

Mode-based Damping Torque Analysis in Power System Low-frequency Oscillations

Jingtian Bi, *Member, CSEE*, Huadong Sun, *Senior Member, IEEE, Fellow, CSEE*, Shiyun Xu, *Member, IEEE, Senior Member, CSEE*, Ruihua Song, Bing Zhao, and Qiang Guo

Abstract—The mode-based damping torque analysis (M-DTA) method for studying the effect of an external controller on power system low-frequency oscillations is proposed in this paper. First, based on the interconnection model between the system and the controller in the frequency domain, the oscillation loop corresponding to the electromechanical oscillation mode is built, and then the mode-based damping torque of the controller can be calculated. Then, the application of the M-DTA method in the power system is illustrated. The derivation shows that in the single-machine infinite-bus power system, the M-DTA method is completely equivalent to the classical damping torque analysis (C-DTA) method. In the multi-machine power system, the mode-based damping torque directly reflects the effect of the controller on the oscillation mode, overcoming the shortcomings of the C-DTA method in which there is no direct correspondence between the damping torque and the oscillation mode. By deriving the relationship with the residue index, the M-DTA method shows higher accuracy than the residue method in applications, such as controller parameter adjustment. Finally, two example power systems are presented to demonstrate the application of the proposed M-DTA method.

Index Terms—Electromechanical oscillation mode, FACTS, interconnection model in the frequency domain, mode-based damping torque analysis (M-DTA), power system low-frequency oscillation, PSS, residue method.

I. INTRODUCTION

THE damping torque analysis method is a main analysis method in the study of power system low-frequency oscillation. The damping torque analysis method was originally proposed in [1] to study the influence of the excitation controller of the synchronous generator on the power system small-signal angular stability. Based on the Phillips-Heffron model of the single-machine infinite-bus power system [2], the electromagnetic torque provided by the excitation controller to the electromechanical oscillation loop of the synchronous generator was decomposed into the synchronous torque which is proportional to the rotor angle, and the damping torque

which is proportional to the rotor angular speed. The damping torque affects the attenuation characteristics of the oscillation mode. The damping torque method in the single-machine infinite-bus power system has clear physical meaning and is easy to understand [3]–[6]. The value of the damping torque directly reflects the impact of the controller on the power system small-signal angular stability.

Many studies have attempted to extend the application of the damping torque analysis method to multi-machine power systems. Reference [7] studied the damping variation and control of low-frequency oscillations in the two-machine power system based on the principle of damping torque analysis. Reference [8] proposed a generalized Phillips-Heffron model of the multi-machine power system, which clearly describes the dynamic interaction between synchronous generators. However, due to the complicated relationship between the model parameters and the operating conditions of the power system, it is difficult to obtain general analysis conclusions according to the model proposed in [8]. Reference [9] proposed to calculate transfer functions by the signal flow graph, and on this basis, the synchronous torque and damping torque of each generator were calculated. References [10]–[14] analyzed the distribution of damping torque in the multi-machine power system with the transfer function block diagram. However, when the number of synchronous generators is very large, the block diagram will be very complicated and it is hard to apply in practice. References [15]–[20] analyzed the damping characteristics of flexible AC transmission system (FACTS) stabilizers in the multi-machine power system. Among them, [16] gave a panoramic demonstration of damping torque distribution and explained how the FACTS stabilizer clearly affects the oscillation mode of the power system. Reference [20] summarized the popularization and application of the damping torque analysis method in multi-machine power systems. Reference [21] mathematically proved the equivalence of the damping torque analysis method and the modal analysis method through the Phillips-Heffron model of the multi-machine power system, providing a rigorous theoretical basis for the damping torque analysis method. In recent years, renewable power generation, such as wind power and photovoltaic power generation, have been integrated into the power system through voltage source converters. The application of damping torque analysis in power systems integrated with renewable power generation is a recent new research interest [22]–[25].

From the above, the damping torque analysis in the multi-machine power system shows the influence path of the con-

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J. T. Bi, H. D. Sun (corresponding author, e-mail: sunhd@epri.sgcc.com.cn), S. Y. Xu, R. H. Song, B. Zhao and Q. Guo are with the State Key Laboratory of Power Grid Safety and Energy Conservation, China Electric Power Research Institute, Beijing 100192, China.

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troller on the oscillation mode through the panoramic demonstration diagram. However, there is no direct correspondence between the oscillation mode and the damping torque contributed to every single synchronous generator, which reduces the applicability of the damping torque analysis method in multi-machine power systems. In this paper, the damping torque analysis method mentioned above is named as the classic damping torque analysis (C-DTA) method.

The remainder of this paper is organized as follows. In the next section, the mode-based damping torque (M-DTA) analysis method is proposed. Based on the interconnection model between the system and the controller in the frequency domain, the oscillation loop corresponding to the electromechanical oscillation mode is built, and the mode-based damping torque of the controller to the oscillation loop can be calculated. Then, the application of the M-DTA method in the power system is introduced. The similarities and differences between the M-DTA method, the C-DTA method and the residue method is illustrated. In Section III, the effects of FACTS and PSS on the power system low-frequency oscillations are studied in the two-machine and two-area four-machine example power system with the M-DTA method respectively, which verifies the correctness of the proposed method. Conclusions of the paper are given in Section IV.

II. MODE-BASED DAMPING TORQUE ANALYSIS METHOD

A. Principles of Mode-based Damping Torque Analysis

The mode-based damping torque analysis (M-DTA) method is applied to study the effect of the external controller on the power system low-frequency oscillation. In this paper, the whole power system is divided into two parts: the controller part and the system part. The controller part consists of the external controller to be studied, and the system part consists of the remaining part of the power system.

According to the physical structure and electromagnetic relationship of the system part and the controller part, a pair of interaction variables between the two parts needs to first be determined. By taking the interaction variables as input and output variables, the state space models of the two parts can be obtained respectively as:

$$\begin{aligned}\Delta \dot{\mathbf{X}}_g &= \mathbf{A}_g \Delta \mathbf{X}_g + \mathbf{B}_g \Delta u \\ \Delta y &= \mathbf{C}_g \Delta \mathbf{X}_g + \mathbf{D}_g \Delta u\end{aligned}\quad (1)$$

$$\begin{aligned}\Delta \dot{\mathbf{X}}_h &= \mathbf{A}_h \Delta \mathbf{X}_h + \mathbf{B}_h \Delta y \\ \Delta u &= \mathbf{C}_h \Delta \mathbf{X}_h + \mathbf{D}_h \Delta y\end{aligned}\quad (2)$$

where $\Delta \mathbf{X}_g$ and $\Delta \mathbf{X}_h$ are state variable vectors of the system part and the controller part respectively, Δu is the input variable of the system part, and the output variable of the controller part, Δy is the output variable of the system part, and the input variable of the controller part.

According to (1) and (2), the transfer function of the system part and the controller part can be obtained as:

$$\Delta y = g(s) \Delta u \quad (3)$$

$$\Delta u = h(s) \Delta y \quad (4)$$

where $g(s) = \mathbf{C}_g(s\mathbf{I} - \mathbf{A}_g)^{-1}\mathbf{B}_g + \mathbf{D}_g$, $h(s) = \mathbf{C}_h(s\mathbf{I} - \mathbf{A}_h)^{-1}\mathbf{B}_h + \mathbf{D}_h$.

According to (3) and (4), the interconnection model between the system part and the controller part can be represented as Fig. 1.

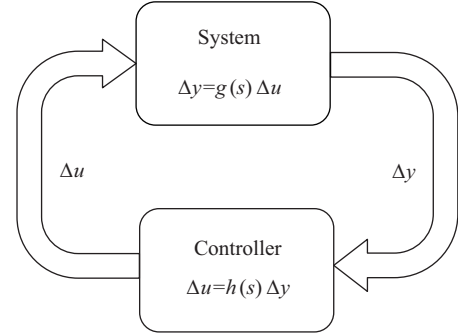


Fig. 1. Interconnection model between the system part and the controller part.

Let the electromechanical oscillation mode to be studied in the system part be $\lambda_0 = \xi_0 + j\omega_0$. The oscillation mode of the power system corresponds to a pair of conjugate complex roots, and the oscillation characteristic term corresponding to the oscillation mode λ_0 is:

$$[s - (\xi_0 + j\omega_0)][s - (\xi_0 - j\omega_0)] = s^2 + ds + k \quad (5)$$

where $d = -2\xi_0$, $k = \xi_0^2 + \omega_0^2$.

Since λ_0 is the eigenvalue of the system part, the denominator polynomial of the transfer function $g(s)$ in (3) contains the term $s^2 + ds + k$. Thus, the relationship between the output variable Δy and the input variable Δu of the system part can be expressed as:

$$\Delta y = \frac{R(s)}{s^2 + ds + k} \Delta u \quad (6)$$

where $R(s) = (s^2 + ds + k)g(s)$.

Equation (6) can be expanded as:

$$(s^2 + ds + k)\Delta y - R(s)\Delta u = 0 \quad (7)$$

Let

$$\Delta z = s\Delta y \quad (8)$$

Substituting (8) to (7), we have:

$$(s + d)\Delta z + k\Delta y - R(s)\Delta u = 0 \quad (9)$$

According to (8) and (9), the oscillation loop corresponding to the oscillation mode λ_0 can be built, as shown in Fig. 2.

The oscillation loop in Fig. 2 is similar to the electromechanical oscillation loop in the classic damping torque analysis (C-DTA) method. In this paper, the oscillation loop in Fig. 2 is named as the mode-based oscillation loop, and the input signal to the mode-based oscillation loop in Fig. 2 is defined as mode-based electromagnetic torque. It should be noted that the nomenclature here is made by analogy. The mode-based electromagnetic torque has no physical meaning of torque.

Adding the transfer function model $\Delta u = h(s)\Delta y$ of the controller part to the mode-based oscillation loop shown in

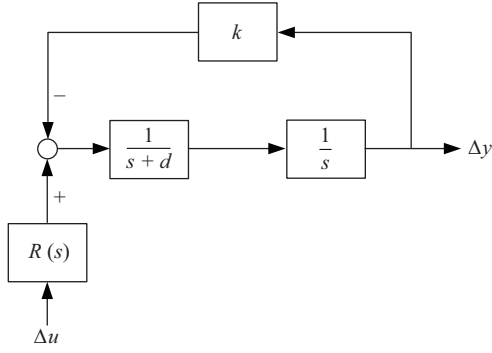
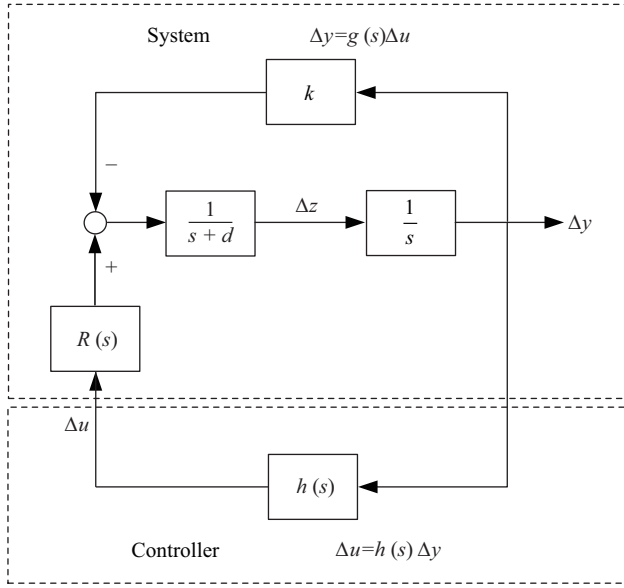
Fig. 2. Mode-based oscillation loop corresponding to λ_0 .

Fig. 3. Transfer function block diagram of the whole power system.

Fig. 2, the interconnection model of the whole power system in the frequency domain can be represented as the transfer function block diagram as shown in Fig. 3.

From Fig. 3, define the mode-based electromagnetic torque as:

$$\Delta T_M(s) = -R(s)h(s)\Delta y \quad (10)$$

Substituting the studied oscillation mode λ for s , the coefficient $-R(\lambda)h(\lambda)$ in (10) is a complex value, which can be decomposed into two real values which are proportional to Δy and Δz respectively.

According to the relationship between Δy and Δz as determined in (8), we have:

$$\Delta T_M = T_{Md}\Delta z + T_{Mk}\Delta y \quad (11)$$

where $T_{Mk} = -\text{Re}[R(\lambda)h(\lambda)] + \frac{\xi}{\omega} \text{Im}[R(\lambda)h(\lambda)]$, $T_{Md} = -\frac{1}{\omega} \text{Im}[K(\lambda)h(\lambda)]$, $\lambda = \xi + j\omega$.

From Fig. 3 and (4)(7)(10)(11), it can have:

$$[s^2 + (d + T_{Md})s + (k + T_{Mk})]\Delta y = 0 \quad (12)$$

It can be seen from (12) that T_{Md} is directly superimposed on the coefficient d of the first-order term, and T_{Mk} is directly

superimposed on the constant term k . T_{Md} and d , T_{Mk} and k have the same effect on the system eigenvalues respectively. The addition of the controller causes the coefficient of the first-order term and constant term to change, and the solution of the equation also changes from the eigenvalue of the open-loop system to the eigenvalue of the closed-loop system.

Following the corresponding definitions in the C-DTA method, define the coefficients T_{Md} and T_{Mk} in (11) to be the mode-based damping torque coefficient and the mode-based synchronous torque coefficient, respectively.

The above are the principles of the M-DTA method. The application of the M-DTA method in the single-machine infinite-bus power system and the multi-machine power system will be explained as follows.

B. M-DTA in Single-machine Infinite-bus Power System

In this section, the M-DTA method is performed on the single-machine infinite-bus power system shown in Fig. 4 to study the effect of the excitation controller on the electromechanical oscillation mode. Since the electromechanical oscillation mode is generated by the rotor motion, the mechanical part of the rotor is selected as the system part, and the other part such as the excitation windings are classified as the controller part. The transient electromotive force E'_q and the rotor angle δ of the synchronous generator are selected as the interaction variables of the two parts.

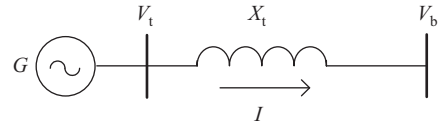


Fig. 4. Configuration of the single-machine infinite-bus power system.

The rotor motion equations of the synchronous generator are:

$$\begin{aligned} \dot{\delta} &= \omega_0(\omega - 1) \\ \dot{\omega} &= \frac{1}{M}[P_m - P_e - D(\omega - 1)] \end{aligned} \quad (13)$$

where δ and ω are the rotor angle and the rotor speed of the synchronous generator, respectively. $\omega_0 = 2\pi f_0$ is the synchronous speed, in which f_0 is the system frequency. M and D are the inertia constant and the damping coefficient of the rotor respectively. P_m and P_e are the mechanical power and the electromagnetic power respectively. P_e can be calculated as:

$$P_e = V_{td}I_d + V_{tq}I_q \quad (14)$$

where V_{td} and V_{tq} are the d-axis and q-axis components of the terminal voltage, I_d and I_q are the d-axis and q-axis components of the output current of the synchronous generator, respectively.

According to the electromagnetic relationship of the synchronous generator, we have:

$$\begin{aligned} V_{td} &= X_q I_q \\ V_{tq} &= E'_q - X'_d I_d \end{aligned} \quad (15)$$

where E'_q is the q-axis transient electromotive force, X'_d and X_q are the d-axis transient reactance and the q-axis reactance of the synchronous generator, respectively.

In addition, according to the voltage and current relationship of the transmission line, we have:

$$\begin{cases} V_{td} = V_b \sin \delta - X_t I_q \\ V_{tq} = V_b \cos \delta + X_t I_d \end{cases} \quad (16)$$

where X_t is the reactance of the transmission line, and V_b is the voltage of the infinite bus, which is generally set to $V_b = 1$.

From linearization of (14) to (16), we have:

$$\Delta P_e = K_1 \Delta \delta + K_2 \Delta E'_q \quad (17)$$

where $K_1 = \frac{E'_q V_b}{X'_d + X_t} \cos \delta_0 - \frac{(X_q - X'_d) V_b^2}{(X'_d + X_t)(X_q + X_t)} \cos 2\delta_0$, $K_2 = \frac{V_b}{X'_d + X_t} \sin \delta_0$.

1) C-DTA

According to (13) and (17), the electromechanical oscillation loop in the C-DTA method can be obtained as shown in Fig. 5(a). The electromagnetic torque ΔT to the electromechanical oscillation loop can be decomposed into the damping torque ΔT_d and the synchronous torque ΔT_s .

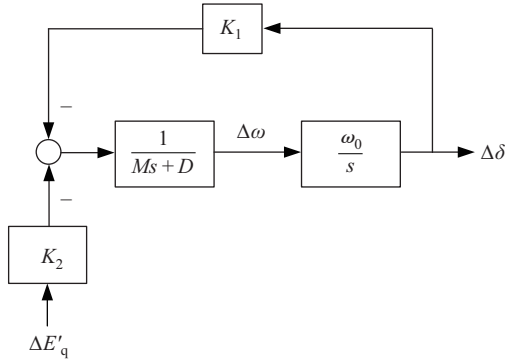


Fig. 5. Electromechanical oscillation loop in C-DTA and mode-based oscillation loop in M-DTA in the single-machine infinite-bus system.

According to the theory of the C-DTA method, the positive damping torque indicates that the controller is beneficial to power system stability, while the negative damping torque indicates that the controller is unfavorable to the power system stability, which causes the oscillation to be low-damped or divergent. In the single-machine infinite-bus power system, the value of the damping torque can be used to directly determine the impact of the controller on the electromechanical oscillation mode.

2) M-DTA

Substituting (17) into the linearization of (13) obtains:

$$Ms^2 \Delta \delta + Ds \Delta \delta + \omega_0 K_1 \Delta \delta = -\omega_0 K_2 \Delta E'_q \quad (18)$$

From (18), the transfer function from input signal $\Delta E'_q$ to the output signal $\Delta \delta$ can be expressed as:

$$\Delta \delta = g(s) \Delta E'_q = \frac{-\omega_0 K_2}{Ms^2 + Ds + \omega_0 K_1} \Delta E'_q \quad (19)$$

According to the M-DTA method introduced in Section II.A, extracting the oscillation characteristic term $s^2 + ds + k$

corresponding to the oscillation mode of the system part, we have:

$$\Delta \delta = g(s) \Delta E'_q = \frac{R}{s^2 + ds + k} \Delta E'_q \quad (20)$$

From (20), the mode-based oscillation loop can be represented as Fig. 5(b).

By comparing (19) and (20), we can easily obtain the relationship between the coefficient in (20) and that in (19) as:

$$\begin{cases} d = \frac{D}{M} \\ k = \frac{\omega_0 K_1}{M} \\ R = -\frac{\omega_0 K_2}{M} \end{cases} \quad (21)$$

From the above analysis, Fig. 5(a) and Fig. 5(b) are in essence two representations of the same oscillation circuit. Therefore, in the low-frequency oscillation analysis of the single-machine infinite-bus power system, the M-DTA method is equivalent to the C-DTA method, and the analysis process and conclusions are all the same.

C. M-DTA in Multi-machine Power System

1) C-DTA

The C-DTA method takes the electromechanical oscillation loop of the synchronous generator as the main analysis object. Previous studies have shown that in the multi-machine power system, the controller not only provides damping torque to the generator at the installation location, but also relates to other generators in the power system. In the application of the C-DTA method in multi-machine power systems, it is necessary to build the electromechanical oscillation loops shown in Fig. 5(a) for all synchronous generators, and to calculate the damping torque for every oscillation loop. The advantage of the C-DTA method is that it shows the impact of the controller on each synchronous generator, which has certain physical significance.

However, the C-DTA method has disadvantages in the following aspects.

1) For each damping torque calculation in the multi-machine power system with the C-DTA method, the order of the transfer function is almost equal to the order of the whole system. Thus, the repeated calculation of the damping torque increases the calculation pressure.

2) The C-DTA method only shows the relationship between the controller and the electromechanical oscillation loop of the synchronous generator. In order to study the effect of the controller on the electromechanical oscillation mode of the system, it is necessary to additionally analyze the sensitivity of the oscillation mode to the damping coefficient of each synchronous generator, as shown in Fig. 6(a). Additional sensitivity calculations undoubtedly increases the complexity of the C-DTA method.

3) In practice, electromagnetic torque T in Fig. 5(a) is not an observable physical quantity. Thus, the coefficient matrices in the C-DTA method cannot be obtained by measurement but can only be obtained by formula derivation.

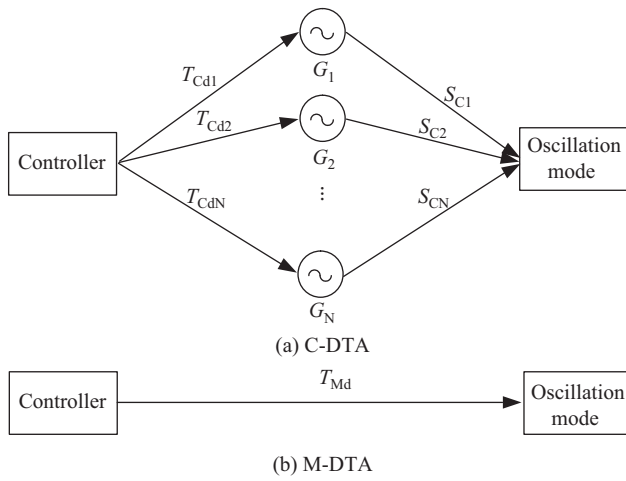


Fig. 6. Calculation processes of C-DTA and M-DTA in multi-machine systems.

2) M-DTA

Compared with the C-DTA method, the M-DTA method has certain advantages in the above aspects.

(1) Calculation pressure.

Different from the C-DTA method, the M-DTA method directly considers the oscillation mode of the power system as the main analysis object. Once the oscillation mode to be studied in the system is selected, there is only one mode-based oscillation loop in the whole system. Thus, the mode-based damping torque only needs to be calculated one time, as shown in Fig. 6(b).

For example, for a power system with N synchronous generators, M candidate installation locations of PSS need to be evaluated. In the application of the C-DTA method, $N \times M$ times the damping torque calculation and N times sensitivity calculation are needed. In contrast, in the application of the M-DTA method, only M times the mode-based damping torque calculation is needed.

(2) Sensitivity.

In the M-DTA method, there is a fixed sensitivity relationship between the oscillation mode and the mode-based damping torque.

For the characteristic equation corresponding to the oscillation mode λ_0 to be studied:

$$s^2 + ds + k = 0 \quad (22)$$

We have:

$$s_{1,2} = \frac{-d \pm \sqrt{d^2 - 4k}}{2} = \xi_0 \pm j\omega_0 \quad (23)$$

where,

$$\begin{aligned} \xi_0 &= -\frac{d}{2} \\ j\omega_0 &= \frac{\sqrt{d^2 - 4k}}{2} \end{aligned} \quad (24)$$

For (23), differentiating the coefficients of the first-order term d (damping coefficient) and the constant term k (synchronous coefficient), we have:

$$\frac{\partial s_{1,2}}{\partial d} = -\frac{1}{2} - j\frac{\xi_0}{\omega_0^2}$$

$$\frac{\partial s_{1,2}}{\partial k} = \pm j\frac{1}{\omega_0} \quad (25)$$

It can be seen from (25) that the real part of the eigenvalue is only affected by the damping coefficient d . For the low-damped electromechanical oscillation mode, $\xi_0 \ll \omega_0^2$ stands, and $\partial s_{1,2}/\partial d \approx -1/2$ can be taken as the approximate calculation.

From (12) and (25), the effect of the controller on the electromechanical oscillation mode to be studied can be quantified as:

$$\Delta\lambda = T_{Md} \cdot \frac{\partial s_{1,2}}{\partial d} + T_{Mk} \cdot \frac{\partial s_{1,2}}{\partial k} \quad (26)$$

(3) Variable accessibility.

In the M-DTA method, the interaction variables u and y are both practically measurable. The transfer function of the system part and controller part can be obtained by the perturbation method.

In summary, the required steps for the application of the M-DTA method in the study of power system low-frequency oscillations are as follows.

Step 1: According to the research purpose, decompose the whole system into the system part and the controller part. The system part contains the oscillation mode to be studied.

Step 2: According to the physical structure and electrical relationship, select the interaction variables of the two parts. The two parts dynamically interact with each other through the interaction variables.

Step 3: If the models and parameters of the power system are known, the transfer function model of the two parts can be obtained by the analytical method. If the model or parameters are unknown, the value of the transfer function at the specific frequency can be obtained by the perturbation method.

Step 4: According to the transfer function model of the system part, extract the oscillation characteristic terms corresponding to the oscillation mode to build the mode-based oscillation loop, and take the transfer function model of the controller part as the feedback loop.

Step 5: Calculate the mode-based electromagnetic torque of the controller and decompose it into the mode-based damping torque and the mode-based synchronous torque.

Step 6: Calculate the fixed sensitivity of the oscillation mode to the damping coefficient.

Step 7: The product of the mode-based electromagnetic torque coefficient and the corresponding sensitivity is the quantitative characterization of the effect of the controller on the oscillation mode.

The M-DTA method can be used for controller damping evaluation and controller design, such as location selection and parameter adjustment of PSSs and FACTS damping controllers. It should be noted that, both M-DTA and C-DTA are small-signal analysis methods based on linearized models, and not applicable for the analysis under “large” disturbances. For example, when another synchronous generator is added to the power system, it will have a great impact on some original electromechanical oscillation modes, and the generators participating in the original oscillation modes will also change. In this case, neither M-DTA nor C-DTA can ensure the analysis

accuracy. In this situation, the eigenvalue calculation method is more reliable.

D. Relationship between M-DTA Method and Residue Method

For the $N \times N$ open-loop state matrix A_g in (1), the left and right eigenvectors corresponding to the i -th open-loop eigenvalue λ_i are w_i^T and v_i , respectively. The mode decomposition of the open-loop system part is shown in Fig. 7.

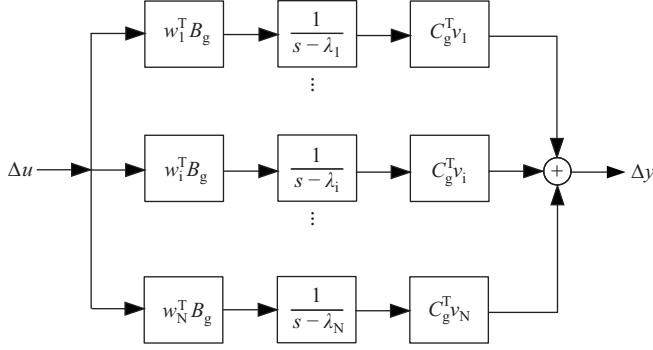


Fig. 7. Mode decomposition of the open-loop system with residues.

From Fig. 7, the relationship between the output variable Δy and the input variable Δu can be expressed with the residue as:

$$\begin{aligned} \Delta y &= \sum_{i=1}^N \frac{w_i^T B_g C_g^T v_i}{s - \lambda_i} \cdot \Delta u \\ &= \sum_{i=1}^N \frac{R_{resi}}{s - \lambda_i} \cdot \Delta u \end{aligned} \quad (27)$$

where $R_{resi} = w_i^T B_g C_g^T v_i$ is the residue corresponding to the i -th eigenvalue λ_i .

It can be seen that the residue method is based on the mode decomposition of the open-loop system. Each open-loop eigenvalue of the system corresponds to a residue. The residue is essentially the “static” indicator corresponding to the open-loop eigenvalue.

Unlike the residue, which is a “static” indicator, the intermediate variable $R(s)$ in (6) in the M-DTA method is a “dynamic” indicator that changes with the eigenvalue s .

Without loss of generality, suppose $\lambda_0 = \xi_0 + j\omega_0$ and $\lambda_0^* = \xi_0 - j\omega_0$ in (5) are the first two eigenvalues of the open-loop state matrix A_g . That is, $\lambda_1 = \lambda_0$, $\lambda_2 = \lambda_0^*$. Equation (27) can then be written as:

$$\begin{aligned} \Delta y &= \sum_{i=1}^N \frac{R_{resi}}{s - \lambda_i} \cdot \Delta u \\ &= \left(\frac{R_{res1}}{s - \lambda_1} + \frac{R_{res2}}{s - \lambda_2} + \sum_{i=3}^N \frac{R_{resi}}{s - \lambda_i} \right) \cdot \Delta u \\ &= \left(\frac{R_{res1}}{s - \lambda_0} + \frac{R_{res2}}{s - \lambda_0^*} + \sum_{i=3}^N \frac{R_{resi}}{s - \lambda_i} \right) \cdot \Delta u \\ &= \frac{(s - \lambda_0^*)R_{res1} + (s - \lambda_0)R_{res2} + \sum_{i=3}^N \frac{(s - \lambda_0)(s - \lambda_0^*)R_{resi}}{s - \lambda_i}}{(s - \lambda_0)(s - \lambda_0^*)} \cdot \Delta u \end{aligned} \quad (28)$$

Since the residues of the conjugate characteristic values are equal, i.e., $R_{res1} = R_{res2}$, then we have:

$$\begin{aligned} \Delta y &= \frac{(s - \lambda_0^*)R_{res1} + (s - \lambda_0)R_{res2} + \sum_{i=3}^N \frac{(s - \lambda_0)(s - \lambda_0^*)R_{resi}}{s - \lambda_i}}{(s - \lambda_0)(s - \lambda_0^*)} \cdot \Delta u \\ &= \frac{(2s - \lambda_0 - \lambda_0^*)R_{res1} + \sum_{i=3}^N \frac{(s - \lambda_0)(s - \lambda_0^*)R_{resi}}{s - \lambda_i}}{s^2 + ds + k} \cdot \Delta u \end{aligned} \quad (29)$$

From (6) and (29), the relationship between the R_{resi} in the residue method and the $R(s)$ in M-DTA method is:

$$R(s) = (2s - \lambda_0 - \lambda_0^*)R_{res1} + \sum_{i=3}^N \frac{(s - \lambda_0)(s - \lambda_0^*)R_{resi}}{s - \lambda_i} \quad (30)$$

If and only if $s = \lambda_0$ or $s = \lambda_0^*$, we have:

$$\begin{aligned} R(\lambda_0) &= j2\omega_0 R_{res1} \\ R(\lambda_0^*) &= -j2\omega_0 R_{res1} \end{aligned} \quad (31)$$

From (31), for the research at the open-loop eigenvalue λ_0 , the residue indicator R_{res} and the M-DTA intermediate variable $R(\lambda_0)$ differ by only a multiple, and the analysis conclusions of the two methods are consistent. However, in the closed-loop system research after the controller is added, the “dynamic” M-DTA intermediate variable $R(s)$ is theoretically more accurate than the “static” residual index R_{res} . The difference between the two methods will be explained in Section III.B by an example.

Another difference between the M-DTA method and the residue method is that the M-DTA method learns from the concept of the C-DTA and extracts the oscillation circuit corresponding to the oscillation mode, thus the damping torque and synchronous torque of other parts of the system can be calculated and graphically decomposed. Through the derivation of the formula in this paper, we conclude that the damping torque only affects the real part of the eigenvalue and the synchronization torque only affects the imaginary part of the eigenvalue approximately.

III. EXAMPLE

In this section, the C-DTA method and the M-DTA method are compared and demonstrated in the two-machine example power system to study the effect of the SVC stabilizer on low-frequency oscillations. In the two-area four-machine power system, the M-DTA method and the residue method are compared for the location selection and parameter adjustment of PSS.

A. Evaluation of Damping Effect of the SVC stabilizer with the C-DTA and M-DTA Method

Configuration of the two-machine power system is shown in Fig. 8. The change of load flow is balanced by G2 at slack bus 4. In this example, the third-order model of the synchronous generator, and first-order model of the automatic voltage regulator (AVR) are used [26]–[29]. The loads are

modeled as constant impedance. Parameters of the system and synchronous generators are given in [29]. The thyristor-controlled reactor and fixed capacitor (TCR-FC) type of the static VAR compensator (SVC) with an additional damping controller (i.e., the SVC stabilizer) are installed at bus 2. The configuration of the TCR-FC is shown in Fig. 9.

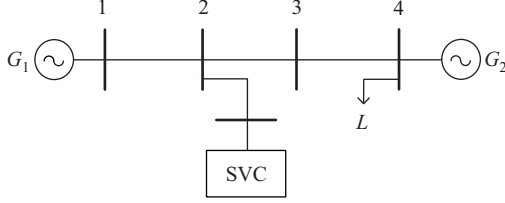


Fig. 8. Configuration of the two-machine power system.

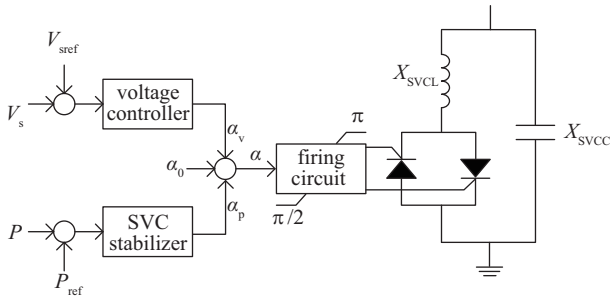


Fig. 9. Configuration of the TCR-FC with SVC stabilizer.

For the TCR-FC shown in Fig. 9, the equivalent susceptance b_{SVC} is:

$$b_{SVC} = \frac{2\alpha - \sin 2\alpha - 2\pi}{2\pi X_{SVCL}} + \frac{1}{X_{SVCC}} \quad (32)$$

where X_{SVCL} and X_{SVCC} are the reactance of the inductor and the fixed capacitor of the TCR-FC, respectively, α is the firing angle of the thyristor-controlled firing circuit, which is modulated by both the voltage controller and the SVC stabilizer. In this paper, the voltage of bus 2 is the control signal of the SVC voltage controller, and the active power from bus 2 to bus 3 is the control signal of the SVC stabilizer. The two controllers are both adopted using the proportional-integral (PI) control method. From Fig. 9, we have:

$$\begin{cases} \alpha = \alpha_0 + \alpha_V + \alpha_P \\ \alpha_V = \left(K_{vp} + \frac{K_{vi}}{s} \right) (V_{sref} - V_s) \\ \alpha_P = \left(K_{pp} + \frac{K_{pi}}{s} \right) (P_{ref} - P) \end{cases} \quad (33)$$

When the SVC stabilizer is not added, the electromechanical oscillation mode of the power system is $\lambda_0 = 0.0103 + j7.2332$. The real part of the eigenvalue is positive, and the system will generate divergent oscillation under disturbance. Therefore, the SVC stabilizer needs to be added to stabilize the oscillation mode. The C-DTA method and M-DTA method are compared to study the damping effect of the SVC stabilizer on the oscillation mode.

1) C-DTA

In the application of the C-DTA method, the damping torque of the SVC stabilizer to the electromechanical oscillation loop of each synchronous generator needs to be calculated first.

According to the configuration of the SVC stabilizer in Fig. 9, for the state space model of the system part in (1), $\Delta u = \Delta \alpha_P$, $\Delta y = \Delta P$. According to [29], it can be obtained that the damping torque to the electromechanical oscillation loop of G1 is $T_{Cd1} = -0.9990 + j10.4905$, and that G2 is $T_{Cd2} = 2.9845 - j2.9722$.

In the C-DTA method, the effect of the controller on the oscillation mode cannot be judged by the above two damping torque values. According to [29], the sensitivity of the electromechanical oscillation mode to the damping coefficient of each synchronous generator needs to be calculated. In this example, the sensitivity of the studied electromechanical oscillation mode to the damping coefficients of G1 and G2 are $S_{C1} = -0.0305 + j0.0034$ and $S_{C2} = -0.0321 - j0.0031$, respectively.

The whole calculation process with the M-DTA method is shown in Fig. 10(a).

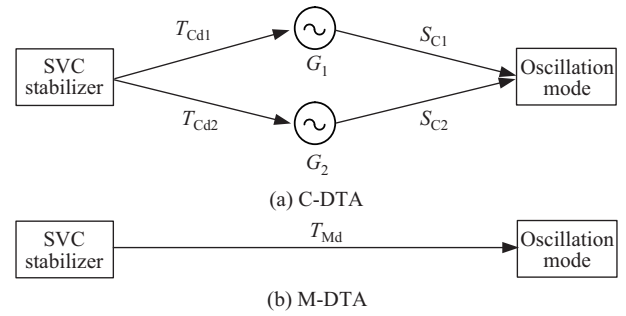


Fig. 10. Comparison of C-DTA and M-DTA in the two-machine power system.

Synthesizing the damping torque and sensitivity, the comprehensive index to characterize the damping effect of the SVC stabilizer is $\Re(T_{Cd1} \cdot S_{C1} + T_{Cd2} \cdot S_{C2}) = -0.1106$.

2) M-DTA

According to the M-DTA method introduced in Section II.C, extracting the oscillation characteristic term $s^2 - 0.3284s + 35.42$ from the transfer function $g(s)$ in (3), we have:

$$R(s) = \frac{0.15395s^3(s + 97.66)(s + 90.29)}{(s + 10.22)(s + 1.133)(s^2 + 2.155s + 35.89)} \\ \frac{s^2(s + 90.63)(s + 75.25)}{(s + 25.75)(s + 9.993)(s + 0.4027)} \\ H(s) = \frac{-2(s + 8)}{s}$$

Substituting $s = \lambda_0$ to $R(s)$ and $H(s)$ obtains $R(\lambda_0) = -1.1542 - j0.4868$, $H(\lambda_0) = -2.0032 + j2.2120$. Furthermore, the mode-based damping torque and synchronous torque can be calculated to be $T_{Md} = 0.2181$, $T_{Mk} = -3.3912$.

From (25), the sensitivity of the oscillation mode to the mode-based damping torque is -0.5 approximately. Thus, the influence of the SVC stabilizer on the real part of the oscillation mode is $\Delta \xi = -0.1091$. Therefore, only by the

value of the mode-based damping torque, the oscillation mode is estimated to be $\xi_0 + \Delta\xi = -0.0988$ after the SVC stabilizer is added. The characteristic structure analysis method is used to obtain the closed-loop oscillation mode of the whole system with the SVC stabilizer as $\lambda = -0.0925 + j7.0364$. It is very approximate to the estimated value, which verifies the correctness of the method.

The whole calculation process with the C-DTA method is shown in Fig. 10(b). Compared with the M-DTA method, the M-DTA method avoids calculating the damping torque for each synchronous generator. It is not necessary to additionally calculate the sensitivity.

Before and after the SVC stabilizer is added, under the same disturbance conditions, the non-linear time domain simulation results of the active power of the transmission line are shown in Fig. 11.

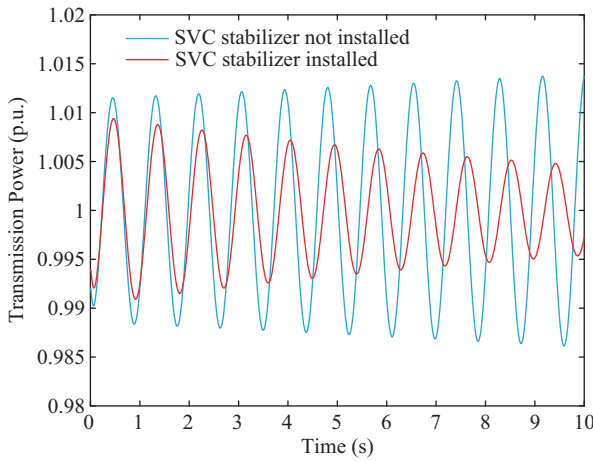


Fig. 11. Simulation results in the two-machine power system.

Both methods reach the same conclusion, which verifies the correctness of the M-DTA method proposed in this paper. Compared with the C-DTA method, the M-DTA method has a very small calculation component. This advantage will become more prominent in the calculation of large systems.

B. Location Selection and Parameter Adjustment of PSS with the M-DTA Method and Residue Method

Figure 12 shows the configuration of a typical two-area interconnected power system with an AC tie-line, which has been used for studying power system low-frequency oscillations on many occasions [26]–[29]. The change of load flow is balanced by G1 at slack bus 1. In this example, the third-order model of the synchronous generator, and first-order model of the automatic voltage regulator (AVR) are used. The loads are

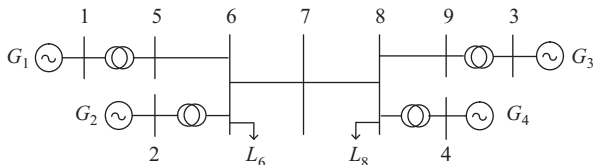


Fig. 12. Configuration of the two-area four-machine power system.

modeled as constant impedance. Parameters of the system and synchronous generators are given in [27].

The interarea oscillation mode of the system is $\lambda_0 = 0.0131 + j3.6729$ before the PSS is added. In this example, the M-DTA method proposed in this paper and the residue method are compared for the location selection and parameter adjustment of the PSS. In this paper, the PSS takes the angular velocity ω of the synchronous generator as the input signal, and the output signal u_{PSS} of the PSS is added to the AVR.

1) Location selection of the PSS with M-DTA Method

In the application of the M-DTA method, the mode-based damping torque to the mode-based oscillation loop by PSS at each candidate installation location needs to be calculated.

When the PSS is installed on G1, for the state space model of the system part in (1), $\Delta u = \Delta u_{PSS1}$, $\Delta y = \Delta \omega_1$, $D_g = 0$. Extracting the oscillation characteristic term $(s - \lambda_0)(s - \lambda_0^*) = s^2 - 0.0262s + 13.49$, the transfer function value from the input signal Δu_{PSS1} to the mode-based oscillation loop can be calculated as $R_1(\lambda_0) = 0.0101 + j0.0129$.

Similarly, when the PSS is installed on G2, G3, and G4, updating the input-output variables and coefficient matrices, the mode-based electromagnetic torques can be obtained as $R_2(\lambda_0) = -0.0086 + j0.0014$, $R_3(\lambda_0) = -0.0524 - j0.0205$ and $R_4(\lambda_0) = -0.0387 - j0.0105$, respectively.

According to the above results, $|R_3(\lambda_0)| > |R_4(\lambda_0)| > |R_1(\lambda_0)| > |R_2(\lambda_0)|$. When the studied oscillation mode is subject to the same damping, the relationship between the magnifications of the four PSSs is $K_{PSS3} < K_{PSS4} < K_{PSS1} < K_{PSS2}$. That is, when PSS is installed on G3, the control cost required for the PSS is minimal. Therefore, PSS should be installed on G3.

If the C-DTA method is applied, for each candidate PSS installation location, 4 times the damping torque and 4 times the sensitivity needs to be calculated. In comparison, the M-DTA method requires less calculations. This advantage will become more prominent in the calculation of large systems.

In the cases where the PSS is installed on different synchronous generators, the open-loop state matrix A_g in (1) are all the same, but B_g and C_g vary. With the residue method in Section II.D, when the PSS is installed on G1, G2, G3 and G4, the residue corresponding to the open-loop eigenvalue λ_0 are $R_{res_G1} = 0.0018 - j0.0014$, $R_{res_G2} = 0.0002 + j0.0012$, $R_{res_G3} = -0.0028 + j0.0071$ and $R_{res_G4} = -0.0014 + j0.0053$, respectively.

As the analysis in Section II.D shows, in this example, for the research at the open-loop eigenvalue λ_0 , the residue indicator $R_{res_Gi}(i = 1, 2, 3, 4)$ and the M-DTA indicator $R_i(\lambda_0)(i = 1, 2, 3, 4)$ differ by only a multiple of $2\omega_0$. $|R_{res_Gi}|$ and $|R_i(\lambda_0)|$ have the same sequence by size, and the two methods draw the same conclusion.

2) Parameter adjustment of the PSS with M-DTA Method

The transfer function model of the PSS used in this paper is:

$$H_{PSS}(s) = K_{PSS} \frac{1 + sT_2}{1 + sT_1} \frac{1 + sT_4}{1 + sT_3} \quad (34)$$

where $T_1 = T_3 = 0.1s$. The value of K_{PSS} , T_2 and T_4 are calculated with the M-DTA method as follows. The control target of the interarea oscillation mode is $\lambda = -0.1 + j4.0$.

The oscillation characteristic term corresponding to the target oscillation mode is $s^2 + 0.2s + 16.01$. Compared with the original oscillation characteristic term, the additional damping torque required by the mode-based oscillation loop is $D_M = 0.2262$, and the additional synchronization torque is $K_M = 2.52$, that is:

$$R(s)H(s) = -0.2262s - 2.52$$

Substituting $s = \lambda = -0.1 + j4.0$, we have:

$$H(\lambda) = \frac{-0.2262s - 2.52}{R_3(\lambda)} = 47.3005 \angle -1.2223^\circ$$

Let

$$K_1 \frac{1 + \lambda T_2}{1 + \lambda T_1} = 47.3005 \angle -0.6112^\circ$$

$$K_1 \frac{1 + \lambda T_4}{1 + \lambda T_3} = 1.0 \angle -0.6112^\circ$$

Solving the above formula, the parameters of PSS can be calculated as: $K_{PSS} = K_1 K_2 = 47.6745$, $T_2 = 0.0970$, $T_4 = 0.0970$.

When the PSS with the above parameters is installed on G3, the closed-loop interarea oscillation mode of the whole power system is calculated to be $\lambda = -0.1001 + j4.0000$, which proves the correctness of the method.

With the residue method in Section II.D, the parameters of the PSS are designed according to the following formula:

$$\lambda - \lambda_0 = R_{\text{res_G3}} \cdot K'_{PSS} \frac{1 + \lambda T'_2}{1 + \lambda T'_1} \frac{1 + \lambda T'_4}{1 + \lambda T'_3}$$

Solving the above formula, the parameters of PSS can be calculated as: $K'_{PSS} = 48.1130$, $T'_2 = 0.0917$, $T'_4 = 0.0917$.

When the PSS, with the above parameters, is installed on G3, the closed-loop interarea oscillation mode of the whole power system is calculated to be $\lambda' = -0.0881 + j4.0028$. Compared with the target characteristic value, the parameter adjustment effect by residue method is less accurate than the M-DTA method.

As can be seen from this example, if the target closed-loop eigenvalue λ is known, the calculation result of $R(s)$ in the M-DTA method, which substitutes the target closed-loop eigenvalue λ , is more accurate than the “static” residue indicator R_{res} which corresponds to the open-loop eigenvalues.

For the following three cases: PSS is not installed, and PSS is installed on G3, and G4 respectively, under the same disturbance conditions, the non-linear time domain simulation results of the active power between the two areas are shown in Fig. 13.

From Fig. 13, with the same value of K_{PSS} , the system oscillation is most suppressed when the PSS is installed on G3. The parameter setting of the PSS also reaches the target damping of the system.

In the application of the controller design, the eigenvalue comparison method is not applicable. Because the location and parameters of the controller are unknown, the closed-loop state matrix of the power system cannot be constructed. This is exactly the advantage of the analysis methods based on the open-loop system (including M-DTA, C-DTA and residue method, etc.), and it is one of the most important application scenarios of the M-DTA method.

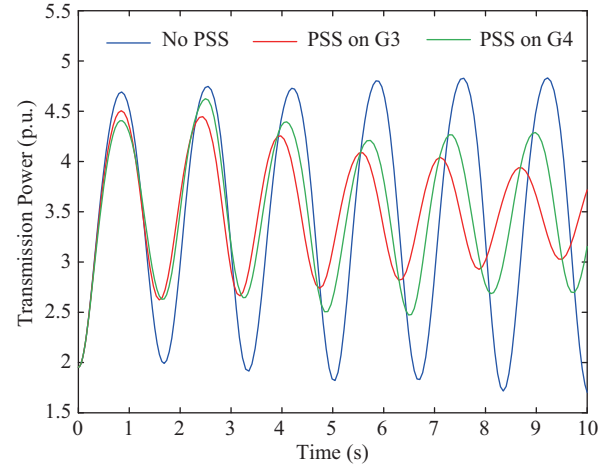


Fig. 13. Simulation results in the two-area four-machine power system.

IV. CONCLUSION

This paper proposes the mode-based damping torque analysis (M-DTA) method for studying the effect of an external controller on the electromechanical oscillation mode of the power system. In the single-machine infinite-bus power system, the derivation shows that the M-DTA method is completely equivalent to the classical damping torque analysis (C-DTA) method. In the multi-machine power system, the M-DTA method takes precedence over the C-DTA method in the following aspects:

(1) In the C-DTA method, there is no direct correspondence between the damping torque and the oscillation mode, and an additional sensitivity calculation is needed. In the M-DTA, the sensitivity relationship between the oscillation mode and the mode-based damping torque is fixed, thus the mode-based damping torque can be used to directly judge the effect of the controller on the studied oscillation mode.

(2) The C-DTA method considers the electromechanical oscillation loop of the synchronous generator as the main analysis object. The repeated calculation of the damping torque increases the calculation pressure in the analysis of multi-machine power systems. The M-DTA method directly uses the oscillation mode of the power system as the main analysis object, thus the mode-based damping torque only needs to be calculated one time.

(3) In the C-DTA method, the electromagnetic torque contributed to the electromechanical oscillation loop is not an observable physical quantity. In the M-DTA method, the interaction variables between the system part and the controller part are all measurable. The transfer function of the two parts can be obtained by the perturbation method.

The M-DTA method can be used for damping evaluation and design of various controllers, such as location selection and parameter adjustments of PSSs and FACTS damping controllers.

Both the M-DTA method and the residue method can be used to analyze the impact of the controller on the low-frequency oscillation stability. However, the two methods decompose the system in different ways. Through theoretical derivation, the relationship between the two methods are

obtained. In the open-loop system analysis, the two methods can reach a consistent conclusion. But in the closed-loop system research after the controller is added, such as controller parameter adjustment in the closed-loop system, the “dynamic” M-DTA indicator is theoretically more accurate than the “static” residual indicator.

Although this paper introduces the M-DTA method based on the single-input single-output (SISO) controller, the M-DTA method can also be extended to the study of multiple-input multiple-output (MIMO) controllers. The research on the latter case is ongoing and has achieved preliminary results, which will be published in the author’s follow-up papers.

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Jingtian Bi received the B.S. degree from Shandong University, Jinan, China, in 2011 and the Ph.D. degree from North China Electric Power University, Beijing, China, in 2018. He worked as a postdoctoral fellow with the China Electric Power Research Institute (CEPRI), Beijing, China, till 2020. He is currently a senior engineer in the Power System Department, CEPRI. His interests mainly include dynamic stability analysis and control for power system with high proportion of power electronics devices.



Huadong Sun received the B.Eng. and M.S. degree in Electrical Engineering from Shandong University, Jinan, China, in 1999 and 2002, respectively. He received the Ph.D. degree in Electrical Engineering from China Electric Power Research Institute (CEPRI) in 2005. He is currently the Vice President and a professorate senior engineer of CEPRI. His research interests include power system analysis and control.



Shiyun Xu received the B.S. degree from Yanshan University, Qinhuangdao, China, in 2005 and the Ph.D. degree in Mechanical Systems and Control from Peking University, Beijing, China, in 2010. She worked as a postdoctoral fellow with the China Electric Power Research Institute (CEPRI), Beijing, China, till 2012. From 2007 to 2008, she was a visiting scholar of Polytechnic Institute, New York University, USA. Currently, she is a professorate senior engineer at CEPRI, Beijing, China. Her research interests include power systems dynamic stability analysis and control with high penetration of renewable energies.



Ruihua Song received the B.Eng. and M.S. degrees in Electrical Engineering from the China Agricultural University, Beijing, China, in 1993 and 1998, respectively. He received the Ph.D. degree from China Electric Power Research Institute (CEPRI), Beijing, China, in 2007. He is currently working as a professorate senior engineer of electrical engineering in the Power System Department of CEPRI, Beijing, China. His research interests include electromagnetic transient simulation, sub-synchronous oscillation of thermal power unit, renewable power wide-frequency oscillation, and power electrical application technology.



Bing Zhao received the B.Eng. and M.S. degrees in Electrical Engineering from the Xi'an University of Technology, Xi'an, China, in 2003 and 2006, respectively. He received the Ph.D. degree from China Electric Power Research Institute (CEPRI), Beijing, China, in 2009. He is currently working as a professorate senior engineer in the Power System Department of CEPRI, Beijing, China. His research interests include power system stability analysis and control, load modelling, renewable power generation and integration, and operation and control of

DC grid.



Qiang Guo received the B.Eng., M.S. and Ph.D. degrees in Electrical Engineering from the Xi'an Jiaotong University, Xi'an, China, in 1993, 1995 and 1998, respectively. He is currently a professorate senior engineer in China Electric Power Research Institute, Beijing, China. His research interests include power system planning and operation analysis.