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Real-Time First Swing Instability Prediction Through Adaptive Time Series Coefficients

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Abstract - A method for predicting in real-time the outcome of any evolving transient behavior in power systems through adaptive time series coefficients is presented. After any contingency, it is fitted an auto-regressive model to the dynamics of a generator power angle, related to a reference, in order to predict the outcome of that swing for future intervals. To estimate the parameters of the model datas are sampled at a rate of 720 times per second. These measurements may be obtained from the synchronized phasor measurement units (PMUs)[1]. Datas of an observation window from one to two cycles of sixty hertzs are used to estimate the parameters of the model. In order to have an adaptive arrangement, new parameters of the model are estimated once the prediction step is completed. The outcome of the swing can be predicted quite easely. The process could be active only in case the generator angle measurement between one step and the forward differs beyond some treshold value.

Keywords: Transiente Stability, Times Series, Prediction of Instability

I. INTRODUCTION

Conventionally the stability analysis in power systems is by direct integration of the differential equations which describe the system dynamics. To do that integration the system loads are normally modeled as constant impedance loads, and then the system is equivalenced to the generator buses. The reason in doing that is the dimensionality problem. However that constitutes, in general, an oversimplification of the system loads behavior. As result the power system transient stability analysis in general will not be reliable. The computations involved in this kind of work are so huge that these techniques are only proper for off-line studies.

To directly determine the critical clearing time (CCT) the method of the transient energy functions [2-13] has been extensively studied. The determination of the instant the system post-fault dynamics leaves the attraction area corresponding to the system pos-fault stable equilibrium point seems to have considerable theoretical difficulties.

In this paper a method to predict the outcome of any evolving dynamics based on adaptive time series approach is developed and tested. A data sample frequency of 720 Hz is used. The model is fixed as an auto-regressive model of order two (AR(2)). According to the values of the model's parameters it can be concluded that the system dynamics is going to be nonstationary (unstable), stationary in a damped sine wave or even in a damped exponential(stable). Many advantages might be obtained from this research results. Among them it could be said it promote and even provide an improved adaptive out-of-step protection functions adapting to changing power system conditions. It is also a contribution to the development of closed loop control of power systems during an emergency situation [14]. It will constitute also an important step forward to the real time monitoring of the power systems.

II. THE POWER SYSTEM MODEL TO SIMULATE THE PMUs

In a **n** machine power system the dynamics of the i^{th} machine, using the n^{th} one as reference frame, may be expressed by the following pair of differential equations, assuming uniform damping coefficients:

$$\dot{\delta}_{in} = \omega_i \quad (1)$$

$$M_i \dot{\omega}_i = P_i - D_i\omega_i - P_{ei} \quad (2)$$

$$i = 1, 2, \ldots, n-1$$

with

$$P_i = P_{mi} - G_{ii}E_i^2 \quad (3)$$

and

$$P_{ei} = \sum_{\substack{j=1 \\ j\neq i}}^{N} [E_iE_jB_{ij}\sin\delta_{ij} + E_iE_jG_{ij}\cos\delta_{ij}] \quad (4)$$

E_i- internal voltage magnitude of generator i
δ_i- power angle of generator i
P_{mi}- mechanical power of generator i
M_i- constant of inertia of generator i
G_{ij}- real part of Y_{ij}
B_{ij}- imaginary part of Y_{ij}
D_i- damping constant of generator i

The generators are represented by constant e.m.f. behind the transient reactance, and the mechanical power is assumed to be constant, both for first swing stability approach. The loads are represented by constant impedances. Those are considerations widely accepted between the power system engineers.

Obs.: To simulate the synchronized phasor measurement unit output, the Extended Midterm Transient Stability Package (EMTSP) was used, but in this case using one machine as refference. For that purpose the power system model, as presented before, was used.

III. THE PREDICTIVE SWING INSTABILITY APPROACH WITH TIME SERIES ANALYSIS

A process Z is said to be stationary if that process is in a particular state of statistical equilibrium; that is, the process behavior exhibit a kind of homogeneity.

In power systems the phase angles between a generator and a reference, after any disturbance, may increase or oscilate without limits, may follow a damped exponential, or even oscilate in a damped way. The first two situations characterize the system as in an unstable behavior since they do not exhibit homogeneity at all. The others two situations otherwise are stable behaviors. This kind of datas behavior can be discriminated by retaining the requirement that their differences be stationary [17]. The auto-regressive model of order two (AR(2)), with one degree of difference, may atend all those situations, and so by using the principle of parsimony it is an appropriate model for predicting any swing instability.

From difference equations the second order auto-regressive process, with one degree of difference, may be written:

$$(1-\phi_1B-\phi_2B^2)(1-B)Z_{t+l} = a_t \quad (5)$$

with $B^mZ_t = Z_{t-m}$, a_t a white shock, $(1-B)Z_t = Z_t - Z_{t-1}$, and $\phi1$, $\phi2$ the parameters of the model.

Equation (5) may be rewritten as

$$Z_{t+l} = (1+\phi_1)Z_{t+l-1} + (\phi_2-\phi_1)Z_{t+l-2} - \phi_2Z_{t+l-3} + a_t. \quad (6)$$

So the predicted values of the serie Z($\hat{z}$) using datas up to time t are:

$$\hat{z}_t(1) = (1+\phi_1)Z_t + (\phi_2-\phi_1)Z_{t-1} - \phi_2Z_{t-2} \quad (7)$$

$$\hat{z}_t(2) = (1+\phi_1)\hat{z}_t(1) + (\phi_2-\phi_1)Z_t - \phi_2Z_{t-1} \quad (8)$$

. . . . .

. . . . .

$$\hat{z}_t(l) = (1+\phi_1)\hat{z}_t(l-1) + (\phi_2-\phi_1)\hat{z}_t(l-2) - \phi_2\hat{z}_t(l-3) \quad (9)$$

where $\hat{z}_t(l)$ is the predicted value of Z, l steps ahead using datas up to time t. In this work the datas will be phase angles of generators in terms of a reference frame.

Obs.: It should be recalled that the approach of time series analysis in stability prediction is no more than using difference equations principles in solving the power system swing equations.

IV. STABILITY CONDITIONS FOR THE AUTO-REGRESSIVE MODEL

The second-order auto-regressive model with one degree of difference may be written as [17]:

$$W_t = \phi_1W_{t-1} + \phi_2W_{t-2} + a_t \quad (10)$$

Where , $\mathbf{W}_t = \mathbf{Z}_t - \mathbf{Z}_{t-1}$.

In compact form, equation (10) turns

$$\phi(B)W_t = a_t \quad or \quad W_t = \Psi(B)a_t$$

with

$$\Psi(B) = \phi^{-1}(B) \quad and$$

$$\phi(B) = 1-\phi_1 B-\phi_2 B^2$$

For the process to be stationary (swing stable) the weights $\Psi 1$, $\Psi 2$ of $\Psi(B)$ must form a convergent serie. In order to satisfy that condition the roots of the characteristic polynomium $\phi(B) = 0$ must lie outside the unit circle. In terms of the parameter of the model otherwise that condition is satisfied if

$$\phi_2+\phi_1<1, \quad \phi_2-\phi_1<1, \quad -1<\phi_2<1. \tag{11}$$

So once the parameters of the model are estimated the swing instability prediction is quite straight forward.

V. ESTIMATING THE PARAMETERS OF THE MODEL

Once the model has been chosen an efficient estimate of the parameters needs to be obtained. Using the least squares technique one needs to minimize

$$S(\phi) = \sum [a_t]^2 \tag{12}$$

with

$$[a_t] = \phi(B)[W_t], \tag{12.a}$$

For a purely auto-regressive process, it can be obtained directly from equation (12.a):

$$\frac{\partial[a_t]}{\partial\phi_i} = -[W_{t-i}] + \phi(B)\frac{\partial[W_t]}{\partial\phi_i}. \tag{13}$$

Now for t - i > 0:

$$[W_{t-i}] = W_{t-i}\ (known\ value), \quad \frac{\partial[W_{t-i}]}{\partial\phi_i} = 0$$

For t - i ≤ 0 otherwise, both

$$[W_{t-i}] \ and \ \frac{\partial[W_{t-i}]}{\partial\phi_i}$$

are function of ϕ and so equation (13) is a non-linear relation.

For the case of AR(2) , i will assume only the values **0, 1, 2,** and the non-linear relation is just due to the starting values $[a_{t,0}]$.

Developing $[a_t]$ in Taylor series and keeping the linear terms only:

$$[a_t]' = [a_t, 0] + \sum_{i=1}^{k} x_{i,t}(\phi_i-\phi_{i,0}) \tag{14}$$

where

$$x_{i,t} = \frac{\partial[a_t]}{\partial\phi_i}\Big|_{\phi_i=\phi_{i,0}},$$

k, the number of elements of the serie and $\phi_{i,0}$ being the starting value of ϕi ; $[a_t]$ and $[a_{t,0}]$ are vectors whose dimensions are the number of elements of the serie.

In equation (14), $a_{t,0}$ is obtained from the relation: $\mathbf{a}_{t,0} = \boldsymbol{\phi}_0\,\mathbf{(B)}\,\mathbf{W}_t$ with the guesses values for ϕ_i equal to zero. Also $x_{i,t}$ can be calculated recursively by:

$$x_t = \phi_{1,0}x_{t-1} + \phi_{2,0}x_{t-2} + a_{t,0}$$

The equation for x_t was obtained directly from equation (12.a), with starting values for a's and x's set equal to zero and

$$x_{i,t} = \frac{\partial[a_t]}{\partial\phi_i} = -[W_{t-i}]$$

So the adjustement $(\phi_i - \phi_{i,0})$ which minimize [12] may be obtained by linear least squares, that is, by regressing the $[a_0]$'s onto the X's. Because the $[a_t]$'s are nonlinear in ϕ, a single adjustement will not immediately produce least squares values.

In this research at most three adjustments were required to find the final parameters ϕ's.

VI. MEASUREMENT AND PROCESSOR SCHEME

The phase angle between the generator bus and the reference may be obtained by synchronized phasor measurement units (PMUs). The phase angle between a generator e.m.f. and its terminal voltage is computed through the use of the generator terminal current and the generator transient impedance.

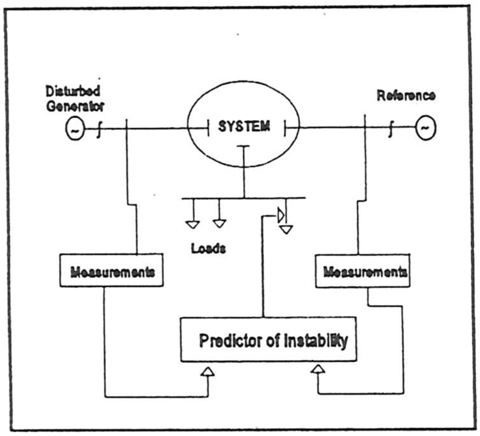

Fig.1 - Measurement representation

The relative phase angle, the generator terminal voltage, and currents are sampled at a frequency of 720 Hz and transmited to the swing instability predictor.

VII. SIMULATIONS DESCRIPTION

The approach of instability prediction as presented before was used to predict the instability of the system as shown in figure 9. The system datas are presented at table I. That system has basicaly two areas; the areas may be visualized by the fact the lines 3-5 and 4-6 having a much more higher series impedance if compared with the other lines of the system.

A switch of seventy per cent of the load in bus number 1 was simulated and half of a second later that load was switched back. The datas corresponding to generator number 6 (angle datas) were used to test the proposed approach. The reason in using those datas is a more severe behavior of that generator angle as compared to the others. The generator number 3 was used as the reference generator.

To simulate that transient the Extended Transient Midterm Stability Package (ETMSP) available at the Power-Lab. of V.P.I. & SU was used.

The simulated stability curves, for that disturbance, are shown at figure 10. As can be seen they indicated first swing stability although unstable after that.

With the simulation output datas many instability prediction situations were tested (for space reasons, just some of them are going to be presented here):

Situation n° 1 -
Non adaptive Model (the parameters of the model are estimated only once):
a) using 12 samples for the instability prediction;
b) using 18 samples for the instability prediction.

Situation n° 2 -
Parcially Adaptive Model (AD3)(each time period of three datas window)the parameters of the model are estimated):
a) using 12 samples for the instability prediction;
b) using 18 samples for the instability prediction;
c) using 24 samples for the instability prediction.

Situation n° 3 -
Completely Adaptive Model (AD1)(each time period of one data window)the parameters of the model are estimated):
a) using 12 samples for the instability prediction;
b) using 18 samples for the instability prediction.

VIII. TEST RESULTS

For the non adaptive model, all the tested predictions situations(a and b) indicated a first swing stable situation for the generator n° 6 dynamics, agreeing in this way with the simulated results (see stability conditions at table II and figures 2 and 3).

In the case of parcially adaptive models (AD3), the first swing of generator n° 6 was also predicted as stable, at the begin, as should be, and unstable later on (see figures 4,5,6, and stability conditions at table II). These results show how important the adaptability is, concerning the instability prediction. The conventional method of first swing stability would indicate a first swing stable system, although the system is not stable after that, leading in this way to an erroneous conclusion.

For the case of completely adaptive models (AD1) the first swing of generator n° 6 was also predicted as stable at the begin and unstable later on (for space reasons it was not shown the stability table corresponding to this situation; see figures 7 and 8).

As can be seen at the simulated curves and predicted one, the prediction quality is quite better as more adaptive the prediction model becomes.

It was observed a poorer quality in the prediction, in the adaptive situation (increase in the difference between estimated value and the simulated one), as the number of samples used to make the parameters estimation increased. The reason for that is since the sampling frequency stays fix that adaptability is becoming lowers because the adaptability time was defined as function of the sampling window.

IX. CONCLUSIONS

The results obtained in this research may be an important contribution in the sense of promoting real time instability prediction and as consequence the possibility of actually monitor the evolution of any transient in real time.

Also it might become a useful aid in the development of closed loop control of power systems during emergency state.

The instability prediction may provide also adaptive out-of-step protection functions, adapting to changing power system conditions. One should have in mind that the approach itself might become reality thanks to the development of synchronized phasor measurements, due to Professor A.G. Phadke and his coleagues at V.P.I. & SU.

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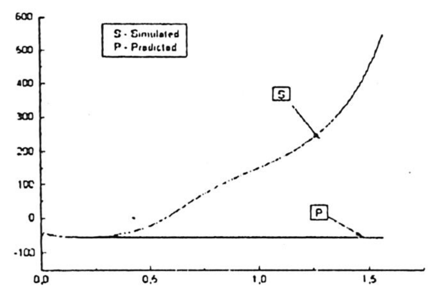

Fig. 2 - Nonadup - 12 datas

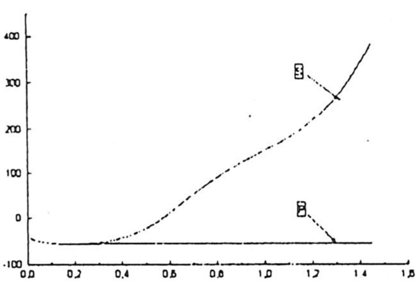

Fig. 3 - Nonadap-18 datas

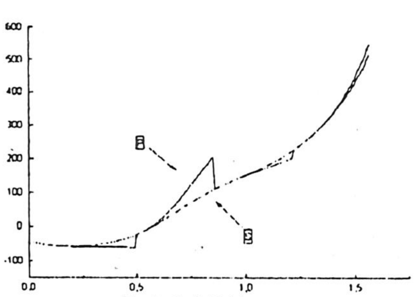

Fig. 4 adap3-12 datas

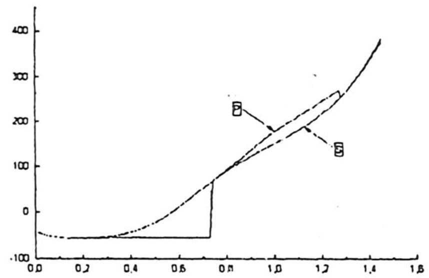

Fig. 5- adap3-18 datas

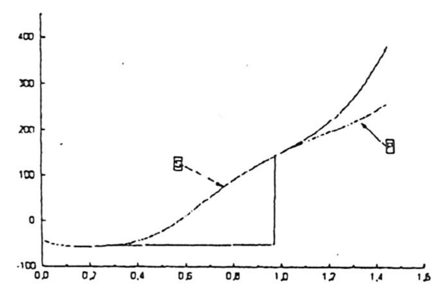

Fig. 6 - adap3-24 datas

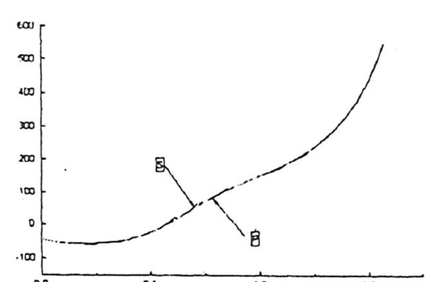

Fig. 7 - adap-12 datas

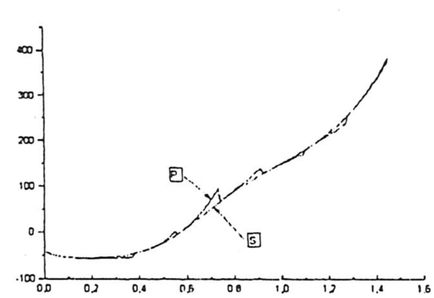

Fig 8 - adap1-18 datas

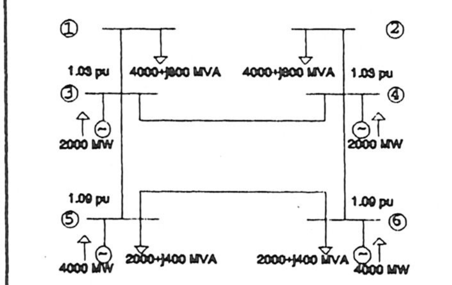

Fig.9. System used for tests.

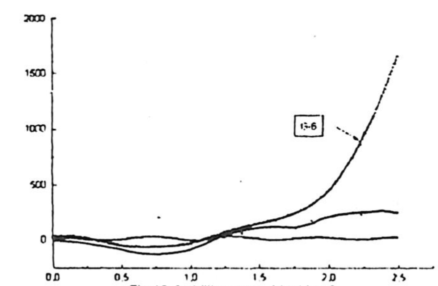

Fig.10-Stability curve - Machine 3 as reference- 70% Swich

Tab.I. Datas for the Tested System

[illegible] 100 MVA [illegible]

LINE	R	X	B	LENGTH
1-3	0.0005	0.005	0.01	1
2-5	0.0005	0.005	0.01	1
3-4	0.001	0.01	0.02	2
5-6	0.003	0.03	0.06	6
3-5	0.02	0.2	0.4	40
4-6	0.02	0.2	0.4	40

machine at bus n° 6: H = 68.696, X_d' = 0.01
machines at buses n° 3,4,5: H = 122 s, X_d' = 0.01

Tab.II. Non-Adaptive Model Datas for Stability Consideration

DATA	$\Phi_1 + \Phi_2 < 1$	$\Phi_2 - \Phi_1 < 1$	$-1 < \Phi_2 < 1$
24	0.8809	-0.9567	0.9188
18	0.8761	-0.9473	0.9117
12	0.8797	-0.9347	0.9072

Tab.III. Adaptive Model (AD3) Datas for Stability Consideration

DATA	$\Phi_1 + \Phi_2 < 1$	$\Phi_2 - \Phi_1 < 1$	$-1 < \Phi_2 < 1$
18	0.8761	-0.9473	0.9117
	1.0061	-1.0651	1.0356
	1.0305	-1.0160	1.0233
12	0.8797	-0.9347	0.9072
	1.0688	-1.1108	1.0898
	0.9825	-0.9901	0.9863
	1.0290	-1.0174	1.0232
	1.0425	-1.0518	1.0472
06	0.8916	-0.9189	0.9053
	1.1168	-1.6204	1.3686
	1.0816	-1.0950	1.0883
	1.0239	-1.0413	1.0326
	0.9836	-0.9889	0.9863
	0.9928	-0.9838	0.9883
	1.0265	-1.0198	1.0232
	1.0341	-1.0322	1.0331