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# New Strategy Agents to Improve Power System Transient Stability

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***Abstract*-- This paper proposes transient angle stability agents to enhance power system stability. The proposed transient angle stability agents divided into two strategy agents. The first strategy agent is a prediction agent that will predict power system instability. According to the prediction agent's output, the second strategy agent, which is a control agent, is automatically calculating the amount of active power reduction that can stabilize the system and initiating a control action. The control action considered is turbine fast valving. The proposed strategies are applied to a realistic power system, the IEEE 50-generator system. Results show that the proposed technique can be used on-line for power system instability prediction and control.**

***Index Terms*-- Multi-agents, Fast Valving, Power System Transient Stability, Prediction methods,**



## I. Introduction

For reliable service, a bulk electricity system must remain intact and be capable of withstanding a wide variety of disturbances. Therefore, it is essential that the system be designed and operated so that the more probable contingencies can be sustained with no loss of load (except that connected to the faulted element). So, the most adverse possible contingencies must not result in uncontrolled, widespread and cascading power interruptions [1].

In the past, when systems were smaller and less complicated informal methods of security, analysis and control, were performed by system operators based upon experience and knowledge of system. Modern power systems are quite large and more extensively interconnected making the task of security analysis and control difficult for the system operator [2]. In case where transient stability is an issue, the conventional methods of stability analysis by a time domain iterative process are too far slow for online operation. This led researchers to explore fast direct methods to analyze transient stability of electric power systems [3].

A new fast learning algorithm that has been used in robotic area and proven its validity to predict ball position for 0.5 s in advance is adapted for power system parameters prediction [3,4,5]. By using prediction agent, power system vulnerability can be easily detected. The detection method will be based on generator rotor angles prediction. The predicted values are linked to a control agent that will apply the control action to stabilize the system when the system is on the verge of becoming unstable, which is called an emergency state. This control action can be generator tripping [6], load shedding, dynamic breaking, transient excitation boosting, or fast valving [7]. Prediction agent and control agent are linked to a measurement agent, which updates the values of the prediction and provides active power measurements for the control agent as shown in Fig. 1. Scenario of the multi-agent technique can be illustrated as

- Three-phase fault occurred on one of the high voltage lines and/or buses adjacent to generation site;
- Clearing the fault according to the calculated critical clearing time (cct) for such fault location;
- Observe the relative generators rotor angle for 0.5 s;
- Prediction generator rotor angle for 0.5 s;
- Apply control agent to the most disturbed generators.

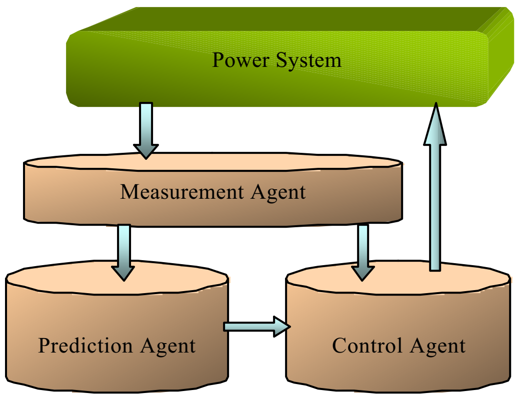


Fig. 1. Power system and multi-agents interaction.

The proposed technique is tested and verified by applying it to the more general case of the IEEE dynamic analysis test system. The Extended Transient & Mid-Term Stability Program (ETMSP) package is used as the electric power system time domain simulation tool (measurements provider). Many different models for various types of power system devices are available. The program uses power flow inputs from Interactive Power Flow Program (IPFLOW) as a starting point for the simulations. ETMSP provides a simulation of the electric power systems using exact dynamic system modeling. With the ability to specify the fault location and various simulation parameters the simulation of real life events is applicable [8]. The block diagram of Fig. 2 shows the steps taken to apply the multi-agent technique.

## II. Prediction Agent

The proposed prediction agent is adapted from a proven robotic ball-catching algorithm. In the robotics area there has been a great effort to predict a moving object trajectory and consequently position to catch the ball. A fast learning algorithm that updates its database according to continuous measurement of the moving object position predicts the position of the moving object. This algorithm controls the robot manipulator to catch the moving object. There was no prior knowledge of the moving object trajectory or position except for the measurement update [9].

The algorithm is coded to be applicable for predicting power system generators rotor angles. The algorithm is simply divided into two parts. These two parts are known as tracking and prediction process.

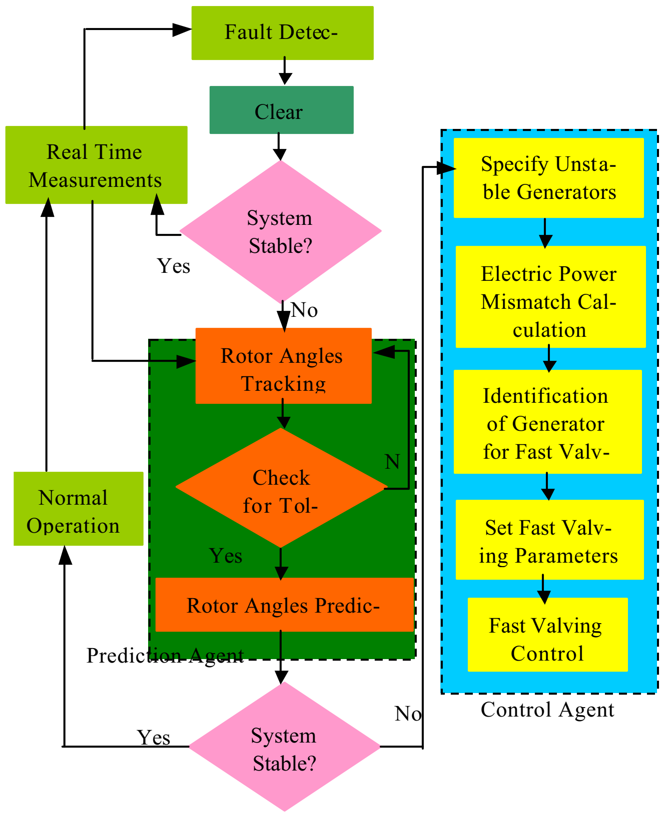


Fig. 2. Multi-Agent Technique.

*A. Tracking process*

The measured relative and tracker rotor angles are denoted by $\delta$ and $\beta$ respectively. The algorithm requires that all positions must be in x-y coordinates. Analyzing both measured and tracker angles in x-y components, the x and y components of the measured relative rotor angles will be $\delta_x = \cos(\delta)$ and $\delta_y = \sin(\delta)$ respectively and the components for the tracker rotor angles will be $\beta_x = \cos(\beta)$ and $\beta_y = \sin(\beta)$ respectively.

For each sampling instant the rotor position components $\delta_x, \delta_y$ will be updated and the new tracker position in $x$-direction is calculated using (1) and the tracker position in $y$-direction is calculated using (2).

$$\beta_{x(k+1)} = \Delta t\,\dot\beta_{x(k)} + \beta_{x(k)} \qquad (1)$$

$$\beta_{y(k+1)} = \Delta t\,\dot\beta_{y(k)} + \beta_{y(k)}. \qquad (2)$$

The measured rotor angle components in $x$- and $y$-direction are successively used to calculate the rotor velocity in $x$- and $y$-direction as being expressed by (5) and (6).

$$\Delta\delta_{x(k+1)} = \delta_{x(k+1)} - \delta_{x(k)} \qquad (3)$$

$$\Delta\delta_{y(k+1)} = \delta_{y(k+1)} - \delta_{y(k)} \qquad (4)$$

$$\omega_{x(k+1)} = \Delta\delta_{x(k+1)} / \Delta t \qquad (5)$$

$$\omega_{y(k+1)} = \Delta\delta_{y(k+1)} / \Delta t \qquad (6)$$

$$\omega_{(k+1)} = \left(\delta_{(k+1)} - \delta_{(k)}\right) / \Delta t. \qquad (7)$$

For each sampling instant the rotor position components $\delta_x, \delta_y$ will be updated. The initial value for the tracker position $\beta$ will be taken as 0.0 deg. The scalar distance, $\varepsilon$ between the end-effector and the ball in meters, which in this case represents the absolute tolerance value, is assumed to be,

$$\varepsilon_{x(k+1)} = \beta_{x(k+1)} - \delta_{x(k+1)} \qquad (8)$$

$$\varepsilon_{y(k+1)} = \beta_{y(k+1)} - \delta_{y(k+1)} \qquad (9)$$

$$\varepsilon_{(k+1)} = \sqrt{\varepsilon^2_{x(k+1)} + \varepsilon^2_{y(k+1)}}. \qquad (10)$$

The above equations will be substituted into the objective function (11) of the tracking stage [7],

$$\underset{T_f,\underline{\dot\beta}}{MIN}\left\{T_f - \rho\left(\underline{\dot\delta}\bullet\underline{\dot\beta}\right) + \sigma\left[\left(\dot\delta_x - \dot\beta_x\right)^2 + \left(\dot\delta_y - \dot\beta_y\right)^2\right]\right\} \qquad (11)$$

where, $T_f$ is a rough estimate of the final tracking. $\rho$ is a constant. $\sigma$ is a function of the absolute tolerance and called the weighing function, which is equal to $10/\sqrt{\varepsilon_{(k+1)}}$ .

Since the end effector position $\beta_x$, $\beta_y$ and the object velocity components $\dot\delta_x$ and $\dot\delta_y$ are known, the end effector velocity can be obtained by solving the objective function for only the minimum time. For each sample, equation (11) can be rewritten as

$$\underset{\dot\beta_y}{MIN}\left\{\frac{\delta_y - \beta_y}{\dot\beta_y - \dot\delta_y} - \rho\left[\left(\frac{\beta_x - \delta_x}{\beta_y - \delta_y}\dot\delta_x + \dot\delta_y\right)\dot\beta_y + \dot\delta^2_x - \frac{\beta_x - \delta_x}{\beta_y - \delta_y}\dot\delta_x\,\dot\delta_y\right]\right.$$

$$\left. + \sigma\left(\dot\delta_y - \dot\beta_y\right)^2\left[\frac{(\beta_x - \delta_x)^2}{(\beta_y - \delta_y)^2} + 1\right]\right\}. \qquad (12)$$

By differentiating the above equation with respect to $\dot\beta_y$, the minimum can be obtained by evaluating the roots of the cubic polynomial,

$$f\left(\dot\beta_{y(k+1)}\right) = a_{0(k+1)} + a_{1(k+1)}\dot\beta_{y(k+1)} + a_{2(k+1)}\dot\beta^2_{y(k+1)}$$

$$+ a_{3(k+1)}\dot\beta^3_{y(k+1)} = 0 \qquad (13)$$

where $a_0, a_1, a_2, and\ a_3$ are the optimization function coefficients. These coefficients are tabulated in Table1.

The real root, which results in both smallest positive value of $T_f$ and the minimum value of the objective function, is chosen to be the $y$-component of the predictor position in the coarse tuning stage. The $x$-components of the predictor position can be evaluated as

$$\dot{\beta}_x = \dot{\delta}_x + \left(\dot{\beta}_y - \dot{\delta}_y\right)\frac{\beta_x - \delta_x}{\beta_y - \delta_y}. \quad (14)$$

For each sampling instant the difference between the actual generator relative rotor angle $\delta$ and the generated relative rotor angle $\beta$ is calculated and compared with a pre-determined tolerance ($TOL$). If the difference $(\delta\text{-}\beta) \le TOL$, the algorithm is switched into the prediction process (fine tuning stage).

TABLE I
OPTIMIZATION FUNCTION COEFFICIENTS

| |
|---|
| $a_{0(k+1)} = \varepsilon_{y(k+1)} - \rho D1_{(k+1)}\dot{\delta}^2{}_{y(k+1)} - 2\sigma_{(k+1)}D2_{(k+1)}\dot{\delta}^3{}_{y(k+1)}$ |
| $a_{1(k+1)} = 2\left(\rho D1_{(k+1)}\dot{\delta}_{y(k+1)} + 3\sigma_{(k+1)}D2_{(k+1)}\dot{\delta}^2{}_{y(k+1)}\right)$ |
| $a_{2(k+1)} = -\rho D1_{(k+1)} - 6\sigma_{(k+1)}D2_{(k+1)}\dot{\delta}_{y(k+1)}$ |
| $a_{3(k+1)} = 2\sigma_{(k+1)}D2_{(k+1)}$ |

*B. Prediction process*

The purpose of this process is to predict the generator rotor angle position after a period of $T_{Pred}$ according to the generator rotor angle trajectory generated in the tracking process. In this stage the third order Taylor series expansion has been used. The Taylor series expansion is used in the prediction process of the adapted ball-catching prediction algorithm. The advantage of this method is that it converges faster than the least square method used in robotic ball catching.

The faulted system states $(\theta_i, \omega_i)$ of the i[th] machine can be expressed by Taylor series expansion as

$$\theta_i(T_{pred}) = \theta_i(0) + \theta_i^{(1)}t + \theta_i^{(2)}\frac{t^2}{2!} + \theta_i^{(3)}\frac{t^3}{3!}\ldots \quad (15)$$

$$\omega_i(T_{pred}) = \theta_i^{(1)} + \theta_i^{(2)}t + \theta_i^{(3)}\frac{t^2}{2!} + \theta_i^{(4)}\frac{t^3}{3!}\ldots \quad (16)$$

where θ(0) is the initial rotor angle and $\theta^{(m)}, m = 1,2,3,\ldots$ is the $m^{th}$ derivative of rotor angle evaluated at $t = 0$ using faulted network measurements (ETMSP output).

Consider the truncated Taylor series expansion of equation (15) having only up to third order derivatives, the predicted rotor angle for the system can be expressed as

$$\begin{aligned}\hat{\delta}_{(T_{pred})} &= \delta_{(k-1)} + \left(T_f - t_{(k-1)}\right)\beta_{(k+1)} \\ &+ \alpha 1_{(k+1)}\left(\frac{T^2{}_f - t^2{}_{(k-1)}}{2} - t_{(k+1)}\left(T_f - t_{(k-1)}\right)\right) \\ &+ \alpha 2_{(k+1)}\left(\frac{T^3{}_f - t^3{}_{(k-1)}}{3} - \left(t_{(k+1)} + t_{(k)}\right)\frac{T^2{}_f - t^2{}_{(k-1)}}{2}\right) \\ &+ \alpha 2_{(k+1)}t_{(k)}t_{(k+1)}\left(T_f - t_{(k-1)}\right). \quad (17)\end{aligned}$$

The time derivative of equation (16) gives the velocity value at the prediction time $T_f$ , which is expressed by

$$\begin{aligned}\hat{\omega}_{(T_{pred})} &= \dot{\beta}_{(k+1)} + \alpha 1_{(k+1)}\left(T_f - t_{(k+1)}\right) \\ &+ \alpha 2_{(k+1)}\left(T_f - t_{(k)}\right)\left(T_f - t_{(k-1)}\right). \quad (18)\end{aligned}$$

The angular velocity ω varies continuously and shows a smooth change because of the large inertia of the turbine-generator.

Specification the stability of each generator in the system is carried out using a simple criterion. This criterion uses the difference between relative rotor angles $\delta(T_f)$ and $\delta(T_f\text{-}0.5)$ along with a threshold value of $\delta(T_f)$ to judge the stability of each generator in the system. If the difference $\delta(T_f) - \delta(T_f\text{-}0.5) > 0.0$ and $\delta(T_f) > 180$ degree, the generator is specified to be unstable. A control agent is automatically initiated according to the prediction results. This control agent depends on controlling generators mechanical power to maintain system stability.

## III. CONTROL AGENT

*A. Fast Valving Characteristics*

Fast valving is one of many supplementary controls that are applied to improve transient stability [10]. Fast valving can be simply described in the following way. Upon the recognition of a potentially unstable generator fast valving is initiated to close the turbine steam valve to the minimal opening position $\mu_{min}$ as rapidly as possible. After a period of dead time during which the valve remains closed, the valve will reopen to an appropriate final position $\mu_{inf}$. This process can be described as a fixed control logic [11], which has a fixed stroke characteristic curve as shown in Fig. 3.

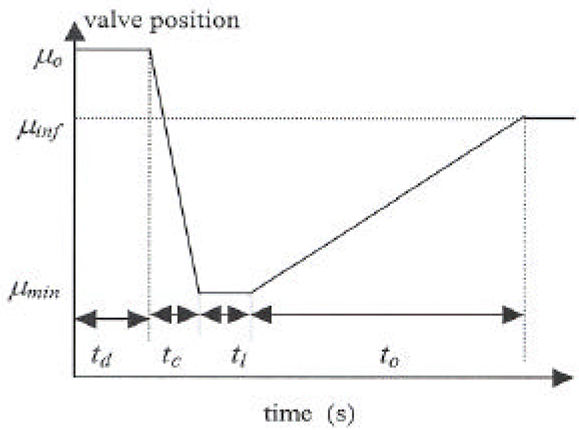


Fig. 3. Valve stroke characteristic curve.

For a turbine-generator unit, valve-closing delay time ($t_d$), valve-closing time ($t_c$), and valve-opening time ($t_o$) are usually fixed but valve minimal opening ($\mu_{min}$), dead time ($t_l$) and valve final opening ($\mu_{inf}$) are controllable.

*B. Selection of Generator for Fast Valving*

The difference between electric power before and after any disturbances (power mismatch) is calculated for each generator unit in the system. The generator to be used for fast valving should be chosen from the list of unstable generators. Among the unstable generators, the unit that has maximum mismatch in electrical power is chosen for fast valving. A mismatch in electrical power is defined by the following equation

$$Pd_i = \frac{(Pc_i - Po_i)}{M_i} - \frac{\sum_{i=1}^{N}(Pc_i - Po_i)}{\sum_{i=1}^{N} M_i} \quad (19)$$

where

$N$ number of generating units;
$M_i$ inertia constant of the $i$'s unit;
$Po_i$ generator electric power output before disturbance;
$Pc_i$ generator electric power output at the instant following fault clearance.

When a generator decelerates with respect to the center of inertia frame after a fault, the mismatch power of the $i$'s generator with respect to the center of inertia, $Pd_i$, becomes positive, and when a generator accelerates, $Pdi$ becomes negative. Therefore, the selected generator for fast valving must be defined from the prediction process as an unstable generator and the mismatch power of this generator should have the largest among the unstable generators.

In this study only the intercept valve characteristic is used. The intercept valve of the turbine-generator is closed rapidly to its specified set point upon recognition of the contingency. The successful operation of fast valving requires that the reduction amount of the turbine input power should match the severity of the fault to assist in preventing instability of the system.

### C. Fast Valving Process

A computer program is designed and coded in MATLAB to apply the proposed fast valving control method. The data input to the MATLAB program are the unstable generators' predicted relative rotor angle and the electric power, which are extracted from the output of the ETMSP program. The output from ETMSP is in binary format. The MATLAB program developed in this study receives these binary output data from ETMSP and transforms the data into decimal format. The process can be simply expressed in the following steps:

- Prepare the switching file for simulation;
- Run ETMSP pre, on, and post fault;
- Obtain the generator's electrical power, and rotor angle in each case;
- Predict the stability of generators;
- Identify the unstable generators;
- Calculate the power mismatch of each unstable unit;
- Calculate the minimal valve position;
- Set a delay time;
- Set the closing time of the valve;
- Set the dead time of the valve;
- Set the opening time;
- Use fast valving to stabilize the system;
  Repeat prediction agent process under the new situation.

## IV. Results of Case Studies

The IEEE 50-generator system is used as a test system. The proposed multi-agent technique has been applied to several three-phase faults with fault locations at both generator and load buses. Only a sample of the simulation results is presented.

A three-phase fault is applied at bus #7 and cleared after 0.1085 s by opening line between bus #6 and bus #7. After clearing the fault two generators NAN18205 and NAN18563 at buses #104 and #111 lose synchronism with the rest of the system. The rotor angles of these two unstable generators along with the rotor angles of generators PIC18252 (bus #105), BRU1853 (bus # 110) and LON1815T (bus # 103) with respect to the generator at bus #145 (8BO2739) are shown in Fig. 4.

From Fig. 4 it is obvious that generators rotor angles increases with time, which indicates instability and remedial control action needs to be taken even after clearing the fault by removing the faulted line. In attempting to avoid out of synchronism of the rest of the generators, the prediction agent is applied. Results of prediction are shown in Fig. 5. From Fig. 5, it is obvious that the tracking period took about 0.5 s. Results shows a precise prediction for a study period of about 3 s. The prediction time is about 0.5 s, which is larger than the critical clearing time of 0.1085 s. To have a good judge on how precise the prediction is, the percentage error is calculated. It was found that most precise prediction must not exceed ± 10 %. This percentage will be used as our reference for prediction accuracy. According to the calculated error percentages, this method can be applicable for on line within acceptable error values.

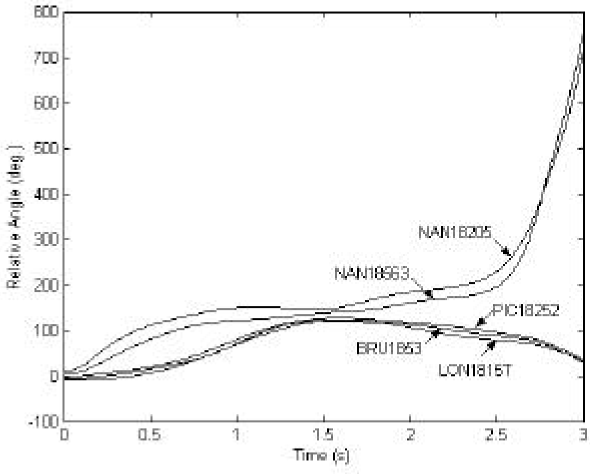


Fig. 4. Unstable generators and sample of stable generators rotor angles.

To stabilize the system a conventional fast valving schemes have been carried out. The effects of different valve actuation times of the conventional fast valving schemes on the behavior of the generators have been studied in detail. The following actuation times have been considered in this case: delay time, $t_d$ = 0.1 s; closing time, $t_c$ = 0.35 s; dead time, $t_l$ = 0.1 s; opening time, $t_o$ = 2.95 s. The input mechanical power and the output electrical power behavior of the generator NAN18205 at bus #104 is shown in Fig. 6. The minimum value of the driving mechanical power is 33.5 %, (67 MW) which is reasonable to be achieved during a closing time of 0.35 s with a closing rate of 191.5 MW/s. The relative rotor angle of the selected generators is shown in Fig. 7 after using the fast valving agent with the above valve actuation times. To ensure the system stability, prediction agent is recalled to predict rotor angle after fast valving. The results show that all the generators are stable at 5.5 s.

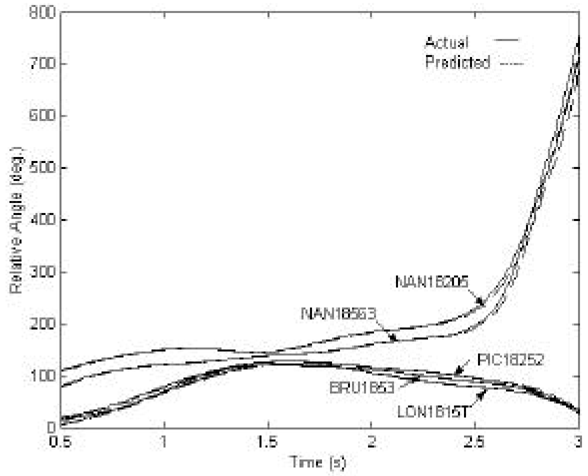


Fig. 5. Actual and predicted rotor angles.

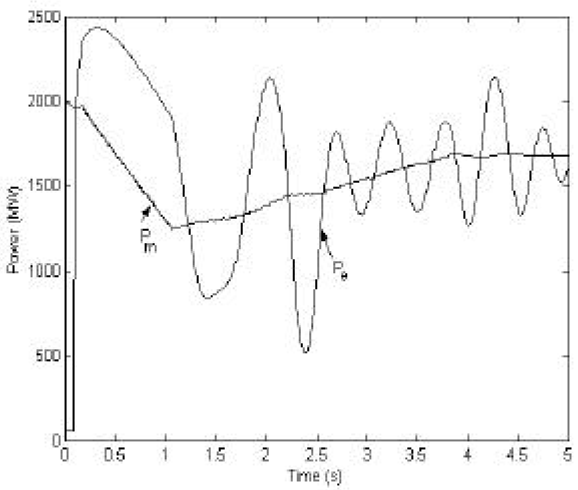


Fig. 6. Mechanical and electrical power of the generator unit NAN18205.

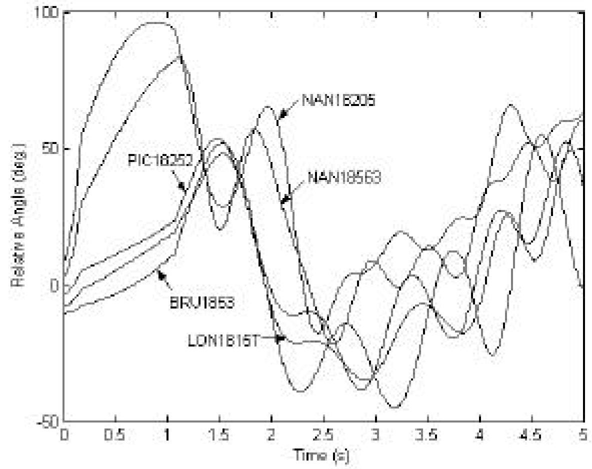


Fig. 7. Relative rotor angle of selected generators after fast valving.

## V. CONCLUSION

A fast learning technique and fast valving control for power system transient stability are presented. The measurement agent provides on-line wide area measurements. Based on on-line measurements of generators' rotor angles and electrical powers of a multi-machine power system the unstable units are predicted using the prediction agent. Applying the control agent to the most disturbed unit identified by the power mis-match technique the stability of the system is established. The stability behavior of the system has been studied before, during and after initiation of the control agent. The prediction agent initiated the control agent automatically if the prediction process shows that the system is unstable.

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