Approximation of the Frequency-Amplitude Curve Using the Homotopy Analysis Method

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***Abstract*—The Frequency-Amplitude (F-A) curve on power system oscillation under a large disturbance characterizes how a natural oscillation mode transitions to nonlinear oscillations with growing amplitudes and decaying frequencies. The existing formulation of the F-A curve is derived by solving elliptical integrals on oscillation of a single-machine-infinite-bus equivalent about the targeted oscillation mode. The formula is (I think infinite series is the only form?) in a form of infinite series and needs to sum a large number of terms for satisfactory accuracy. This paper introduces an explicit, approximate expression obtained from the Homotopy Analysis Method on the F-A curve. The proposed F-A curve expression is derived from an SMIB system and verified on the IEEE 3-machine 9-bus system to show how the oscillation frequency of a dominant mode varies with oscillation amplitude under large disturbances.**

***Keywords*—Frequency-Amplitude (F-A) curve, Homotopy Analysis Method, power system oscillation.**

I. Introduction

As a great threat to power system operations and stability, electromechanical oscillations of generators under large disturbances can exhibit apparent aharmonicity and nonlinearity due to the nonlinear nature of power systems, and may even lead to system instability. As pointed out in [1], the existing small-signal analysis methods ignore nonlinearities of electromechanical oscillaitons and are not suitable for analyzing or monitoring power system oscillations under large disturbances [2]; besides, the measurement-based methods including the Prony analysis method, Eigensystem Realization Algorithm, Matrix Pencil method, etc., assume a constant natural frequency for each oscillation mode, which is only true under ideally small disturbances [3][4][5]. To fully study the nonlinearities of power system oscillations, paper [1] and its following study in [6] proposed the concept of the Frequency-Amplitude (F-A) curve that describes how the oscillation frequency of an undamped single-machine-infinite-bus (SMIB) system can change with the oscillation amplitude. Also, a measurement-based estimation method on the F-A curve was proposed for the dominant mode of a multi-machine system. However, the F-A curve expression is complex and needs to sum a large number of series terms for a good numerical approximation of the curve because the approach needs to solve elliptical integrals of the first kind.

To develop an approach for more efficiently solving the F-A curve for understanding the tendency of oscilation frequency change during large-disturbance oscillations, this paper derives an approximate F-A curve expression by solving the swing equation of an SMIB system having a single oscillation mode using the Homotopy Analysis Method (HAM). The expression is also verified on a multi-machine power system. The HAM is a mathematical method originates from topology and has successful applications in many nonlinear boundary value problems including boundary-layer flow and resonance of periodic traveling water waves [7]. The HAM uses the solutions of simple linear equations to approximate the solution of a nonlinear differential equation. Thus the HAM provides an alternative approach for an approximate analytical solution of the swing equation unlike traditional numerical approaches. Besides, a convergence control parameter can be added to the HAM to ensure and accelerate the convergence of the approximation, making it superior to other approximation methods such as the Adomian Decomposition Method and Homotopy Perturbation Method.

The rest of this paper is organized as follows. Section II describes the mathematical derivation of the F-A curve expression for an SMIB system by the HAM. Section III presents one case study of the proposed method on an SMIB system and the IEEE 3-machine 9-bus system, respectively. Conclusions and future work are discussed in section IV.

II. Approximating the F-A Curve by the HAM

This section gives the detailed mathematical derivation of solving the swing equation of an SMIB system using the HAM, and formulates an approximate F-A curve expression based on the first order homotopy solution.

A. Build a homotopy equation

The swing equation of an SMIB system in the classical model is a nonlinear second-order differential equation:

$$(\Delta\delta)'' + \frac{D}{2H}(\Delta\delta)' + \frac{\omega_s P_{\max}}{2H}[\sin(\Delta\delta+\delta_s)-\sin\delta_s] = 0 \quad (1)$$

where $\Delta\delta$ is the angle deviation from stable equilibrium δ_s, D is the damping coefficient, H is the inertia, ω_s is the synchronous frequency, and $P_{\max}$ is the maximum transfer power.

As pointed out in [1], the F-A curve with or without consideration of damping ratio D are very close to each other. So, the damping is ignored in the following derivation, and

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considering that the rotor angle deviation is a function of time, equation (1) is re-written as:

$$[\Delta\delta(t)]'' + \beta[\sin(\Delta\delta(t)+\delta_s) - \sin\delta_s] = 0 \tag{2}$$

where

$$\beta = \frac{\omega_s P_{\max}}{2H} \tag{3}$$

The initial state is assumed to be:

$$\Delta\delta(t)\big|_{t=0} = \Delta\delta_{\max} \tag{4}$$

$$(\Delta\delta)'\big|_{t=0} = 0 \tag{5}$$

where $\Delta\delta_{max}>0$ is the oscillation amplitude.

Then, suppose the oscillation frequency to be ω and replace t with ωt in (2) to get:

$$\omega^2[\Delta\delta(\tau)]'' + \beta[\sin(\Delta\delta(\tau)+\delta_s) - \sin\delta_s] = 0 \tag{6}$$

where

$$\tau = \omega t \tag{7}$$

Thus, oscillation frequency ω appears in the equation, which is oscillation amplitude dependent and should be differentiated from the constant natural frequency with the linearized model. From (6), a homotopy equation is built as:

$$\begin{aligned}&(1-q)\xi[\Delta\delta(\tau)-\Delta\delta_0(\tau)]\\ &= q\left\{\omega^2[\Delta\delta(\tau)]'' + \beta[\sin(\Delta\delta(\tau)+\delta_s) - \sin\delta]\right\}\end{aligned} \tag{8}$$

where q is an embedded parameter to increase the dimension of the system by one to connect its solution with trivial solutions of linear equations governed by the operator ξ, and $\Delta\delta_0(\tau)$ is a guessed periodic seed solution of $\Delta\delta(\tau)$ which satisfies the initial states, as shown below:

$$q \in [0,1] \tag{9}$$

$$\xi(x) = x'' + x \tag{10}$$

$$\Delta\delta_0(\tau) = \Delta\delta_{\max}\cos(\tau) \tag{11}$$

Obviously, when q=0, eq. (8) becomes:

$$\xi[\Delta\delta(\tau)-\Delta\delta_0(\tau)] = 0 \tag{12}$$

This is a linear equation, and the corresponding solution is:

$$\Delta\delta(\tau)\big|_{q=0} = \Delta\delta_0(\tau) \tag{13}$$

When q=1, eq. (8) is exactly the nonlinear differential equation (6) to be solved.

Thus, when the embedded parameter q changes smoothly from 0 to 1, the homotopy equation (8) changes from a simple linear differential equation (12) to a nonlinear differential equation (6). Because the solution of $\Delta\delta(\tau)$ in (8) depends also on the value of q, $\Delta\delta$ is now a function of both τ and q, i.e. $\Delta\delta(\tau,q)$, and note that ω is a function of q, i.e. $\omega(q)$.

B. Solution approximation based on Taylor series

The solution of (8) can be formulated by Talyor series:

$$\Delta\delta(\tau,q) = \sum_{k=0}^{\infty}\Delta\delta_k q^k \tag{14}$$

$$\omega^2(q) = \sum_{k=0}^{\infty}\omega^2{}_k q^k \tag{15}$$

where

$$\Delta\delta_k = \frac{1}{k!}\frac{d^k\Delta\delta(\tau,q)}{dq^k}\Big|_{q=0} \tag{16}$$

$$\omega^2{}_k = \frac{1}{k!}\frac{d^k\omega^2(\tau,q)}{dq^k}\Big|_{q=0} \tag{17}$$

The solution of the nonlinear swing equation (6) is

$$\Delta\delta(\tau) = \Delta\delta(\tau,q=1) = \sum_{k=0}^{\infty}\Delta\delta_k \tag{18}$$

$$\omega^2 = \omega^2(q=1) = \sum_{k=0}^{\infty}\omega^2{}_k \tag{19}$$

These two equations mean that the solution of the nonlinear equation (6) can be approximated by the solutions $\Delta\delta_k$ of linear equations which are much easier to be solved.

However, it is usually impossible to obtain infinite terms of the Taylor series to calculate the exact value. And generally, the accuracy of the approximation increases, not necessarily in a monotonic way, with the number of summed terms if the Taylor series converges. Thus, finite terms can be used to calculate an approximate value. The first-order homotopy solution is derived in the following part.

C. Derivation of the first-order homotopy solution

The first-order solutions of ω^2 and $\Delta\delta$ denoted by $\omega^2{}_0$ and $\Delta\delta_1$ can be obtained as follows. Firstly, take the derivative of(8) with respect to q, and substitute q=0. Then, get:

$$(\Delta\delta_1)'' + \Delta\delta_1 = \omega^2{}_0\Delta\ddot{\delta}_0 + \beta\sin(\Delta\delta_0+\delta_s) - \beta\sin\delta_s \tag{20}$$

From (11), the first two terms on the right-hand side of (20) become (21) and (22), respectively.

$$\omega^2{}_0\Delta\ddot{\delta}_0 = -\omega^2{}_0\Delta\delta_{\max}\cos(\tau) \tag{21}$$

$$\begin{aligned}\beta\sin(\Delta\delta_0+\delta_s) &= \beta\sin(\delta_s)\cos(\Delta\delta_{\max}\cos(\tau))\\ &\quad+\beta\cos(\delta_s)\sin(\Delta\delta_{\max}\cos(\tau))\end{aligned} \tag{22}$$

Secondly, substitute identities (23)-(25) below into (22) [8]. Here, because $\Delta\delta_{max}<\pi$, using only three terms on the right-hand sides of (23) and (24) would be accurate enough to approximate $\sin(\Delta\delta_{max}\cos(\tau))$ and $\cos(\Delta\delta_{max}\cos(\tau))$.

$$\sin(\Delta\delta_{\max}\cos(\tau)) = 2\sum_{m=0}^{\infty}(-1)^m J_{2m+1}(\Delta\delta_{\max})\cos((2m+1)\tau) \tag{23}$$

$$\cos(\Delta\delta_{\max}\cos(\tau)) = J_0(\Delta\delta_{\max}) + 2\sum_{m=1}^{\infty}(-1)^m J_{2m}(\Delta\delta_{\max})\cos(2m\tau) \tag{24}$$

$$J_n(\Delta\delta_{\max}) = \sum_{k=0}^{\infty} \frac{(-1)^k (0.5\Delta\delta_{\max})^{2k+n}}{k!(k+n)!} \tag{25}$$

Thirdly, solve ω^2_0 and $\Delta\delta_1$ with equation (20) and an implicit requirement. Here, because the angle oscillation has a constant amplitude when the damping is ignored, we need to eliminate the term $\cos(\tau)$ in the right-hand side of (20) as this term would bring a term $\tau\cos(\tau)$ which has a time-varying amplitude to the solution of $\Delta\delta_1$. Thus, after substituting (21)-(25) into (20), there is:

$$2\beta\cos(\delta_s)J_1(\Delta\delta_{\max})\cos(\tau) - \omega^2_0\Delta\delta_{\max}\cos(\tau) = 0 \tag{26}$$

$$\omega^2_0 = 2\beta\cos(\delta_s)\frac{J_1(\Delta\delta_{\max})}{\Delta\delta_{\max}} \tag{27}$$

After eliminating the term $\cos(\tau)$ to satisfy the implicit requirement, eq. (20) becomes:

$$\begin{aligned}(\Delta\delta_1(\tau))'' + \Delta\delta_1(\tau) \approx{}& \beta\sin(\delta_s)J_0(\Delta\delta_{\max}) - \beta\sin\delta_s - 2\beta\sin(\delta_s)J_2(\Delta\delta_{\max})\cos(2\tau) \\ & - 2\beta\cos(\delta_s)J_3(\Delta\delta_{\max})\cos(3\tau) + 2\beta\sin(\delta_s)J_4(\Delta\delta_{\max})\cos(4\tau)\end{aligned} \tag{28}$$

Eq. (28) is a second-order linear differential equation, and the solution is easily calculated as:

$$\begin{aligned}\Delta\delta_1(\tau) ={}& \beta\sin(\delta_s)J_0(\Delta\delta_{\max}) - \beta\sin\delta_s \\ & + [\beta\sin\delta_s - \beta\sin(\delta_s)J_0(\Delta\delta_{\max}) - \frac{2}{3}\beta\sin(\delta_s)J_2(\Delta\delta_{\max}) \\ & - \frac{2}{8}\beta\cos(\delta_s)J_3(\Delta\delta_{\max}) + \frac{2}{15}\beta\sin(\delta_s)J_4(\Delta\delta_{\max})]\cos(\tau) \\ & + \frac{2}{3}\beta\sin(\delta_s)J_2(\Delta\delta_{\max})\cos(2\tau) + \frac{2}{8}\beta\cos(\delta_s)J_3(\Delta\delta_{\max})\cos(3\tau) \\ & - \frac{2}{15}\beta\sin(\delta_s)J_4(\Delta\delta_{\max})\cos(4\tau)\end{aligned} \tag{29}$$

D. High-order homotopy solution

High-order solutions ω^2_{n-1} and $\Delta\delta_n$ can be obtained by basically the same steps as the first-order solutions:

1) Take the derivative of (8) with respect to q for n times;
2) Substitute the low-order solutions already obtained to the equation obtained in step 1;
3) Calculate ω^2_{n-1} by eliminating $\cos(\tau)$ term;
4) Solve a second-order linear differential equation for $\Delta\delta_n$.

E. Approximate the F-A curve expression

Although a high-order solution would generally have a better accuracy when finite terms are used to approximate the solution, it will significantly increase the complexity of the analytical expressions. As a proof-of-concept study on this HAM based approach, this paper only focuses on the first-order homotopy solution.

From (27), the F-A curve expression can be approximated by the first-order homotopy solution as shown in (30).

$$f \approx \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{2\beta\cos(\delta_s)\frac{J_1(\Delta\delta_{\max})}{\Delta\delta_{\max}}} \tag{30}$$

Because of $\Delta\delta_{max}$<180°, using six terms of Bessel function $J_1(\Delta\delta_{max})$ already provides a rather accurate result:

$$\frac{J_1(\Delta\delta_{\max})}{\Delta\delta_{\max}} \approx \frac{1}{2} - \frac{(\Delta\delta_{\max})^2}{2^4} + \frac{(\Delta\delta_{\max})^4}{3\times 2^7} - \frac{(\Delta\delta_{\max})^6}{9\times 2^{11}} + \frac{(\Delta\delta_{\max})^8}{45\times 2^{15}} - \frac{(\Delta\delta_{\max})^{10}}{675\times 2^{18}} \tag{31}$$

Thus, a simple, approximate expression is provided by (30)-(31) on the F-A curve under large disturbances.

III. Case Studies on Power Systems

This section tests the accuracy of the resulting approximate expression on the F-A curve first on an SMIB system and then on the IEEE 3-machine 9-bus system.

A. Case study on an SMIB system

Without loss of generality, first, we build an SMIB system with the same parameters D=0, H=3s, $P_{\max}$=1.7p.u. and ω_s=2π×60 rad/s as in [1]. The equilibrium angle δ_s is increased from 5° to 25° to test the performance of the approximate expression. The simulation results are compared with the accurate benchmark results provided by the numerical method in [1], as shown in Fig. 1-Fig. 3.

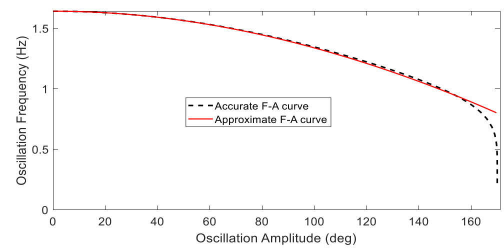

Fig.1. Approximate F-A curve when δ_s =5°

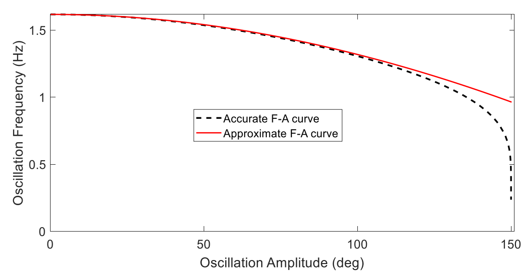

Fig.2. Simulation results of F-A curve when δ_s =15°

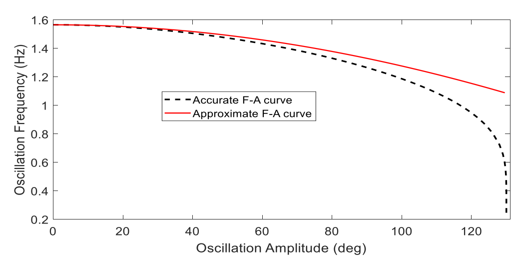

Fig.3. Simulation results of F-A curve when δ_s =25°

The error of oscillation frequency corresponding to four oscillation amplitutes under different equilibrium is shown in Table I, where error is defined as:

$$error = \left|\frac{estimate\ value - benchmark\ value}{benchmark\ value}\right| \times 100\% \tag{32}$$

TABLE I. ESTIMATION ERROR ON AN SMIB SYSTEM

$\Delta\delta_{max}$ / δ_s	20°	40°	60°	80°	100°
5°	0.00 %	0.02 %	0.09 %	0.25 %	0.56 %
15°	0.06 %	0.20 %	0.35 %	0.53 %	0.94 %
25°	0.23 %	0.83 %	1.83 %	3.60 %	7.56 %

From the simulation results, it can be observed that the approximate F-A curve has a good accuracy with small δ_s, and the error grows with the increase of δ_s. The reasoning is that the nonlinearity of an oscillation is mainly affected by both δ_s, i.e. the system stable equilibrium, and the oscillation amplitude representing the size of the disturbance. Besides, the increase of error is caused by the limited capability of the first-order HAM to approximate the solution of the nonlinear swing equation. However, the oscillation amplitude $\Delta\delta_{max}$ is generally less than 60° in practical, and the corresponding error is less than 2% as shown in Table I. Thus, the feasibility of the proposed approximation method is validated, and a high-order HAM is perfered when nonlinearity is strong.

Besides, the method in [1] and the proposed method respectively take 0.4 s and 0.001 s to compute, indicating the better time performance of the proposed method.

B. Case Study on the IEEE 9-bus system

An accurate formulation on the F-A curve of each electromechanical mode in a multi-machine system has not been solved. Paper [1] hypothesizes that the F-A curve on a dominant mode of a multi-machine system also follows the same formulation of an SMIB system. Thus, measurement data on power system oscillations can be used to identify the F-A curve for a targeted mode. This paper adopts the same approach to verify the derived approximate expression for a dominant mode of a multi-machine system. Measurement data on oscillating rotor angles are fitted into the approximate expression on F-A curve. After signal selection and pre-processing on the data, a number of data points on the oscillation F-A plane can be obtained. Then, the natural frequency f_n is estimated as the average frequency of those points having a small oscillation amplitude. The next step is the estimation of the parameters in the expression. Different from solving an optimization problem in [1], the unknown term $\beta\cos(\delta_s)$ in (30) can be calculated by (33). The final estimated F-A curve expression is obtained by substituting (33) into (30).

$$\beta\cos(\delta_s) = 4\pi^2 f_n^2 \tag{33}$$

The tested IEEE 3-machine 9-bus system is shown in Fig. 4. As observed from simulation results on the SMIB system, the error of the approximate F-A curve expression grows with the increase of the equilibrium angle, which corresponds to the increase of its loading level. To fully investigate the performance of the proposed method on the IEEE 9-bus system, the load and generation are gradually increased from 40% of the basecase values, and then the results are compared with the benchmark results provided by the numerical method in [1].

There are two oscillation modes in the IEEE 9-bus system, whose natural frequencies under the basecase condition are 0.94 Hz (Mode-1) and 1.76 Hz (Mode-2). Changes of their natural frequencies with the loading condition are insignificant and are hence ignored in this study.

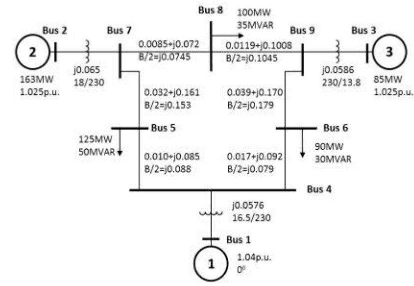

Fig.4. IEEE 9-bus system

1) F-A curve of Mode-1

In this scenario, a three-phase fault is added on bus 7 at t=1 s and then cleared at t=0.16 s without tripping any line. Generators 1 and 2 participate mainly in Mode-1 around 0.94 Hz while Mode-2 around 1.76 Hz is relatively quiescent. Consider 40%, 70% and 100% of the basecase load level. Fig. 5-Fig. 7 and Table II compare estimated F-A curves on Mode-1 obtained by the proposed method and benchmark results.

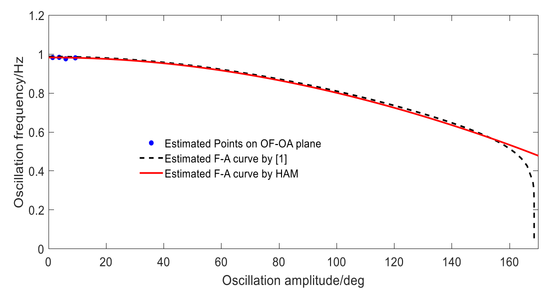

Fig.5. Estimated F-A curve for Mode 1 under a 40% loading condition

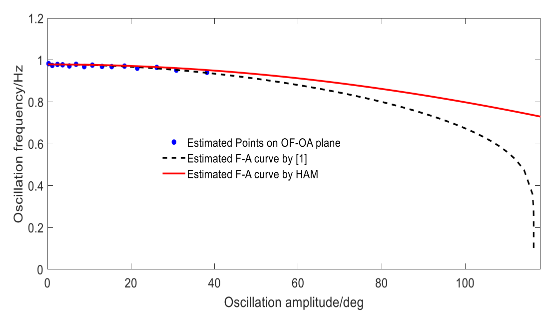

Fig.6. Estimated F-A curve for Mode 1 under a 70% loading condition

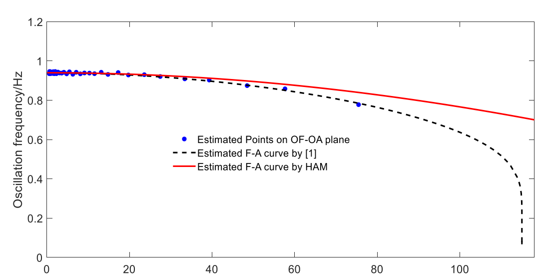

Fig.7. Estimated F-A curve for Mode 1 under the basecase condition

TABLE II. ESTIMATION ERROR OF MODE-1

$\Delta\delta_{max}$ / *Load*	20°	40°	60°	80°	100°
40 % basecase	0.04 %	0.05 %	0.12 %	0.29 %	0.61 %
70 % basecase	0.20 %	1.37 %	3.50 %	7.62 %	18.42 %
basecase	0.44 %	1.69 %	3.96 %	8.43 %	20.47 %

2) F-A curve of Mode-2

In this scenario, Mode 2 around 1.76 Hz is excited using the same approach as [1] while Mode 1 is relatively quiescent. Fig. 8-Fig. 10 and Table III compare the estimated F-A curves under three loading conditions.

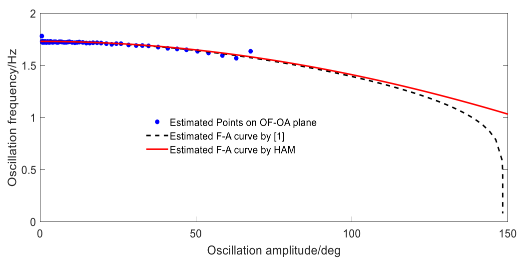

Fig.8. Estimated F-A curve for Mode 2 under a 40% loading condition

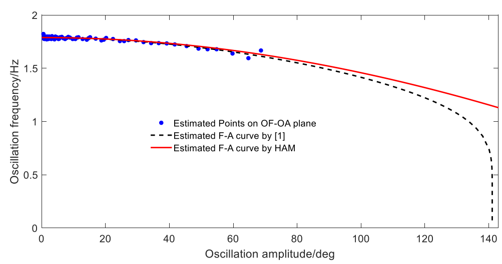

Fig.9. Estimated F-A curve for Mode 2 under a 70% loading condition

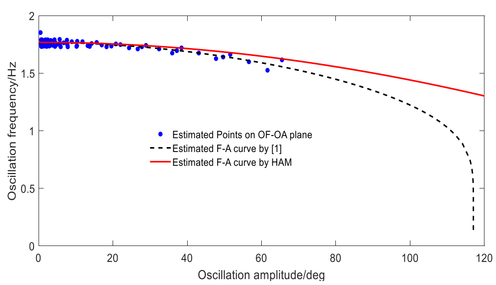

Fig.10. Estimated F-A curve for Mode 2 under the basecase condition

TABLE III. ESTIMATION ERROR OF MODE-2

$\Delta\delta_{max}$ / *Load*	20°	40°	60°	80°	100°
40 % basecase	0.05 %	0.12 %	0.32 %	0.58 %	1.17 %
70 % basecase	0.06 %	0.25 %	0.69 %	1.40 %	2.93 %
basecase	0.08 %	1.22 %	3.27 %	7.24 %	17.5 %

As shown in Fig. 5-Fig. 10 and Table II-III, on both modes, the approximate F-A curves based on the first order HAM are very close to the benchmark results especially when the system is not heavily loaded. For instance, as shown by Fig. 5, under a light load condition, the proposed expression provides a fairly accurate approximation of the F-A curve for oscillation amplitude growing up to 150°. The increase of the loading level will influence the accuracy of the estimated F-A curve with large oscillation amplitude but a correct trend can still be provided on how frequency decays with the increase of amplitude under large disturbances. Besies, the error when $\Delta\delta_{max}$ is less than 60° which is generally true in practical is less than 4%, indicating the feasibility of the method in engineering applications. Also, the high efficiency of the proposed method is validated by the result: the method in [1] and the proposed method take about 0.23 s and 0.002 s, respectly, to compute.

IV. CONCLUSION

This paper proposes an approach for approximating the F-A curve by the HAM considering nonlinearities, and a simple expression on the F-A curve is derived based on the first order HAM and tested on both an SMIB system and a multi-machine system. Although the accuracy could be affected by system loading level, the feasibility, high efficency and potential of the proposed approach are verified. The future work will include investigations on more accurate expressions based on a high-order HAM for power system electromechanical oscillations with strong nonlinearities.

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