

Improved method for Real-Time Transient Stability Assessment of Power Systems

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Resume— This paper presents a new approach to predict the time evolution of rotor angles of synchronous machines based on a modification of the Taylor series expansion in order to assess the transient stability of power systems in real time. To demonstrate the benefits of the proposed approach, a comparative analysis is made with other approaches which have been used for predicting the rotor angles, namely regression and interpolation algorithms and an approach based on original Taylor series expansion. The different prediction approaches are applied to the New England benchmark power system to predict the time evolution of the rotor angles in terms of stability and instability of first and second swing. The obtained results highlight the prediction accuracy of the proposed approach and the fulfilment of computational time requirements concerning real time applications.

Index Terms – Rotor angle prediction, PMU, real time assessment, Taylor series, transient stability, WAMS.

I. INTRODUCTION

THE main cause of widespread blackouts is large rotor angle deviations [1]. This underlines the importance of large-disturbance rotor angle stability (i.e. transient stability), which deals with the ability of a power system to maintain synchronism when subjected to a large disturbance [2].

Traditionally, the transient stability assessment has been conducted by considering contingencies using off-line dynamic simulations. Besides, this framework has been widely used for design and tuning of protective systems and to provide guidelines for secure operating conditions. By contrast, the transient stability assessment in real time is of interest for monitoring the progress of system transients [3]. Nowadays, there are important efforts to develop new tools for real time control, monitoring and supervisory tasks, which utilize developments in the wide-area measurement system technology (WAMS) [4]. Some of the examples are the PMUs (Phasor Measurement Units) technology and WAMS (Wide Area Measurement Systems), which enable the measurement of electrical quantities at a sampling rate that allows monitoring post-fault transients in real time [5].

This work was supported in part by the German Academic Exchange Service (Deutscher Akademischer Austauschdienst/DAAD).

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Over recent years, rotor angle prediction based on polynomial regression curve fitting has been attempted [6]. However, numerical instability is an issue that remains to be overcome. Alternatively, the application of the spline interpolation algorithm has been attempted in [7]. The basic idea is to adjust a set of polynomial functions to fit time series data. Although this approach is quite accurate, its high computational time prevents its real time applications. An earlier attempt based on the Taylor series expansion concept has been reported in [8]. The calculation is mathematically simple and requires short computational time, but a satisfactory computing precision cannot be always accomplished.

This paper presents a new approach to predict the time evolution of rotor angles of synchronous generators from a set of measurements acquired in real time after occurrence and clearing of a fault or other disturbance (i.e. immediate post-fault conditions [9]) by using a modification of the Taylor series expansion in combination with the finite difference method. The aim of the proposed approach is to alleviate the computational burden while maintaining satisfactory accuracy. The feasibility of the proposed approach is tested on the New England benchmark power system by comparing the results with those obtained through the afore-mentioned algorithms.

The outline of the paper is as follows: Section II gives some background information on power system modelling and the PMU technology. Section III provides a brief overview of three algorithms from literature for rotor angle prediction. The proposed approach is described in Section IV. Section V presents test results and a comparative analysis between the proposed approach and the algorithms in the literature, and finally, Section VI provides some conclusions.

II. POWER SYSTEM MODEL AND THE PMU TECHNOLOGY

Mathematically, for each synchronous generator in a power system, the rotor angle δ_i ($i=1,2,\dots,n$) is determined by the swing equation [10]:

$$\frac{d\delta_i(t)}{dt} = \omega_i(t) - \omega_0 \quad (1)$$

$$\frac{d\omega_i(t)}{dt} = \frac{1}{M_i} [P_{m_i}(t) - P_{e_i}(t)] \quad (2)$$

where M is the moment of inertia, P_m is the mechanical power input, P_e is the electrical power output, and ω is the speed of the generator rotor.

When a fault occurs, the electrical power output undergoes an abrupt change, but the mechanical power input remains unchanged. If the sampling interval Δt is very short, it is assumed that the production of electric power is constant during this time interval. Therefore, the swing equation in discrete form for each generator is expressed as follows [10]:

$$\Delta t = t_k - t_{k-1} \quad (3)$$

$$\Delta \omega_i(t_k) = \frac{P_{m_i}(t_k) - P_{e_i}(t_k)}{M_i} \Delta t \quad (4)$$

$$\omega_i(t_k) = \omega_i(t_{k-1}) + \Delta \omega_i(t_k) \quad (5)$$

$$\delta_i(t_k) = \delta_i(t_{k-1}) + \frac{1}{2} [\omega_i(t_{k-1}) + \omega_i(t_k)] \Delta t \quad (6)$$

Equations (5) and (6) resemble the backward Euler scheme and the trapezoidal rule, respectively. The values of the angles for each time instant t_k are calculated from measurements of magnitude and phase of voltages and currents provided by PMU devices located at system high voltage buses. This procedure is necessary since PMU devices do not provide information that can be directly used for transient stability analysis [11]. Such devices measure electrical variables in real time (e.g. voltages and currents), whereas mechanical variables are needed for transient stability assessment (e.g. generator rotor angle and speed). Hence, the proposed approach will use the methodology presented in [12] to derive directly the generator rotor angles. Basically, the equation to be used is:

$$\delta = \tan^{-1} \left(\frac{(X_q + X_e) I \cos \phi}{V_t + (X_q + X_e) I \sin \phi} \right) \quad (7)$$

where the terminal current I , the terminal voltage V_t , and the voltage angle ϕ , are available signals from PMU devices. X_e constitutes the reactance between the machine terminal and the point in the network where the PMU device is installed whereas X_q is the quadrature-axis reactance.

The sampling interval $\Delta t = 20$ ms is to be used throughout this paper (i.e. to best match typical PMU sampling rate at 50 Hz [13]).

III. LITERATURE METHODS FOR ROTOR ANGLE PREDICTION

The following is a brief review of some literature methods used to predict the time evolution of the generators' rotor angle.

A. Polynomial Curve Fitting Method

The basic idea behind polynomial curve fitting is to find a polynomial that best fits to a series of data points. The quality of the fit is measured by the quantity L :

$$L = \sum_{i=1}^n |F_i - f_i|^2 \quad (8)$$

where F_i is the i -th value of data set, and f_i is the value obtained from the fit.

The tendency of the rotor of each machine is computed by using a polynomial function:

$$\delta(t) = p_n t^n + p_{n-1} t^{n-1} + \dots + p_2 t^2 + p_1 t + p_0 \quad (9)$$

where p_n are the coefficients of the polynomial which are obtained by solving (10) using the least squares criterion [14].

$$\begin{bmatrix} \delta_0 \\ \delta_1 \\ \vdots \\ \delta_k \end{bmatrix} = \begin{bmatrix} t_0^n & t_0^{n-1} & \dots & t_0 & 1 \\ t_1^n & t_1^{n-1} & & t_1 & 1 \\ \vdots & \vdots & & \vdots & \vdots \\ t_k^n & t_k^{n-1} & \dots & t_k & 1 \end{bmatrix} \begin{bmatrix} p_n \\ p_{n-1} \\ \vdots \\ p_0 \end{bmatrix} \quad (10)$$

where the values δ_k ($k = 0, 1, 2, \dots$) are the computed values of rotor angle from PMU measurements for each time instant t_k .

After obtaining the polynomial coefficients, the rotor angle of each machine can be predicted using (9).

B. Spline Interpolation Method

In the mathematical subfield of numerical analysis, a spline is a curve that is piecewise n -th degree polynomial. Thus, the key idea of spline interpolation-based methods is to fit a piecewise curve defined by [15]:

$$S(t) = \begin{cases} s_1(t) & t_0 \leq t < t_1 \\ s_2(t) & t_1 \leq t < t_2 \\ \vdots & \\ s_i(t) & t_{k-1} \leq t < t_k \end{cases} \quad (11)$$

$s_i(t)$ is a third order polynomial defined by (12) that represents a section of the curve of the rotor angle behaviour:

$$s_i(t) = a_i t^3 + b_i t^2 + c_i t + d_i \quad (12)$$

where a_i , b_i , c_i and d_i are the polynomial coefficients. The spline algorithm is subject to the following constrains:

$$s(t_k) = \delta_k \quad (13)$$

$$s_i(t_k) = s_{i-1}(t_k) \quad (14)$$

$$s'_i(t_k) = s'_{i-1}(t_k) \quad (15)$$

$$s''_i(t_k) = s''_{i-1}(t_k) \quad (16)$$

Equation (13) indicates that the spline passes through each point (t_k, δ_k) . The δ_k values are the calculated values of rotor angle, from the PMU measurements for each time instant t_k .

Finally, equations (13) to (16) are solved to determine the polynomial coefficients needed in equation (12), which can be used to predict the values of generators rotor angles.

C. Taylor Series Expansion Method

The general formula for computing the Taylor series expansion of a function around the point a is [16]:

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} \cdot (x-a)^n \quad (17)$$

where $n!$ is the factorial of n , and $f^{(n)}(a)$ is the n -th derivative

of n evaluated at the point a .

The purpose of this method is to predict the position of the rotor angle of each generator for a subsequent time t_p . The Taylor series expansions of the rotor angle and speed of each generator are used to perform prediction of these variables [16].

$$\delta_i(t_p) = \delta_i(0) + \delta_i^{(1)}t + \delta_i^{(2)}\frac{t^2}{2!} + \delta_i^{(3)}\frac{t^3}{3!} + \dots \quad (18)$$

$$\omega_i(t_p) = \omega_i^{(1)} + \delta_i^{(2)}t + \delta_i^{(3)}\frac{t^2}{2!} + \delta_i^{(4)}\frac{t^3}{3!} + \dots \quad (19)$$

The equation that is used to predict the speed of each machine is then obtained based on the Taylor series expansion truncated to the third order and given that values of the speed at the instants t_k , t_{k-1} and t_{k-2} are known [17], that is

$$\omega_i(t_p) = \omega_i(t_{k-2}) + \alpha_1(t_p - t_{k-2}) + \alpha_2(t_p - t_{k-1})(t_p - t_{k-2}) \quad (20)$$

where

$$\alpha_1 = \frac{\omega_i(t_{k-2}) - \omega_i(t_{k-1})}{t_{k-2} - t_{k-1}} \quad (21)$$

$$\alpha_0 = \frac{\omega_i(t_{k-1}) - \omega_i(t_k)}{t_{k-1} - t_k} \quad (22)$$

$$\alpha_2 = \frac{\alpha_1 - \alpha_0}{t_{k-2} - t_k} \quad (23)$$

By definition [8]:

$$\delta_i(t_p) = \int_{t_k}^{t_p} [\omega(t) - \omega_0] dt + \delta_i(t_k) \quad (24)$$

Then, by solving the integral (24), the equation to predict the rotor angle of each generator is [17]:

$$\begin{aligned} \delta_i(t_p) = & \delta_i(t_k) + \omega_i(t_{k-2})(t_p - t_k) \dots \\ & + \alpha_1 \frac{(t_p^2 - t_k^2)}{2} + \alpha_1 t_{k-2}(t_p - t_k) \dots \\ & + \alpha_2 \left[\frac{(t_p^3 - t_k^3)}{3} - (t_{k-1} + t_{k-2}) \frac{(t_p^2 - t_k^2)}{2} \right] \dots \\ & + \alpha_2 t_{k-1} t_{k-2} (t_p - t_k) \end{aligned} \quad (25)$$

Fig.1 shows the minimum amount of data required for prediction purposes. In this case, three points of ω at t_k , t_{k-1} , and t_{k-2} , are used to predict the value of the speed at the subsequent time t_p (e.g. after 100 ms). Fig. 2 shows δ at the instant t_k , calculated from equation (25), and the instant of prediction t_p .

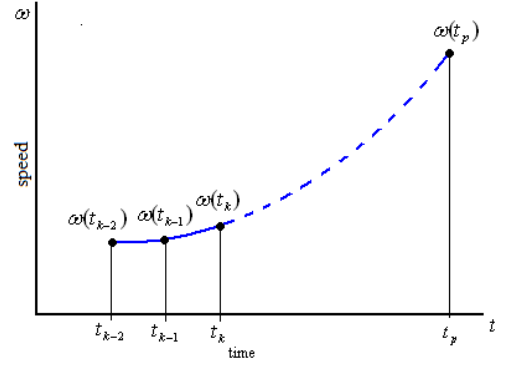


Fig. 1. Prediction of the speed at time t_p

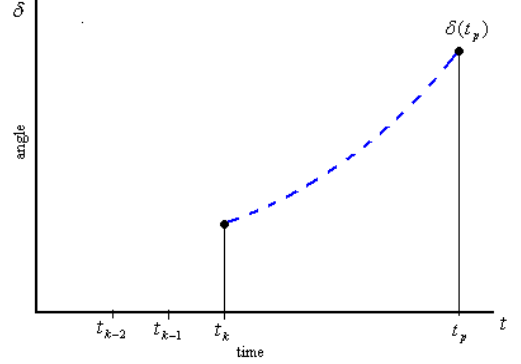


Fig. 2. Prediction of rotor angle at time t_p

IV. PROPOSED APPROACH

The proposed approach is based on Taylor series expansion, but in contrast to the one presented in Section III, the prediction of rotor angle is performed directly without using the rotor speed measurement. This task is accomplished by using the finite difference method to predict the rotor angle position at a later time point t_p .

The finite difference method attempts to find approximate values of the functions' derivatives in discrete time instants [18]. Discrete data result from the PMU measurements and the rotor angle estimates obtained through the methodology discussed in Section II. The following are approximations for the first and second derivative of a discrete function:

$$\left(\frac{\partial u}{\partial x} \right)_k \approx \frac{u_k - u_{k-1}}{x_k - x_{k-1}} \quad (26)$$

$$\left(\frac{\partial^2 u}{\partial x^2} \right)_k \approx \frac{2 \left(\frac{u_k - u_{k-1}}{x_k - x_{k-1}} - \frac{u_{k-1} - u_{k-2}}{x_{k-1} - x_{k-2}} \right)}{x_k - x_{k-2}} \quad (27)$$

An expression for estimating the angle δ at a later time point t_p is obtained by applying the above approximations to equation (18) and provided that values of δ at the instants t_k , t_{k-1} and t_{k-2} are known:

$$\delta_i(t_p) = \delta_i(t_{k-2}) + \beta_1(t_p - t_{k-2}) + \beta_2(t_p - t_{k-1})(t_p - t_{k-2}) \quad (28)$$

where

$$\beta_1 = \frac{\delta_i(t_{k-2}) - \delta_i(t_{k-1})}{t_{k-2} - t_{k-1}} \quad (29)$$

$$\beta_0 = \frac{\delta_i(t_{k-1}) - \delta_i(t_k)}{t_{k-1} - t_k} \quad (30)$$

$$\beta_2 = \frac{\beta_1 - \beta_0}{t_{k-2} - t_k} \quad (31)$$

Fig.3 shows the minimum amount of data necessary for prediction. In this case, three points of δ at the instants t_k , t_{k-1} , and t_{k-2} , are used to predict the rotor angle at the instant t_p . Remarkably, from equations (28) - (31), note that the rotor speed values are not needed for the predicting the rotor angle.

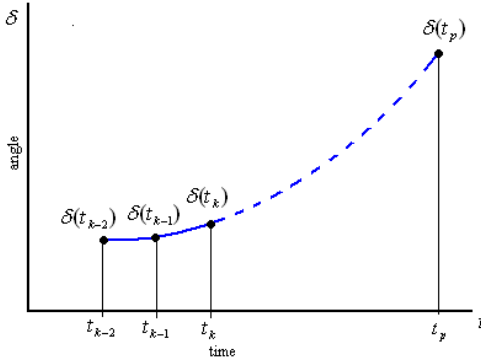


Fig. 3. Prediction of rotor angle at time t_p

V. TEST RESULTS

The proposed methodology is tested and compared with the literature approaches discussed in this paper. For this purpose, the prediction of rotor angles of the generators of the New England benchmark power system is performed. The single line diagram is shown in Fig.4. This system has been widely used for power system dynamic analysis and it comprises of 39 buses and 10 generators [19]. Generators are modeled using the 4-th order model and equipped with fast static exciters and a simple thermal turbine-governor system whereas loads are modeled as constant impedances. Time domain simulations and PMU measurements were generated using the Power System Analysis Toolbox (PSAT) [20]. Simulation of the proposed and the literature approaches were accomplished by several routines written in Matlab [21]. The prediction calculations start once a fault is cleared in the system and consider at least three measurements at the time points $t_k - 2\Delta t$, $t_k - \Delta t$, t_k . The PMU sampling rate is 20 ms, and in each case the forecast was made at a 100 ms later time point.

A. Case study: first-swing instability

A three-phase fault occurs in line 2-25 near bus 25. The angle trajectories estimated with the prediction methodologies applied to PMU measurements are compared with those from

time domain simulations.

The fault occurs at $t=0.1$ s and is cleared at $t=0.2$ s by opening circuit breakers at both ends of the line, which leads to unstable conditions. In Fig 5 to Fig. 8, it is shown the simulated angles of machines G1, G6, and G8 (blue points) and the predicted angles (red small circles) with the literature and the proposed prediction algorithms, respectively. Results for all the machines are not included for the sake of brevity and clarity. In the figures, the growing gap between the angles of the machines indicates that the system would be in a first-swing unstable condition.

B. Case Study: second-swing instability

A three-phase fault occurs in line 16-21 near bus 21. The fault occurs at $t=0.1$ s and is cleared at $t=0.245$ s by opening circuit breakers at both ends of the line, resulting also in unstable conditions. In Fig. 9 to Fig. 12, it is shown the simulated angles of machines G1, G6, and G8 (blue points) and the predicted angles (red small circles) with the literature and the proposed prediction algorithms, respectively.

In this case, the growing gap between the angles of the machines resembles that of second-swing instability, since during the first swing the angles of the rotors tend to return to equilibrium, but the system does not have enough (potential energy) inertia to absorb the kinetic energy produced by generators and the system becomes unstable.

C. Case Study: stable conditions

Finally, in order to analyze the performance of prediction algorithms in stable conditions, a three-phase fault in line 2-25 near Bus 25 is simulated. The fault occurs at $t=0.1$ s and is cleared at $t=0.180$ s by opening circuit breakers at both ends of the line 2-25. Fig. 13 to Fig. 16 show the simulated angles of machines G1, G6, and G8 (blue points) and the predicted angles (red small circles) with the literature and the proposed prediction algorithms, respectively.

In this case the system has enough (potential energy) inertia to absorb all the kinetic energy produced by the generators and the system is transiently stable. It should be noted, however, that in contrast to the previous two unstable cases, the switches are more quickly opened to clear the fault.

In addition, Table I summarizes results about the accuracy of the prediction methods. This assessment was carried out by calculating the root mean square deviation (RMSD) as follows [22]:

$$\text{RMSD} = \left[\frac{1}{n} \sum_{i=1}^n (x_i - u_i)^2 \right]^{1/2} \quad (32)$$

where x_i is the rotor angle data from PMU measurements, u_i is the rotor angle data calculated using prediction algorithms, and n is the total number of data points. The RMSD is given in degrees.

Table II shows the computing time used for rotor angle prediction. Simulations were performed on a computer with a 3.00 GHz Pentium IV processor with 2 GB of RAM under a Windows XP (SP3) operating system.

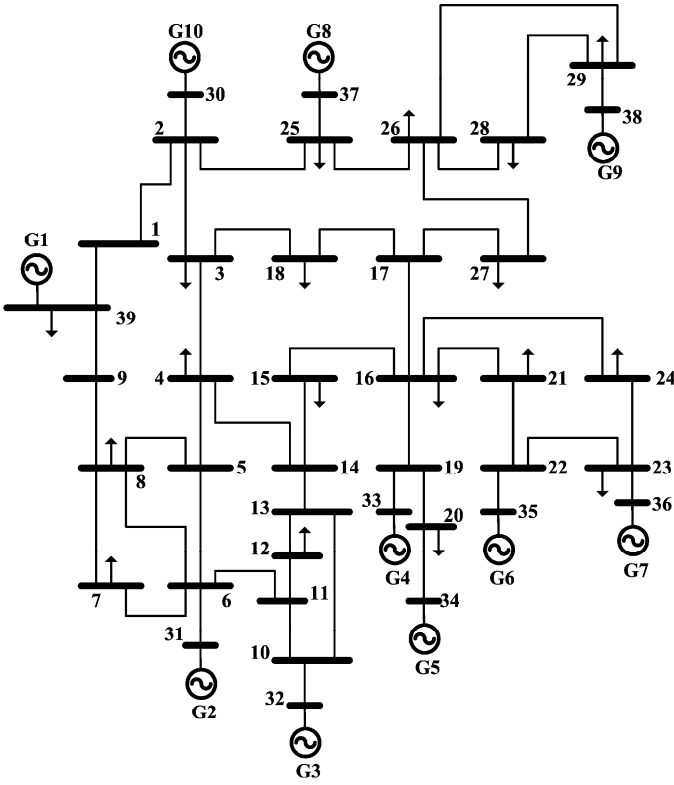


Fig. 4. New England benchmark power system

From Table I and Table II, note that the rotor angle prediction for the first-swing instability case, results with satisfactory accuracy are obtained by using the polynomial curve fitting-based and spline-based methods (see also Fig. 4, Fig. 5). However, the computing time for rotor angle prediction is inadequate for real-time transient stability assessment purposes. On the other hand, the computing times for the earlier Taylor series expansion-based and the proposed Taylor series-finite differences methods are negligible in all cases. But, by contrast, as shown in Table I, the proposed method provides better results in terms of accuracy.

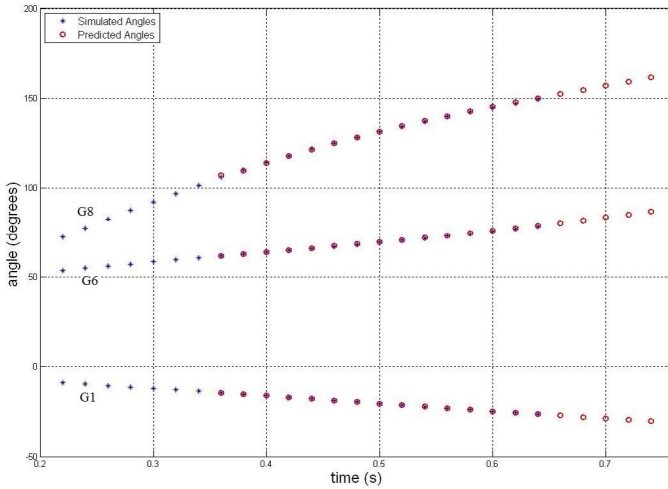


Fig. 5. Prediction using Polynomial Curve Fitting

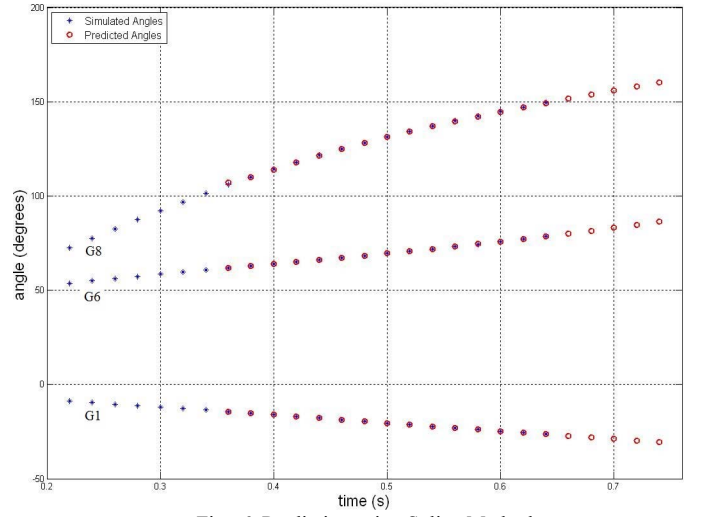


Fig. 6. Prediction using Spline Method

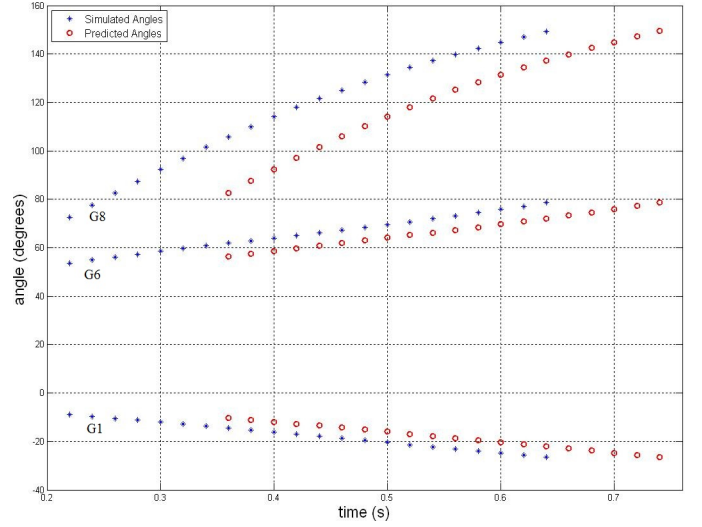


Fig. 7. Prediction using Original Taylor Series Expansion

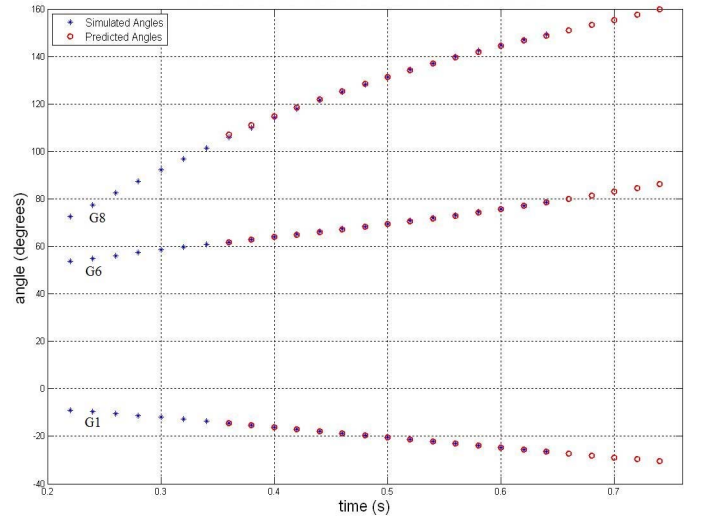


Fig. 8. Prediction using Taylor Series – Finite Difference (proposed)

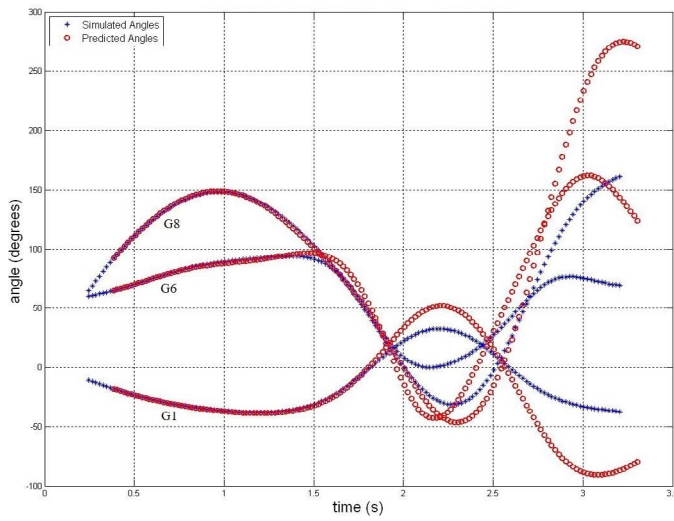


Fig. 9. Prediction using Polynomial Curve Fitting

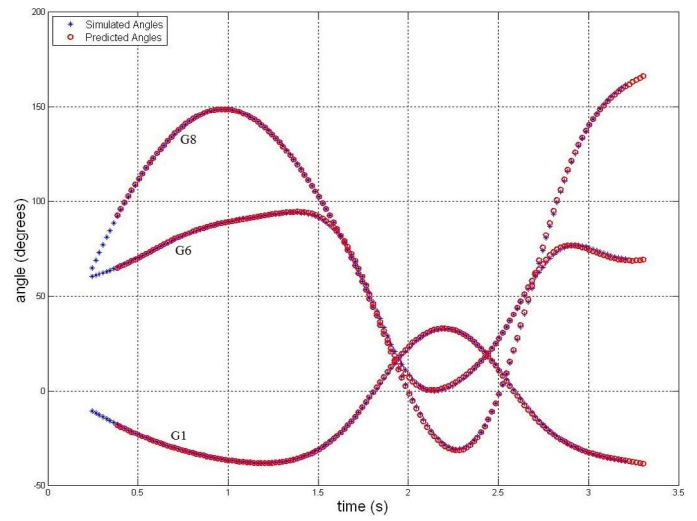


Fig. 12. Prediction using Taylor Series – Finite Difference (proposed)

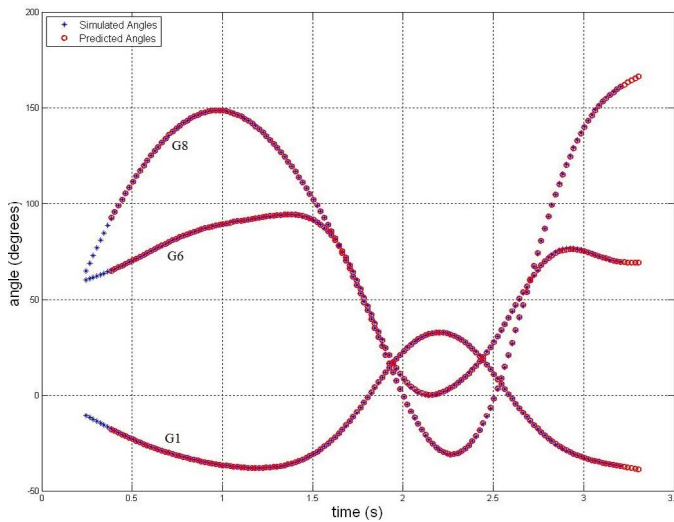


Fig. 10. Prediction using Spline Method

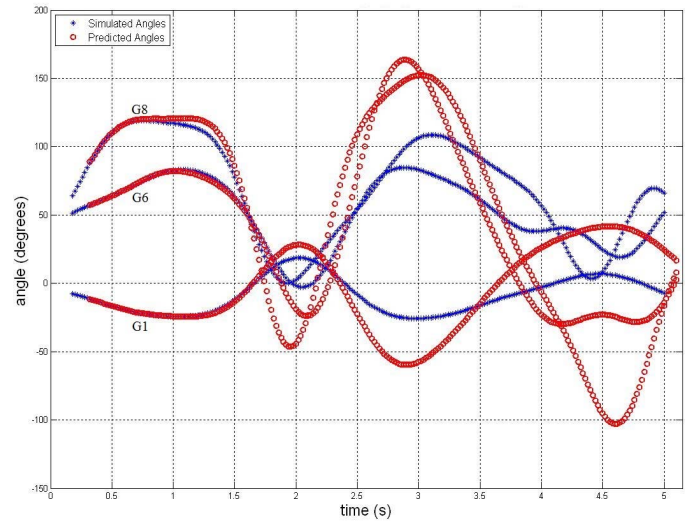


Fig. 13. Prediction using Polynomial Curve Fitting

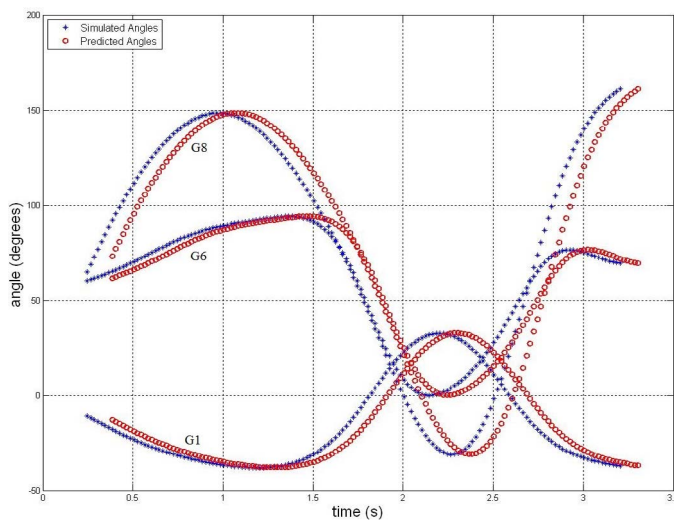


Fig. 11. Prediction using Original Taylor Series Expansion

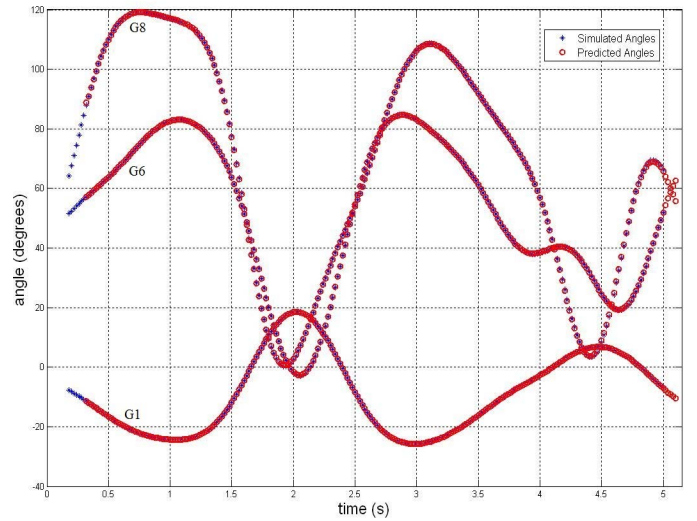


Fig. 14. Prediction using Spline Method

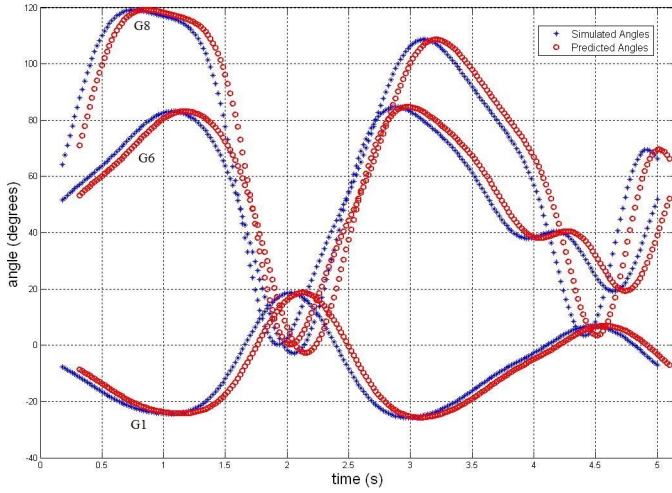


Fig. 15. Prediction using Original Taylor Series Expansion

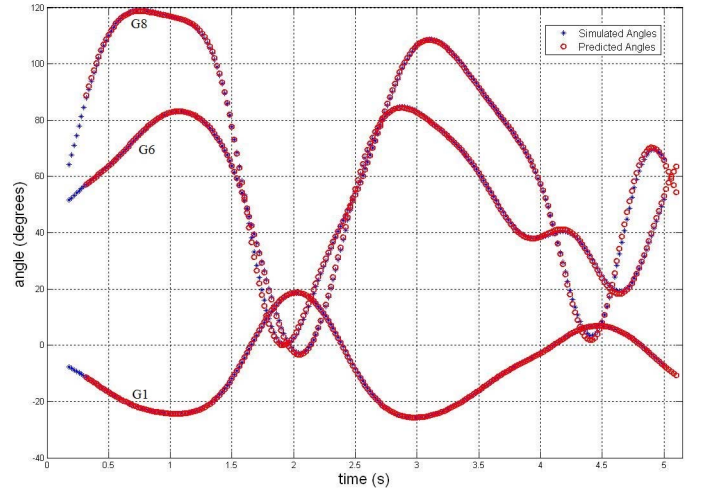


Fig. 16. Prediction using Taylor Series – Finite Difference (proposed)

TABLE I
Root mean square deviation of the rotor angle prediction methods

Prediction Method	Unstable Case 1st. Swing			Unstable Case 2nd. Swing			Stable Case		
	m1	m6	m8	m1	m6	m8	m1	m6	m8
Taylor Series - Finite Difference	0.06	0.12	0.52	0.32	0.59	0.75	0.15	0.50	0.87
Taylor Series	3.31	5.23	11.6	7.05	17.6	9.66	3.80	7.94	11.2
Spline Method	0.02	0.04	0.26	0.07	0.13	0.24	0.03	0.12	0.25
Polynomial Fitting	0.16	0.30	0.85	21.9	35.5	34.8	20.6	39.7	55.4

TABLE II
Computation Time of rotor angle prediction methods

Prediction Method	Unstable Case 1st. Swing	Unstable Case 2nd. Swing	Stable Case
Taylor Series - Finite Difference	0.03 ms	0.03 ms	0.03 ms
Taylor Series	0.04 ms	0.04 ms	0.04 ms
Spline Method	2.3 ms	2.6 ms	2.8 ms
Polynomial Fitting	25 ms	25 ms	27 ms

For the second-swing instability and stable cases, it was found out that the polynomial curve fitting-based method provides inaccurate estimates when a large number of data points is used (see Fig. 9 and Fig. 13). Moreover, the spline-based method provides very good results in terms of accuracy (see Table I, Fig. 10 and Fig. 14), but the computing time would be prohibitive for real-time applications. Finally, as shown in Table I and Fig. 16, the proposed Taylor series-finite differences method requires less computational burden and exhibits satisfactory computing precision.

VI. CONCLUSIONS

The speed and rotor angle data series can be synthesized from PMU measurements of voltages and currents. Besides, this information can be used to predict rotor angle at subsequent time points. Therefore, this paper proposes a new approach for rotor angle prediction based on the Taylor series expansion in combination with the finite difference method, which would be an alternative tool for real-time transient

stability assessment. Comparisons with other prediction methods show that the proposed algorithm is better in terms of accuracy and computing time. The implementation of the proposed prediction method in connection with other tools, such as the E-SIME method [23], would allow evaluating and predicting the transient stability in real-time.

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