ECE 5520 Power Systems and Market Operation

Final Project

Energy Imbalance Management Using a Robust Pricing Scheme

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I. Introduction

Price is an important element of market behavior and is closely related to energy management. From consumer's perspective, the demand increase/decrease as the marginal benefit higher/lower than the market price. From the producer's perspective, the generation increase/decrease as the production cost lower/higher than the market price. This paper considers the energy imbalance management in a microgrid system. Suppose in a microgrid, the demand and supply change according to the price at the time. Then by properly designing the pricing scheme, the energy imbalance in the microgrid can be controlled.

Unlike the traditional power grid, microgrid can obtain energy from a renewable energy sources (RES) such as solar panel of wind turbine. Microgrid contain components include, dynamical load, RES and dynamic generation. The energy in the microgrid should be balanced in anytime, that is the sum of demand equals the sum of generation. However, the intermittency of RES brings uncertainty to the system and make the system imbalanced. To balance the system, a pricing scheme termed area control error (ACE) pricing has been studied. The ACE pricing uses the rate of energy imbalance to control the rate of change of the price. However, in this paper, simulation result shows that the performance of ACR pricing will degrade when additional intermittent power input is involved.

In this paper, a novel robust pricing scheme is proposed to deal with the uncertainty caused by RES. The novel pricing scheme is based on fuzzy interpolation techniques. The uncertainty caused by intermittent RES is addressed by H_∞ performance criterion design; that's to say, over all the possible disturbances, the uncertainty and the fluctuating effects is less than a fixed attenuation level. The pricing parameters can be solved by a linear matrix inequality, which is convex and can be solved efficiently.

II. Problem Formulation

This section presents the dynamic of each element in the microgrid. The dynamic of generation p_g is expressed as

$$\dot{p_g}(t) = \frac{1}{\tau_g} \times \left\{\lambda(t) - \left(b_g + c_g p_g(t)\right) - ke(t)\right\} \tag{1}$$

where, τ_g is the scale factor, $\lambda(t)$ is the market price at time t, $b_g + c_g p_g(t)$ is production cost, especially, b_g is the initial supplier cost, c_g is supplier's demand elasticity, $ke(t)$ is the additional cost for the energy imbalance.

By considering the stochastic of power supply, $b_g = \widehat{b_g} + \Delta_g(t)$, the dynamic of the generation becomes

$$\dot{p_g}(t) = \frac{1}{\tau_g} \times \left\{\lambda(t) - \left(\widehat{b_g} + \Delta_g(t) + c_g p_g(t)\right) - ke(t)\right\} \tag{2}$$

The dynamic of demand can be expressed as

$$\dot{p_d}(t) = \frac{1}{\tau_d} \times \left\{\left(b_d + c_d p_d(t)\right) - \lambda(t)\right\} \tag{3}$$

where τ_d is the scale factor, $b_d + c_d p_d(t)$ is the marginal benefit. To model the uncertainty of demand $b_d = \widehat{b_d} + \Delta_d(t)$ is incorporated into the equation. The dynamics becomes

$$\dot{p_d}(t) = \frac{1}{\tau_d} \times \left\{ \left(\widehat{b_d} + \Delta_d(t) + c_d p_d(t) \right) - \lambda(t) \right\} \tag{4}$$

The dynamic of power imbalance can be expressed as

$$\dot{e}(t) = p_g(t) + in(t) - p_d(t) \tag{5}$$

From above equation, the overall dynamic of the microgrid can be formulated as the below state space system.

$$x(t) = \left[p_g(t)\ p_d(t) e(t) \right]^T, b = \left[-\frac{\widehat{b_g}}{\tau_g}\ \frac{\widehat{b_d}}{\tau_d}\ 0 \right]^T$$

$$w(t) = \left[\Delta_g(t)\ \Delta_d(t)\ in(t) \right]^T, \tau = \left[\frac{1}{\tau_g} - \frac{1}{\tau_d}\ 0 \right]^T$$

$$A = \begin{bmatrix} -\frac{c_g}{\tau_g} & 0 & -\frac{k}{\tau_g} \\ 0 & \frac{c_d}{\tau_d} & 0 \\ 1 & -1 & 0 \end{bmatrix}, B = \begin{bmatrix} -\frac{1}{\tau_g} & 0 & 0 \\ 0 & \frac{1}{\tau_d} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\dot{x}(t) = Ax(t) + b + \tau\lambda(t) + Bw(t) \tag{6}$$

For the case where $w(t) = 0$, no uncertainty is being considered.

III. Proposed Robust Pricing Scheme

First, $Ax(t) + b$ will be interpolated in several different operation regions by several linear system of the form $A_m x(t)$. That is,

$$y = Ax(t) + b = \sum_{m=1}^{M} h_m\big(x(t)\big) A_m x(t) + \Delta_x \tag{7}$$

Where $h_m\big(x(t)\big) = \frac{F_{m1}\left(p_g(t)\right) F_{m2}\left(p_d(t)\right) F_{m3}\left(e(t)\right)}{\sum_{m'=1}^{M} F_{m'1}\left(p_g(t)\right) F_{m'_2}\left(p_d(t)\right) F_{m'_3}\left(e(t)\right)}$, Δ_x is the approximation error, which can be very small if sufficient fuzzy rule are used. Similar to (7), the pricing scheme can be expressed as

$$\lambda(t) = \sum_{m=1}^{M} h_m\big(x(t)\big) K_m x(t) \tag{8}$$

where K_m is the control gain to be designed. Incorporate (7) and (8) into (6) we will have the dynamic of the market becomes

$$\dot{x}(t) = \sum_{m=1}^{M} h_m\big(x(t)\big) \tilde{A}_m x(t) + Bw(t) \tag{9}$$

where $\tilde{A}_m = A_m + \tau K_m$. To deal with the uncertainty caused by $w(t)$, (9) should be designed to satisfy H_∞ performance criterion.

$$\int_0^\infty z(t)^T z(t) - \gamma^2 w(t)^T w(t) dt < 0 \tag{10}$$

where, $z(t) = [e(t)\ \epsilon\lambda(t)]^T$, γ is the attenuation level. ϵ is used to prevent large price perturbation. To design K_m which satisfy (10) we can solve an LMI equation

$$\begin{pmatrix} A_m + Q + \tau Y_m + (*) & B & QC^T + Y_m^T D^T \\ * & -\gamma^2 I_3 & 0 \\ * & * & -I_2 \end{pmatrix} \prec 0 \tag{11}$$

$K_m = Y_m Q^{-1}, Q \succ 0$, (*) is the transpose term, for all m.

III. Simulation Result

K_m can be obtained as following. Generate a sequence of input vectors $x_l, l = 1, \dots, L$ from input space $[5, 25] \times [5,25] \times [-10,10]$. Choose $L = 1500$, a sequence of output vector y_l can be obtained be substitute x_l into $y = Ax(t) + b$. Substitute x_l and y_l into (7), we have $3L$ equation with A_m. A_m can be obtained by least square methods. After obtaining A_m, by solving (11), we can obtain K_m which can be used to produce pricing signal (8). Fig. 1 shows the dynamic of proposed pricing scheme and ACE pricing without uncertainty being involved. Fig. 2 shows the dynamic of system with uncertainty, e.g. $w(t) = [rand_{(-1.5,1.5)}(t), rand_{(-1.5,1.5)}(t), rand_{0,2}(t)]$.

It's can be observed that the proposed robust pricing can eliminate the energy imbalance faster than ACE pricing. When consider the uncertainty, ACE pricing cause large fluctuation; however, the proposed robust pricing scheme has less fluctuation magnitude, but higher fluctuation frequency. It's can be observed that ACE and the proposed method converge to the same equilibrium operation point. The robust pricing scheme uses information of the generation, demand and power imbalance to design the price; in contrast, ACE pricing only use information of power imbalance.

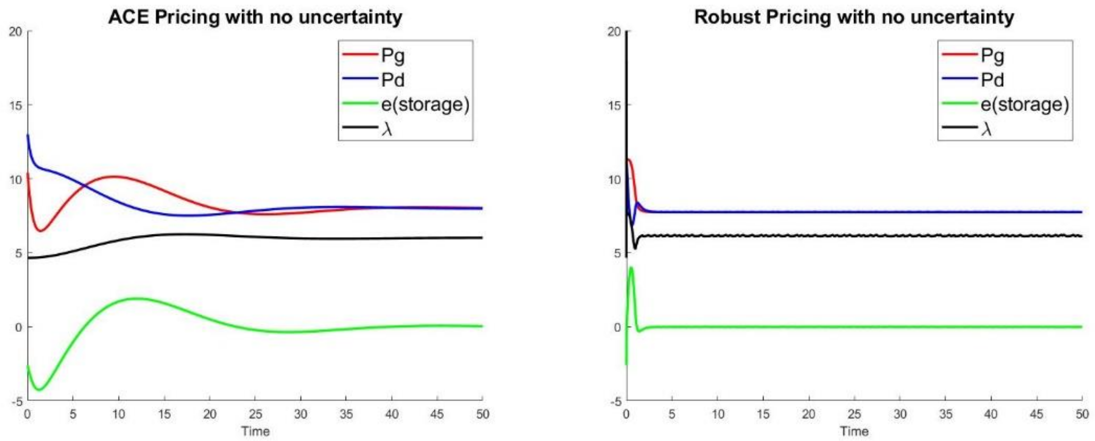

Figure 1. Dynamic without uncertainty.

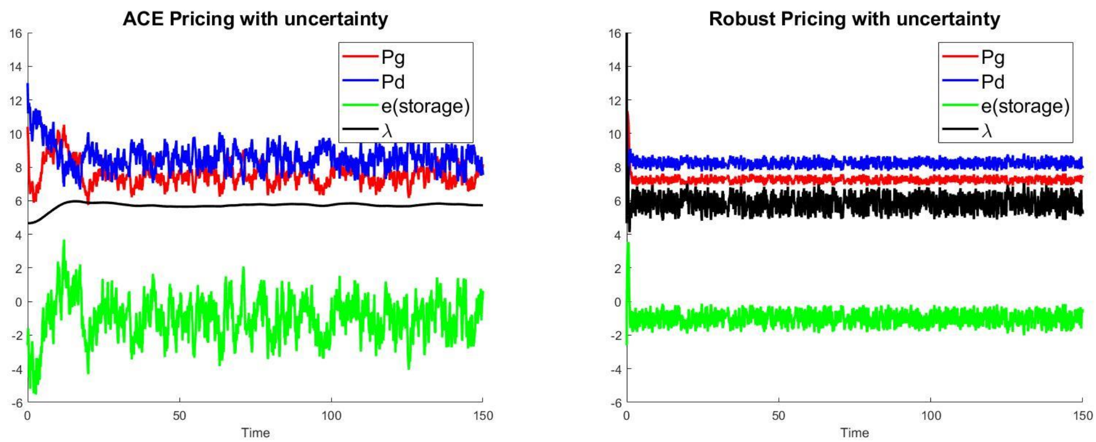

Figure 2. Dynamic with uncertainty.

IV. Conclusion

In this paper, the dynamic of the microgrid market is modeled as a linear state space system. And the robust pricing is developed through fuzzy logic and solving LMI equation. The proposed pricing scheme uses information of all system to derive a pricing scheme which is robust to possible uncertainty event. The simulation result shows that the robust pricing scheme achieve the same equilibrium operation point with ACE pricing, but the proposed method can achieve solution faster. It's needed to note that the robust pricing uses frequent price vibration to stable the system.

V. Comment

The paper demonstrates an interested approach to design the pricing under uncertainty being involved e.g. renewables. By using fuzzy logic and LMI equation, certain amount of robustness can be guaranteed. However, from the practical viewpoint, there's some concerns exist in this paper.

This paper models the microgrid market as a continuous linear state space system and allow the price to fluctuate in a very high frequency behavior. Even though this paper has included the economic profit of suppliers and consumers into the model. In real world, the dynamic of demand/supply may not adjust their consumption/generation according to the price under such a high frequency. Therefore, the model used should be further examined. Instead of considering a continuous system, I think the better approach to model the microgrid market is to consider a discrete system with a large enough step time (e.g. the dispatch time-interval of utilities). That's to say, the speed of each generation/consumption unit should be clearly defined. For example, usually, the storage system can adjust their generation or consumption in a faster manner than traditional power plant unit, and also consumer which participates in demand-response management can adjust their demand in a fast manner. In short, to align with the real-world power market dispatch operation, a discrete system with proper operation time step of each unit should be considered. The proposed method in this paper should be transformed into discrete state form to make the algorithm more practical. If the units in a system couldn't adjust generation/demand in a high frequency manner shows in Fig. 2. Then the effectiveness of the method should be further discussed.

Reference

[1]. W.-Y. Chiu, H. Sun, and H. V. Poor, ''Energy imbalance management using a robust pricing scheme,'' IEEE Trans. Smart Grid, vol. 4, no. 2, pp. 896–904, Jun. 2013