributors to the variability of power flow on the grid, prosumers should have a role in controlling the grid frequency, as an ancillary service. Loads can be signaled to respond to deviations or prosumers can respond to a real-time frequency based price [16]. Previous work has shown that prosumers can bring frequency deviations back to their nominal values after small perturbations [17]. In the bulk power system, governor response is used to balance instantaneous perturbations as primary regulation and automatic generation control (AGC) finds a generation-load balance as secondary regulation [18]. The response of loads and DER should be shared with the synchronous generators. System frequency elasticity has been defined along with a price droop signal in order to adjust the sensitivity of DER response to changes in the system frequency [19]. Using frequency to generate a real-time price is an easy way to simulate what a future transactive price may look like for a prosumer. In practice, it is an autonomous signal that can be measured by the prosumer at their location and requires no communications with other devices [16].

This paper explores the benefits of real-time, dynamic pricing for residential prosumers. Section II will be the problem set-up including the rate structure and linear programming problem definition. Section III will be the simulation results and Section IV will be the conclusion and future work.

II. Problem Set-Up

A. Energy Management Design

Fig. 1 proposes a day-ahead and real-time energy management framework for a residential prosumer. While, the prosumer's response is purely reactive in this work (there are no incentives for the prosumer to inject power onto the grid or methods to negotiate a price), a similar structure may be used for other types of hybrid rates or energy transactions and negotiations among prosumers. In this analysis, the prosumer uses linear programming to make a scheduled P_{grid} reference based on it's known TOU prices and solar and load predictions for one day. As the day progresses, the prosumer calculates the real-time energy price by reading the grid frequency every one second and processing and averaging the data to determine the real-time price every one minute. The real-time price, which the prosumer will ultimately be billed for, is the frequency based price added to the existing TOU price for each minute. At one minute intervals, the prosumer measures its current energy storage state of charge (SOC), and current solar and load values, allowing for errors between the forecasted and actual amounts to be considered.

B. Hybrid Rate

A hybrid rate was constructed using a TOU rate plus a frequency based rate. Frequency data measured every 0.10 seconds was obtained from FNET through CURENT, the University of Tennessee, Knoxville, and Oak Ridge National Laboratory. From the data, a one minute and a seven minute moving average were calculated as shown in Fig. 2 and a price was assigned to each frequency calculation as shown in Fig. 3. A new average was calculated every one minute for a total of 1440 data points for one day. The baseline TOU price for the hybrid rate was based on TOU rates from Southern Edison (SE). With an off-peak rate of 0.12 \$/kWh, the maximum and minimum thresholds for the frequency based price were set to $\pm$ 0.12 \$/kWh to maintain symmetry and prevent the total price from being negative. The price vs. frequency function in Fig. 3 is based on previous work in [16].

Two hybrid rates were designed by adding the frequency based price to the TOU SE baseline. One used the one minute moving average and the other the seven minute moving average. These two hybrid rates were compared to three other commonly used rates: a flat rate, a TOU rate based from Duke Energy Progress (DEP), and the TOU SE based from Southern

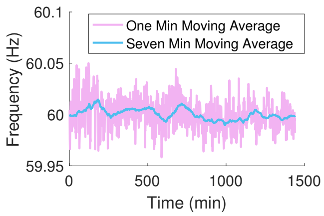

Fig. 2. Frequency moving average

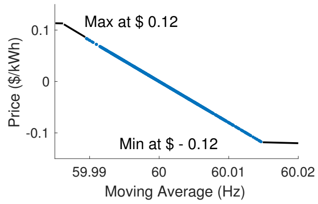

Fig. 3. Price vs. Moving Average

TABLE I
RATES, PRICE/KWH

Rate	Details
Flat Rate	$0.20
TOU DEP	Off-peak (8 p.m. - 11 a.m.): $0.12
	On-peak (1 p.m. - 6 p.m.): $0.28
	Shoulder: $0.22
TOU SE	Off-peak (10 p.m. - 8 a.m.): $0.12
	On-peak: $0.28
Seven Min Hybrid	TOU SE ± $0.12 max
One Min Hybrid	TOU SE ± $0.12 max

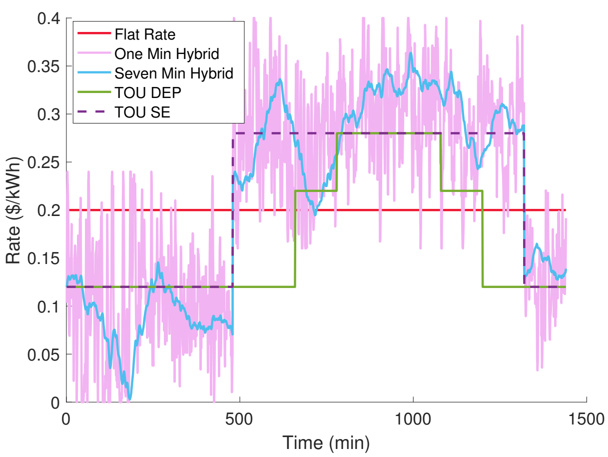

Fig. 4. Electricity Rates

Edison. The TOU SE rate was chosen because it defined peak hours to be during the challenging early evening hours of the duck curve. The TOU DEP does not schedule it's peak hours during this time, but has a shoulder category during May, when the load data was measured. For sake of comparison both TOU rates were designed to have the same peak and off-peak price. These rates are detailed in Table I and shown together in Fig. 4. For a flat, 1 kW daily load, all five rates are about the same: $4.80 for the Flat Rate, $4.08 for the TOU DEP, $5.12 for the TOU SE, $5.05 for the Seven Min Hybrid, and $5.11 for the One Min Hybrid rate.

C. Optimization Formulation

Linear Programming was used to solve for the lowest energy price to the prosumer, using a given rate, load, solar photovoltaic (PV) curve, and energy storage device [13]. Implementation of a hybrid rate is proposed according to Fig. 1, where linear programming would solve for the day-ahead schedule using the known TOU price and then a smart algorithm or artificial intelligence would measure the frequency and device parameters, determine the frequency based real-time price, and make adjustments to the day-ahead schedule. In this work, linear programming was used to solve for the total hybrid price (day-ahead plus real-time) in order to compare the optimal outcome with other rates (TOU and flat rate). Implementation of the hybrid rate would be expected to near the mathematical optimum.

In this problem, $\min_x\{f^T x\}$, the decision variables are $x = [P_{grid}(t), P_{pv_{used}}(t), P_{charge}(t), P_{discharge}(t), SOC(t)]$. The total cost of energy to the prosumer should be minimized for one day according to the objective function

$$Min \quad f = \sum_{t=1}^{T} \tau C_{grid}(t) P_{grid}(t) + k(P_{charge}(t) + P_{discharge}(t)) \quad (1)$$

For the equality constraints, the power balancing equation for the prosumer is

$$P_{grid}(t) = P_{load}(t) - P_{pv_{used}}(t) + P_{charge}(t) - P_{discharge}(t) \quad (2)$$

and the SOC for the battery, housed as an Energy Storage System (ESS) is

$$SOC(t) = SOC_i + \frac{\tau}{cap} \sum_{j=1}^{t} (P_{charge}(j) - P_{discharge}(j)) \quad (3)$$

The inequality constraint is

$$P_{pv_{used}}(t) \leq P_{pv}(t) \quad (4)$$

In (1), t is the time in minutes (where T is 1440 minutes in one day), τ is the time constant in hours, $C_{grid}(t)$ is the cost of electricity (the electricity rate) in $/kWh, and $P_{grid}(t)$ is the power in kW flowing through the meter, while k is a constant in $/kW to account for the cost to the lifetime of the battery, multiplied by the power in kW charging or discharging, $P_{charge}(t)$ and $P_{discharge}(t)$. The constant, k, was set to 0.0002 $/kW, estimated from partial charges occurring in a 10 kWh ESS costing 200 $/kWh with about 3000 full cycles until failure. Modeling a more detailed battery cost function is the future work.

Equation (2) includes the load, $P_{load}(t)$ and PV generation, $P_{pv_{used}}(t)$. In (3), SOC_i is the initial SOC (at t = 0) measuring 0.3 and the cap is the capacity of the ESS at 10 kWh. As shown in (4), if excess PV power is generated, but cannot be stored or used, it is assumed to be curtailed or wasted in

TABLE II
UPPER AND LOWER BOUNDS FOR OPTIMIZATION VARIABLES, IN KW EXCEPT FOR SOC (OUT OF 1)

Variable	Lower Bound	Upper Bound
$P_{grid}(t)$	0	15
$P_{pv_{used}}(t)$	0	10
$P_{charge}(t)$	0	4
$P_{discharge}(t)$	0	4
$SOC(t)$	0.3	0.99

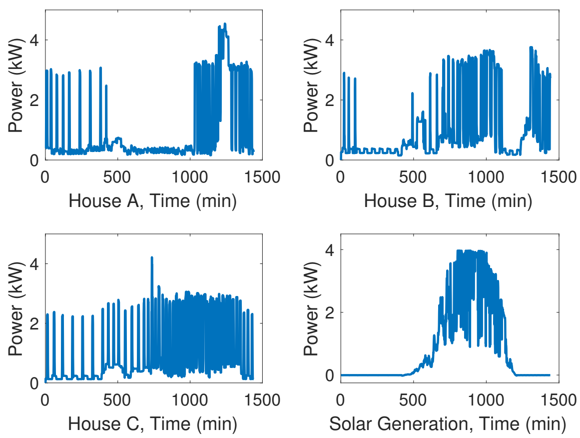

Fig. 5. Load and Solar Profiles, Source: Pecan Street Inc. Dataport 2016

this formulation. The $P_{pv}(t)$ is the generation potential and $P_{pv_{used}}(t)$ is the portion after curtailment.

The upper and lower bounds for each of the x variables are defined in Table II. There are no incentives to inject power onto the grid, so $P_{grid}(t)$ is defined as one directional power flow to the prosumer. Future work will consider the cases where power flow is bi-directional.

III. SIMULATION RESULTS

Residential data from Pecan Street Inc. Dataport 2016 was used to analyze various home load and solar curves and to size energy storage for such homes. In Fig. 5, three houses (A, B, and C) were selected in order to compare different load patterns. The data was taken from three different houses, measured every one minute, all located in Austin, Texas, in May 2012. Each home has a corresponding PV generation curve for each day, but one curve was chosen as shown in Fig. 5, in order to compare the load types. The PV generation was fairly similar between each house, as they are all located in Austin. As commonly cited in the solar industry [20], two days for one house have more similar load curves than two different houses during the same day. House A has a night focus, House B has a day focus, and House C has a mostly equal, but day/evening focus pattern.

The lowest energy cost for each house was calculated according to each of the five rates using the linear programming equations. The results are shown in Table III. The energy cost

TABLE III
ENERGY COST FOR ONE DAY (\$), SOURCE: PECAN STREET INC. DATAPORT 2016

		Load Only	Load with PV	Pgrid: Load PV, ESS	Cost to ESS
Flat Rate	House A	4.6084	3.6126	2.0497	0.1875
	House B	4.8136	2.4129	0.8584	0.186
	House C	4.8448	2.6534	0.9688	0.2021
TOU DEP	House A	3.6045	2.4285	1.2305	0.1875
	House B	4.8345	1.7662	0.515	0.186
	House C	4.709	1.9684	0.5813	0.2021
TOU SE	House A	5.0712	3.6787	1.4083	0.1999
	House B	5.7746	2.4152	0.515	0.2182
	House C	5.8769	2.8105	0.5813	0.2289
Seven Min Hybrid	House A	5.2043	3.6839	1.0847	0.2739
	House B	6.0999	2.4282	0.1835	0.2555
	House C	6.0755	2.7312	0.1962	0.2837
One Min Hybrid	House A	5.1859	3.7267	0.6837	0.337
	House B	5.956	2.4646	0.0496	0.2729
	House C	5.9958	2.7984	0.0687	0.3028

was optimized so that the sum of the third and fourth columns were the lowest. The third column, the cost related to P_{grid}, is the amount the prosumer owes to its local energy provider, while the fourth column, the cost to its Energy Storage System (ESS), is an internal cost to the prosumer. The focus of the simulation is to optimize for variable costs in order to study the effects of load patterns and rate structures on energy scheduling.

The total daily consumption was similar for each house. House A had a load of 23.04 kWh, House B a load of 24.07 kWh, and House C a load of 24.22 kWh, as is shown for the flat rate with House A having the lowest price for its load only. PV generation was 21.63 kWh. With the addition of PV (the second column), House A became more expensive than the other houses. House B and C were able to utilize the majority of their PV generation because more of their energy consumption occurred during the day. Adding an ESS did help House A, as shown in the third column, but the benefits were much greater to the other two houses, who could store most of their excess solar in a 10 kWh battery ESS. House A would need a larger ESS to see these benefits.

The P_{grid} cost to the prosumer did not fluctuate between the TOU rates for House B and C. There was enough PV generation and ESS capacity during the peak and shoulder hours that the difference between these two rates did not affect the total cost to the prosumer.

By far, the hybrid rates proved to be the most economical to all three houses. The advantage of such a dynamic rate is that high and low prices are distributed more evenly instead of being clumped together during peak and off-peak hours, allowing for more economical use of energy storage. The cost to ESS is slightly higher during the hybrid rates than the other

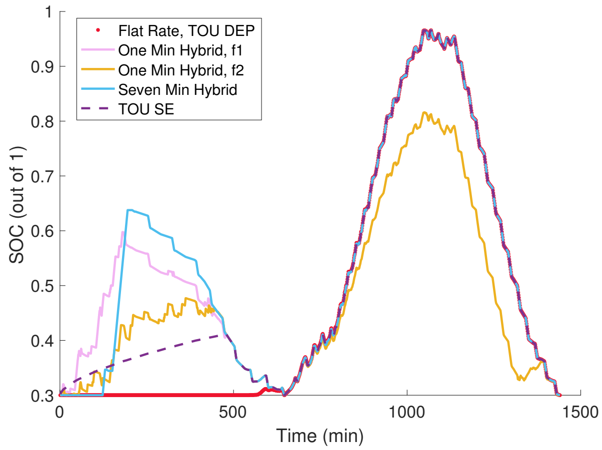

Fig. 6. SOC for House C, Source: Pecan Street Inc. Dataport 2016

rates, as a result. Despite the increase of Cost to ESS, the one minute hybrid rate is the most economical, charging \$0.4096 to House B and \$0.0687 to House C. The strength of this rate is that it can essentially lower the prosumer's bill to zero while providing one minute frequency regulation and maintaining smart use of energy storage.

In Fig. 6, the SOC is plotted for House C for each of the rates. Compared to the TOU and flat rates, the hybrid rates encourage the ESS to charge and discharge during the morning, increasing the time it is used for the day, and lowering the total energy cost to the prosumer. There are two one minute hybrid rates graphed in Fig. 6. The first, f1, is the one minute hybrid rate in the simulation. The second, f2, uses frequency data from the following day. The energy prices using a second frequency curve for the one minute hybrid rate are similar: \$0.5089 for House A, \$0.131 for House B, and \$0.1567 for House C. Unlike the other rates, the f2 rate requires less charging during the second half of the day for House C (Fig. 6), possibly indicating that a smaller ESS could be used.

IV. Conclusion

As shown in this work, real-time, dynamic prices benefit the prosumer and create an economical case for energy storage. Prosumers with load and PV save more by using an ESS under a real-time one minute or seven minute hybrid rate than under a standard TOU rate. As renewable generation grows, PV penetration onto the grid will become more prevalent, contributing to the duck curve. To solve this problem, prosumers must be disincentivized to inject their excess generation onto the grid. By responding to a real-time rate that reflects current supply and demand, prosumers will see more savings with energy storage and be incentivized to help balance the grid. The grid frequency provides a signal for energy imbalance and is an easy, autonomous way to construct a real-time price and provide ancillary services. Similar to the energy markets of ISOs, this work proposes that prosumers respond to dynamic markets in a similar fashion: a day-ahead schedule for known energy transactions, such as the TOU rate, and a real-time adjustment for grid balancing, via a real-time price.

Future work will use additional data to prove the frequency based pricing concept and consider the role of DSOs and mechanism for grid balancing in a future grid with high DERs.

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