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Judith Cardell
Smith College, jcardell@smith.edu

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Judith Cardell
Smith College

Distributed Resource Participation in Local Balancing Energy Markets

Judith B. Cardell, *Member, IEEE*

***Abstract*— In response to the new and potentially conflicting economic and technical demands of independent, distributed resources, the power system requires a new means for coordinating system and market operations. Price signals are one mechanism available to coordinate the operation of a power system in the emerging competitive markets. This paper discusses the integration of distributed resources into the operations of the power system by means of organizing the resources into microgrids and allowing them to participate in local electricity markets through responding to price signals. The simulations of price signals proposed in this paper successively expand upon the current open loop market framework. For distributed resources to participate in energy markets and provide energy balancing two new price mechanisms are introduced and analyzed. First, an open loop strategy is introduced, based upon the concept of a proposed price-droop. Second, a closed loop strategy using a hypothesized dynamic cost equation is introduced. The behavior of distributed resources responding to these two proposed mechanisms is compared to their behavior in a strictly competitive environment.**

***Index Terms*—distributed resources, microgrid, price droop, price signal**

I. INTRODUCTION

Interest in distributed resources represents one component of the broader theoretical concept of a distributed utility, which focuses on the evolution of the power system as it responds to technological advances, environmental regulations, industry restructuring and the uncertainties associated with these changes. The prospect of independent ownership for distributed technologies is encouraged by the deregulation of generation, yet at the same time distributed generation is commonly categorized as T&D rather than generation, in the United States, and thus remains in the regulated industry sector. Clustered into microgrids, distributed resources could become part of the generation sector, and so be able to participate in electricity markets. In response to the growing number of small market participants, the power system will require a new means for coordinating system and market operations. Price signals are one mechanism available to coordinate the operation of a power system in the emerging competitive environment.

This paper discusses the integration of distributed resources into the operations of the power system by means of organizing distributed resources into microgrids that can participate in electricity markets. The options for such participation that are discussed in this paper include participation in regional versus strictly local markets, comparing open and closed loop control strategies. Fully decentralized, open loop decision-making is possible within microgrids when they remain connected to the high voltage grid. For operation when islanded, new open loop and closed loop control strategies are proposed and compared. The open loop strategy is based upon the concept of price-droop, and the closed loop strategy upon a hypothesized dynamic cost equation for each technology.

Extensive work is being performed worldwide in the area of microgrids. Much of this focus is on the operational aspects of microgrids as separate from market integration, with pioneering work done through CERTS and the University of Wisconsin [1] and industrial implementations through Tecogen [2], Northern Power Systems [3] and Encorp [4]. Significant work is being performed throughout Europe, with much of this effort coordinated via [5], [6]. Interest in integrating distributed resources into markets is also evident in [7], [8], [9]. This paper expands upon these other projects through the proposal of two new market based price mechanisms for distributed resources to participate in local energy balancing markets in a decentralized manner.

II. BACKGROUND

A. Distributed resources and balancing energy markets

In the United States, existing installations of distributed generation consist mainly of backup generators such as diesel gensets and microturbines, as well as cogeneration facilities. There is activity in both federal and individual state agencies to develop policies that promote the increased use of distributed resources [10], [11], [12]. These efforts tend to emphasize system interconnection, operations and reliability issues. Less attention has been paid to the potential for distributed resources to participate in electricity markets, including balancing and frequency regulation.

Rules for participation in ancillary services markets vary regionally, yet tend to include similar requirements for facilities and associated communications capabilities. There is increasing pressure for operators to define rules to facilitate load participation in energy and ancillary services markets.

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J. Cardell is with Smith College, Northampton, MA USA (phone: 413-585-7000; fax: 413-585-7001; e-mail: jcardell@smith.edu).

[13], [14]. This trend demonstrates a shift toward the increasing possibility that a large number of distributed resources – generation and load – will be active in system and market operations. A result of this shift is a number demand response programs that rely upon price signals rather than upon the centralized command and control framework of historical direct load control [15], [16], [17].

B. A Distributed Utility

At a more idealized level, the gradual inclusion of distributed resources into the power system is part of the evolution of the power system to a distributed utility. A distributed utility can be defined as a power system for which, given the currently available technology, there are no additional technologies or operating and control strategies that could be installed or implemented to improve system efficiency. In this broad definition, the term efficiency represents not only a technical ratio of output to input, but also includes efficiency as attained through competitive markets. Market design to date has focused on the bulk power system. Expanding electricity markets to include distributed resources will further promote their use and the evolution of the power system to a distributed utility.

This system evolution requires not only new generating technologies, but also a gradual shift toward more distributed and decentralized control strategies. This paper introduces a larger project that is investigating these issues. The simulations and results presented in section IV discuss scenarios of distributed resources participating in electricity markets for balancing energy in both centralized and decentralized frameworks, responding to open loop and closed loop price signals designed for least cost system operation.

III. OPEN AND CLOSED LOOP PRICE SIGNALS

The figures in section IV illustrate the behavior of distributed resources responding to three different market dynamics, or signals. The discussion below introduces these dynamics. The first mechanism discussed below is the basic competitive market dynamic of customers and suppliers responding to a change in price according to their individual supply and demand curves, and without any direct coordination to their actions. The second dynamic introduces the concept of price droop, modeled upon generator frequency droop, which is coordinated at a system level. The third dynamic introduces an alternative response in the form of a closed loop price signal.

A. Competitive market open loop price signal

The basic market clearing dynamic in a competitive market relies upon the independent actions of customers and suppliers as they respond to price changes according to their own price elasticities. Price elasticity is defined as the percent change in quantity (demand or supply) for a given percent change in price. This is an open loop response, and within an isolated system could lead to instability, as shown in example 1 below.

Typically, a price increase would cause suppliers to increase their output, in hopes of increasing profit, while customers would decrease their demand in order to avoid paying the higher price. Distributed resource response based strictly upon own price elasticities is consistent with competitive markets, and acceptable for DG participation in *bulk* energy markets. However, this dynamic could result in a net energy imbalance within a *closed* system if resources respond strictly in an open loop manner, based on their independently determined price elasticity. Graphs of this dynamic are presented in example 1. Two alternatives to this behavior, which are designed to prevent a local energy imbalance, are introduced next.

B. Coordinated price droop response

Building upon the concept of frequency droop, this paper proposes the concept of price droop as a means for coordinating market behavior and facilitating distributed resource participation in the local balancing market. Patterned after the definition of frequency droop, price droop is defined to be the percentage change in price for a given percentage change in quantity. For a given operating point, as determined by running a power flow program, price droop values for all participating resources can be calculated in a coordinated fashion, which will ensure cooperative behavior. This mechanism could be particularly useful in microgrids that are dominated by facilities interconnected via power electronics, and are thus without synchronized generators with large inertia to provide the traditional frequency droop.

Beginning with a specified disturbance from the operating point, the price change, $\Delta\lambda$, can be determined through multiple simulations with an optimal power flow program. Next, the desired response from each resource, ΔP, can be calculated, for example, by prorating each resource's response based on the relative capacities of all participating resources.

Once each ΔP value is determined, the price droop for each resource can be calculated according to

$$\text{droop} = \frac{\Delta\lambda / \lambda_0}{\Delta P_{G,L} / P_{G0,L0}}$$

where λ is the price, $P_{G,L}$ represents either generator output or load consumption, respectively, and the subscript '0' indicates the reference values (*i.e.,* the initial price, or the maximum load or generating capacity). Use of the price droop ensures that distributed resources act together to maintain a local energy balance, rather than fighting against each other as they can when acting strictly with individual price elasticities. The use of the price droop is demonstrated in example 2.

C. Closed loop price signal model

Though the price droop is designed such that distributed resource responses are coordinated to recover the energy balance following a disturbance, it is an open loop response and so cannot guarantee stability. The price signal defined below is a closed loop signal that captures the market clearing dynamic of a competitive market in the dynamics of feedback control. The price signal model demonstrates that both the short run energy and the services markets can be operated competitively. For distributed generators, the closed loop price signal corresponds to the marginal revenue earned by a participating plant.

This section discusses the mathematical framework for a proposed closed loop price signal, designed to coordinate distributed resources as they participate in both the short run energy market and the ancillary services market. This mechanism is the second option proposed in this paper for coordinating distributed resource participation in local ancillary services markets [18].

The development of the closed loop price model begins by expressing the cost of power generation in terms of the state variables in generator and load state space equations [19] which can be expressed in the form

$$\dot{x} = \mathbf{A}x + \mathbf{B}u$$

where x is the state vector, u is the control input, and **A** and **B** are system matrices.

Cost can then be incorporated into the state space generator models via an output equation that captures the variable costs associated with generating power from any given technology. Referring to the standard steam turbine – generator model with the swing equation, ω_G, and additional equations for the turbine power output, P_T, and governor control, a, [19], the cost equation would be written as

$$c = c_w \varpi_G + c_P P_T + c_a a + c_g P_G$$

The coefficients in this equation represent the marginal cost associated with each piece of equipment or process represented by the specified state variable. In particular, c_g is the marginal fuel cost. The significance of the values of the coefficients in the cost equation lies not in the absolute values chosen, but rather in the relative values of the coefficients between the different technologies and distributed generators. It is the relative cost values that capture the real-time differences in using one technology before another. The generators and the system will respond to the price signal at specific intervals, depending upon the response capability of the resource, the communications infrastructure and the requirements of the market.

To develop the dynamic form of the model, the cost equation is added to the set of state space equations for the system, all time derivatives are set equal to zero since the primary dynamics following a system disturbance are assumed to have settled before the close-loop price signal acts. The equations are then solved for cost. Assuming for now that the markets are perfectly competitive, price is assumed to be equal to marginal cost, so that the discrete time cost equation can be expressed in terms of price as

$$x_\rho[\mathrm{k}+1] = x_\rho[\mathrm{k}] + \mathbf{C}_1 u_\rho[\mathrm{k}] + \mathbf{C}_2(\varpi_G[\mathrm{k}+1] - \varpi_G[\mathrm{k}])$$

where x_ρ is the price-based state space, $u_\rho[k]$ is the control input to be determined, $(\omega_G[k+1] - \omega_G[k])$, a measured change in frequency, is the system input, and the matrices $\mathbf{C}_1$ and $\mathbf{C}_2$ are algebraic expressions of the cost coefficients of all participating distributed resources.

Given the dynamic equation, the next step is to define the control law. The control signal for updating each generator's reference frequency, based upon basic feedback control concepts, is proportional to the difference between the marginal cost of power at the given generator and the system or market price.

$$\mathbf{u}_\rho \equiv -\mathbf{K}_\rho \mathbf{x}_\rho$$

or

$$\mathbf{u}_\rho \equiv -\mathbf{K}_\rho (\lambda_i - \lambda_0)$$

where $\mathbf{u}_\rho$ is the control signal to the generator's governor, λ_i is the price for real power at generator i at the current production level, λ_0 is the price the system is willing to pay the distributed generators, and so represents the marginal revenue to these generators, and the constant of proportionality, $\mathbf{K}_\rho$, is the controller gain. The basic objective of the feedback control is to drive the system to an equilibrium state where $u_\rho \equiv 0$, implying that $\lambda_i = \lambda_0$, for all participating distributed resources.

Different methods for determining $\mathbf{K}_\rho$ have varying data requirements and different implications for the extent that control can be decentralized. A discussion of these tradeoffs is part of a larger project, but beyond the scope of this paper. What is interesting to note here is that alternative methods for determining $\mathbf{K}_\rho$ may have implications in terms of system performance, the expense of monitoring and data gathering, and the sensor and communications architecture required to support the use of this proposed closed loop price signal.

IV. EXAMPLES

As discussed above, electricity market prices are typically determined via open loop prices for which information (bids and offers) is gathered and used by a central operator to calculate a market clearing price. For standard ISO markets in the United States, such as day ahead and hour ahead markets, there is no feedback dynamic through which market participants can modify their previously submitted response.

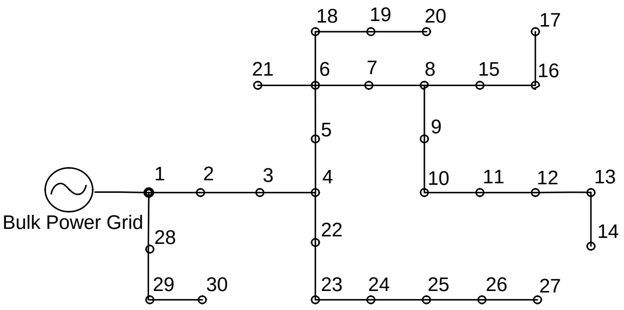

Fig. 1. 31 Bus test system.

In the case of real-time balancing markets, the price is typically not even known until after the designated power generation and consumption have occurred. Thus the existing markets do not rely upon the dynamic of sending a price signal to generators and loads in order to cause the desired response (generation or consumption) that will maintain the least cost dispatch. Instead, these markets collect information from generators and loads in order to establish the dispatch in a centralized manner and then inform the market participants of the binding dispatch and the resulting market price.

The simulations of price signals proposed in this paper successively expand upon this existing price framework to include distributed resources in the low voltage distribution system and that provide local and system energy balancing first by responding to a price signal from the high voltage grid, and second by responding to local signals when the microgrid is either islanded or not participating in the bulk energy markets as coordinated by the central operator.

Fig. 1 presents a 31 bus test distribution system used for the simulations in this paper. Generators are located at buses 10, 17 and 24 with load at all the remaining buses except for buses 1, 3, 5, 6, 7, 8. For example 1a there is also a large generator at the 'Bulk Power Grid' bus, representing the high voltage grid.

A. Example 1a: Microgrid price response when connected to the high voltage grid

In the first example, shown in fig. 2, a disturbance on the high voltage grid causes a price change at the substation bus, which in turn causes the distributed generators to increase their output in response.

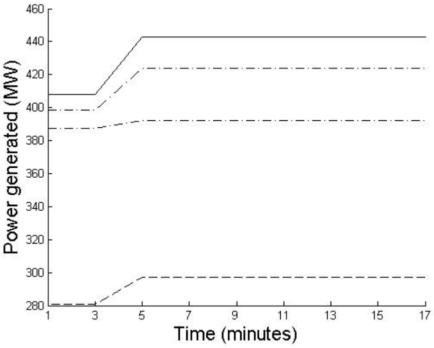

Fig. 2. Distributed generator response to a price increase caused on the high voltage grid.

For the same disturbance and price change at the local substation, responsive load alters its consumption, as shown in fig. 3 for five of the load buses. (The behavior of the remaining load buses is similar.) For this simulation the initial dispatch is determined with Matpower [20] and the subsequent distributed generator and responsive load response is based on elasticities based on data from New England and California [21], [22], [23]. In this example the load response is based on the price elasticity of electricity demand modeled with values between -0.05 and -1.60. Values for generator elasticity are between 0.6 to 2.9.

The total load and generation before the disturbance are 1452MW and 1474MW respectively, with 22MW of losses. After the increase in price on the high voltage grid, load decreases to 1433MW and the generator output increases to 1556MW. The total load and generation is not in balance within the microgrid, indicating that after accounting for losses, the microgrid is exporting approximately 100MW to the high voltage grid.

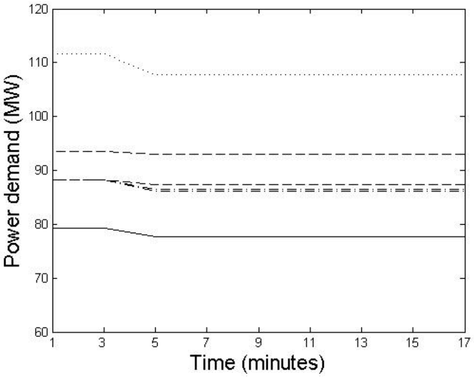

Fig. 3. Responsive load response to a price increase caused on the high voltage grid.

B. Example 1b: Microgrid price response when islanded, open loop response using individual elasticities

Similar results are found if the price change is caused by a local disturbance and the microgrid is isolated from the high voltage grid, as shown in fig. 4, which differs from fig. 2 in that only the three local distributed generators are available to supply local load. The load response is similar to that in fig. 3 and is not shown. What is relevant in this example is that the net power flow to the power grid in example 1, now becomes an energy imbalance since the high voltage grid is not available to assist in local energy balancing.

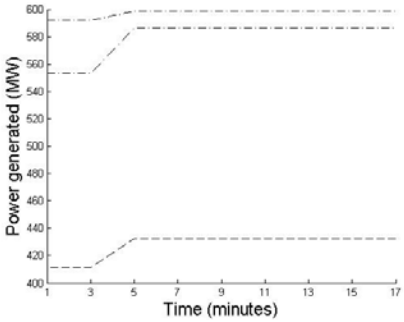

Fig. 4. Distributed generator response to a price increase caused in the local microgrid.

Figs. 2 through 4 demonstrate an open loop price signal with and without the participation of the high voltage grid in the local, microgrid energy balance. If the microgrid becomes islanded, or is otherwise maintaining its local energy balance strictly with local resources, these examples show that response to a price signal based exclusively on individual elasticities will lead to significant imbalances and subsequent system failure. The purpose of presenting these first two examples is to demonstrate a local energy imbalance and motivate the development of different price frameworks for a local ancillary services market to maintain the energy balance.

C. Example 2: Microgrid price response when islanded, open loop response using coordinated price droop

Price elasticities are determined independently by resources based on their own costs and bidding strategy. They are not calculated in a coordinated manner and so do not account for the necessity of maintaining system services in a coordinated strategy. The concept of a price droop is introduced in this paper as one mechanism for maintaining coordinated system behavior.

For the example shown in figs. 5 and 6, the initial price, before any disturbance is $10.41/MWh. Compiling results from multiple optimal power flow simulations using Matpower [20], and following the procedure outlined in section III-B, an average load price droop value of 2.3 and generator price droop value of 2.9 were calculated. At time = 3 minutes, a load disturbance of -50MW occurs, and acting via the price droop mechanism,generators respond by decreasing output while responsive load responds by increasing output, in order to regain the energy balance. Fig. 5 shows the generator response while fig. 6 shows the load disturbance with a few responding loads.

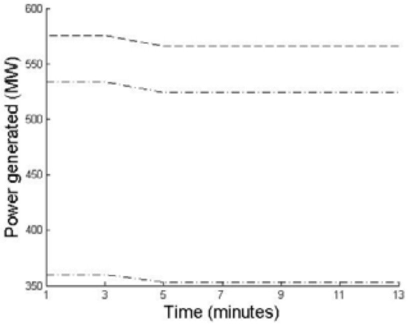

Fig. 5. Distributed generator response to a local load disturbance and price change, based on coordinated price droop.

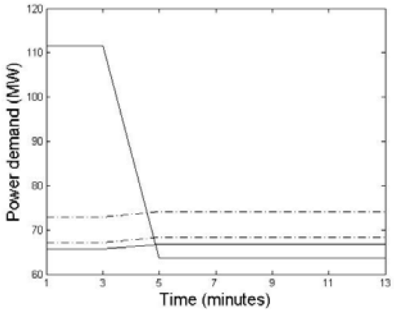

Fig. 6. Responsive load behavior after a load disturbance of -50MW and local price change, based on coordinated price droop.

The initial generator output and load consumption were 1469MW and 1452MW (note the resulting losses are lower than when the microgrid was exporting electricity). Following the load disturbance, the distributed resources respond according to the previously coordinated price droop values. The total power generation and load are now 1441MW and 1426MW. Accounting for losses, the microgrid remains in balance after the disturbance, by responding to the open loop signal using the previously coordinated price droop response.

D. Example 3: Microgrid price response when islanded, closed loop price signal

The behavior in example 2 is preferred to that of example 1, when resources respond strictly based on own price elasticities. The use of the price droop requires coordination between resources however, and the calculation of price droop is estimated, based on quantities for a given operating point. When the system is at a different operating level (different total system load), the static price droop values may not result in post-disturbance energy balance. This could be remedied by maintaining different price droop response values for different operating levels (*e.g.,* time of day). The mechanism itself could also be improved upon by implementing a closed loop price signal as discussed in section III, and as presented in this example.

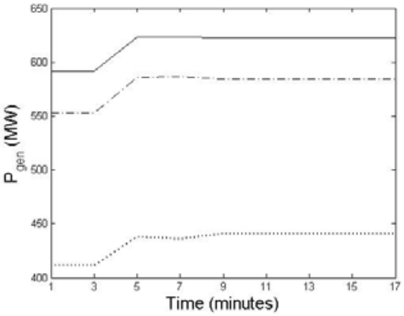

Fig. 7. Distributed generator response to a local load disturbance and price change, based on the closed loop price signal.

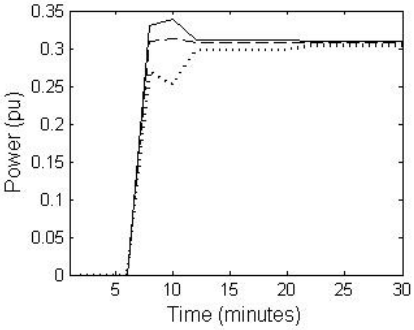

Fig. 8. Distributed generator response as deviations from the initial output values, based on the closed loop price signal.

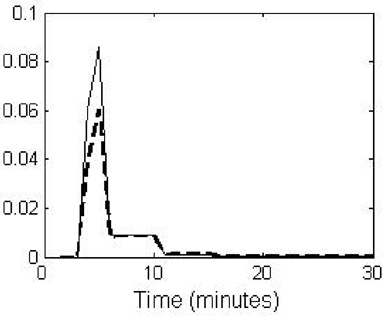

Fig. 9. Distributed generator deviations from the reference price, responding to the closed loop price signal.

Fig. 7 shows the generator response to an increase in load of 40MW. The initial response is seen to be gradually adjusted as the closed loop price signal acts successively to bring the microgrid back to balance.

Fig. 8 further clarifies the distributed generator response by graphing the deviation of generator output. Fig. 9 further emphasizes the nature of the price signal by plotting the convergence of two of the individual distributed generator local bus prices (representing marginal cost in these graphs) to the reference price (selected to be the third generator for this example).

V. CONCLUSION

The goal of the price response mechanisms introduced in this paper is to provide a decentralized control mechanism which allows each generator to operate independently while also providing an incentive for the generators in aggregate to produce at the efficient level and maintain the energy balance. The price signals facilitate the creation of a decentralized system in which distributed generators are free to act independently, though with some initial coordination.

The use of the price droop requires a centralized calculation of the droop value for each resource, given a system operating point. For the closed loop price signal, resources are not required to give control of their facility to a centralized authority, yet as with the price droop mechanism, some centralized data acquisition and calculation is required for calculating the control signal for the closed loop price signal.

Both of these mechanisms could be automated with the implementation of data gathering and communications architecture that would facilitate a close to real time calculation of droop values or price signal. Ongoing work through [24] is investigating the sensor and communications network requirements, along with the potential security and privacy concerns surrounding the data gathering.

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Judith B. Cardell received BSEE and AB degrees from Cornell University in 1989 in electrical engineering and government. She received MS and PhD degrees in TPP and EECS from MIT in 1994 and 1997. She is currently an assistant professor at Smith College, Northampton MA in the engineering and computer science departments. Previously she worked at FERC and as a consultant to the electric power industry with TCA in Cambridge, MA. Her research interests include the integration of distributed resources into power system and market operations, and electricity market design. Dr. Cardell is a member of TBΠ and HKN.