SMART GRID INTEROPERABILITY PANEL

Smart Grid System Stability with Broadcast Communications

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Disclaimers

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Contents

About the Smart Grid Interoperability Panel

The Smart Grid Interoperability Panel (SGIP) is a consortium that securely accelerates and advances Grid Modernization through interoperability and the leadership talents of its members. SGIP is committed to improving individual quality of life by integrating energy resources securely, intelligently and efficiently. To learn more about SGIP, visit http://sgip.org.

1 Background

This paper expands upon the SGIP paper[4] "Broadcast-based H2G Communication Solutions" published in 2014 to address the issue of system stability arising from broadcasting *prices to devices*[1]. The concept of stability is based on system control theory, which is summarized. Various control strategies are presented to enable optimization of the intended operational goals while ensuring system stability.

For the purpose of this paper, "prices" can be in many forms such as:

- Wholesale: Locational Marginal Price (LMP)
- Retail: Time of Use (TOU)
- Predictive: relative index
- Critical: Critical Peak Pricing (CPP), emergency, etc.

There can also be two types of price streams: those that the customer is actually paying, and those that the customer is not. For either, there doesn't need to be any restriction on how the price is determined. The one most useful to a utility is the price stream that most effectively balances instantaneous supply and demand.

Radio broadcasting is a powerful and low cost method to reach a large number of energy-consuming devices and therefore has many obvious benefits, some of which include:

- No limit to multipoint receiving devices.
- Nearly instantaneous and simultaneous message delivery.
- Easy to install/setup.
- Preservation of customer privacy.
- Acceptance by consumers.
- Amenable to convenient mass deployment.

The scope of the system under study is primarily broadcasting prices to devices with implications not only for Demand Response but also for renewable generation and Transactive Energy architectures.

[1] *Prices-to-devices* is a service mark of the Electric Power Research Institute.

2 Control systems

Figure 1 shows a classical control system with feedback.

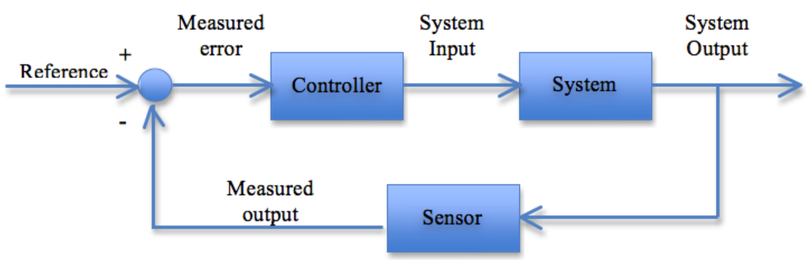

Figure 1 – Classical control system

2.1 Key features of control system

- Input, system process, output, and feedback via a sensor.
- Output is referenced to desired performance goals.

2.2 Concept of "Feed Forward"

Another consideration for system stability is the concept of "feed forward." With feed-forward control[7] the disturbances are measured and accounted for before they have time to affect the system. In a feed-forward system, the control variable adjustment is not error-based. Instead it is based on knowledge about the process in the form of a mathematical model of the process and knowledge about or measurements of the process disturbances.

2.3 What is stability?

Stability is the desired system response in achieving system operational goals in a controlled and non-oscillating manner. System operational goals are sometimes expressed in a matrix of a Performance Index. An example of elements of a Performance Index matrix is shown in Appendix D.

2.4 Factors to achieve system objectives and stability

Practical examples of classical control systems can be found in modern aircraft control systems, where the pilot enters a desired course heading. The guidance system along with aircraft sub-system controls calculate the needed changes in control surfaces (rudder, aileron, elevator, flaps, etc.) to achieve the desired new heading, attitude, and speed. In this example, the "input" is the new course heading; the "process" is the calculation and execution of new settings for the control surfaces (rudder etc.). The "measurement" is sampled from the new course heading measured against the desired course heading.

Stability is achieved when the new course heading is within a small tolerance of the desired heading with no change in time. Instability would be the new course angle oscillating in time.

For frequency regulation in a grid application (referencing the elements in Figure 1), a reference 60.0 Hz is desired. The control elements include:

1. The Controller is a Demand Response (DR) signal generator.
2. The System is a collection of DR responsive and non-responsive devices.
3. The Sensor is frequency measurement.

The Controller continuously generates various Demand Response messages to the System of devices, and the grid sensor measures the frequency to ensure it is within a specified tolerance, say +/- 0.01Hz.

In the example of broadcasting prices to devices, the desired output is likely a composite of reduced (or increased) consumption of electricity from the population of connected appliances. As stated in the SGIP paper “Broadcast-based H2G Communication Solutions,” confirmation of aggregate response can be obtained by feeder and sub-station real time measurements. From a practical perspective, if the feeder lines have kilowatt and second(s) resolution, such confirmation can be obtained quite reliably. In some embodiments, such as ANSI/CEA-2045[8], it is also possible to obtain device-level confirmation if a Hybrid UCM (Universal Communication Module) is so equipped and the end user permits sampled data from the host device to be sent from the equipment in the home. Such hybrid systems are useful for system calibration and pilot purposes. It is anticipated that for mass deployment, the vast majority of customers may not desire the needed installation complexity, costs, and possible dissemination of private consumption data needed for device-level confirmation.

This paper addresses a concern for system instability possibly resulting from broadcasting real time prices to devices. Part of the concern cited was based on an interpretation of the first of a series of papers by authors[2] from MIT. It would be appropriate to have an understanding of the full context of the entire series of related papers. While these three papers are highly technical and are extensive in their mathematical rigor, much can be extracted from the abstracts and conclusions. [3]

3 Summary notes from the MIT papers

Appendix A: Volatility of Power Grids under Real-time Pricing

- Latency of process and feedback can be theoretically unstable if control laws are not carefully designed.
- Types of pricing and algorithms contemplated: Predictive, Current, Historical, etc.

[2] See Appendix A

- A new notion of generalized price-elasticity is introduced.
- Price volatility can be characterized in terms of the system maximal relative price-elasticity, defined as the maximal ratio of the generalized price-elasticity of consumers to that of the producers.
- As this ratio increases, the system becomes more volatile and eventually unstable. As new demand response technologies and distributed storage increase the price-elasticity of demand, the architecture under examination is likely to lead to increased volatility and possible instability.
- This highlights the need for assessing the architecture systematically in advance in order to achieve an optimal tradeoff among volatility, economic efficiency, and system reliability.

Appendix B: Dynamic Pricing and Stabilization of Supply and Demand in Modern Electric Power Grids

- The paper proposes a mechanism for real-time retail pricing of electricity in smart power grids, with price stability as the primary concern.
- In previous articles, the authors argued that relaying the real-time wholesale market prices to the end consumers creates a closed loop feedback system, which could be unstable or lack robustness, leading to extreme price volatility.
- In this paper, a mathematical model is developed for characterizing the dynamic evolution of supply, (elastic) demand, and market clearing (locational marginal such as LMP) prices.
- This paper presents examples of stabilizing pricing algorithms and characterizes the effects on system efficiency. Numerical simulations are used to illustrate the stabilizing effect of the mechanism and its robustness to disturbances.

Appendix C: Equilibrium price distributions in energy markets with shiftable demand

- The paper examines the existence of equilibrium price distributions in energy markets with real-time pricing and consumers with time-flexible demands.
- Individual and aggregate consumer responses are taken into account.
- The aggregate response from the consumers could affect wholesale market and therefore the real time prices.
- The paper shows that under technical regularity assumptions on the model components, the price distribution has at least one equilibrium point.
- Thus, there exists at least one price process that is consistent both with the consumption behavior of the aggregate of consumers and the marginal cost pricing mechanism of the ISO.

4 Practical considerations for grid stability

Low latency or speed of propagation of messages is a critical element to achieving stability or to preventing instability due to “out of phase” messages. In a simple example, if the system propagation of a grid message or pricing is so slow due to congestion such that by the time the message arrives at the SGD (smart grid device), the timing could be 180 degrees out of phase. This might cause a “load shed” at a time when a “load up” is desired. If the entire system is time synchronized and a “valid time” is attached to the message, such out of phase response could theoretically be limited. Thus, phase errors result from not having meaningful or timely connectivity.

One reality is that unless an appliance receives real time grid information in a timely manner, it cannot meaningfully consume electricity in a manner optimized for the grid. It can, however, be optimized for the individual user preference independent of the grid. In other words, Egonetics[4] vs Alonetics [5]design. Egonetics and Alonetics design should intersect with appropriate pricing of energy.

In an SGIP paper titled “Barriers to Responsive Appliances at Scale,” [5] some of the factors preventing meaningful scaling are identified as being consumer centric. These include:

- Ease of installation.
- Preservation of privacy.
- Economic value.

Industry experts estimate that currently in the US marketplace, less than 1% of all household appliances receives and acts upon real time grid information. Therefore, in the near term, the issue of system instability due to smart grid broadcast is unlikely to arise before meaningful system performance targets are met. Even so, the various operational characteristics of SGD (smart grid devices) such as water heaters, electric vehicle charging stations, and pool pumps, need to consider factors such as synchronous cycling (on or off at the same time causing step functions in grid circuits). In other words, designers of communication systems and SGDs need to work together to enable randomization within a useful tolerance of, say, some seconds within the useful window of “load shed or cycle down” or “load up or cycle up” for some minutes at a time.

For the scenario of emergency or blackout recovery, such randomization within a synchronous communication signal could inherently help shorten the “bootup” period due to the elimination of synchronous loads by high load SGDs, if so designed.

5 Security & stability

Breach of security can potentially cause grid instability due to untimely or malicious out-of-sync pricing or load messages. As a first line of defense, encrypted authentication via public and private keys will likely be deployed. Moreover, physical and cyber security at broadcast centers is already in place, with additional measures as the programs scale to

[4] Egonetics design: Device design method that is optimized to serve the individual consumer preference.

[5] Alonetics design: Device design method that is optimized to support operation of the electric grid beneficially and the consumer.

comply with utility and regulatory security guidelines. In addition, another method of mitigation is to limit the impact of a particular broadcast message by dividing the target SGDs into sub-groups accessed via redundant and overlapping transmitter towers. This segmentation of customer equipment also helps with the synchronous step function described in the previous section as well as providing additional levels of redundancy in RF reception performance.

A more complete discussion on the issue of broadcast communications security will be covered under a separate SGIP paper under development by the SGIP Home-to-Grid Domain Expert Working Group (H2G DEWG).

6 Conclusions & recommended next steps

In this paper, basic control theories were reviewed with a more in-depth look at the reference papers, which state that due care in design of the control laws is needed to ensure system stability in dissemination of real time pricing within a closed loop system. In addition, the papers theorize that a stabilizing pricing algorithm can be constructed along with a conclusion that price distribution has at least one equilibrium point. The numerical simulations performed by the MIT papers suggest that optimization of pricing schemes relative to performance index is theoretically possible.

It appears that actual field calibration of various pricing schemes in real-life conditions represent the next logical step. The authors are aware of a number of proposed and planned projects involving the broadcast of dynamic pricing to consumer devices in 2015. Much can be learned from field testing the various pricing schemes, communication standards such as ANSI/CEA-2045, OEM appliances response to price signals, and consumer experience and preferences in these tests. Perhaps data from these field tests could also validate the premise presented in reference 6, “Economic Value of the Integration of Consumption Preferences in Electric System Planning.” This paper focuses on the economic benefit that would be achieved if consumption choices were made using transparent market prices. The ultimate goal is for smart connected-appliances to react to real time pricing in a manner that benefits the grid and the consumer operationally and economically simultaneously.

APPENDIX A

Volatility of Power Grids under Real-Time Pricing [1]

Mardavij Roozbehani, Member, IEEE, Munther A Dahleh, Fellow, IEEE, and Sanjoy K Mitter, Life Fellow, IEEE

***Abstract*—**The paper proposes a framework for modeling and analysis of the dynamics of supply, demand, and clearing prices in power system with real-time retail pricing and information asymmetry. Real-time retail pricing is characterized by passing on the real-time wholesale electricity prices to the end consumers, and is shown to create a closed-loop feedback system between the physical layer and the market layer of the power system. In the absence of a carefully designed control law, such direct feedback between the two layers could increase volatility and lower the system's robustness to uncertainty in demand and generation. A new notion of *generalized price-elasticity* is introduced, and it is shown that price volatility can be characterized in terms of the system's *maximal relative price elasticity,* defined as the maximal ratio of the generalized price-elasticity of consumers to that of the producers. As this ratio increases, the system becomes more volatile, and eventually, unstable. As new demand response technologies and distributed storage increase the price-elasticity of demand, the architecture under examination is likely to lead to increased volatility and possibly instability. This highlights the need for assessing architecture systematically and in advance, in order to optimally strike the trade-offs between volatility, economic efficiency, and system reliability.

http://www.mit.edu/~mardavij/publications_files/Volatility.pdf

APPENDIX B

Dynamic Pricing and Stabilization of Supply and Demand in Modern Electric Power Grids [2]

Mardavij Roozbehani, Member, IEEE, Munther A Dahleh, Fellow, IEEE, and Sanjoy K Mitter, Life Fellow, IEEE

***Abstract*—**The paper proposes a mechanism for real-time retail pricing of electricity in smart power grids, with price stability as the primary concern. In previous articles, the authors argued that relaying the real-time wholesale market prices to the end consumers creates a closed loop feedback system which could be unstable or lack robustness, leading to extreme price volatility. In this paper, a mathematical model is developed for characterization of the dynamic evolution of supply, (elastic) demand, and market clearing (locational marginal) prices under real-time pricing. It is assumed that the real-time prices for retail consumers are derived from the Locational Marginal Prices (LMPs) of the wholesale balancing markets. The main contribution of the paper is in presenting a stabilizing pricing algorithm and characterization of its effects on system efficiency. Numerical simulations conform with our analysis and show the stabilizing effect of the mechanism and its robustness to disturbances.

http://cnls.lanl.gov/~chertkov/SmarterGrids/w_sh_10/Talks/Mitter.pdf

APPENDIX C

Equilibrium Price Distributions in Energy Markets with Shiftable Demand [3]

Donatello Materassi, Mardavij Roozbehani, Munther A. Dahleh

***Abstract*—**The paper examines existence of equilibrium price distributions in energy markets with real-time pricing and consumers with time-flexible demands. Previous works have examined consumer optimal policies for shifting time-flexible loads up to a deadline, in response to an exogenous and stochastic price process. It is shown here that under some mild assumptions on the stochastic price process and the information structure in the market, the individual consumer's optimal policy is a threshold policy. The threshold policy indicates that a consumer will consume only when the price falls below a certain threshold which depends on the time left to his deadline and the information on the price process. This behavior by individual consumer leads to an aggregate behavior by a large number of consumers who implement threshold policies in reaction to the price process; although at each instant of time, different consumers may have different thresholds due to different deadlines and different information assumptions. The aggregate response from the consumers determines the state of the wholesale market, and thus, affects the price process. The question that we intend to answer in this paper is that of consistency of assumptions on the price process and the market outcomes. It is assumed that the price at each time interval is determined by the Independent Service Operator (ISO) on the basis of an estimate of the global consumption as a function of price. It is shown that under technical regularity assumptions on the model components, the price distribution has at least one equilibrium point. Thus, there exists at least one price process that is consistent both with the consumption behavior of the aggregate of consumers who individually implement threshold policies, and the marginal cost pricing mechanism of the ISO.

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6425845&refinements%3D4258794927%26filter%3DAND%28p_IS_Number%3A6425800%29

APPENDIX D

Example Elements of a Performance Index

Utility values:

1. Traditional Peak Load Management (avoidance of new peaking capacity): MW
2. Avoidance of peak demand charges (corollary of item 1 for service providers that buy wholesale): MW & $
3. Arbitrage on-peak versus off-peak power costs: MW & $
4. Firming forecast error from wind/solar generation: MW & $
5. Sink for excess renewables generation (when renewables generation exceeds load): MW
6. Providing a service option for customers (perceived as option to control bill size): $
7. Fossil fuel and CO^2 reduction from implementing items 1 (or 2), 3, 4, & 5 (bragging rights in the short run with real dollars likely in the long run): Tons of $C0^2$

Consumer values:

1. Minimum capital costs (via incentives/rebates etc.): $
2. Minimum operating costs: $
3. Maximum performance/convenience: typically min time
4. Minimum carbon footprint: Tons of $C0^2$
5. Maximum green credits/recognition: TBD

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[6] LeVee, et. al., "Economic Value of the Integration of Customer Preferences in System Planning". A white paper developed by the H2G DEWG of the Smart Grid Interoperability Panel, to be published in 2015.

[7] http://en.wikipedia.org/wiki/Feed_forward_(control)

[8] ANSI/CEA-2045, "Modular Communications Interface for Energy Management," American National Standard, 2013.