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Transient Stability Improvement Using the Associate Hermite assisted Prediction Technique

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***Abstract*—Researchers have investigated different techniques to improve damping for transient stability events. Off-line security analysis and day-ahead studies are scenarios where unacceptable damping levels for oscillatory instabilities may be detected. One type of correction to improve damping is to re-dispatch generation. In this paper, a new prediction method will use data from a conventional transient stability simulation to predict transient performance over an abbreviated observation window. Damping levels will be calculated using a simple iterative technique and the Stability Output Fourier Transformation method. If damping levels are found to be insufficiently small, improvement will be demonstrated after generation has been re-dispatched. Several examples will show that the new prediction method along with the damping calculation technique can estimate transient stability performance before and after implementing a re-dispatching scheme to improve damping.**

***Index Terms*—transient stability, curve fitting, generation re-dispatch, power systems, security analysis, Associate Hermite expansion, oscillatory instabilities.**

I. Introduction

THE increasing cost of materials and labor along with additional regulatory authority has put increased pressure on the construction of new transmission facilities. As a result, fewer transmission lines are being built or are often delayed. However, the demands on existing transmission facilities such as the addition of renewable resources and growing native load requirements continue to increase. These restrictions make assessing transmission performance critically important particularly when unscheduled outages occur and the need for quick assessment of transmission capability is essential. Transmission performance assessment must also be timely as utilities perform day-ahead scheduling.

The fast execution of operating studies or security analysis is viewed as a necessity for quickly determining transfer capability levels. Thermal and post-transient analyses have small computational requirements in terms of time. On the other hand, transient stability analysis is computationally intensive and often requires hours of simulation time. Transient stability analysis is typically the time limiting element when transmission performance is assessed.

When insufficient damping is detected through transient stability analysis [1] mitigation by means of generation re-dispatch is often the quickest and least expensive option to optimize available transmission capacity within the electrical network. Researchers have proposed many methods to detect transient stability problems in either off-line or real-time scenarios. Most methods provide a means of quantitatively estimating damping that could be used to measure improvements as a result of changes in generation patterns. Some techniques that detect transient instabilities and provide an ability to measure changes in damping include using Lyapunov exponents indices [2], neural networks [3-5] and adaptive time series functions [6]. Modified kinetic and potential energy based schemes has also been used to predict instabilities [7-8]. Researchers have developed a lookup table and curve fitting technique for estimating and mitigating real-time instabilities [9]. This method could also be extended to provide re-dispatch schedules for improving damping, as is directly suggested by other researchers [10-11] as a means to improving stability performance.

A new prediction method is used here to detect poorly damped transient stability events in a minimum amount of time. The method, known as the Associate Hermite expansion (AHE) method, uses a modified orthogonal polynomial to provide a spectrum of the disturbance. After an event has been detected, damping is assessed using the Stability Output Fourier Transformation (SOFT) technique [12-13] along with an iterative method to calculate the damping percentage. Generation re-dispatch is then implemented to improve damping at critical generators. Examples of damping before and after re-dispatch are provided.

This proposed AHE method could aid those individuals performing real-time, off-line security analysis particularly in the case of when unscheduled outages occur. The method may also aid those performing assessments on day-ahead scheduling patterns. In this case once generation patterns, loads, planned outages and schedules are tentatively set the engineer could quickly test damping levels. If damping levels were found to be unacceptable then re-dispatch schedules could be deployed to improve performance. Alternately,

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special protective schemes (SPS) using existing relays could be put into service if changes to generation levels are deemed impractical. Both scenarios require quick analysis of transient stability that is normally performed using a conventional transient stability program and visual inspection of the results.

In this paper, the proposed AHE prediction algorithm is described in section II. Section III gives examples of detected transient stable events and the effects of improvements in damping levels through re-dispatch of generation. Finally, section IV lists conclusions about the applicability and advantages of the AHE prediction method.

II. AHE Prediction algorithm

A. AHE functions

Previous researchers [14] have used the AHE functions to study electromagnetic responses to conducting bodies. This was accomplished by simultaneously extrapolating in time and frequency domains using initially calculated data. Later, a modified version of the AHE functions [15] was found to effectively model high frequency effects in chip design. This modified version used only initial time domain data and extrapolated entirely in the frequency domain. This version of the AHE functions is utilized here to process angular data and to extrapolate their frequency spectrums.

The AHE functions are described by (1) where p_m is the m^{th} order Hermite orthogonal polynomial and λ is the time scaling factor. Like other orthogonal polynomials, the

$$H_m(t,\lambda)=\frac{p_m(t/\lambda)}{\sqrt{2^m m!}}\frac{e^{\frac{-t^2}{2\lambda^2}}}{\sqrt{\sqrt{\pi}\,\lambda}}, \qquad m=0,1,2,\cdots,M \tag{1}$$

Hermite polynomial has a recursive relationship that allows quick calculation of successively higher orders of the AHE functional values without using (1). The recursive form of (1) is given in (2) for orders 2 and above. Equation (3) shows the first two values of the original Hermite polynomial that are needed for (2).

$$H_m(t,\lambda)=\frac{1}{\sqrt{m}}\left[\sqrt{2}\left(\frac{t}{\lambda}\right)H_{m-1}\left(\frac{t}{\lambda}\right)-\sqrt{(m-1)}\,H_{m-2}\left(\frac{t}{\lambda}\right)\right], m\ge 2 \tag{2}$$

$$\begin{aligned} p_0(t)&=1\\ p_1(t)&=2t\\ p_m(t)&=2tp_{m-1}(t)-2(m-1)p_{m-2}(t), \qquad m\ge 2 \end{aligned} \tag{3}$$

A real angular signal $x(t)$ can be represented using the relationship in (4) where the coefficients a_m are computed through a singular value decomposition solution. Using these coefficients, the

$$x(t)=\sum_{m=0}^{\infty}a_m H_m(t,\lambda) \tag{4}$$

frequency spectrum of the signal can be calculated by replacing f/μ for t/λ in (2) and using (5) and (6) to obtain the expanded real and imaginary Fourier components. The frequency scaling factor μ is related to the time scaling factor λ by μ=1/2πλ.

$$X_R(f)=\sum_{k=0}^{M\ge 2k}(-1)^k a_{2k}H_{2k}(f,\mu) \tag{5}$$

$$X_I(f)=-\sum_{k=0}^{M\ge 2k+1}(-1)^k a_{2k+1}H_{2k+1}(f,\mu) \tag{6}$$

Using (5) and (6), the expandable magnitude response is shown in (7).

$$X(f)=\sum_{k=0}^{M}(-1)^k a_k H_k(f,\mu) \tag{7}$$

Since the rotor angle representation is real, the Fourier magnitude response has to be even. Examination of (5) and (7) show that both functions are indeed even. If $\hat{x}(t)$ represents the rotor angle measurement, then (4) is used to generate the matrix equations in (11). With the coefficients calculated, (5) and (6) are then used to create the matrix equations in (12) and (13) where $\hat{X}_R(f)$ and $\hat{X}_I(f)$ are the extrapolated spectrum components, *N* is the number of time samples, *P* is the number of frequency samples and *M* is the final order.

B. Calculation of the time and frequency domain order

The order of the both the time domain and the subsequent frequency spectrum approximations are calculated through the elimination of the weak singular values of the time domain *H* matrix. Singular value decomposition is applied to factor the *H* matrix into right eigenvector, left eigenvector and singular matrices using (8). The component matrices are recalculated into V^r, S^r and U^r after the weak singular values are removed with the help of (9), where σ_i is the ith singular value of the *H* matrix and *K* is the new order of the approximations. The values of the coefficients a_m are calculated using the reduced versions of the component matrices using the pseudoinverse [16] of (10), where *T* represents the Hermitian transpose.

$$(U,S,V)= \quad svd\ (H) \tag{8}$$

$$\sigma_i \ge \sigma_{max}\times tol \qquad i=0,1,\ldots,K,\ldots,M-2,M-1 \tag{9}$$

$$a_m=\left(V^r\, S^{r^-} U^{rT}\right)\times x(t) \tag{10}$$

C. AHE algorithm

As explained before, one scenario where a quick transient stability analysis is needed could occur do to an unplanned outage while another application would involve testing transmission performance for use in day-ahead scheduling. Regardless of the situation, data will need to be downloaded into a conventional stability program, a set of contingencies are simulated to 5 seconds, the AHE functions are fitted to the angular data from certain generators, and spectrums from two different windows are extrapolated.

$$\begin{bmatrix} H_0(t_1,\lambda) & H_1(t_1,\lambda) & H_2(t_1,\lambda) & \cdots & H_{M-2}(t_1,\lambda) & H_{M-1}(t_1,\lambda) & H_M(t_1,\lambda) \\ H_0(t_2,\lambda) & H_1(t_2,\lambda) & H_2(t_2,\lambda) & \cdots & H_{M-2}(t_2,\lambda) & H_{M-1}(t_2,\lambda) & H_M(t_2,\lambda) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ H_0(t_{N-1},\lambda) & H_1(t_{N-1},\lambda) & H_2(t_{N-1},\lambda) & \cdots & H_{M-2}(t_{N-1},\lambda) & H_{M-1}(t_{N-1},\lambda) & H_M(t_{N-1},\lambda) \\ H_0(t_N,\lambda) & H_1(t_N,\lambda) & H_2(t_N,\lambda) & \cdots & H_{M-2}(t_N,\lambda) & H_{M-1}(t_1,\lambda) & H_M(t_N,\lambda) \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{M-1} \\ a_M \end{bmatrix} = \begin{bmatrix} \hat{x}(t_1) \\ \hat{x}(t_2) \\ \vdots \\ \hat{x}(t_{N-1}) \\ \hat{x}(t_N) \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} H_0(f_1,\mu) & 0 & -H_2(f_1,\mu) & 0 & H_4(f_1,\mu) & \cdots & (-1)^{M/2} H_M(f_1,\mu) \\ H_0(f_2,\mu) & 0 & -H_2(f_2,\mu) & 0 & H_4(f_2,\mu) & \cdots & (-1)^{M/2} H_M(f_2,\mu) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ H_0(f_{P-1},\mu) & 0 & -H_2(f_{P-1},\mu) & 0 & H_4(f_{P-1},\mu) & \cdots & (-1)^{M/2} H_M(f_{P-1},\mu) \\ H_0(f_P,\mu) & 0 & -H_2(f_P,\mu) & 0 & H_4(f_P,\mu) & \cdots & (-1)^{M/2} H_M(f_P,\mu) \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{M-1} \\ a_M \end{bmatrix} = \begin{bmatrix} \hat{X}_R(f_1) \\ \hat{X}_R(f_2) \\ \vdots \\ \hat{X}_R(f_{P-1}) \\ \hat{X}_R(f_P) \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} 0 & -H_1(f_1,\mu) & 0 & H_3(f_1,\mu) & 0 & \cdots & (-1)^{M/2} H_M(f_1,\mu) \\ 0 & -H_1(f_2,\mu) & 0 & H_3(f_2,\mu) & 0 & \cdots & (-1)^{M/2} H_M(f_2,\mu) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & -H_1(f_{P-1},\mu) & 0 & H_3(f_{P-1},\mu) & \cdots & (-1)^{(M/2)-1} H_{M-1}(f_{P-1},\mu) & 0 \\ 0 & -H_1(f_P,\mu) & 0 & H_3(f_P,\mu) & \cdots & (-1)^{(M/2)-1} H_{M-1}(f_P,\mu) & 0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{M-1} \\ a_M \end{bmatrix} = \begin{bmatrix} \hat{X}_I(f_1) \\ \hat{X}_I(f_2) \\ \vdots \\ \hat{X}_I(f_{P-1}) \\ \hat{X}_I(f_P) \end{bmatrix} \tag{13}$$

Damping is estimated using the SOFT method and through an iterative method that calculates damping ratio. Figure 1 shows a flowchart of the AHE algorithm using the day-ahead scheduling scenario along with a generation re-dispatch step.

III. PREDICTION RESULTS AND STABILITY IMPROVEMENT

A. Data fitting and spectrum extrapolation

Rotor angle data from a 5 second transient stability simulation is fitted to the AHE functions. Next, the frequency spectrums for two time windows are extrapolated and stability performance is estimated by assessment of the damping ratio. The details of this process are provided in the following.

Step 1) Calculate the time domain H matrix with an initial value of the model order. For a window length of 5 seconds and a frequency range of .3 to 2 Hz, set the time scaling factor to 0.6.

Step 2) Factor the H matrix using singular value decomposition and reduce the component matrices by excising the weakest singular values. The new order of the time and frequency approximations is taken to be the dimension of the singular matrix.

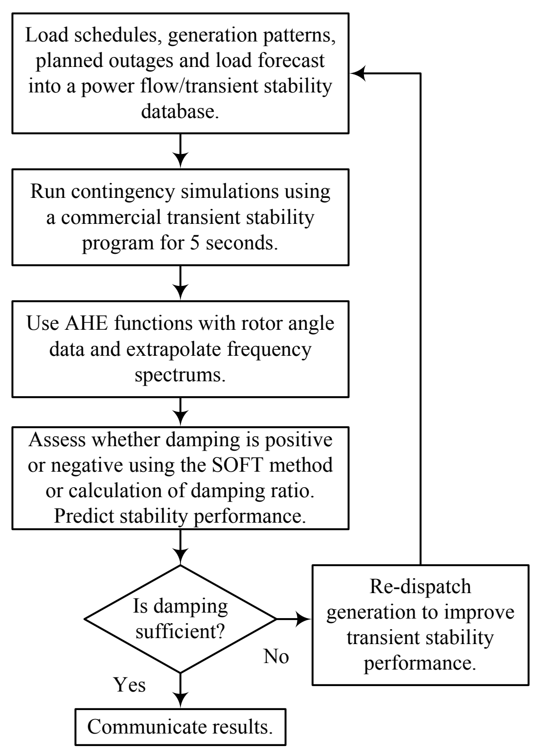

Fig. 1. AHE algorithm for estimating transient stability performance and re-dispatching generation.

Step 3) Remove the dc component and apply a Kaiser window to the rotor angle data. Use the Moore-Penrose pseudoinverse to calculate the a_m coefficients.

Step 4) Calculate the real and imaginary Fourier components of the reduced H matrix. Extrapolate the spectrums using the a_m coefficients and the Fourier components of the H matrix.

B. Stability estimation

The SOFT method is used to estimate whether damping is either positive or negative using two frequency spectrums generated from two time domain windows (Fig. 2) that have a window length defined as T_W and a start time of T_G. Each spectrum represents a time domain window and the comparison of the magnitudes of the major frequency components (MFC) yields the stability result. Fig. 3 shows the two spectrums where f_0 is the major frequency component (MFC), $|F_A|$ is the Fourier magnitude from the first window, and $|F_B|$ is the Fourier magnitude of the second window. If $|F_A|>|F_B|$ then the stability response is considered damped, or the response is considered undamped if $|F_A|<|F_B|$.

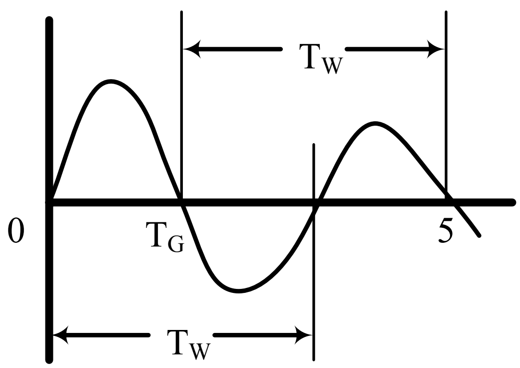

Fig. 2. Rotor angle approximation divided into two windows.

To provide a comparison to a more recognizable measurement, a method to iteratively calculate the percent damping ratio at a given frequency using the ratio of Fourier transforms of two damped sinusoids was employed. The configuration in (14) shows the ratio of the two transforms

$$\frac{F_1(\omega_0)}{F_2(\omega_0)}=\frac{\int_0^{T_W} e^{\alpha t}\cos(\omega_0 t)e^{-j\omega t}dt}{\int_{T_G}^{T_W+T_G} e^{\alpha t}\cos(\omega_0 t)e^{-j\omega t}dt} \tag{14}$$

where T_G is the difference in start times for the two sliding windows, ω_0 is equal to $2\pi f_0$ at the spectrum peaks, F_1 (ω_0) is the spectrum peak of the first window and F_2 (ω_0) is the spectrum peak of the second window. A simple Newton-Raphson iterative routine is then used to solve for α with an initial estimate.

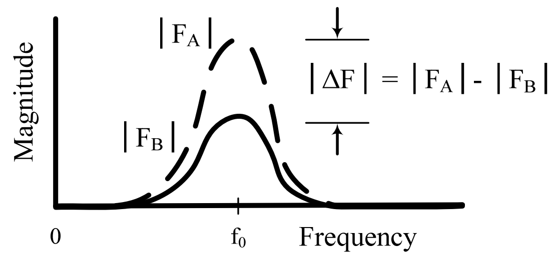

Fig. 3. Spectrums from two rotor angle window approximations.

C. Examples of stability predictions and re-dispatch effects

To demonstrate the ability of the AHE method with the help of the SOFT technique and the iterative method to predict stability performance, a few examples are provided in this section. Also included are examples of re-dispatch scenarios that show improvements in damping. The analysis was performed using only 5 seconds of simulated data from a transient stability program. Fig. 4 shows a lightly damped rotor angle plot and Fig. 5 shows the frequency spectrums of two overlapping windows.

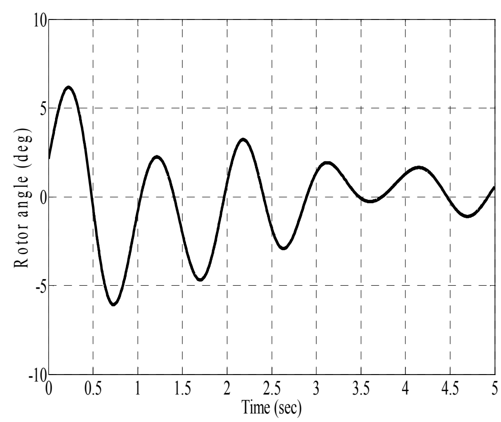

Fig. 4. Rotor angle before re-dispatch of generation.

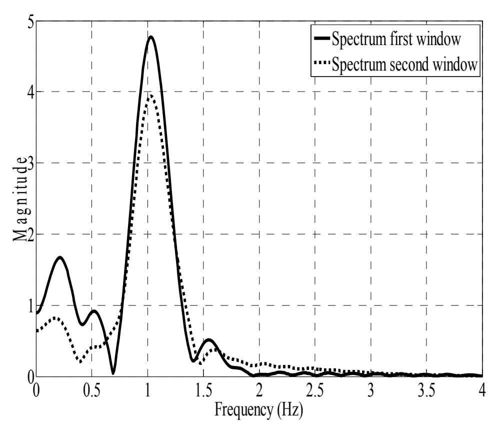

Fig. 5. Spectrums showing a mode at 1.03 Hz before re-dispatch of generation.

After a re-dispatch in generation of 150 MW, the same disturbance was simulated and the same rotor angle was approximated. Fig. 6 shows the rotor angle of the same generator and its two spectrums are given in Fig. 7. The MFC of interest is at 1.03 Hz with a damping ratio of 8.31%. After the re-dispatch, the damping ratio improves to 10.69%.

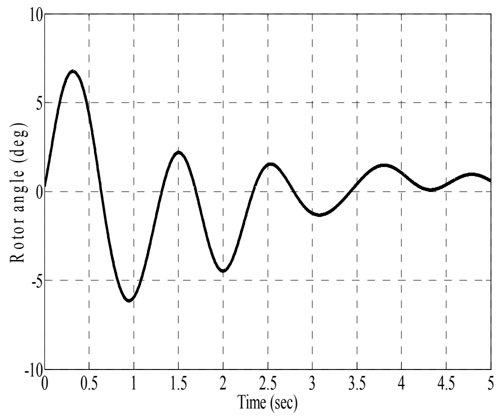

Fig. 6. Rotor angle plot after re-dispatch of 150 MW of generation.

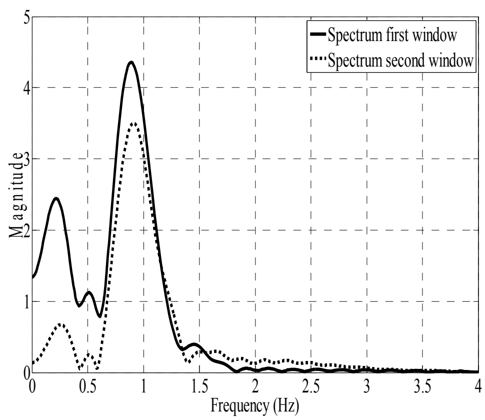

Fig. 7. Spectrums of a damped rotor angle oscillation after re-dispatch of 150 MW of generation.

Another example of the use of the AHE prediction method is the assessment of the rotor angle in Fig. 8 and its spectrums shown in Fig. 9. The damping percentage is 10.27% using the iterative calculation before re-dispatch. Fig. 10 shows the

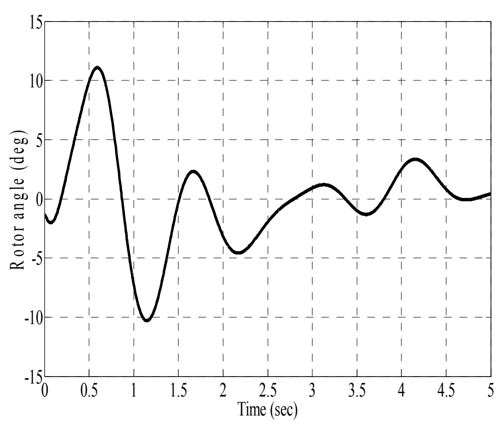

Fig. 8. Rotor angle plot before re-dispatch of generation.

rotor angle measurement after re-dispatch. Fig. 11 shows the extrapolated spectrums from the two sliding windows after re-dispatch of generation. A re-dispatch of 200 MW caused the damping to increase to 11.83%.

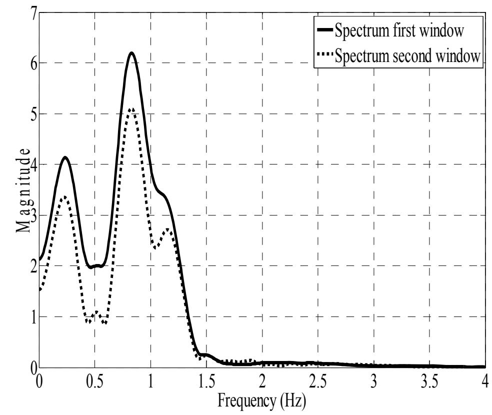

Fig. 9. Spectrums before re-dispatch of generation showing a mode at .83 Hz.

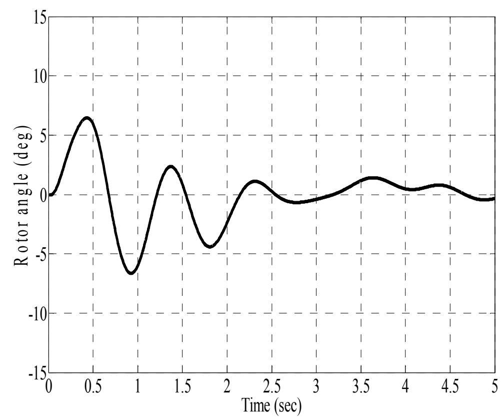

Fig. 10. Rotor angle plot after re-dispatching 200 MW of generation.

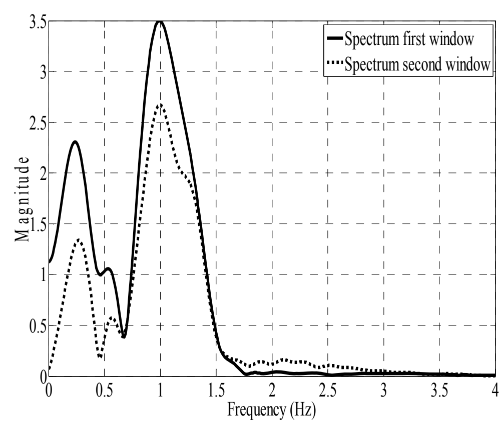

Fig. 11. Spectrums after re-dispatch of generation showing a mode at 1 Hz.

IV. Conclusions

In this paper a method has been used to use to predict oscillatory behavior as a result of transient stability simulations in power systems. The method is the Associate

Hermite expansion technique that detects oscillations and damping is evaluated using the SOFT method and an iterative method. In essence, the AHE method takes a relatively small amount of angular data from a conventional transient stability program and extrapolates the spectrums of the data. Then the SOFT method and a simple Newton-Raphson technique to calculate the damping percentage at the frequency of interest. Examples of the assisted method were provided. In addition, generation is re-dispatched in the given examples are used to show improvement in damping. Benefits of the proposed AHE prediction method demonstrate the following advantages.

- Using only 5 seconds of simulation time, prediction times of the AHE method are substantially less than visually inspecting transient stability results which takes up to 20 seconds.
- The AHE method provides an objective means of assessing transient stability performance as compared to visually inspecting results.

One application where the AHE method may be used is in the execution of off-line studies. Unscheduled outages often require a fast assessment of transient stability performance to confirm whether transfer capabilities can be maintained. The AHE method affords a quicker assessment than a visual estimation of performance. Day-ahead scheduling is also another scenario that the AHE method could be deployed in lieu of conventional stability analysis. After schedules, generation levels, planned outages and load forecasts have been determined for the following day, a quick estimation of transient stability behavior is needed to ascertain if acceptable damping levels are present.

V. Acknowledgment

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VII. Biographies

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George G. Karady (SM'70, F'78) received BSEE and Doctor of Engineering degree in electrical engineering from Technical University of Budapest. Dr. Karady was appointed to Salt River Project Chair Professor at Arizona State University in 1986. Previously, he was with EBASCO Services where he served as Chief Consulting Electrical Engineer. He was Electrical Task supervisor for the Tokomak Fusion Test reactor project in Princeton. He worked for the Hydro Quebec Institute of Research as a Program manager. He also worked for the Technical University of Budapest as Deputy Department Head. Dr. Karady is a registered professional engineer in New York, New Jersey and Quebec. He is the author of more than 100 technical papers.