A Model-Independent Delay Compensation Method for Power Systems

Muyang Liu, *Student Member, IEEE*, Georgios Tzounas, *Student Member, IEEE*, Federico Milano, *Fellow, IEEE*
School of Electrical and Electronic Engineering, University College Dublin, Ireland
{muyang.liu, georgios.tzounas}@ucdconnect.ie, federico.milano@ucd.ie

***Abstract*—The paper provides a simple and robust model-independent compensation technique to mitigate the impact of time delays on power system stability. As the proposed approach requires the first derivative of the delayed signal, the resulting model of the power system with inclusion of compensation is in the form of neutral delay differential-algebraic equations. The paper also provides a systematic approach to evaluate the small-signal stability of the compensated system. This is done through a descriptor model transformation, Chebyshev discretization, and Newton correction. The IEEE 14-bus system is utilized to test the effectiveness and robustness of the proposed compensation technique.**

***Index Terms*—Delay compensation, small-signal stability analysis, neutral delay differential equation (NDDE), delay differential-algebraic equation (DDAE).**

I. Introduction

A. Motivation

Wide-area measurements and controllers inevitably introduce time delays into power systems. The magnitude of these time delays are usually around 100 - 200 ms (but can be up to 700 ms [1]) and tend to deteriorate the oscillation modes and even destabilize power systems [2]–[4]. Delay compensation is a common approach to mitigate the impact of time delays on power system stability. This paper proposes a new simple and robust delay compensation technique for power system controllers only based on delayed signals.

B. Literature Review

Smith predictor is the most widely used delay-compensation approach [5], [6]. In the power system context, Smith predictors have been proposed to compensate the delayed signal feeding a power system damping controller [7], [8]. Such a controller is implemented at the power plant from where the signal is transmitted. In practice, however, it might not be possible to implement the control loop at the signal sending-end side due to technical, security and/or ownership issues.

Advanced controllers, such as H_∞ [9], sliding-mode [10] and hybrid [11] controllers, are also developed to mitigate the stability impact of time delays on power system. Apart from applications of the newly-developed advanced controllers, updating the parameters through adaptive or fuzzy strategies of existing controllers also improves the robustness of power systems against time delays [12]. The proposed delay-compensation technique is much more straightforward than above control approaches and still improves the system delay margins. Meanwhile, it is also possible to combine the proposed method with the advanced controllers.

The stability analysis of a system that includes the proposed delay-compensation technique is not straightforward. The proposed technique, in fact, requires the first derivatives of delayed variables, thus leading to a model formulated in terms of neutral delay differential equations [13]. Most stability analysis approaches for neutral delayed systems are based on Lyapunov-Krasovskii Functional (LKF) [14]–[16]. However, LKF approaches are model-dependent, over-conservative, and too computational demanding to be applied systematically to real-world power systems [13]. To avoid these issues, the small-signal stability analysis considered in this paper is based on frequency-domain and Chebyshev discretization. Such a small-signal stability analysis is comprehensively described in previous works by the authors [2], [13], [17]–[19].

C. Contributions

To the best of our knowledge, this is the first attempt to implement a model-independent delay compensation technique for power system control. Moreover, compared to the Smith predictor, the proposed technique is more general and more feasible to implement in power systems.

The specific contributions of the paper are the following.

- A proposal of a simple but efficient model-independent delay compensation technique.
- A discussion on how to implement the proposed delay compensation technique in power system devices as well as in Time Domain Integration (TDI) routine.
- A systematic two-step approach to evaluate the small-signal stability of the power system implemented with the proposed delay compensation.

The latter approach can be utilized to obtain the delay margin of the system and find the optimal gain of the compensation plant. It can also be utilized to generate stability maps to define the relationship between the compensation gain and delay magnitude.

This work was supported by: Science Foundation Ireland, by funding Muyang Liu, Georgios Tzounas and Federico Milano under Grant No. SFI/15/IA/3074.

D. Organization

The paper is organized as follows. Section II introduces the proposed model-independent delay compensation technique and considers an illustrative numerical example to show the effect of the technique. Section III explains the small-signal stability analysis approach of the power system implemented with the proposed delay compensation. Section IV provides the case study based on the IEEE 14-bus system. The proposed method is utilized to compensate the delayed input signal of the Power System Stabilizer (PSS) in the power system. Section V provides conclusions and outlines future work.

II. Delay Compensation Method

This section presents the proposed delay-compensation technique and provides a numerical example to illustrate its effectiveness.

A. Proposed Method

The basic idea of the proposed delay-compensation technique is straightforward. Let us assume that a system is stable without introducing any time delay but is unstable if a sufficiently large delay is introduced. To stabilize the delayed system, one of the most straightforward choices is to make the delayed signal more *like* the non-delayed one. With this idea, we consider a compensation technique based on the first derivative of the delayed signal.

Consider a signal $x(t)$. The delayed signal is $x_d(t) = x(t-\tau)$. If τ is small, the following approximation holds:

$$\dot{x}(t) \approx \frac{x(t) - x(t-\tau)}{\tau} \ , \tag{1}$$

thus,

$$x(t) \approx x(t-\tau) + \tau\, \dot{x}(t) \ . \tag{2}$$

At the receiving end, the time derivative of the non-delayed signal is unknown, so we consider the following approximation:

$$\dot{x}(t) \approx \dot{x}(t-\tau) \ . \tag{3}$$

The compensated signal $x_{\rm com}$ that mimics the original signal x based on the delayed signal x_d can be deduced:

$$x_{\rm com}(t) = x_d(t) + K_\tau\, \tau\, \dot{x}_d(t) \ , \tag{4}$$

where K_τ is the gain of the compensation. The purpose of this gain is to compensate numerical errors of the approximations considered in (1) and (2) as well as reduce the impact of estimation errors of the value of τ. According to our experience, $K_\tau \in (0, 2.0]$.

In practice, the first derivative of the delayed signal can always be calculated numerically:

$$\dot{x}(t) \approx \frac{x(t) - x(t-\Delta t)}{\Delta t} \ , \tag{5}$$

where Δt is a small time step that can be chosen according to the sampling rate of the measurements. In the TDI simulations carried out in the case study, Δt is set as the magnitude of the TDI time step, namely 1 ms.

B. Numerical Example

Consider the following simple signals:

$$x(t) = \begin{cases} 0, & \text{if } t < 0 \\ \sin(t), & \text{if } t \geq 0 \end{cases}$$
$$x_d(t) = x(t-\tau) \ ,$$

with $\tau = 0.5$ s. The compensated signal is 0 for $t \in [0, \tau]$ s. For $t \geq \tau$, one has:

$$\begin{aligned} x_{\rm com}(t) &= x_d(t) + K_\tau\, \tau\, \dot{x}_d(t) \\ &= \sin(t-\tau) + K_\tau\, \tau\, \cos(t-\tau) \ , \end{aligned}$$

where we choose $K_\tau = 1.2$.

Figure 1 shows the comparison of the original non-delayed signal x, the delayed signal x_d and the compensated signal $x_{\rm com}$ for $t \in [0, 2\pi]$ s. The compensated signal $x_{\rm com}$ effectively approximates the non-delayed signal x for $t \in [\tau, 2\pi]$ s.

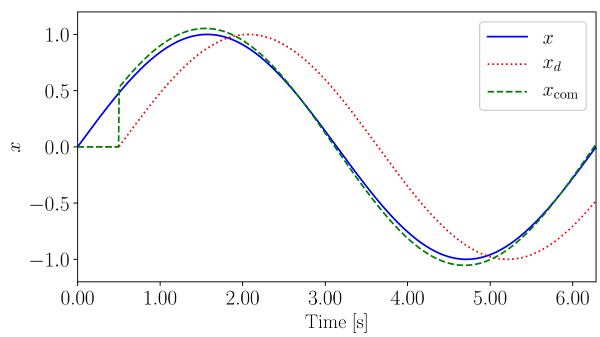

Fig. 1: Trajectories of the signals x, x_d and $x_{\rm com}$ for the numerical example.

The compensation of delays in real-world applications is clearly more complex than this example. It is worth noticing, however, that the main goal of the compensation technique in power system applications is not to perfectly mimic the original signal, but rather to improve the robustness of the system against time delays. This point is further discussed in Section IV, which presents a case study based on a standard power system.

III. Small-Signal Stability Analysis

This section provides a systematic small-signal stability analysis approach to depict the effect of the proposed delay-compensation technique on power system stability. Subsection III-A introduces the mathematical model of the power system implemented with the proposed delay compensation. Subsection III-B explains the approach to evaluate the small-signal stability of this model.

A. Delay Differential-Algebraic Equations

Power systems with inclusion of delays can be modeled as a set of index-1 Hessenberg form Delay Differential Algebraic Equations (DDAEs) [2]:

$$\begin{aligned}\dot{\boldsymbol{x}}(t) &= \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{x}(t-\boldsymbol{\tau}), \boldsymbol{y}(t-\boldsymbol{\tau}), \boldsymbol{u}(t)) \\ \boldsymbol{0} &= \boldsymbol{g}(\boldsymbol{x}(t), \boldsymbol{y}(t), \boldsymbol{x}(t-\boldsymbol{\tau}), \boldsymbol{u}(t)) \ ,\end{aligned} \tag{6}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are state variables and algebraic variables, $\boldsymbol{u}$ are discrete variables modelling events, e.g, line outage, and $\boldsymbol{\tau}$ are time delays.

The differentiation of (6) at an equilibrium point leads to:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}_o \boldsymbol{x}(t) + \sum_{i=1}^{n_\tau} \boldsymbol{A}_i \boldsymbol{x}(t-\tau_i) \ , \tag{7}$$

where $\boldsymbol{A}_o$ is the conventional state matrix of the system, and $\boldsymbol{A}_i$ are the parameter matrices of the delayed variables and n_τ is the number of the delayed variables [2].

Consider a general solution of (12), $\boldsymbol{x}(t) = e^{-\lambda t}\boldsymbol{\nu}$, where $\boldsymbol{\nu}$ is a non-trivial vector called *eigenvector* and λ is the *eigenvalue*. Then, the characteristic equation of (12) can be obtained from solving the following problem:

$$\Delta(\lambda)\boldsymbol{\nu} = \boldsymbol{0} \ , \tag{8}$$

or, equivalently:

$$\det\Big(\Delta(\lambda)\Big) = 0 \ , \tag{9}$$

where

$$\Delta(\lambda) = \lambda \boldsymbol{I} - \boldsymbol{A}_o - \sum_{i=1}^{n_\tau} \boldsymbol{A}_i \, e^{-\lambda \tau_i} \ . \tag{10}$$

$\Delta(\lambda)$ is called *characteristic matrix*. As it is well known, the roots of (10) define the local stability properties of (6).

In the case study, the damping ratio of the critical right-most eigenvalues is relevant. This is defined as follows:

$$\zeta = \frac{-\alpha}{\sqrt{\alpha^2 + \beta^2}} \ , \tag{11}$$

where α and β are the real and imaginary part of a pair of complex eigenvalues, namely, $\lambda = \alpha \pm j\beta$.

B. Neutral Delay Differential Equations

If the delay-compensation technique is applied to power systems, the delayed variables $\boldsymbol{x}(t-\tau_i)$ in (7) are replaced by the compensated variables as in (4). Thus, the standard form for the small-signal model of the power system implemented with the proposed delay compensation is:

$$\begin{aligned}\dot{\boldsymbol{x}}(t) &= \boldsymbol{A}_o \boldsymbol{x}(t) + \sum_{i=1}^{n_\tau} \boldsymbol{A}_i \boldsymbol{x}_{\rm com}(t) \\ &= \boldsymbol{A}_o \boldsymbol{x}(t) + \sum_{i=1}^{n_\tau} \boldsymbol{A}_i \Big(\boldsymbol{x}(t-\tau_i) + K_{\tau,i}\,\tau_i\,\dot{\boldsymbol{x}}(t-\tau_i)\Big) \ .\end{aligned} \tag{12}$$

The proposed compensation technique introduces the time-derivatives of delayed variables $\dot{\boldsymbol{x}}(t-\tau_i)$ and makes the overall system a set of Neutral Delay Differential Equations (NDDEs) which are not standard index-1 Hessenberg form DDAEs.

To cope with this difficulty, this subsection presents a method to compute the eigenvalues of (12). The method includes two steps: (i) compute the approximated eigenvalues of a comparison system through Chebyshev discretization; and (ii) correct the approximated eigenvalues through Newton iterations based on the characteristic equation of (12).

1) Comparison System and Approximated Eigenvalues: References [18] [13] by the first and the third authors provide a general approach to compute the approximated eigenvalues of the system in the form of the following NDDE:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{x}(t-\boldsymbol{\tau}), \dot{\boldsymbol{x}}(t-\boldsymbol{\tau})) \ . \tag{13}$$

Interestingly, differentiating (13) leads to a set of equations that have the same structure of (12). Hence, the approximated eigenvalues of (12) can be solved according to the approach discussed in [18] and [13]. An outline of the steps required to define the comparison system and compute its approximated eigenvalues is as follows:

- Consider a comparison system of (12) in non-index-1 Hessenberg form [17]:

$$\begin{aligned}\dot{\boldsymbol{x}}(t) &= \boldsymbol{z}(t) \\ \boldsymbol{0} &= \boldsymbol{A}_o \boldsymbol{x}(t) - \boldsymbol{z}(t) + \sum_{i=1}^{n_\tau} \Big(\boldsymbol{A}_i \boldsymbol{x}_{d,i}(t) + \boldsymbol{B}_i \boldsymbol{z}_{d,i}(t)\Big) \ ,\end{aligned} \tag{14}$$

  where $\boldsymbol{z}$ are auxiliary algebraic variables and:

$$\begin{aligned}\boldsymbol{x}_{d,i}(t) &= \boldsymbol{x}(t-\tau_i) \\ \boldsymbol{z}_{d,i}(t) &= \boldsymbol{z}(t-\tau_i) \\ \boldsymbol{B}_i &= \boldsymbol{A}_i K_{\tau,i}\tau_i \ ,\end{aligned}$$

  The comparison system (14) has identical eigenvalues with (12), which is proved in [13]. This is a typical descriptor model transformation [14].
- The characteristic matrix of (14) is:

$$\Delta(\hat{\lambda}) = \hat{\lambda}\boldsymbol{I} - \boldsymbol{A}_o - \sum_{i=1}^{n_\tau} \boldsymbol{C}_i^0 e^{-\hat{\lambda}\tau_i} - \sum_{i=1}^{n_\tau}\sum_{k=1}^{\infty} \boldsymbol{C}_i^k e^{-\hat{\lambda}\tau_i} \ . \tag{15}$$

  where:

$$\boldsymbol{C}_i^k = \boldsymbol{B}_i^k(\boldsymbol{A}_i + \boldsymbol{A}_o\boldsymbol{B}_i) \ . \tag{16}$$

  The deduction from (14) to (15) is explained in [17]. If the spectral radius of the eigenvalues of $\boldsymbol{B}_i$, $\forall i \in [1, n_\tau]$, is smaller than 1 (i.e., $\rho(\boldsymbol{B}_i) < 1$), the characteristic matrix (15) converges. Effectively, an upper boundary $k_{\max}$ of k has to be chosen to truncate the series of the last right-hand side term of (15).
- The eigenvalues of (14) with characteristic matrix (15) can be estimated through computing the eigenvalues of the Chebyshev discretized matrix $\boldsymbol{M}$ of (15), where:

$$
M = \left[\begin{array}{cccc}
\multicolumn{4}{c}{\mathrm{diag}(\hat{\mathbf{\Psi}} \otimes \mathbf{I}_p, i_{\max})} \\
\hline
\hat{C}_{1,N} & \hat{C}_{1,N-1} & \dots & \hat{C}_{1,0} \\
\vdots & \dots & & \vdots \\
\hat{C}_{n_\tau,N} & \hat{C}_{n_\tau,N-1} & \dots & \hat{C}_{n_\tau,0}
\end{array}\right] ,
$$

$\otimes$ indicates the *tensor product* or the Kronecker product, $\hat{\mathbf{\Psi}}$ is a matrix composed of the first $N-1$ rows of $\mathbf{\Psi}$ defined as

$$
\mathbf{\Psi} = -2\mathbf{\Xi}_N/\tau ,
$$

where $\mathbf{\Xi}_N$ is the Chebyshev discretization matrix of order N. The matrices $\hat{C}_{i,k}$ are the interpolation matrices defined according to C_i. The details about the interpolation can be found in [17]. The eigenvalues of M are the approximated eigenvalues of (12).

The key parameters that impact on the accuracy of the approximated eigenvalues are the upper boundary $k_{\max}$ and the order of Chebyshev discretization N. The parameters $k_{\max}$ and N should be big enough to obtain relatively accurate results [18]. However, considering that the Newton correction discussed below can improve the accuracy of the eigenvalues, $k_{\max}$ and N does not need to be large, which help to keep the computational burden tractable.

2) Newton Correction: The eigenvalues obtained in the previous step are inevitably affected by numerical errors. The Chebyshev discretization, in particular, may introduce *spurious* eigenvalues [13]. The Newton correction step aims at improving the accuracy of the eigenvalues.

The approximated eigenvalues λ are utilized as the initial guess of the Newton iterations on the characteristic equation (10). For each approximated eigenvalue λ_n, the m-th Newton iteration solves the equation:

$$
\begin{bmatrix} \delta \boldsymbol{v}_{n,m} \\ \delta \lambda_{n,m} \end{bmatrix} = \begin{bmatrix} \boldsymbol{r}_{n,m} & \boldsymbol{r}'_{n,m} \boldsymbol{v}_{n,m} \\ \boldsymbol{v}^H_{n,0} & \mathbf{0} \end{bmatrix}^{-1} \begin{bmatrix} -\boldsymbol{r}_{n,m} \boldsymbol{v}_{n,m} \\ 1 - \boldsymbol{v}^H_{n,0} \boldsymbol{v}_{n,m} \end{bmatrix} , \quad (17)
$$

where:

$$
\begin{aligned}
\boldsymbol{r}_{n,m} &= \Delta(\lambda_{n,m}) , \; \boldsymbol{r}'_{n,m} = \frac{d\boldsymbol{r}}{d\lambda}|_{\lambda=\lambda_{n,m}} \\
\lambda_{n,m} &= \lambda_{n,m-1} + \delta\lambda_{n,m-1} , \\
\boldsymbol{v}_{n,m} &= \boldsymbol{v}_{n,m-1} + \delta \boldsymbol{v}_{n,m-1} .
\end{aligned}
$$

Consider a tolerance ϵ for the iteration. For each λ_n, the iteration stops at m-th time if $|\delta\lambda_{n,m}| < \epsilon$ or $||r_{n,m}||_2 < \epsilon$, the iteration result $\lambda_{n,m}$ is the corrected eigenvalue. If m reaches the maximal iteration, the iteration terminates without finding any corrected eigenvalue. Reference [19] provides the details of the Newton correction approach.

IV. Case Study

The IEEE 14-bus system model serves to illustrate the feasibility and robustness of the numerical approach discussed above. The topology of the test system is shown in Fig. 2.

The IEEE 14-bus system includes an Automatic Voltage Regulator (AVR) for each synchronous machine and a PSS connected to the synchronous machine at bus 1 [20]. The parameters of the controllers can be found in [21]. The signal feeding the PSS is assumed to be delayed and compensated. The control scheme of the PSS is shown in Fig. 3.

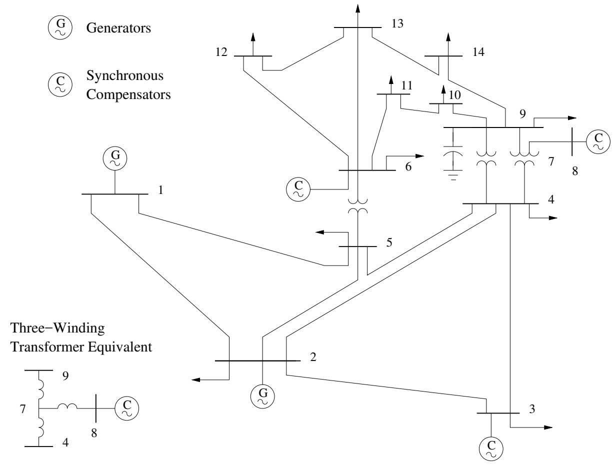

Fig. 2: One-line diagram of the IEEE 14-bus system.

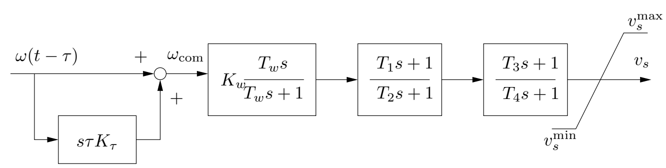

Fig. 3: Power system stabilizer control diagram with compensated input signal.

All simulations are obtained using the Python-based software tool DOME [22]. The DOME version utilized here is based on Fedora Linux 25, Python 3.6.2, CVXOPT 1.1.9, KLU 1.3.8, and MAGMA 2.2.0.

A. Small-signal Stability Analysis

The IEEE 14-bus system is stable and well-damped ($\zeta = 96.01\%$) with $\tau = 0$. The small-signal stability delay margin of the system is about 95 ms. For $\tau \in [80, 95]$ ms, the system is poorly damped ($\zeta < 5\%$).

The small-signal stability map of τ against K_τ is shown in Fig. 4 to depict the effect of the proposed delay compensation on the IEEE 14-bus system. The stability map is obtained through $30 * 50$ times small-signal stability analysis through the approach discussed in Section III for $\tau \in (0, 150]$ ms and $K_\tau \in (0, 2]$.

The solution of the rightmost eigenvalue spectrum for each given point in the parameter space takes about 1.3 s with $N = 6$ and $k_{\max} = 6$ to solve the approximated eigenvalues; the tolerance and the maximal iteration time of Newton Correction are 10^{-5} and 20 respectively.

According to Fig. 4, the proposed delay-compensation technique can increase the small-signal stability delay margin from 95 to 130 ms and the well-damped delay margin from 80 to 125 ms, with the proper choice of the gain K_τ. Figure 4 also shows that with the increase of delay magnitude τ, the range

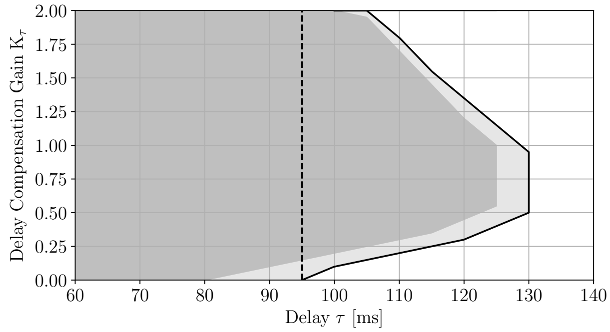

Fig. 4: Stability map of the $K_\tau - \tau$ plane for the IEEE 14-bus system. Shaded regions are stable. Dark shaded regions indicate the damping ratio greater than 5%. The dashed line is the stability delay margin of the system without delay compensation.

of values of the gain K_τ that allow stabilizing the system or provide good damping ratio becomes increasingly smaller.

B. N-1 Contingency Test

The effect of the proposed delay-compensation technique is tested in this section against large-disturbances. In the following, the delay of the PSS input signal is assumed to be 110 ms. The contingency is Line 2-5 outage. Three scenarios with different compensation gains K_τ are compared to the system without compensation. The corresponding pre- and post-contingency rightmost eigenvalues are shown in Table I.

TABLE I: Rightmost eigenvalues of the IEEE 14-bus system with delay compensation at PSS.

K_τ	Pre-contingency	Post-contingency
0.0	$0.2718 \pm j11.3779$	$0.3055 \pm j11.3227$
0.3	$-0.0895 \pm j11.8747$	$0.0067 \pm j11.3287$
1.0	$-0.1319 \pm j0.0384$	$-0.1316 \pm j0.0390$
1.8	$-0.0312 \pm j15.4017$	$-0.0254 \pm j15.34760$

According to Table I, the scenarios with $K_\tau = 1.0$ and 1.8 remain stable at the post-contingency steady state. The damping ratio ζ for the scenario $K_\tau = 1.0$ is 95.87%. While the scenario $K_\tau = 1.8$ is poorly-damped for $\zeta = 0.17\%$.

The TDI results are consistent with the above analysis. Figures 5 depict the frequency trajectories of Generator 1 of each scenario following the contingency. The no-compensation scenario shows that the system falls on a stable limit-cycle following the contingency; the scenario $K_\tau = 0.3$ mitigates the oscillations at the beginning but it is unstable in the post-contingency configuration, and thus oscillations increase (slowly due to the small positive post-contingency eigenvalues). The other two scenarios with negative post-contingency rightmost eigenvalues are always stable. The scenario $K_\tau = 1.0$ is particularly well damped; whereas the poorly-damped scenario $K_\tau = 1.8$ shows small-amplitude oscillations at the new steady state.

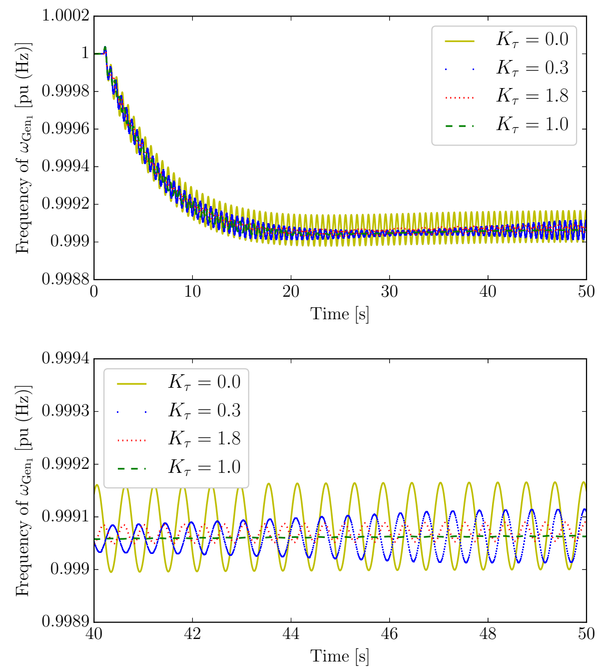

Fig. 5: Line 2-5 outage for the IEEE 14-bus system Trajectories of the frequency of Generator 1 with different delay compensation gain K_τ.

To further understand the effect of the compensation gain K_τ, Fig. 6 shows the trajectories of the non-delayed, delayed and compensated signals for various values of the compensation gain K_τ.

According to Fig. 6, all the three compensated signals better track the variation trend of original signals comparing with the delayed signals. For $K_\tau = 0.3$, the compensation effect is too small to mimic the variation trend of the non-delayed signal; while for $K_\tau = 1.8$, the compensation amplifies too much the dynamic variations of the original signal and, thus, decreases the damping ratio comparing with the trajectory obtained for $K_\tau = 1.0$. Interestingly, even in the most stable scenario, i.e., $K_\tau = 1.0$, the compensated signal does not closely approximate the original non-delayed frequency measure.

Finally, it is worth noting that the proposed compensation technique does not require a perfect knowledge of the delay. The compensation channel, in fact, depends on the product $K_\tau \tau$. An approximated estimation of the average value of the delay τ allows tuning the gain K_τ. Note also that the compensation stabilizes the system in a range of values of K_τ. The compensation channel is thus fairly robust.

V. Conclusions

This paper proposes a novel model-independent delay compensation technique to mitigate the impact of time delays on power system stability. The paper also provides a systematic small-signal stability analysis approach of the system implemented with the proposed compensation. The effect of the

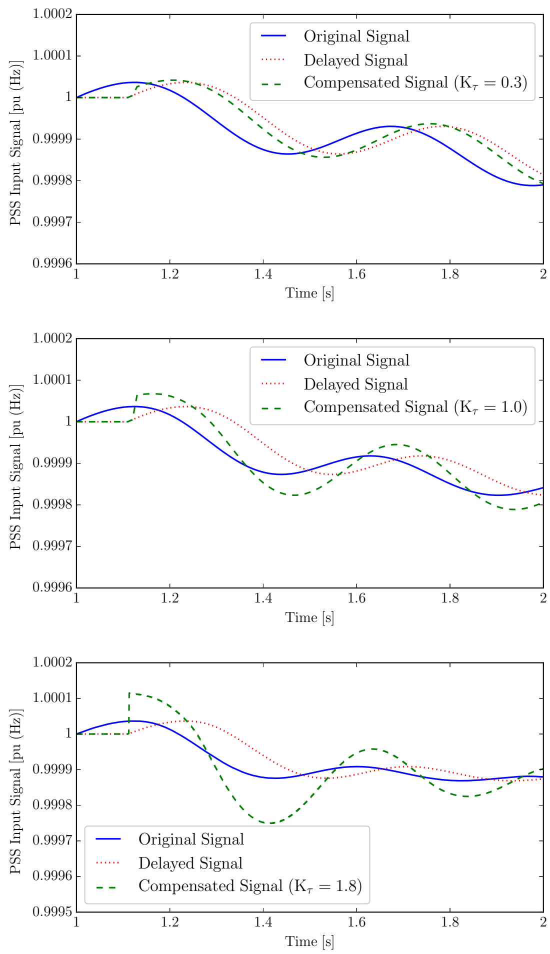

Fig. 6: Trajectories of non-delayed, delayed and compensated frequency signals for the IEEE 14-bus systems for various values of the compensation gain K_τ.

proposed technique is proved through the tests based on the IEEE 14-bus system with inclusion of constant time delay.

Future work will extend the proposed technique to compensate the realistic time-varying delays such as those described in [19]. It also appears interesting to combine the proposed technique with advanced control strategies. Especially if the compensation gain K_τ is adaptive and updated according to the variations of the delayed signal, the compensation technique should fulfill a better effect on improving the robustness of power systems against time delays.

References

[1] V. Terzija, G. Valverde, D. Cai, P. Regulski, V. Madani, J. Fitch, S. Skok, M. M. Begovic, and A. Phadke, "Wide-area monitoring, protection, and control of future electric power networks," *Procs of the IEEE*, vol. 99, pp. 80–93, Jan 2011.

[2] F. Milano and M. Anghel, "Impact of time delays on power system stability," *IEEE Trans. on Circuits and Systems - I: Regular Papers*, vol. 59, pp. 889–900, Apr. 2012.

[3] F. Milano, "Small-signal stability analysis of large power systems with inclusion of multiple delays," *IEEE Trans. on Power Systems*, vol. 31, pp. 3257–3266, July 2016.

[4] H. Ye, Y. Liu, and P. Zhang, "Efficient eigen-analysis for large delayed cyber-physical power system using explicit infinitesimal generator discretization," *IEEE Trans. on Power Systems*, vol. 31, pp. 2361–2370, May 2016.

[5] A. González, M. Aranda, G. López-Nicolás, and C. Sagüés, "Time delay compensation based on Smith predictor in multiagent formation control," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 11645 – 11651, 2017. 20th IFAC World Congress.

[6] A. González, M. Aranda, G. López-Nicolás, and C. Sagüés, "Time delay compensation based on Smith predictor in multiagent formation control," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 11645 – 11651, 2017. 20th IFAC World Congress.

[7] R. Majumder, B. Chaudhuri, B. C. Pal, and Q.-C. Zhong, "A unified Smith predictor approach for power system damping control design using remote signals," *IEEE Transactions on Control Systems Technology*, vol. 13, pp. 1063–1068, Nov 2005.

[8] H. Ziyuan, Z. Lanlan, and F. Minrui, "Robust auto tune Smith predictor controller design for plant with large delay," in *Bio-Inspired Computational Intelligence and Applications* (K. Li, M. Fei, G. W. Irwin, and S. Ma, eds.), (Berlin, Heidelberg), pp. 666–678, Springer Berlin Heidelberg, 2007.

[9] Y. Zhang and A. Bose, "Design of wide-area damping controllers for interarea oscillations," *IEEE Transactions on Power Systems*, vol. 23, pp. 1136–1143, Aug 2008.

[10] K. Vrdoljak, I. Petrovic, and N. Peric, "Discrete-time sliding mode control of load frequency in power systems with input delay," in *2006 12th International Power Electronics and Motion Control Conference*, pp. 567–572, Aug 2006.

[11] T. Ahmed-Ali, V. V. Assche, J. Massieu, and P. Dorleans, "Continuous-discrete observer for state affine systems with sampled and delayed measurements," *IEEE Transactions on Automatic Control*, vol. 58, pp. 1085–1091, April 2013.

[12] S. Liu, P. X. Liu, and X. Wang, "Stability analysis and compensation of network-induced delays in communication-based power system control: A survey," *ISA Transactions*, vol. 66, pp. 143 – 153, 2017.

[13] M. Liu, I. Dassios, and F. Milano, "On the stability analysis of systems of neutral delay differential equations," *Circuits, Systems, and Signal Processing*, Sep 2018.

[14] E. Fridman, "New Lyapunov-Krasovskii functionals for stability of linear retarded and neutral type systems," *Journal of systems and control Letters*, vol. 43, pp. 309–319, Feb. 2001.

[15] C.-J. Cheng, T.-L. Liao, and C.-C. Hwang, "Globally asymptotic stability of a class of neutral-type neural networks with delays," *IEEE Trans. on Systems, Man and Cybernetics*, vol. 36, pp. 1191–1195, Oct. 2006.

[16] X. G. Li and X. J. Zhu, "Stability analysis of neutral systems with distributed delays," *Automatica*, vol. 44, pp. 2197–2201, 2008.

[17] F. Milano and I. Dassios, "Small-signal stability analysis for non-index 1 Hessenberg form systems of delay differential-algebraic equations," *IEEE Trans. on Circuits and Systems - I: Regular Papers*, vol. 63, pp. 1521–1530, Sept. 2016.

[18] M. Liu, I. Dassios, and F. Milano, "Small-signal stability analysis of neutral delay differential equations," in *43th Annual Conference of the IEEE Industrial Electronics Society (IECON 2017)*, (Beijing, China), Oct. 2017.

[19] M. Liu, I. Dassios, G. Tzounas, and F. Milano, "Stability analysis of power systems with inclusion of realistic-modeling of WAMS delays," *IEEE Trans. on Power Systems*, pp. 1–8, 2018.

[20] F. Milano, "Power System Modelling and Scripting," *London: Springer*, 2010.

[21] M. Liu and F. Milano, "Small-signal stability analysis of power systems with inclusion of periodic time-varying delays," in *Procs of the 20th Power System Computation Conference*, (Dublin, Ireland), June 2018.

[22] F. Milano, "A Python-based software tool for power system analysis," in *Procs of the IEEE PES General Meeting*, (Vancouver, BC), July 2013.