Stability of Wide-Area Power System Controls With Intermittent Information Transmission

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***Abstract*—This paper investigates the stability problem of wide-area damping controllers with intermittent information transmission. Due to the interruption in communication links between remote measurements and damping controller or from the damping controller to the damping actuators, the closed-loop system might become unstable. The instability is strongly related to the duration of interruption of information transmission. To estimate instability, this paper formulates the problem as continuous/discrete-time switched system and the stability conditions are derived using time-scale theory. This method allows us to handle continuous and discrete dynamics as two pieces of the same framework, such that the system will switch between a continuous-time subsystem (when the communication occurs without any interruption) and a discrete-time subsystem (when the communication fails). The contribution is to estimate the maximum allowable value of the time of interruption of information transmission that does not violate the exponential stability of the closed-loop system. The findings are useful in specifying the minimum requirements for communication infrastructure and the time to activate remedial action schemes. Simulations are performed based on both linear and nonlinear systems to validate the theoretical development.**

***Index Terms*—Low-frequency oscillations, intermittent information, time scale theory, switched systems.**

I. Introduction

WITH increasing interconnection complexity, modern grids are more vulnerable to system-wide disturbances. These wide-area disturbances require more sophisticated measurement systems and coordinated control actions to avoid system collapse as local responses (delivered based on the local observations) are not sufficient. This will bring new challenges as coping with instability problems requires wide-area measurement and control systems (WAMCS) [1]. Phasor measurement units (PMUs) can play a crucial role in these applications by providing the necessary measurement infrastructure.

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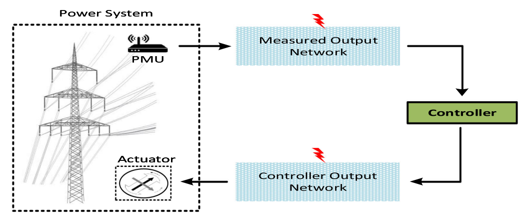

Fig. 1. A networked control system with components that are remotely operated over a communication network.

Traditionally, PMU data has been used only for off-line post event analysis. However, with recent advancement in communications (e.g. faster communication channels) and processing power, it is now possible to use geographically dispersed PMUs for real-time applications in power systems [2]. PMUs are currently installed in different point in the North American grid, to record and communicate GPS-synchronized, hight sampling rate (60 sample/sec), dynamic power systems data. They can be used to address the problem of inter-area oscillations which happens between several areas and require wide-area supervision and control schemes. In these applications, usually damping controllers (located in control centers, substations), sensors (e.g. PMUs) and actuators (e.g. synchronous generators, FACTS devices and energy storage systems) are located remotely and can only communicate with others over a communication network as shown in Fig. 1.

Implementation of damping controllers over a network such that, the portions of the control system located remotely, might create challenges as the closed loop performance is highly dependent on the communication network. In this study, we aim to consider the effect of the communication network in our analysis. The main question is what happens when the communication is lost during some periods. The network may experience constant or time varying delays [3], packet dropout [4] or packet disordering [5]. Hence, the communication network introduces uncertainty in the operation and the performance of the closed-loop system.

In the power systems literature, communication effects are often ignored [6], [7]. Reference [8] studied the impact of induced network delays using LMIs but only for state feedback controllers. In [9], [10], simple models were considered to capture the effects of communication failure with known lower and upper bounds. The problem of network control system with data packet dropout and transmission delays, was studied in several ways in the literature [11]–[13]. In fact, existing methods based on sampling signal output such that, the samples only arrive at the destination after a (possibly variable) delay which is assumed always smaller than one sampling interval, but the delays longer than one sampling interval may result in more than one signal arriving. Other approaches consider the problem as a differential equations with delay (where the restriction to assuming delays smaller than one sampling interval is lifted). The Lyapunov–Krasovskii and the Razumikhin theorems are the two main tools available to study the stability of such systems and some LMI-based conditions are derived [14], [15]. However, the required communication time rate conditions are rather complex to verify.

Motivated by that, in this paper, new stability conditions are derived using time scale theory. Dynamical systems modeled using time scales theory shows promise as a new approach to solve this problem. Based on this theory, it will be shown that the problem of communication loss can be converted into the asymptotic stabilization problem of a switched system on a particular non-uniform time domain, formed by a union of disjoint intervals with variable lengths and variable gaps [16], [17]. Indeed, the closed loop system evolves during some continuous time intervals when the communication occurs without any intermittence in information transmission. When the communication fails, the control will not evolve, holds its last value and it will be updated after some periods (considered to be variable). In this case, the system acts as if discretized with a variable step size and the system will be modeled as a switched system between a continuous-time dynamics with variable intervals length and a discrete-time dynamics with variable step size. Thus, it is of interest to mix the continuous-time and discrete-time cases under a unified framework [18]–[20]. In this paper, new conditions are derived to estimate the allowable value of the time of interruption in information transmission in order to maintain the exponential stability of the closed loop power system. The findings are useful in specifying the minimum requirements for communication infrastructure and the time to activate remedial action schemes to avoid the critical situation [21]. Moreover, we have explored realistic cases involving sensor-to-controller and/or controller-to-actuator communication failures.

The remainder of this paper is organized as follows. Background on time scale theory is presented in Section II. In Section III, it is shown that the stability problem of linear system with intermittent information transmission is equivalent to the stabilization of a switched system consisting of a linear continuous-time and discrete-time subsystem. A set of conditions on the maximum time of interruption to guarantee the exponential stability of the closed-loop power system is derived in Section III. Numerical results and conclusions are presented in Section IV and Section V, respectively.

II. Preliminaries on Time Scale Theory

Basic notations and properties of time scales theory [18] are presented in this section. A *time scale*, noted $\mathbb{T}$ is an arbitrary nonempty closed subset of $\mathbb{R}$. The usual integer sets $h\mathbb{Z}$, $\mathbb{N}$, the real numbers $\mathbb{R}$, any discrete subset or any combination of discrete points with union of closed intervals, are examples of time scales. The *forward jump operator* $\sigma(t) : \mathbb{T} \to \mathbb{T}$ is defined by $\sigma(t) := \inf\{s \in \mathbb{T} : s > t\}$. The mapping $\mu : \mathbb{T} \to \mathbb{R}^+$, called the *graininess function*, is defined by $\mu(t) = \sigma(t) - t$, which measure the distance between two consecutive points. In particular, if $\mathbb{T} = \mathbb{R}$, $\sigma(t) = t$ and $\mu(t) = 0$. If $\mathbb{T} = h\mathbb{Z}$, $\sigma(t) = h$ and $\mu(t) = h$. For $\mathbb{T} = \cup_{k=0}^{\infty}[k(a+b), k(a+b)+a]$, with $a, b \in \mathbb{R}$,

$$\sigma(t) = \begin{cases} t, & t \in \cup_{k=0}^{\infty}[k(a+b), k(a+b)+a[\\ t+b, & t \in \cup_{k=0}^{\infty}\{k(a+b)+a\} \end{cases}$$

$$\mu(t) = \begin{cases} 0, & t \in \cup_{k=0}^{\infty}[k(a+b), k(a+b)+a[\\ b, & t \in \cup_{k=0}^{\infty}\{k(a+b)+a\} \end{cases}$$

Let $f : \mathbb{T} \to \mathbb{R}$. The Δ-*derivative* of f at $t \in \mathbb{T}$ is defined as

$$f^{\Delta}(t) = \lim_{s \to t} \frac{f(\sigma(t)) - f(s)}{\sigma(t) - s} \tag{1}$$

The Δ-derivative, unify the derivative in the continuous sense and the difference operator in the discrete sense. If $\mathbb{T} = \mathbb{R}$, $\sigma(t) = t$ and $f^{\Delta}(t) = \dot{f}(t)$. If $\mathbb{T} = h\mathbb{Z}$, $\sigma(t) = t + h$ and $f^{\Delta}(t) = \frac{f(t+h) - f(t)}{h}$. In particular, if $h = 1$, $f^{\Delta}(t) = f(t+1) - f(t) = \Delta f(t)$, the difference operator. Note that the Δ-derivative, generalizes the continuous and discrete derivatives. A function $f : \mathbb{T} \to \mathbb{R}$ is *regressive* if $1 + \mu(t)\, f(t) \neq 0, \ \forall t \in \mathbb{T}$. A matrix A is called *regressive*, if $\forall t \in \mathbb{T}$, the matrix $(I + \mu(t)A)$ is invertible, where I is the identity matrix (equivalently, $(1 + \mu(t)\lambda_i) \neq 0, \forall t \in \mathbb{T}$, for all eigenvalues λ_i of A [18]). We denote the set of all regressive functions by $\mathcal{R}$ and by $\mathcal{R}^+$, if they satisfies $1 + \mu(t)f(t) > 0$, $\forall t \in \mathbb{T}$ (positively regressive). The *generalized exponential function* of $p \in \mathcal{R}$ is expressed by

$$e_p(t, t_0) = \begin{cases} e^{\int_{t_0}^{t} \frac{\log(1+\mu(\tau)p(\tau))}{\mu(\tau)} \Delta\tau}, & \text{if} \quad \mu(\tau) \neq 0 \\ e^{\int_{t_0}^{t} p(\tau)\Delta\tau}, & \text{if} \quad \mu(\tau) = 0 \end{cases} \tag{2}$$

where $s, t \in \mathbb{T}$, $\log$ is the principal logarithm function and the delta integral is used [18], [22]. Let $p \in \mathcal{R}$ and $t_0 \in \mathbb{T}$, for $\mathbb{T} = \mathbb{R}, e_p(t, s) = \exp(\int_s^t p(\tau)\, d\tau)$ and for $\mathbb{T} = h\mathbb{Z}, e_p(t, s) = \prod_{\tau=s}^{t-h}(1 + hp(\tau))$. Notice that the regressivity of p is needed for the exponential function to be well defined, in particular on discrete time scales.

Let A be a regressive matrix. The unique matrix-valued solution of

$$x^{\Delta}(t) = A\, x(t), x(t_0) = x_0, t \in \mathbb{T}, \tag{3}$$

is the generalized exponential function denoted by $e_A(t, t_0)x_0$.

The dynamical system (3) is exponentially stable on an arbitrary time scale $\mathbb{T}$, if there exists a constant $\beta \geq 1$ and a constant $\lambda < 0$ and $\lambda \in \mathcal{R}^+$, such that the corresponding solution satisfies $\|x(t)\| \leq \beta\|x_0\|e_{\lambda}(t, t_0), \forall t \in \mathbb{T}$.

This characterization is a generalization of the definition of exponential stability for dynamical systems defined on $\mathbb{R}$ or $h\mathbb{Z}$. More specifically, the condition that $\lambda < 0$ and $\lambda \in \mathcal{R}^+$ in the characterization of exponential stability is reduced to $\lambda < 0$ for $\mathbb{T} = \mathbb{R}$, and to $0 < 1 + \mu(t)\lambda < 1, \ \forall t \in \mathbb{T}$ (an arbitrary discrete time scale). Since, the generalized exponential function can be negative, the positive regressivity of λ is needed (see [18]).

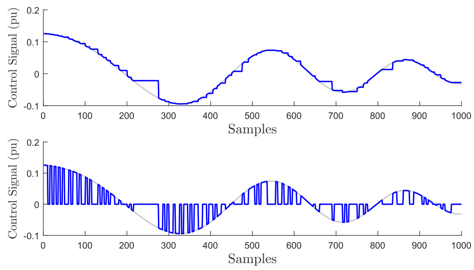

Fig. 2. Sample of control signal with intermittent communication transmissions when assigning a value a) equal to zero (zero strategy) and b) equal to the previous value (hold strategy).

III. Wide Area Control With Intermittent Information Transmission

Damping controllers relying on a communication network where portions of the control system are located remotely, creates challenges. The closed loop performance is highly dependent on the communication network. In this study, we consider the effects of the communication network in the stability analysis. To begin, nonlinear power system models can be expressed as the following differential algebraic equations

$$\dot{x}(t) = f\big(x(t), y(t), u(t)\big) \tag{4}$$

$$0 = g\big(x(t), y(t)\big) \tag{5}$$

where x is the state vector, y is a vector of algebraic variables, u is the vector of control inputs and t is the time variable. Linearizing the power system model (4) around the operating point leads to the following generalized form

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{6}$$

$$y(t) = Cx(t) \tag{7}$$

where A and B are constant real matrices with appropriate dimensions such that (A, B) is stabilizable and $u \in \mathbb{R}^m$ is the control input. The aim in this section is to estimate the time of interruption of information transmission and analyze what happens when the communication network is no longer perfect due to packet loss, delay or any other common communication failure.

Two general schemes are generally used when faced with intermittent communication: the zero strategy, in which the input/measurement of the plant is set to zero if a packet is dropped, and the hold strategy, in which the latest arrived/measured packet is kept constant until the next packet arrived/measured [23] (see Fig. 2,). In this paper, the hold strategy is used in control and measurement loops in which the last value of the control before communication failure is hold and continues to be used when packet dropouts happen. However, if the failure time becomes large, and since the control will not evolve, the system may become unstable. Hence, communication network reliability is a key requirement and the goal is to estimate the maximum time of interruption of communication that does note violate the stability of the system.

Fig. 3. Time scale $\mathbb{T} = \mathbb{P}_{\{\sigma(t_i), t_{i+1}\}}$.

A. State Feedback Problem Formulation

Consider the particular time scale $\mathbb{T} = \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}]$, where $\sigma(.)$ is the forward jump operator, such that, $\sigma(t_0) = t_0$ and the graininess function $\mu(t_i) = \sigma(t_i) - t_i, \forall i \in \mathbb{N}^*$ (Fig. 3). To solve the power systems problem under intermittent information transmission between generators and controllers, the following switched control law is applied

$$u(t) = \begin{cases} Kx(t), & \text{if } t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ Kx(t_{i+1}), & \text{if } t \in \cup_{i=0}^{\infty}[t_{i+1}, \sigma(t_{i+1})) \end{cases} \tag{8}$$

where K is an appropriate state feedback controller. The union of time intervals over which the communication occurs is represented by $\cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1})$. The remaining intervals represent the time intervals over which the feedback does not evolve (i.e., maintained constant to its value at the switching times instants t_{i+1}) due to the absence of local information. The time sequence $\{t_1, t_2, t_3, \ldots\}$ characterizes the time when the communication failure occurs with no accumulation points. The duration of a communication failure equal to $\mu(t_i)$ which is assumed to be variable and bounded, $\forall i \in \mathbb{N}^*$. With the control law (8), the dynamical system (6) is equivalent to

$$\dot{x}(t) = \begin{cases} (A + BK)x(t), & \text{if } t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ Ax(t) + BKx(t_{i+1}), & \text{if } t \in \cup_{i=0}^{\infty}[t_{i+1}, \sigma(t_{i+1})). \end{cases} \tag{9}$$

Since the feedback does not evolve when local information is not available, the study of system (9) is not trivial. There exist previous works dealing with the stabilization of linear systems under variable sampling periods or by considering a differential equations with delay. The approaches are usually based on LMIs and derived using Lyapunov-Razumikhin stability conditions, which are rather complex to verify [24], [14], [15]. To reduce the conservatism and facilitate the analysis, the problem (9) is converted to a switched system on time scale $\mathbb{T} = \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}]$ such that, the communication fails at t_{i+1} and only the behavior of the solution of the second equation in (9) at the discrete times $\{t_{i+1}\}$ and $\{\sigma(t_{i+1})\}$ is considered. The descritization is as follows (for more details see [25]):

For $t \in [t_{i+1}, \sigma(t_{i+1})),\ i \in \mathbb{N}$, we have

$$\dot{x} = Ax(t) + Bu(t_{i+1}) \tag{10}$$

such that $u(t_{i+1}) = Kx(t_{i+1})$ is constant on the time interval $[t_{i+1}, \sigma(t_{i+1}))$. The solution of (10) is given by

$$\begin{aligned} x(t) &= e^{A(t-t_{i+1})}\left[x(t_{i+1}) + A^{-1}Bkx(t_{i+1})\right] - A^{-1}BKx(t_{i+1}) \\ &= e^{A(t-t_{i+1})}\left[I + A^{-1}BK\right]x(t_{i+1}) - A^{-1}BKx(t_{i+1}) \end{aligned}$$

At time $t = t_{i+1}$, the Δ-derivative of $x(t)$ is given by

$$x^{\Delta}(t_{i+1}) = \frac{x(\sigma(t_{i+1})) - x(t_{i+1})}{\sigma(t_{i+1}) - t_{i+1}} = \left(\frac{e^{A\mu(t_i)} - I}{\mu(t_i)}\right)\left[I + A^{-1}BK\right]x(t_{i+1}).$$

By using the above development, the closed-loop system (9) is modelled as the following switched linear system

$$x^{\Delta}(t) = \begin{cases} (A+BK)x(t), & t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ \left(\frac{e^{A\mu(t)} - I}{\mu(t)}\right)\left(I + A^{-1}BK\right)x(t), & t \in \cup_{i=0}^{\infty}\{t_{i+1}\} \end{cases} \tag{11}$$

on $\mathbb{T} = \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}]$. The derived system commutes between a stable continuous-time linear subsystem (on continuous intervals with variable length) and may be an unstable discrete-time linear subsystem with variable discrete-step size $\mu(t)$, which corresponds to the interruption time of the control evolution. Note that, the stability and instability of the discrete-time subsystem is strongly related to $\mu(t)$ [17], [25], [26]. It is known that switching between stable and unstable (or even between stable) systems may make the overall system unstable if we will not put some restriction on the dwell time of each subsystem [27], [28].

B. Stability Criteria

In this section, sufficient conditions are derived to guarantee the stability of system (11).

Proposition 1: Consider the switched system (11), and suppose that the following assumptions are fulfilled:

i) (A, B) is stabilizable and the matrix control law K is determined such that $(A + BK)$ is stable.

ii) Suppose that $\mu(t)$ is bounded and the discrete subsystem is regressive and can be stable or unstable.

iii) Let $\tau(t_i) = t_{i+1} - \sigma(t_i)$ be the duration of each continuous-time subsystem, such that $\forall i \in \mathbb{N}$, we have

$$\left\| e^{(A+BK)\tau(t_i)}\left[I + \left(e^{A\mu(t_i)} - I\right)(I + A^{-1}BK)\right]\right\| < 1. \tag{12}$$

Then the switched system (11) is exponentially stable.

Proof: For the proof see Appendix B ■

Remark 1: Notice that, if A is not invertible, we can always determine the discrete matrix via the convergence power series

$$\mathcal{E}(A\mu(t)) = \sum_{n=1}^{\infty}\frac{(A\mu(t))^{n-1}}{n!}, \tag{13}$$

and the matrix of the discrete subsystem in (11) is equal to

$$\mathcal{E}(A\mu(t))(A + BK).$$

Condition (12) will be: $\forall i \in \mathbb{N}$,

$$\left\| e^{(A+BK)\tau(t_i)}\ [I + \mu(t_i)\mathcal{E}(A\mu(t_i))(A + BK)]\right\| < 1. \tag{14}$$

C. Extension to Dynamic Output-feedback

In practical applications for power systems, the full state vector is not available. Consequently, it is desirable to adopt the dynamic output-feedback controller to directly use the measured output signals for damping the oscillations. This type of controller can be defined as

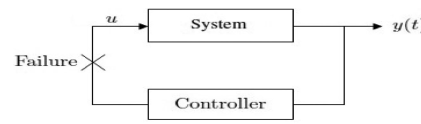

Fig. 4. Failure of communication in the output-controller.

$$\dot{x}_c(t) = A_k x_c(t) + B_k y(t) \tag{15}$$

$$u(t) = C_k x_c(t) + D_k y(t) \tag{16}$$

where $x_c \in \mathbb{R}^n$ is the controller states, A_k, B_k, C_k, D_k are an appropriate matrices to be designed, u and y are the controller and system outputs, respectively. This controller yields with (6) and (7) the following system.

$$\dot{\hat{x}}(t) = \begin{bmatrix} A & 0 \\ B_k C & A_k \end{bmatrix}\hat{x}(t) + \begin{bmatrix} B \\ 0 \end{bmatrix}u(t) \tag{17}$$

$$u(t) = \begin{bmatrix} D_k C & C_k \end{bmatrix}\hat{x}(t) \tag{18}$$

where $\hat{x}^T = [x^T x_c^T]$ is the augmented system state vector, and the closed loop matrix is

$$A_{cl} = \begin{bmatrix} A + BD_k C & BC_k \\ B_k C & A_k \end{bmatrix}.$$

Consider the case where a communication failure happens in the control signal (as is shown in Fig. 4). The system can be rewritten on the time scale $\mathbb{T} = \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}]$ as follows

$$\dot{\hat{x}}(t) = \begin{cases} \begin{bmatrix} A + BD_k C & BC_k \\ B_k C & A_k \end{bmatrix}\hat{x}(t), & t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ \begin{bmatrix} A & 0 \\ B_k C & A_k \end{bmatrix}\hat{x}(t) + \begin{bmatrix} B \\ 0 \end{bmatrix}u(t_{i+1}), \\ \quad t \in \cup_{i=0}^{\infty}[t_{i+1}, \sigma(t_{i+1})), \end{cases}$$

with $u(t_{i+1}) = \begin{bmatrix} D_k C & C_k \end{bmatrix}\hat{x}(t_{i+1})$ is maintained constant on $[t_{i+1}, \sigma(t_{i+1})]$. So we get

$$\dot{\hat{x}}(t) = \begin{cases} \begin{bmatrix} A + BD_k C & BC_k \\ B_k C & A_k \end{bmatrix}\hat{x}(t), & t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ \begin{bmatrix} A & 0 \\ B_k C & A_k \end{bmatrix}\hat{x}(t) + \begin{bmatrix} B \\ 0 \end{bmatrix}\begin{bmatrix} D_k C & C_k \end{bmatrix}\hat{x}(t_{i+1}), \\ \quad t \in \cup_{i=0}^{\infty}[t_{i+1}, \sigma(t_{i+1})). \end{cases} \tag{19}$$

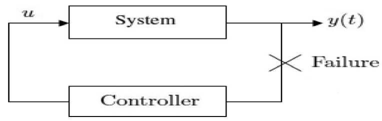

Fig. 5. Failure of communication in the output measurement.

Similarly to the above analysis, the system can be rewritten as follows:

$$\hat{x}^{\Delta}(t) = \begin{cases} \begin{bmatrix} A+BD_kC & BC_k \\ B_kC & A_k \end{bmatrix}\hat{x}(t), \; t\in \cup_{i=0}^{\infty}[\sigma(t_i),t_{i+1}) \\ \dfrac{\left(e^{\begin{bmatrix} A & 0\\ B_kC & A_k\end{bmatrix}\mu(t)} - I\right)}{\mu(t)} \times \\ \left[I + \begin{bmatrix} A & 0\\ B_kC & A_k\end{bmatrix}^{-1}\begin{bmatrix} BD_kC & BC_k\\ 0 & 0\end{bmatrix}\right]\hat{x}(t), \\ \text{if } \; t\in\cup_{i=0}^{\infty}\{t_{i+1}\}\end{cases} \tag{20}$$

The stability criteria (21), shown at the bottom of this page, can be formulated for the augmented system with output-feedback controller and communication failures in the control signal.

Similarly, for the case where a communication failure happens in the measurement signal (Fig. 5), the output feedback controller (15) and (16) with (6) and (7) yields the following system:

$$\dot{\hat{x}}(t) = \begin{bmatrix} A & BC_k \\ 0 & A_k \end{bmatrix}\hat{x}(t) + \begin{bmatrix} BD_k \\ B_k \end{bmatrix} y(t) \tag{22}$$

$$y(t) = \begin{bmatrix} C & 0 \end{bmatrix}\hat{x}(t) \tag{23}$$

such that $y(t_{i+1}) = [C \;\; 0]\,\hat{x}(t_{i+1})$ is constant on $[t_{i+1}, \sigma(t_{i+1}))$ when communication fails at t_{i+1}. The switched system on the time scale $\mathbb{T} = \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}]$ will be

$$\hat{x}^{\Delta}(t) = \begin{cases} \begin{bmatrix} A+BD_kC & BC_k \\ B_kC & A_k \end{bmatrix}\hat{x}(t), \\ \quad t\in \cup_{i=0}^{\infty}[\sigma(t_i),t_{i+1}) \\ \dfrac{\left(e^{\begin{bmatrix} A & BC_k\\ 0 & A_k\end{bmatrix}\mu(t)} - I\right)}{\mu(t)} \times \\ \left[I + \begin{bmatrix} A & BC_k\\ 0 & A_k\end{bmatrix}^{-1}\begin{bmatrix} BD_kC & 0\\ B_kC & 0\end{bmatrix}\right]\hat{x}(t), \\ \quad t\in\cup_{i=0}^{\infty}\{t_{i+1}\}\end{cases} \tag{24}$$

The stability criteria (25), shown at the bottom of this page, is deduced for the augmented system with output-feedback controller and communication failure in the measurement signal.

Remark 2: Note that, the matrix $\left[\begin{smallmatrix} A & 0 \\ B_kC & A_k \end{smallmatrix}\right]$ is invertible if both A and A_k are invertible. If not, we can always use the convergence power series as in (13).

IV. Application to Power Systems

In this section, stability conditions provided above, will be applied to the Single-Machine Infinite Bus (SMIB) and Kundur's two-area power systems. Both systems are modified to have undamped inter-area modes and the accuracy of the stability conditions will be verified. In case of two-area system, the dynamic output feedback controller has been designed based on a reduced model and the results has been tested for a large system. In practice, use of the reduced model avoid feasibility problem and realize practical lower-order controller. The reduced model is based on the balanced model truncation method, which retains the most important states variables for control purposes. The appropriate order of the reduced model can be determined by comparing the accuracy of frequency response of the full order and the reduced order system which has a closer response to the full-order system.

A. Case Study I: SMIB Power System

In this subsection, a SMIB power system model is considered. As shown in Fig. 6, this system consists of a synchronous

$$\left\| e^{\begin{bmatrix} A+BD_kC & BC_k \\ B_kC & A_k \end{bmatrix}\tau(t_i)} \left[I + \left(e^{\begin{bmatrix} A & 0 \\ B_kC & A_k \end{bmatrix}\mu(t_i)} - I \right) \left(I + \begin{bmatrix} A & 0 \\ B_kC & A_k \end{bmatrix}^{-1} \begin{bmatrix} BD_kC & BC_k \\ 0 & 0 \end{bmatrix} \right) \right] \right\| < 1, \; \forall i \in \mathbb{N} \tag{21}$$

$$\left\| e^{\begin{bmatrix} A+BD_kC & BC_k \\ B_kC & A_k \end{bmatrix}\tau(t_i)} \left[I + \left(e^{\begin{bmatrix} A & BC_k \\ 0 & A_k \end{bmatrix}\mu(t_i)} - I \right) \left(I + \begin{bmatrix} A_k & 0 \\ BC_k & A \end{bmatrix}^{-1} \begin{bmatrix} BD_kC & 0 \\ B_kC & 0 \end{bmatrix} \right) \right] \right\| < 1, \; \forall i \in \mathbb{N} \tag{25}$$

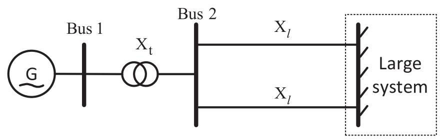

Fig. 6. A single-machine infinite-bus (SMIB) power system.

generator connected through two transmission lines to an infinite bus that represents an approximation of a large system. A flux-decay model of the synchronous generator equipped with a fast excitation system can be represented by the following set of dynamic equations

$$\dot{\delta} = \omega_s(\omega_r - 1) \tag{26}$$

$$\dot{\omega_r} = \frac{1}{2H}\left[T_M - \left(E'_q I_q + (X_q - X'_d)I_d I_q + D\omega_s(\omega_r - 1)\right)\right] \tag{27}$$

$$\dot{E}'_q = -\frac{1}{T'_{d0}}\left[E'_q + (X_d - X'_d)I_d - E_{fd}\right] \tag{28}$$

$$\dot{E}_{fd} = -\frac{E_{fd}}{T_A} + \frac{K_A}{T_A}\left[V_{ref} - V_t + \mathrm{sat}(V_s)\right] \tag{29}$$

while satisfying the following algebraic equations

$$R_e I_q + X_e I_d - V_q + V_\infty \cos(\delta) = 0 \tag{30}$$

$$R_e I_d - X_e I_q - V_d + V_\infty \sin(\delta) = 0 \tag{31}$$

$$V_t = \sqrt{V_d^2 + V_q^2} \tag{32}$$

where R_e and $X_e = X_t + \frac{1}{2}X_l$ are the total external resistance and reactance respectively. The SMIB power system is considered to demonstrate the idea and verify the resulting improvement. The parameters of the machine, excitation system, transformer and transmission lines are listed as follows

$$X_t = 0.1, X_l = 0.8, \quad R_e = 0, \quad V_\infty = 1.05\angle 0^\circ,$$
$$X_d = 2.5, X_q = 2.1, \quad X'_d = 0.39, \quad V_t = 1\angle 15^\circ,$$
$$T'_{d0} = 9.6, \quad H = 3.2, D = 0, \quad \omega_s = 377,$$
$$T_A = 0.02, K_A = 100, \quad V_s^{\max} = -V_s^{\min} = 0.05,$$

where $V_s^{\max} = -V_s^{\min} = 0.05$ are the saturation limit considered for the control signal. In case of generator supplementary damping controller (SDCs), saturation limit should be considered in the supplementary control input signal and are usually in the range of ± 0.05 to ± 0.1 per unit. These limits allow an acceptable control rang in the excitation system to prevent undesirable tripping of the equipments protection initiated by over-excitation or under-excitation of generators. The above nonlinear model can be linearized around the nominal operating point and expressed in the following fourth order state-space representation, such that $x = [\Delta\delta \;\; \Delta\omega_r \;\; \Delta E'_q \;\; \Delta E'_{fd}]$

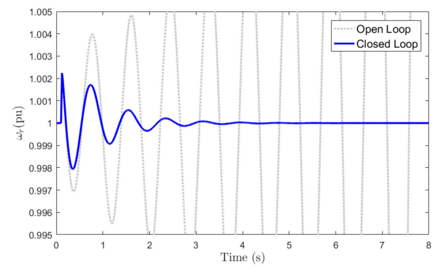

Fig. 7. System performance of the closed loop and open loop SMIB power system with ideal network communication.

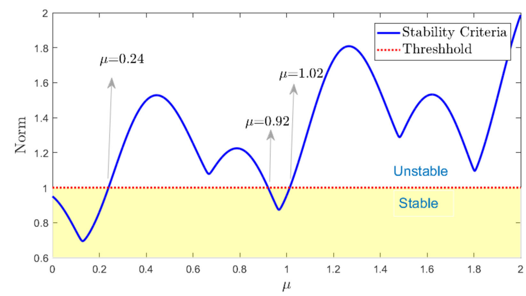

Fig. 8. Stability criteria for SMIB power system.

and $\dot{x}(t) = Ax(t) + B\mathrm{sat}(V_s)$, with $V_s = Kx(t)$.

$$A = \begin{bmatrix} 0 & \omega_s & 0 & 0 \\ -\frac{K_1}{2H} & -\frac{D\omega_s}{2H} & -\frac{K_2}{2H} & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & -\frac{1}{K_3 T'_{d0}} & \frac{1}{T'_{d0}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} \tag{33}$$

and $K_1 - K_6$ are the well-known linearization constants based on the system parameters [29]. Eigenvalue analysis shows that the open loop system has unstable complex eigenvalues of $+0.2423 \pm 7.6064i$ with frequency of 1.21 Hz and damping of -3.18%. Using LQR control design method, the following state-feedback damping controller is designed in [30] to enhance the damping performance by regulating the exciter of SMIB system.

$$K = [-0.22 \;\; 7.75 \;\; -0.28 \;\; -0.0006]. \tag{34}$$

The controller is designed such that, a domain of attraction (DA) is estimated to guarantee a safety region and the state trajectories must remain inside the (DA) to guarantee the stability. In practice, these controllers can be implemented based on dynamic state estimation using PMUs measurement. For ideal network communications, the performance of the closed-loop system is shown in Fig. 7. Consider now the case where communication fails, for some time variable duration μ and assume that the duration of the ideal communication is $\tau = 0.2$ s. Using the stability criteria (21), two intervals can be found analytically (without any simulations) to determine the time of interruptions to be respected in order to maintain the stability of the system, as shown in Fig. 8. In Table I, these intervals are compared with the real values found using trial and error simulations. Compared to the

TABLE I
COMMUNICATION FAILURE DURATION FOR SMIB SYSTEM

	First Interval μ	Second Interval μ
Stability Condition	$(0, 0.24)$	$(0.92, 1.02)$
Simulation (Linear System)	$(0, 0.30)$	$(0.8, 1.18)$
Simulation (Nonlinear System)	$(0, 0.32)$	$(0.85, 1.12)$

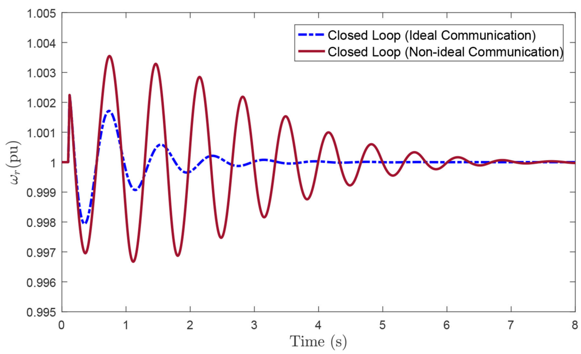

Fig. 9. Speed deviation of the closed loop SMIB power system in case of ideal and non-ideal ($\tau = 0.2$ and $\mu = 0.23$) communication network which is stable.

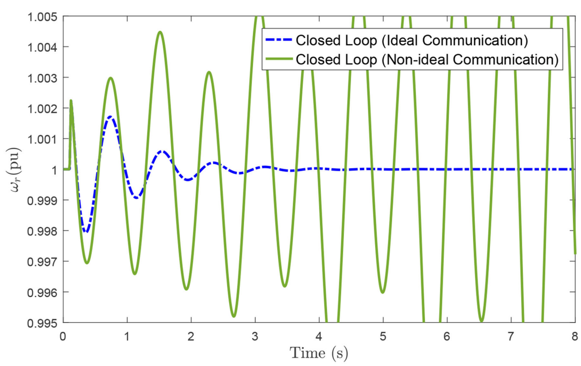

Fig. 10. Speed deviation of the closed loop SMIB power system in case of ideal and non-ideal ($\tau = 0.2$ and $\mu = 0.35$) communication which is instable.

developed stability criteria, excessive effort is needed to identify the unstable regions.

From Table I it can be seen that the stability condition is conservative but reasonably characterizes the limits. The system response for the case of ideal communication time duration $\tau = 0.2$ s and communication failure $\mu = 0.23$ s is also shown in Fig. 9, where the conditions of stability is respected and the system is stable. It is shown in Fig. 10, that if the controller is blocked for duration $\mu = 0.35$ s, then the system will be unstable. It can be seen that the performance of damping controller with non-ideal communication network has been degraded significantly. In practice, in case these intervals are violated (e.g. having a longer communication failure), they can be used as thresholds to activate remedial action schemes [21].

B. Case Study II: Kundur's Two-Area System

In this subsection, the developed stability condition is applied to a modified Kundur two-area system [31], shown in Fig. 11.

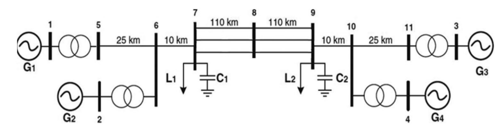

Fig. 11. A two-area Kundur power system.

TABLE II
CRITICAL MODES OF TWO-AREA SYSTEM

Mode type	**Without WADC**		**With WADC**	
	Freq. (Hz)	Damping (%)	Freq. (Hz)	Damping (%)
Inter-area	0.666	-1.68	0.657	11.37
Local	1.092	5.62	0.971	12.96
Local	1.125	16.35	1.119	16.23

Area 1 is transferring 550 MW of active power to area 2. Generators are represented by a fourth-order model and equipped with a high-gain excitation system. Generator G_1 and G_3 are equipped with IEEE standard speed-based PSS to damp the local modes. More details of the parameters can be found in [31].

The modal analysis summarized in Table II, show that the system without a controller has a negatively damped inter-area mode at 0.666 Hz with damping ratio of -1.68% and two damped local modes. The generator supplementary excitation control and speed deviation are chosen as candidates for the actuator and measurement signals of WADC system, respectively. G_1 is chosen as the nominal actuator and measurement signals of WADC system, respectively. G_1 is chosen as the nominal actuator for damping controller. Based on the controllability measure, speed deviation of G_3 is identified as the best candidate measurement signals for the controller, as it has the highest geometric observability over the first critical mode [32].

Hankel norm approximation [33] can be used to obtain the reduced-order model where the order of the model reduction can be determined by examining the Hankel singular values. The linear model is reduced to a second-order model and the following output feedback controller, shown as follows, is designed using multi-objective optimization to meet or exceed 11% damping over all inter-area and local mode, and optimize the H_2/H_∞ performance to limit the control efforts and avoid high gains in the WADC, since, large gain can lead the system to saturation, more details can be found in [32]. For the ideal communication network, the performance of the closed loop system is shown in Fig. 12. Assuming the maximum time duration of perfect communication as $\tau = 0.2$ s and using stability criteria (25), two intervals can be found analytically (without simulations) for the time of interruption in the control signal as shown in Fig. 13. In Table III, these intervals are compared with the real values using try and error simulations. It can be seen that the stability condition is again conservative but reasonably characterizes the limits. Compared to the analytical stability condition (25), excessive efforts are needed to explore huge numbers thresholds through simulation. The system response for the cases of perfect communication duration $\tau = 0.2$ s and communication failure $\mu = 0.16$ s is shown in Fig. 14, where the condition of stability is respected. For $\mu = 0.32$ s is shown in Fig. 15. It is shown in

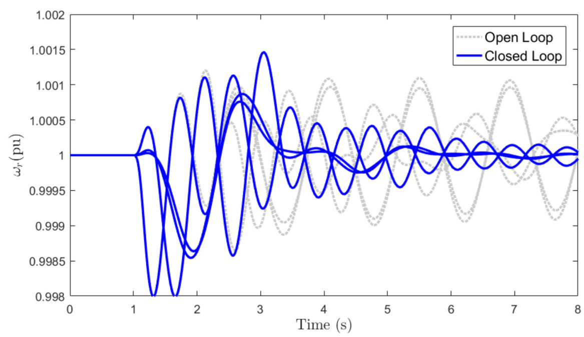

Fig. 12. Speed deviation of the closed loop and open loop two-area Kundur power system in case of ideal communication network.

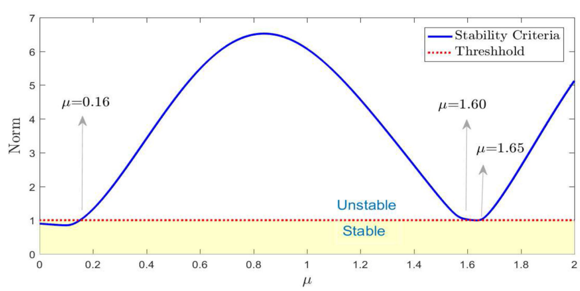

Fig. 13. Stability criteria for two-area Kundur power system.

TABLE III
COMMUNICATION FAILURE DURATION FOR KUNDUR'S TWO-AREA SYSTEM

	First Interval μ	Second Interval μ
Stability Condition	$(0, 0.16)$	$(1.60, 1.65)$
Simulation (Linear System)	$(0, 0.33)$	$(1.50, 1.81)$
Simulation (Nonlinear System)	$(0, 0.32)$	$(1.53, 1.76)$

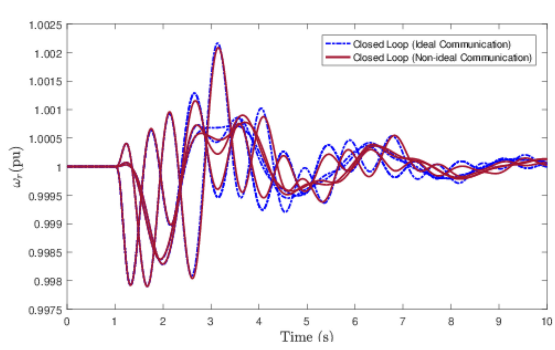

Fig. 14. Speed deviation of the closed loop two-area Kundur power system in case of ideal and non ideal ($\tau = 0.2$ s and $\mu = 0.16$ s) communication network which is stable.

Fig. 16, that if the controller is blocked for duration $\mu = 0.35$ s, the system will become unstable. It can be seen that the performance of the damping controller with non-ideal communication network has been degraded significantly. In Table III, these intervals are compared with the real values using try and error simulations. It can be seen that the stability condition is again conservative but reasonably characterizes the limits.

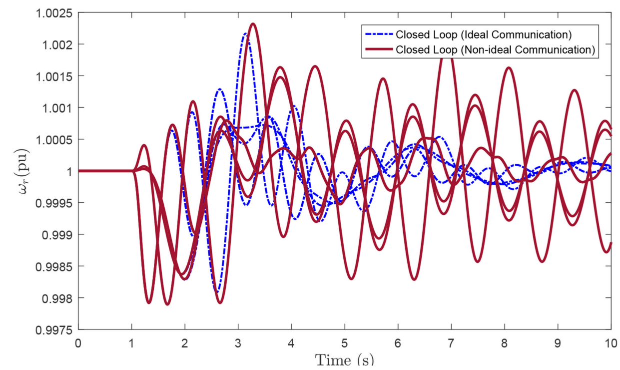

Fig. 15. Speed deviation of the closed loop two-area Kundur power system in case of ideal and non ideal ($\tau = 0.2$ s and $\mu = 0.32$ s) communication network which is stable.

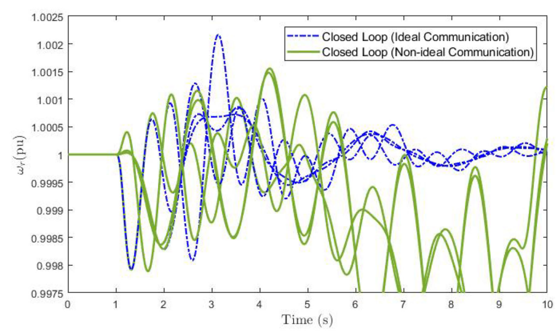

Fig. 16. Speed deviation of the closed loop two-area Kundur power system in case of ideal and non ideal ($\tau = 0.2$ s and $\mu = 0.35$) communication which is unstable.

V. CONCLUSION

In this paper, the problem for power systems with intermittent information transmissions is analyzed using time scale theory. This problem is proposed as a particular problem of switched linear system which consists of a set of linear continuous-time and linear discrete-time subsystem on a specific time scale. Using the derived stability criteria, bounds of the communication loss duration, which guarantees the stability of the system, has been computed in case of state-feedback and output-feedback controllers. Numerical results show the effectiveness of the proposed scheme. It is also found that the results based on the linear model are reasonably accurate for the nonlinear system. Further research is needed to model randomness of intermittent transmission and random packet losses.

APPENDIX A

Proof: Consider the switched system (11). Let $A_c = A + BK$ and $A_d = [(\frac{e^{A\mu}-I}{\mu})(I+A^{-1}BK)]$. Using the generalized exponential function in time scale theory, the solution of the switched system (11), for $\sigma(t_k) \leq t \leq t_{k+1}$, is given by (see [25])

$$x(t) = e^{A_c(t-\sigma(t_k))}(I + \mu(t_k)A_d)e^{A_c(t_k-\sigma(t_{k-1}))} \times \cdots (I + \mu(t_1)A_d)e^{A_c t_1} x_0. \quad (35)$$

So, for $t = t_{k+1}$, we have

$$\begin{aligned} x(t_{k+1}) &= \prod_{i=0}^{k} e^{A_c(t_{k+1-i}-\sigma(t_{k-i}))}(I+\mu(t_{k-i})A_d)\, x_0 \\ &= \prod_{i=0}^{k} e^{(A+BK)(t_{k+1-i}-\sigma(t_{k-i}))} \\ &\quad \times \left[I+\mu(t_{k-i})\left(\frac{e^{A\mu(t_{k-i})}-I}{\mu(t_{k-i})}\right)(I+A^{-1}BK)\right] x_0 \\ &= \prod_{i=0}^{k} e^{(A+BK)(t_{k+1-i}-\sigma(t_{k-i}))} \\ &\quad \times \left[I+\left(e^{A\mu(t_{k-i})}-I\right)(I+A^{-1}BK)\right]\, x_0. \quad (36) \end{aligned}$$

Let $0 < a < 1$ such that, $\forall 0 \leq i \leq k$ and $\tau_i = t_i - \sigma(t_{i-1})$,

$$\left\| e^{(A+BK)\tau_i}\, \left[I+\left(e^{A\mu(t_i)}-I\right)(I+A^{-1}BK)\right]\right\| \leq a. \quad (37)$$

So, the upper bound of $x(t_{k+1})$ is given by

$$\begin{aligned} &\|x(t_{k+1})\| \\ &\leq \prod_{i=0}^{k} \left\| e^{(A+BK)\tau_i}\left[I+\left(e^{A\mu(t_i)}-I\right)(I+A^{-1}BK)\right]\right\| \|x_0\| \\ &\leq a^{k+1}\, \|x_0\| = e^{(k+1)\log(a)}\, \|x_0\|. \quad (38) \end{aligned}$$

Since $\log(a) < 0$, so the solution $x(t)$ of (11) converges exponentially to zero when $t \to \infty$ (i.e., $k \to \infty$). ■

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