DYNAMIC COUPLING BETWEEN POWER MARKETS AND POWER SYSTEMS

Wellington S. Mota
Departamento de Engenharia Eletrica
UFPB - Campina Grande PB - BRASIL
wsmota@dee.ufpb.br

Fernando L. Alvarado
Department of Electrical and C. Engineering
The University of Wisconsin - Madison
alvarado@engr.wisc.edu

Abstract

Power System Markets represented by dynamic equations provide insights into the market behaviour which are not available from static models. A combination of aggressive energy imbalance regulation and fast response of the market can lead to unstable market conditions. The dynamic properties of the market (as characterized by the eigenvalues of the market dynamic equations) are first determined by representing the power system by means of algebraic equations. Next, the coupling between energy imbalance and market dynamics is studied by modelling the market dynamics together with the electro-mechanical power system dynamics. MATLAB-based software is used to evaluate the eigenvalues of a linearized version of the various models of interest. Numerical results are presented to illustrate the effects of interaction between markets and power system parameters. The main result from this paper is that when a stable market model is combined with a stable electro-mechanical system model, the resulting combined system can exhibit unstable behaviour. The implications of this result are significant: either those designing the rules for market operation must accommodate to the dynamic needs of the system, or those designing system electro-mechanical controls and stabilizers must take into consideration the conditions that will be imposed on the system by operation in a market-driven environment.

Keywords: Market dynamics, Power System Dynamics, eigenvalues.

1 INTRODUCTION

The potential for increased competition in the electric power industry has long been discussed. Back when interconnected system took shape after the innovation of high voltage transmission, the electric power system exhibited the characteristics of a natural monopoly. In general, as a network becomes better connected, the number of potential options available increases, and the pressure for greater reliance on market mechanisms grows stronger (Hung-Po, 1996).

The design and operation of an interconnected power system requires the design of well behaved (stable) system. This paper studies the stability of interconnected power systems when market dynamics are considered. Several assumptions are made in Alvarado (1997):

- Marginal production costs λ_g are linear functions of generation power order P_g.
- Marginal benefit functions λ_d are negatively-sloping linear functions of power consumption P_d.
- Response of suppliers and consumers to observed prices is not instantaneous. It is governed by first order single time constant differential equations.
- If power is not balanced precisely at all times, an energy imbalance results. An energy imbalance leads to the need to control such imbalance to prevent system damage or unwanted relay action.
- Synchronous generators are represented by differential equation models. Some of these models include the effect of voltage regulator and Power System Stabilizing Signals (PSSS).
- The action of the governor/turbine system is representable by a differential equation model.
- Generation is a function of marginal cost and price. Demand is a function of marginal benefit, price, and system voltage.
- The network is representable as a set of linear algebraic equations.

The two last assumptions above provide the coupling between market and network.

2 ENERGY IMBALANCE MARKET DYNAMICS

In a real power system, energy imbalance is never sustained indefinitely (Alvarado, (1997). It must be reduced or driven to

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zero. In a traditional utility environment, such an objective is attained by automatic generation control (AGC). In the Market-driven model, it must be assumed that prices will reflect the degree of energy imbalance. That is, an excess of power supplied to the grid will slightly depress the value of the power, and thus will decrease the price. Such a situation can be represented by adjusting prices depending on the degree of energy imbalance. This point was the basis for the proposals by (Bohn,1984). and has been recently promoted further by (Hist, 96) and (Hist, 97). The changing of price depending on excess or shortfall or real time energy balance is referred as frequency regulation pricing or ACE (Area Control Error) pricing. The equations representing the dynamics of ACE pricing for m suppliers n consumers are:

$$
\begin{aligned}
\tau_{gj}\dot{P}_{gj} &= -b_{gj} - c_{gj}P_{gj} + \lambda - K_j E, j = 1, m &(1)\\
\tau_{di}\dot{P}_{di} &= b_{di} + c_{di}P_{di} - \lambda, \quad i = 1, n &(2)\\
\dot{E} &= \sum_{j=1}^{m} P_{gj} - \sum_{i=1}^{n} P_{di} &(3)\\
\tau_{\lambda}\dot{\lambda} &= -E &(4)
\end{aligned}
$$

where

$b_{gi} + c_{gi}P_{gi}$	is the Marginal Cost of supplier j
$b_{dj} + c_{dj}P_{dj}$	is the Marginal Benefit of consumer i
λ_{gj}	is the Power Generation Order time constant of supplier j
λ_{di}	is the Demand time constant of consumer i
λ	is the Market Price
τ_{λ}	is the Market Price time constant
E	is the Power System excess Stored Energy
K_{gj}	is a coefficient for the Market Stabilizer Signal sent to supplier j

The interpretation of these equations is as follows: generators act in a way that tends to increase production when prices exceed production marginal costs. Demands act in a way that tends to increase consumption when marginal benefits exceed price. Since it may be impossible to perfectly balance supply and consumption at all times, any discrepancy accumulates as an energy error. In practical system, this results in either an increase in frequency or an increase in the ACE. The result of an excess of energy is a reduction in the system price, which takes place according to some time constant τ_{λ}. This reduction in system price increases consumption and decreases production, thereby leading to a decrease in the excess energy. Stability requirements also necessitate the presence of a supplementary stabilizing price signal to be sent to either the suppliers or the consumers (Alvarado, 1999). Here, the signal is sent to the suppliers. The stabilizing signal is a constant gain times the accumulated energy error. This can be interpreted as a bias that is added to prices whenever the energy error is nonzero. This supplementary signal is essential to stable market behavior.

3 POWER SYSTEM ELECTRO-MECHANICAL DYNAMICS

The unit generations are modeled according to the classic machine model used for transient stability studies (Martins, 1996) and (Kundur, 1993). The developed software allows to represent synchronous machines for several models according the user requirements. For example, the user may be interested only on eigenvalues calculation of the electro-mechanical power system. In this case a sixty order synchronous machine model can be used. On the other hand, to study the dynamic coupling between market and power system, a third order machine model is enough.

3.1 Turbine/Governor dynamic model

The Turbine/Governor is modeled according to the block diagram figure 1, where P_g corresponds to the Power Generation Order associated with the market model, ω is the machine velocity, Y is the valve position, and P_m the mechanical power output.

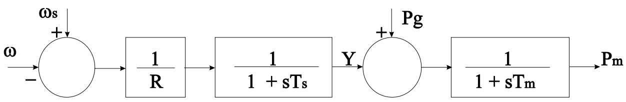

Figure 1: Governor Turbine block diagram

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3.2 Automatic Voltage Regulator (AVR) model

The AVR is modeled according the block diagram in figure 2, where the AVR type is selected by an appropriate choice of parameters. The PSSS is selected by an appropriate choice of parameters.

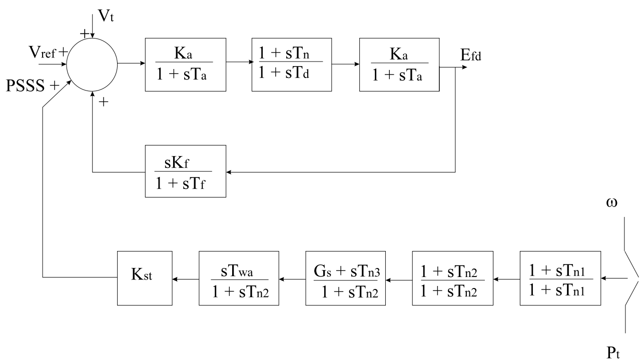

Figure 2: AVR model block diagram

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3.3 Synchronous Machine dynamic model

The general synchronous machine model is a sixth order model, according to dynamic equations:

$$
\dot{E}_d' = \frac{1}{T_{q0}'}[\frac{x_q - x_q'}{x_q' - x_l}E_d'' - \frac{x_q - x_l}{x_q' - x_l}E_d'
$$

$$
+\frac{(x_q - x_q')(x_q'' - x_l)}{x_q' - x_l}I_q] \qquad (5)
$$

$$
\dot{E}_q' = \frac{1}{T_{d0}'}[E_{fd} + \frac{x_d - x_d'}{x_d' - x_l}E_q''
$$

$$-\frac{x_d - x_l}{x_d^{'} - x_l}E_q^{'} + \frac{(x_d - x_d^{'})(x_d^{''} - x_l)}{x_d^{'} - x_l}I_d] \quad (6)$$

$$\dot{E}_d^{''} = \frac{1}{T_{q0}^{''}}[-E_d^{''} + E_d^{'} + (x_q^{'} - x_q^{''})I_q] + \frac{x_q^{''} - x_l}{x_q^{'} - x_l}\dot{E}_d^{'} \quad (7)$$

$$\dot{E}_q^{''} = \frac{1}{T_{d0}^{''}}[-E_q^{''} + E_q^{'} - (x_d^{'} - x_d^{''})I_d] + \frac{x_d^{''} - x_l}{x_d^{'} - x_l}\dot{E}_q^{'} \quad (8)$$

$$\dot{\omega} = \frac{1}{2H}(P_m - P_e - D(\omega - 1)) \quad (9)$$

$$\dot{\delta} = \omega_s(\omega - 1) \quad (10)$$

Algebraic equations for:

Terminal Voltages

$$V_t^2 = V_d^2 + V_q^2$$

Internal Voltages

$$V_d - E_d'' = x_q'' I_q - R_a I_d$$

$$V_q - E_q'' = x_d'' I_d - R_a I_q$$

Terminal Power

$$P_t = V_d I_d + V_q I_q$$

Air-gap Power

$$P_e = P_t + R_a(I_d^2 + I_q^2)$$

3.4 Transmission System

The transmission system is represented through the nodal admittance matrix expanded into its real and imaginary components.

$$I_{DQ} = Y V_{DQ}$$

3.5 Load Representation

The reactive load is represented by a constant admittance and the active load by a function of terminal bus voltage and bus current.

$$P_L = V_D I_D - V_Q I_Q$$

3.6 Axis Transformation

In order to transform voltage and current from system reference to machine reference frame, the following axis transformation is required:

$$\begin{bmatrix} V_D \\ V_Q \end{bmatrix} = \begin{bmatrix} \sin\delta & \cos\delta \\ -\cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Z \end{bmatrix}$$

4 MARKET/POWER SYSTEM LINEARIZED MODEL

The Market and the Power System are represented in a linearized fashion around an operating point by a set of differential equations together with a set of algebraic equations in the form Mota, (1997):

$$\begin{bmatrix} \Delta\dot{X} \\ 0 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Z \end{bmatrix} \quad (11)$$

where

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$$

is the Jacobian matrix.

The symbol Δ signifies an incremental change from a steady-state value and will be omitted in the remainder of this paper. Equation (11) can be organized as follows:

$$\begin{bmatrix} \dot{E} \\ \dot{\lambda} \\ \dot{P}_d \\ \dot{P}_g \\ \dot{x}_{\text{gov}} \\ \dot{x}_{\text{avr}} \\ \dot{x}_{\text{syn}} \\ \hline 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{array}{c} \overbrace{\quad}^{x_{\text{mkt}}} \overbrace{\quad}^{x_{\text{gen}}} \overbrace{\qquad}^{z} \\ \left[\begin{array}{c|c} J_1 & J_2 \\ \hline J_3 & J_4 \end{array}\right] \end{array} \begin{bmatrix} E \\ \lambda \\ P_d \\ P_g \\ x_{\text{gov}} \\ x_{\text{avr}} \\ x_{\text{syn}} \\ \hline P_t \\ V_t \\ V_{DQ} \\ I_{DQ} \\ V_{dq} \\ I_{dq} \end{bmatrix}$$

4.1 State Variables

For one market and ng generation units, the state vector is formed from:

$$X = \begin{bmatrix} X_{\text{mkt}} \\ X_{\text{gen}_k} \end{bmatrix}, k = 1, ng$$

where for m suppliers and n consumers:

$$X_{\text{mkt}} = \begin{bmatrix} E \\ \lambda \\ P_{di} \\ P_{gj} \end{bmatrix}, \quad i = 1, n; j = 1, m$$

is the market state vector and:

$$X_{\text{gen}_k} = \begin{bmatrix} X_{\text{gov}} \\ X_{\text{avr}} \\ X_{\text{syn}} \end{bmatrix}, \quad k = 1, ng$$

where
X_{gov} State vector for the turbine/governor.
X_{avr} State vector for the AVR including PSSS.
X_{syn} State vector for the generator.

4.2 Algebraic Variables

The vector of algebraic variables Z is defined as:

$$Z = \begin{bmatrix} P_t \\ V_t \\ V_{DQ} \\ I_{DQ} \\ V_{dq} \\ I_{dq} \end{bmatrix}$$

where

P_t	Generator terminal power vector.
V_t	Generator terminal voltage magnitude vector.
V_{DQ}	Real and imaginary components of bus voltage (system reference) vector.
I_{DQ}	Real and imaginary components of bus injected current vector.
V_{dq}	Real and imaginary components of the generator voltage (machine reference) vector.
I_{dq}	Real and imaginary components of the generator terminal current (machine reference) vector.

4.3 Market/Power System state matrix

The Market/Power System state matrix can be obtained by eliminating the vector of algebraic variables ΔZ from equation (11).

$$\Delta\dot{X} = (J_1 - J_2 J_4^{-1} J_3)\Delta X$$

$$\Delta\dot{X} = AX$$

The coupled market/power system dynamic model can be best viewed from the diagram of figure 3.

5 NUMERICAL EXAMPLE

A three generator/infinite bus 7 line and 6 bus system (shown in figure 4) is used to illustrate the proposed techniques. For this system, three suppliers and two consumers are considered. Numerical values for the market parameters are presented in the appendix. The parameters c_g, c_d,b_g,b_d are given to mach the equilibrium equations (1) and (2) and the power flow results for

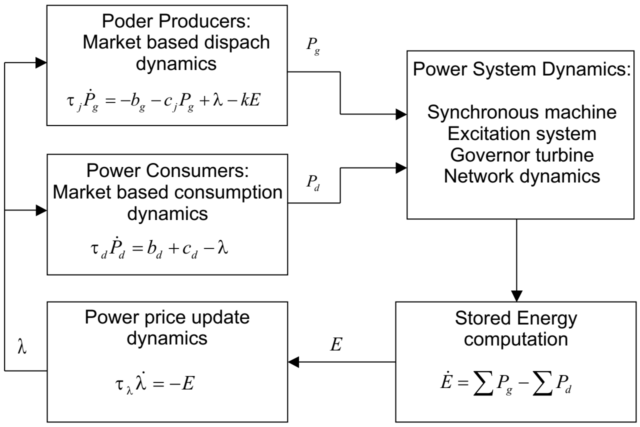

Figure 3: Coupled market/power system dynamic model

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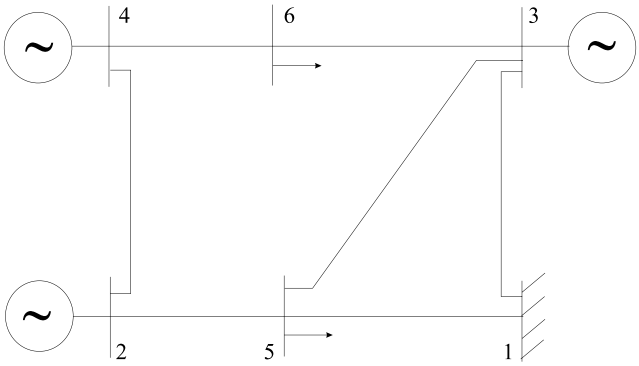

Figure 4: Single Line Diagram of the Three Generators One Infinite Bus System

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the example system based on the power price in \$/MWh. Once we obtain the right hand side parameters, it is easy to get producer and consumer response constants τ_g and τ_d by assuming a ramp rate for generators and consumers in MW/min. The sensivity of power price change to the curent price λ is dictated by the time constant τ_λ. The smaller of τ_λ the more the market tends to be stable. Time constants for electro-mechanical systems are well known.

5.1 Eigenvalue calculation

Table 1 shows the eigenvalues of the isolated market model. This model is stable.

Table 2 shows the eigenvalues of the electro-mechanical power system dynamic model. This model is also stable.

Table 1: Eigenvalues of the Dynamic Market Model.

Market Dynamic Model
-0.1541
$-0.6453 + 0.8338i$
$-0.6453 - 0.8338i$
-1.5006
-2.6938
-2.5183
-2.4093

Table 2: Eigenvalues of the Electro-mechanical Power System Model.

Electro-mechanical Power System Dynamic Model
-38.1403
-23.1261
$-9.7165 + 15.2503i$
$-9.7165 - 15.2503i$
$-0.9064 + 12.8937i$
$-0.9064 - 12.8937i$
-9.0060
$-1.8453 + 8.3847i$
$-1.8453 - 8.3847i$
$-0.8063 + 6.0034i$
$-0.8063 - 6.0034i$
-1.3901
-0.9766
-0.9890
-0.2022
-0.2021
-0.9937
-0.2012

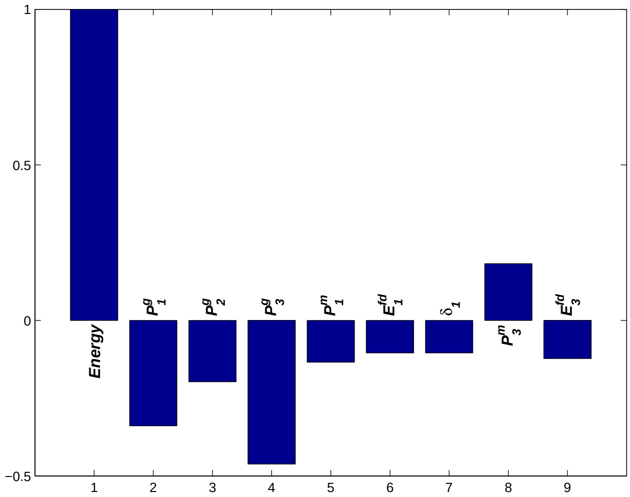

Figure 5: Normalized participation factors diagram

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The stable market and the stable power system are modelled together, equation (11). The interconnected dynamic model market/power system produce instability of the system. See the first column of table 3. The pair of unstable mode is mainly associated with system energy imbalance and generation power order as shown in figure 5 through the corresponding normalized participation factors. The interconnected dynamic model market/power system produces an instability because free trades with free generation cost are permitted among all parties.

Modified values are chosen for the suppliers marginal cost to affect generation mechanical power(Data in appendix, modified case). Now, the interconnected dynamic model market(modified case)/power system produces a stable system. See the second column of table 3.

Table 3: Eigenvalues of the interconnected dynamic model (market/power system).

Base case (Unstable)	Modified case (Stable)
-38.2443	-38.2443
-23.1212	-23.1212
$-9.8264 + 14.7135i$	$-9.8264 + 14.7135i$
$-9.8264 - 14.7135i$	$-9.8264 - 14.7135i$
$-0.9059 + 12.8649i$	$-0.9059 + 12.8649i$
$-0.9059 - 12.8649i$	$-0.9059 - 12.8649i$
-9.0093	-9.0095
$-1.6308 + 8.6433i$	$-1.6309 + 8.6433i$
$-1.6308 - 8.6433i$	$-1.6309 - 8.6433i$
$-0.8342 + 6.0593i$	$-0.8332 + 6.0586i$
$-0.8342 - 6.0593i$	$-0.8332 - 6.0586i$
-3.0161	-5.0030
-2.5083	-3.0096
-2.4064	-2.5087
$\mathbf{0.0266} + 0.4544i$	-2.4073
$\mathbf{0.0266} - 0.4544i$	-2.3430
-1.6899	$-0.0098 + 0.3531i$
-1.4098	$-0.0098 - 0.3531i$
-0.1199	-1.4110
-1.0684	-0.1364
-0.9784	-0.9788
-1.0000	-0.9896
-0.2016	-0.2014
-0.2020	-0.9943
-0.9890	-0.2020

6 CONCLUSIONS

The Market dynamics study requires the consideration of the Power System dynamics. This article has presented a specific example where a stable isolated market model lead to instability when connected to a stable power system. Improper application of free cost coefficients, characteristic of competitive market, could result in a de-stabilization of the electro-mechanical system. The implications of this result are important: The power exchange policies and rules for de regulated power market must accommodate to the dynamic needs of the system. Also, designing system electro-mechanical controls must take into account the conditions that will be imposed on the power system by operation in a market-driven environment.

APPENDIX 1 MARKET DATA

Three-supplier two-consumer data (Base case)

Suppliers Data				Consumers Data		
τ_g	c_g	b_g	K_g	τ_d	c_d	b_d
0.1	0.3	1.0	0.1	0.2	-0.5	10.0
0.3	0.5	2.0	0.1	0.25	-0.6	8.0
0.2	0.2	1.0	0.1			

τ_λ = 100

Three-supplier two-consumer data (Modified case)

Suppliers Data				Consumers Data		
τ_g	c_g	b_g	K_g	τ_d	c_d	b_d
0.1	0.5	1.0	0.1	0.2	-0.5	10.0
0.3	0.7	2.0	0.1	0.25	-0.6	8.0
0.2	0.6	1.0	0.1			

APPENDIX 2 ELECTRO-MECHANICAL SYSTEM DATA

Transmission System (P.U. of 100 MVA)

From	To	R	X	Y
4	6	0.0101	0.0615	0.8000
3	6	0.0057	0.0460	0.0980
3	5	0.0836	0.2360	0.1856
1	3	0.0628	0.1100	0.3654
1	5	0.0033	0.0313	1.1443
2	5	0.0255	0.1720	0.6500
2	4	0.0836	0.2360	0.1856

Power in Mw and MVar

Bus	V	θ	P_g	Q_g	P_l	Q_l
1	1.02	0.0	147.2	302.0	0.00	0.00
2	1.00	7.3	72.0	11.0	0.00	0.00
3	1.01	7.0	135.0	48.0	0.00	0.00
4	1.01	12.6	170.0	7.2	0.00	0.00
5	0.92	-3.7	0.0	0.0	400.8	380.0
6	0.96	8.2	0.0	0.0	99.8	200.0

Generator Data

Bus	H	$X_d\prime$	X_d	X_q	R_a	$T_{do}\prime$
2	8.2	0.093	0.950	0.900	0.020	6.2
3	4.3	0.179	1.750	1.680	0.015	5.2
4	6.3	0.114	0.825	0.800	0.018	4.8

Excitation System

Bus	K_a	T_a
2	100.0	0.04
3	50.0	0.02
4	200.0	0.05

Turbine/Governor System

Bus	R	T_s	T_m
2	0.05	1.0	5.0
3	0.05	1.0	5.0
4	0.05	1.0	5.0

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