Proposing a Frequency Based Real-Time Energy Market and Economic Dispatch Strategy

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***Abstract*—Smart grid technology and the Energy Internet are reliant on a new, competitive, deregulated energy market, that supports energy transactions among energy players: utilities, consumers, and prosumers, alike. Such an energy market is being developed to ensure grid reliability, health, and economic operation with the emergence of microgrids, distributed renewable generation, Distributed Energy Storage Devices (DESDs), controllable loads, and Energy Cells. The solid-state transformer (SST) presents a new opportunity to regulate power flow from Energy Cells to the grid in real-time. As the proposed Energy Router of the smart grid, the SST will facilitate energy transactions as an intelligent node, providing communication, frequency and power management. In this work, a frequency based real-time energy market is proposed. Here, it is demonstrated that the grid frequency is a real-time price signal (measured by the SST) which can be used to autonomously calculate the real-time energy price for all energy players, reducing the need to establish complicated networks to determine the market clearing price. In addition to providing a real-time price, frequency based pricing increases grid reliability as energy players respond to frequency deviations and provide frequency regulation as an ancillary service. A simulation was designed to respond to the steady-state frequency deviation in five minute intervals. A pricing curve and DESD response curve were designed to identify key parameters and solve for optimal solutions that benefit energy producers and consumers.**

I. Introduction

As the generation of renewable energy and use of energy storage becomes more popular in the future grid, there will be a need to establish a new energy market. Much of this generation and storage is expected to operate on the distribution level as consumers become prosumers [1]. The deregulation of utilities has started to promote the competitive environment needed [2] to support bi-directional flow of energy which should be designed to benefit prosumers and utilities alike. Research in transactive energy and distribution locational marginal pricing has helped determine how energy prices could be set in this new competitive market, the Energy Internet.

The Energy Internet is envisioned to exist as a competitive marketplace, which supports real-time energy transactions among energy players. The solid-state transformer (SST) has been developed as a smart transformer and is a revolutionary piece of technology that will enable real-time energy transactions. The SST is proposed to be the Energy Router of the smart grid [3] as shown in Fig. 1. The functionality of an Energy Router is to control power flow to and from the existing grid to smaller microgrids, or Energy Cells. In addition to power flow regulation, the SST will measure grid frequency, provide power management and grid stability, connect and disconnect Energy Cells as needed (referred to as islanding), and house distributed grid intelligence (DGI) needed to communicate with other SSTs and energy nodes in the smart grid [4][5].

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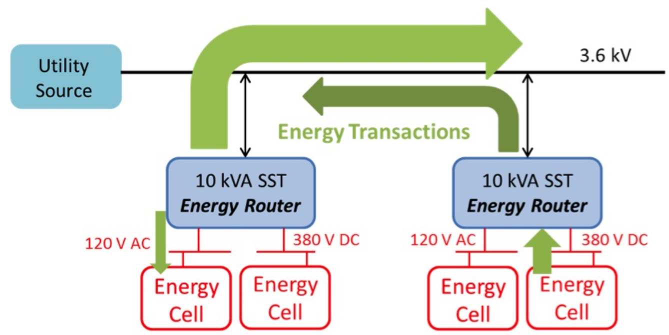

Fig. 1. Energy Router Concept

From the utility's perspective, the price of energy corresponds to the number of generators online and the type of plant and fuel being used along with ancillary services paid to keep the grid stable and functional. The utility uses mature day-head and hour-ahead load forecasting to plan ramping schedules for generation. But it also has to adjust for smaller variations that take place in the matter of seconds or minutes, instantaneously, which create deviations from the expected frequency value [6]. A combination of primary and secondary control is used to adjust the grid frequency during these deviations. Primary control can react in seconds, while secondary control reacts a little slower, in minutes. Control loops such as automatic generation control (AGC) are a form of secondary control that automatically adjust the grid frequency according to a frequency reference [6]. The frequency of the grid is maintained at 60 Hz in the United States and its nominal operating range is 59.98 to 60.02 Hz.

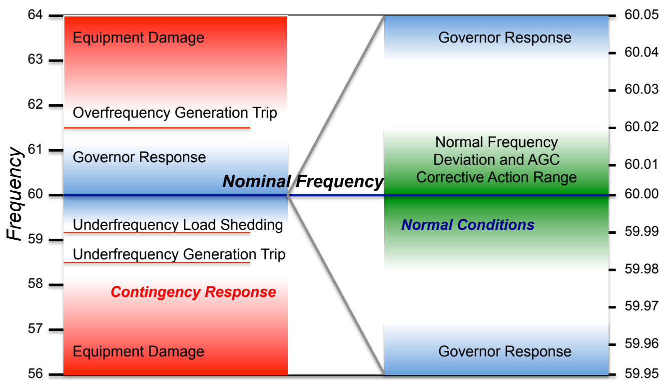

Fig. 2. Grid Frequency and Control, adapted from [7]

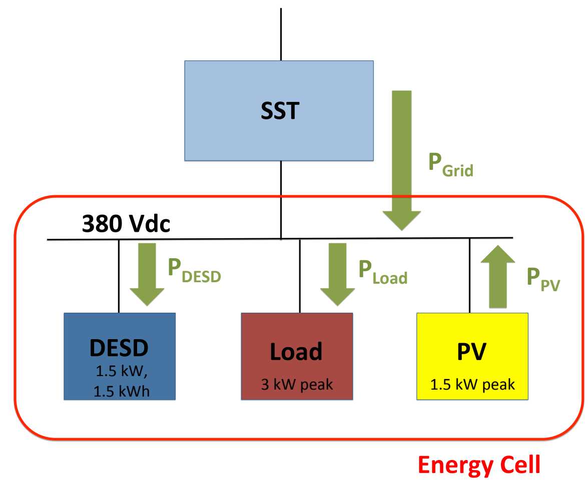

Fig. 3. SST enabled Energy Cell, adapted from [3]

As seen in Fig. 2, governors and devices providing ancillary services must respond if the frequency leaves the nominal range. The grid can be thought of as a container that has water flowing into it at the top and out of it through a hole in the bottom. To maintain a steady level of water in the container (60 Hz grid frequency), the water flowing into the container (supply) must match the speed of the water flowing out (demand) [6]. Around the limit of 59.1 Hz, underfrequency load shedding will start to occur, which means that loads will involuntarily be dropped from the grid. At the upper and lower limits of 61.5 and 58.5 Hz, the generators will trip in order to prevent equipment damage (see Fig. 2).

Power injection onto the grid can be viewed by the utility as an ancillary service, when conducted during periods of low frequency. As shown in [8] the utility will pay a price, an average of 33 Euros/MWh, in this case, for upward frequency regulation. In terms of ancillary services there are often different prices for upward and downward regulation [9]. Rules have been developed to compensate frequency regulation according to performance and reliability enhancement which will encourage better use of devices providing ancillary services [9][10]. However, these rules should influence the cost of energy in order to affect the behavior of consumers and prosumers at the distribution level. As explained in [11], a frequency dependent price component called the Unscheduled Interchange Charge was introduced in India in 2002 as part of a pricing scheme called the Availability Based Tariff, creating a real-time market, which has been successful in regulating the Indian grid frequency. Additional control schemes for demand and energy storage have been proposed for this market.

Many have proposed a structure for transactive energy for microgrids [12]. There is concern that as renewables increase, energy will become more expensive. As the utility generates less revenue, consumers without generation will pay more to make up the difference. Transactive energy will allow energy players to buy and sell energy, providing grid reliability and economic optimization [13]. Game theoretic methodologies have been proposed to determine equilibrium prices in the proposed transactive Energy Internet [14]. Locational marginal pricing is another factor used to determine how an energy transaction should be priced depending on its distance traveled, according to line capacity contraints and predicted losses [15][16].

This paper proposes a transactive energy market that utilizes the grid frequency to determine the real-time price of energy. Smart transformer technology in the form of the SST will read the frequency signal in real-time and conduct energy transactions by controlling power flow between Energy Cells as an Energy Router. This pricing scheme will incentivize prosumers and consumers to limit frequency deviations, operating as an ancillary service and creating a smoother, more stable grid while also allowing increased participation of renewable energy sources and energy storage. The ability to react in real-time will eliminate excessive communication amongst devices to set a market price and will facilitate a fast response to utility frequency control.

II. Frequency Based Pricing

A. Background

This work will explore economic dispatch for one SST enabled Energy Cell (see Fig. 3). Analysis and design of a system of multiple SSTs and the subsequent effects of pricing on grid frequency in a transactive energy system will be the future work.

Why frequency based pricing?

1) Generation and loads can respond in real-time and provide frequency regulation as an ancillary service
2) Does not require communication with other devices to determine a price
3) Directly responds to the needs of the utility. Rather than reacting only to peak price periods over a longer timescale (hours), there becomes motivation for customers to smooth frequency deviations in the grid.
***For example, a prosumer may curtail or store renewable generation that would otherwise be injected*

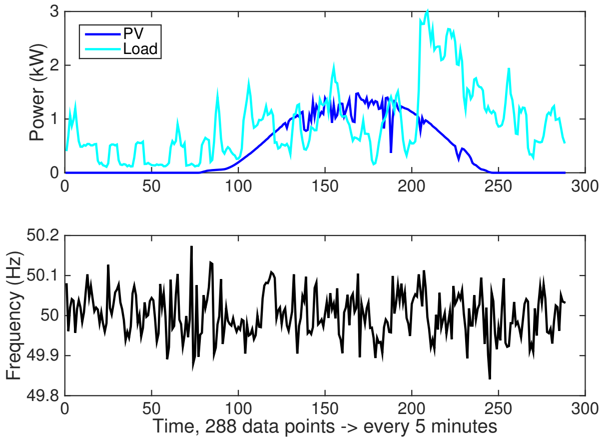

Fig. 4. Solar (PV), Load, and Frequency curves for one day

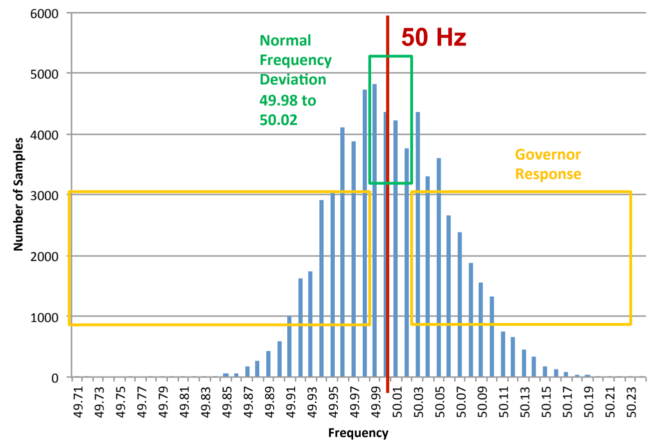

Fig. 5. Number of Samples vs Frequency (UK), five min samples, one year

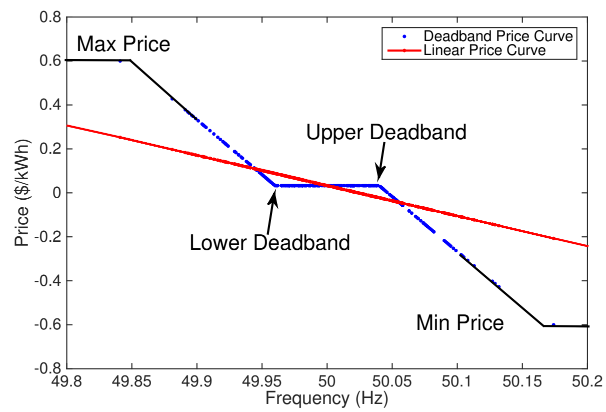

Fig. 6. Linear and Deadband Price Curves

onto the grid at an inopportune time as a reaction to a frequency based price.

4) Time Of Use (TOU) prices can also play a role in a hybrid scheme to establish a baseline price and reflect the cost of the generators online.

There is concern that a decentralized approach to frequency regulation such as the one proposed here, will be a challenge to system operators as the system response of thousands or millions of unknown devices will be difficult to predict and that a price-based signal might result in spontaneous oscillations as devices overcompensate for small frequency deviations, achieving the opposite of the desired frequency restoration objective [17]. However, these studies focus on the behavior of consumers as they consider load control to be the primary means of frequency regulation at the distributed level. This work emphasizes control of energy storage and possible photovoltaic (PV) generation curtailment, while maintaining a desired load. Every five minutes, the average frequency measurement will determine the price of energy and subsequent energy storage and PV response in order to correct the steady state frequency deviation. With this time-scale, pre-existing algorithms will facilitate the response, reducing hard to predict consumer behavior. Price response forecasts and coordinated efforts among utilities and devices are also possible [17].

B. Simulation

Frequency data from the U.K. national grid status, available at [18] in five minute intervals, was used for this simulation. PV data from a rooftop array in Raleigh, NC and a simulated household load were obtained in five minute increments. These three inputs can be seen in Fig. 4.

The spectrum of common frequency values of the U.K. grid was plotted in Fig. 5. There was some inconsistency in the number of values falling in the normal frequency deviation range, with more values found [49.97-49.98] and [50.02-50.03] than in [50.01-50.02], which falls within the normal range. However, the far ends of the frequency spectrum did not exceed the range of governor response into forced load shedding or tripped generation (refer to Fig. 2).

A deadband pricing scheme was designed based on the general range of the TOU rates published in [19]. In Fig. 6, the deadband price curve and its linear variation intersect at (50 Hz, 0.033 $/kWh). The 0.033 $/kWh price corresponds to the off-peak price in [19]. The maximum price for the linear price curve just exceeds the on-peak price of 0.171 $/kWh. The absolute maximum and minimum prices are set at 0.6 $/kWh and -0.6 $/kWh, respectively, for both curve types, as shown by the deadband price curve. This price design allows the utility to charge a low rate for power consumed at normal frequency and creates a cap for the maximum charge allowed, protecting the utility and consumer from extreme power charges.

As a result, the upper and lower frequency sections of the price curve are calculated according to

$$Price = x_1(frequency - f_t) + C_d \quad (1)$$

where f_t is the relevant deadband frequency threshold, C_d is the deadband price, and x_1 is the slope parameter. As

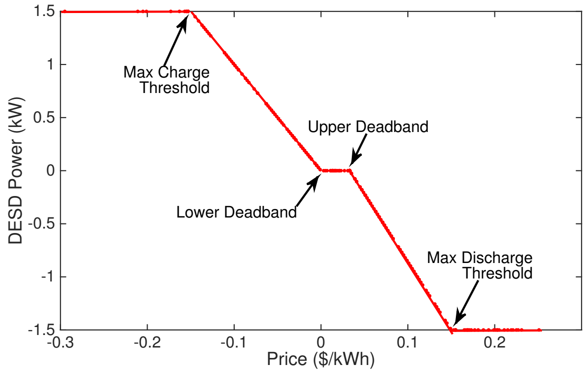

Fig. 7. DESD Response Curve

mentioned, the limits of the price curve are constrained at $\{C_{min} < Price < C_{max}\}$.

The proposed pricing scheme features positive and negative market prices. A positive price of 0.07 $/kWh, for example, indicates that the utility will charge the consumer for power at this rate. A prosumer may also decide to sell power to the utility at this rate. At 0.07 $/kWh, the utility will pay the prosumer for the injected power. The positive price encourages upward frequency regulation, by creating an incentive for less consumption and more power injection. Conversely, a negative price of -0.06 $/kWh, for example, indicates that the utility will pay the consumer for power consumption. At the same time, a prosumer who wants to sell power to the grid, must pay the utility to inject power. The negative price encourages downward frequency regulation, by creating an incentive for more consumption and less power injection. The design of positive and negative prices allows the utility to have greater influence on consumer and prosumer behavior, while keeping the cost of energy low for consumers without generation or storage and creating greater savings for prosumers that do.

III. Economic Dispatch (ED)

In response to the frequency based price curve, the SST enabled Energy Cell must determine its operation and optimize for economics. The Energy Cell will be billed according to its P_{Grid}, which is $P_{Grid} = P_{DESD} + P_{Load} - P_{PV}$ (Fig. 3). In this Energy Cell, the load will operate as given, the Distributed Energy Storage Device (DESD) will charge and discharge as needed, and the PV can be curtailed.

The DESD response curve is calculated very similarly to the price curve (Fig. 7)

$$P_{DESD} = (P_{lim} - P_d)\frac{Price - C_{ct}}{C_{ct} - C_{dt}} + P_{lim} \qquad (2)$$

where P_{lim} is the charge or discharge power limit, P_d is the deadband power, C_{ct} is the maximum charging or discharging price threshold, and C_{dt} is the relevant deadband price threshold. The response is calculated once for charging and once for discharging, as was the price for upper and lower frequency. The limits of the power curve were constrained at $\{-P_{lim} < P_{DESD} < P_{lim}\}$, where P_{lim} = 1.5 kW and the state of charge (SOC) limits for the DESD were constrained at $\{0.3 < SOC < 0.7\}$ with an initial SOC at 0.4.

TABLE I
Results, Energy Cost in $

	Load Cost	Load with PV	Final Price with DESD & ED	Algorithm Savings
$f_{deadband} =$ [50] (linear) x_1=-7 $C_{ct} = \pm 0.11$	0.2457	0.2035	-7.5244	7.7279
with $P_{DESD} = P_{lim}$	0.2457	0.2035	-7.4132	7.6166
$f_{deadband} =$ [50] (linear) x_1=-2 $C_{ct} = \pm 0.10$	0.5877	0.3252	-1.5480	1.8732
with $P_{DESD} = P_{lim}$	0.5877	0.3252	-1.9602	2.2854
$f_{deadband} =$ $[49.97 - 50.03]$ x_1=-5 $C_{ct} = \pm 0.07$	0.4562	0.2879	-2.3773	2.6652
with $P_{DESD} = P_{lim}$	0.4562	0.2879	-2.3430	2.6310
$f_{deadband} =$ $[49.93 - 50.07]$ x_1=-7 $C_{ct} = \pm 0.10$	0.6005	0.3302	-0.7542	1.0844
with $P_{DESD} = P_{lim}$	0.6005	0.3302	-0.6132	0.9434

The deadband and maximum charging and discharging price thresholds were designed to optimize P_{DESD}. Generally, charging should happen at negative prices (the utility pays the prosumer to charge) and the prosumer should charge any unused PV or curtail it. Discharging should happen at positive prices (the utility pays the prosumer to discharge) and the prosumer should limit its grid consumption. As the price increases, the level of discharging should increase (P_{DESD} becomes more negative) in proportion to the price. However, at a certain threshold price, C_{ct}, the prosumer would want to discharge as much as possible, at its P_{lim}. The response curve deadband may prevent draining DESD capacity before the most profitable time. For example, the price curve deadband, C_d = 0.033 $/kWh, causes many frequency values to yield that price. In most cases, it is profitable to eliminate discharging during that frequency range, f_t.

Solar was curtailed if the price was negative and P_{Grid} was negative, meaning that the Energy Cell was paying to inject power onto the grid. In that case, P_{PV} was decreased (after P_{DESD} was optimized to charge) until P_{Grid} was zero.

Table 1 lists several results after optimizing for various parameters of the price and response curves for the Energy

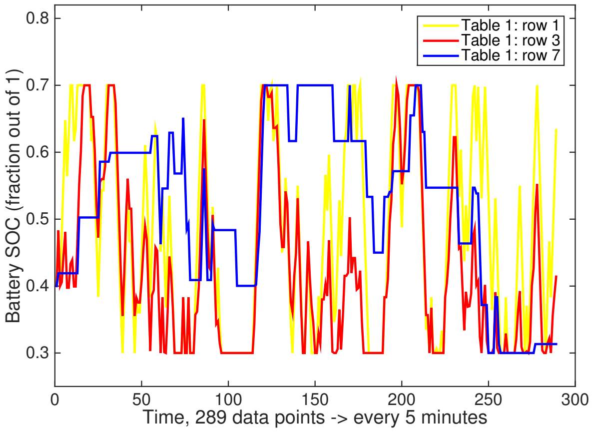

Fig. 8. SOC curve for rows 1, 3, 7

Cell. As x_1 becomes more negative, the load cost tends to decrease and the algorithm savings increase. As the price curve frequency deadband, $f_{deadband}$, narrows, savings tend to increase since there are more times available to charge and discharge. While it makes sense to operate the DESD at full P_{lim} only during times of high and low price, the results show that often it is profitable to operate at P_{lim} during every charge and discharge. It can be more economical to react to every shift in frequency, rather than waiting for the boundary values, since periods of charging and discharging closely follow each other in this frequency based pricing scheme. When proportional charging and discharging is more economical, the charging price threshold C_{ct} can be adjusted to find the optimum. The consumer is likely to favor high savings and low load cost, while the utility favors a higher final price and load cost. The third and seventh rows in Table 1 are good common ground solutions. The SOC plot of these solutions is found in Fig. 8.

Other parameters were adjusted during the simulation, such as discharging to provide for the load or charging to prevent solar injections, but these additions had little positive effect on the final results. Simulations with a larger dataset are needed to confidently recognize patterns in the data.

IV. Conclusion

Smart grid and the Energy Internet have set the stage for a new, competitive, transactive, energy market. In this work, a frequency based real-time energy market was proposed, simulated, and optimized. The relevant parameters were identified in the design of a frequency derived pricing curve and subsequent DESD response curve for economic dispatch. Operation of the P_{DESD} was optimized in order to trigger a P_{Grid} reference for an SST enabled Energy Cell. In this proposed system, energy transactions will be conducted in real-time while responding to deviations in the grid frequency, therefore providing grid frequency regulation.

The future work should account for the efficiency of the DESD and consider operation based on lifetime and state of health, in addition to price.

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