Wide-area Damping Control Under Limited Data Feedback Condition: An Observer Driven System Copy Approach

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***Abstract*— Limited data feedback rate, e.g. 1-10 samples per second instead of 25-60, causes adverse effect on wide-area damping control (WADC). An observer driven system copy (OSC) approach is suggested here to deal with low data rates. The basic idea is to use the knowledge of nominal system dynamics to approximate the actual system behavior during intervals when data from phasor measurement units (PMUs) is not available. This is corrected whenever the most recent states are obtained from the observer at the PMU location. The closed-loop performance deteriorates as the operating condition drifts away from the nominal dynamics. Nonetheless, significantly better performance compared to conventional feedback (CF) is obtained under low feedback data rate condition. The deterioration in performance is quantified in terms of the difference between the nominal and off-nominal dynamics.**

***Index Terms*— Wide-area Damping Control, Observer, Data Feedback Rate, Wide-area Measurement Systems, State-feedback**

List of Abbreviations and Notations

WADC	Wide-area Damping Control
PMU	Phasor Measurement Unit
WAMS	Wide-area Measurement Systems
SCADA	Supervisory Control and Data Acquisition
PDC	Phasor Data Concentrator
OSC	Observer Driven System Copy
CF	Conventional Feedback
FACTS	Flexible AC Transmission Systems
TCSC	Thyristor Controlled Series Capacitor
G_n	Reduced order state space model of power system at nominal condition (for system copy)
G_i	Reduced order state space model of power system at i^{th} off-nominal condition
L	Observer gain vector
K	State feedback gain vector
σ	Time interval between consecutive samples arriving at control center
$\bar{x}$	State vector estimated by the observer
x_i	State vector of reduced power system model under i^{th} off-nominal condition
x_n	State vector estimated by system copy
t_k	Time instant of state resetting in copy
x_0	Observer estimated state at time t_k
x_0'	Actual state of reduced power system model at time t_k
$u(t)$	Control input to the actuator
$\bar{u}(t)$	Control input calculated at the PMU location
$\tilde{A}, \tilde{B}, \tilde{C}$	Deviation in actual operating condition from nominal
$e(t)$	Error between observer and estimated (by system copy) states
$E(t)$	Error between estimated (by system copy) and actual states of reduced model
$\lVert\cdot\rVert$	Euclidian norm of a vector or a matrix
t^*	Time instant when $\lVert E(t)\rVert$ is maximum

I. Introduction

Effectiveness of wide-area damping control (WADC) employing measurements from remote phasor measurement units (PMUs) is well reported in literature [1], [2], [3], [4]. Conventional feedback (CF) is usually used for WADC wherein the measured signals (magnitude/phase angles of voltage, current) from PMUs are transmitted via communication link to remote control centers. Although wide-area measurement systems (WAMS) has primarily been used in monitoring and discrete control [5], [6], [7], some utilities have shown interest in using this infrastructure for closed loop continuous control. One of the major concerns, however, is the risk associated with occasional problems in communication links.

Currently both wired (e.g. telephone lines, fibre-optic, power lines) and wireless (e.g. satellites, microwave) options are employed for WAMS [8]. Use of telephone lines are common but provide a relatively low data rate due to isolation requirements at the substations. Power line communication is emerging as a preferred option because it provides improved bit-error-rate [9] and offers about 4 Mbps bandwidth (BW) via the existing electric supply grid. Fibre-optic links are used by many utilities to exploit high available BW (more than 50 Mbps). Utilities like Bonneville Power Administration (BPA) have started replacing their point to point analog microwave links with fibre-optic communication networks [10]. Although

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digital microwave links are preferred over their analog counterpart [11], their propagation distance is usually limited to about 30 miles [8]. Low-earth orbiting satellite technology can overcome the above limitation but suffers from narrow BW and associated problem of latency.

Utilities with years of experience with WAMS, are contemplating wider use of networked communication (e.g. UDP Multicast) in place of dedicated serial communication in future. The idea is to utilize the available BW partly for WAMS usage and partly for providing other data intensive services like video-conference facility [12]. This highlights an exciting prospect in favor of the fibre-optic technology - which incurs high initial investment - but provides massive BW and inherent immunity to radio frequency. Similarly, there are plans to share power line communication for WAMS, substation networking [13] and broadband service [14]. A recent paper on latency computation for a hypothetical WADC in the context of Western Electricity Coordinating Council (WECC) system conjectured a hierarchical configuration of data communication [15]. Possible use of a networked communication was indicated for implementation of WADC with a large number of sensory signals from diverse geographical locations communicated to many distant zonal phasor data concentrators (PDCs) [15].

With networked communication likely to be more common, impact of feedback data rate on the performance of WADC is a matter of concern. It should be reiterated that limited data rates, although not common in state-of-the-art dedicated serial links, is more of a possibility in shared networked communication especially, with growing traffic through bandwidth constrained channels. In this context a method for effective WAMS based control is proposed here to ensure satisfactory performance in spite of occasional low data feedback rates.

Evidently, there is a tradeoff between the satisfactory closed-loop control (CF) and feedback data rate. Better performance and stability margins are obtained by having feedback measurements in a timely manner [16]. Dedicated WAMS infrastructure typically uses a fast data rate of 25 to 60 samples per second (samples/s) [8], [5] which is more than adequate for WADC of low frequency (0.1 to 2.0 Hz) oscillations. However, with lower data rates there could be adverse impacts on closed-loop performance. A case study is presented in Section IV-A to show that the performance with CF deteriorates quite significantly below a data rate of 10 samples/s.

A novel control architecture is suggested here based on a predictor-corrector approach to achieve satisfactory closed-loop control under limited data rate condition. This architecture is referred to as the observer driven system copy (OSC) approach for the rest of the paper. It should be mentioned that with normal feedback data rates WADC would use conventional feedback (CF) as usual. The proposed OSC approach would be employed only when data rate is below a certain threshold as indicated by the time-stamp information at either end [17].

Two reduced order linearized models of the power system around the nominal condition, known as system copy, are considered at the PMU and the actuator locations. The first copy is employed to create an asymptotic observer using measured output from the PMU. This observer estimates the states of reduced system which are communicated to the actuator location. The states of the second copy at the actuator location are reset by the fresh samples received from the observer. During the inter-sample interval the states are allowed to evolve on their own. The basic idea is to use the knowledge of nominal system dynamics to approximate the actual behavior during time intervals when PMU data is not available [16], [18], [19].

It is intuitive that the performance of the OSC scheme would depend to a large extent on the difference between the actual operating condition and the one considered for system copy. The deterioration in performance is quantified in terms of the difference between the linearized systems at nominal and off-nominal operating conditions. Nonlinear simulation results for a range of operating scenarios are presented to verify this linear analysis. These results are compared with a conventional feedback (CF) control for different feedback data rates. Despite the deterioration under off-nominal conditions, OSC produces significantly better performance than CF with limited data rates.

The main contributions of this paper are:

- Investigation of the impact of low data rate rate on wide-area damping control (WADC)
- Application of a predictor-corrector approach for acceptable system response even with low data rate
- Analyze the effect of difference between the nominal (used to predict and correct) and off-nominal operating conditions on the closed-loop performance using linearized system models
- Compare the behavior of a conventional feedback (CF) and the proposed OSC scheme under low data rate condition

It should be pointed out that this paper does not propose the use of low feedback data rate for WADC as output feedback with adequate data rate is always recommended from robust performance point of view. However, under unusual circumstances leading to data rates (detected from time-stamp information at both ends [17]) below a threshold, it is preferable to switch to the proposed OSC, rather than CF and continue to benefit from wide-area information.

The rest of the paper is organized as follows. Following this introductory section, the principles of the OSC approach is described in Section II. Quantification of performance deterioration under off-nominal conditions is presented in Section III. A case study on a 16-machine, 5-area test system is presented in Section IV to illustrate the effectiveness of the OSC approach under low data rate condition.

II. Observer Driven System Copy (OSC) Approach

Wide-area damping control (WADC) usually employs output feedback where measured signals from PMUs are communicated to the controller. Here the rate at which data is transmitted is critical for ensuring satisfactory closed-loop performance. Data rates lower than a threshold could lead to unacceptable system response as illustrated in Sec IV-A. The OSC approach addresses this problem by exploiting the knowledge of the nominal system dynamics to predict the actual system behavior between two consecutive data samples.

Following [19], [18], a predictor corrector approach is applied here to estimate (predict) the states with a reduced order linearized nominal model of the system (referred to as system copy) at the actuator location. These are updated (corrected) periodically at a lower rate (depending on feedback data rate) with the most recent states estimated by an observer at the PMU location as shown in Fig. 1.

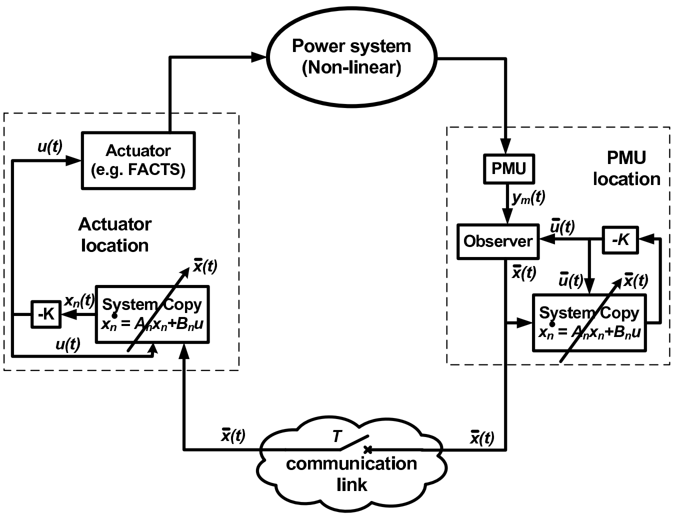

Fig. 1. Observer Driven System Copy (OSC) Approach

The reduced order linearized model of the power system around the nominal operating condition G_n is given by:

$$G_n = \left[\begin{array}{c|c} A_n & B_n \\ \hline C_n & 0 \end{array}\right] \tag{1}$$

where, $A_n \in \Re^{m\times m}$, $B_n \in \Re^{m\times n}$ and $C_n \in \Re^{p\times m}$. Reduced order linearized model under i^{th} operating condition G_i (e.g. corresponding to a line outage) is denoted as:

$$G_i = \left[\begin{array}{c|c} A_i & B_i \\ \hline C_i & 0 \end{array}\right] \tag{2}$$

where, $A_i = A_n + \tilde{A}$, $B_i = B_n + \tilde{B}$, $C_i = C_n + \tilde{C}$ and $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ represent the deviation around the nominal operating condition. The states of G_n and G_i are denoted as $x_n(t)$ and $x_i(t)$, respectively. Exogenous disturbances could also be incorporated in (2), if required.

An observer (3) at the PMU location estimates the system states $\bar{x}$ which are transmitted through the communication network to the controller. The state equation of the observer is:

$$\dot{\bar{x}} = (A_n - LC_n)\bar{x} + B_n\bar{u} + LC_ix_i \tag{3}$$

Note that the observer at the PMU location requires knowledge of control input u(t) which is calculated $(\bar{u}(t))$ using the system copy model and the state-feedback gain vector K, see Fig. 1. The system copy at the actuator location is based on the nominal model described by the following equation:

$$\dot{x}_n\,(t) = A_nx_n(t) + B_nu(t) \tag{4}$$

Depending on the data rate available, the communication channel transmits data between the remote observer location and the local system copy based controller, only at time instants $\{t_k\}_{k=0}^{\infty}$. It is assumed that this "sampling" of remote data occurs at equally spaced intervals so that the inter-sample time is $t_{k+1} - t_k = \sigma\ \forall k = 0, 1, ...$ Hence the states of (4) are reset to the states estimated by (3) at the sampling instants $\{t_k\}_{k=0}^{\infty}$.

$$x_n(t_k) = \bar{x}(t_k) \text{ for all } k = 0, 1, 2, ... \tag{5}$$

The input used to control G_i is synthesized using the nominal model (4) and (5) according to the following equation:

$$u(t) = -Kx_n(t) \tag{6}$$

where $K \in \Re^{1\times m}$ is the state feedback gain vector designed based on the nominal system model G_n.

During time interval σ, when the system states are not available from PMU location (i.e. T is open, see Fig. 1) the system copy predicts the states. Upon arrival of the next available sample of $\bar{x}(t)$ the states of the system copy are corrected/reset leading to a switched control strategy. This setup is referred to as observer driven system copy (OSC) in this paper.

Combining equations (2), (4), (6) and (3) the overall system dynamics during the time interval $t \in [t_k, t_{k+1})$, $t_{k+1} - t_k = \sigma$ can be described as:

$$\begin{bmatrix} \dot{x}_i \\ \dot{x}_n \\ \dot{\bar{x}} \end{bmatrix} = \begin{bmatrix} A_i & -B_iK & 0 \\ 0 & A_n - B_nK & 0 \\ LC_i & B_nK & A_n - LC_n \end{bmatrix} \begin{bmatrix} x_i \\ x_n \\ \bar{x} \end{bmatrix} \tag{7}$$

with the additional condition imposed by (5) at all t_k. The initial condition $x_i(0)$ is usually unknown while the initial conditions for the nominal and the observer states are assumed to be zero $x_n(0) = 0$ and $\bar{x}(0) = 0$.

Following [19], the error $e = \bar{x} - x_n$ is defined as the difference between the nominal and estimated (observer) states. Using a linear transformation (7) can be re-written in terms of the error $e(t)$ as follows:

$$\begin{bmatrix} \dot{x}_i \\ \dot{\bar{x}} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_i & -B_iK & B_iK \\ LC_i & A_n - LC_n - B_nK & B_nK \\ LC_i & -LC_n & A_n \end{bmatrix} \begin{bmatrix} x_i \\ \bar{x} \\ e \end{bmatrix} \tag{8}$$

It can be proved that the system (8) is globally, exponentially stable around the solution $[x_i\ \bar{x}\ e]^T = [0\ 0\ 0]^T$ if and only if the eigenvalues of (9) lie inside the unit circle [19].

$$\Lambda = \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{\Gamma\sigma} \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{9}$$

where Γ is the overall state matrix in (8). Maximum allowable update interval σ i.e. minimum data rate can be obtained from stability of (8).

It should be noted here that while (9) characterizes global exponential stability of the linear switched system (8), it does not formally establish the stability of the non-linear power system under switching [20]. However, for practical purposes, stability and performance is guaranteed through extensive simulations reported in Section IV.

III. Inter-Sample Error Estimate

It was shown in the previous section that the asymptotic behavior of the OSC scheme is guaranteed to be exponentially stable under appropriate conditions. However, it would be useful to estimate the deterioration in performance under off-nominal conditions, which depends on the evolution of the states of G_i during the period between two consecutive feedback samples. This is quantified in this section in terms of the difference between the nominal and off-nominal operating conditions.

From dynamics of the combined nominal, off-nominal and observer systems (7) during the inter-sample period $[t_k, t_{k+1})$, it is observed that the responses of $x_i(t)$ and $x_n(t)$ are uncoupled with that of the observer $\bar{x}(t)$. Hence, the left upper block can be considered separately for analysis during $t \in [t_k, t_{k+1})$. Thus, neglecting observer dynamics without loss of generality, (7) can be rewritten as:

$$\begin{bmatrix} \dot{x}_i(t) \\ \dot{x}_n(t) \end{bmatrix} = \begin{bmatrix} A_i & -B_iK \\ 0 & A_n - B_nK \end{bmatrix} \begin{bmatrix} x_i(t) \\ x_n(t) \end{bmatrix} \tag{10}$$

The initial conditions are the states at the last available sampling instant t_k. Assuming

$$\begin{bmatrix} x_i(t_k) \\ x_n(t_k) \end{bmatrix} = \begin{bmatrix} x'_0 \\ x_0 \end{bmatrix}$$

It is to be noted that the state $x_n(t_k)$ is reset to the estimated observer state $\bar{x}(t_k)$ according to (5). Solution of (10) gives:

$$\begin{bmatrix} x_i(t) \\ x_n(t) \end{bmatrix} = e^{\Delta(t-t_k)} \begin{bmatrix} x'_0 \\ x_0 \end{bmatrix}, \; t \in [t_k, t_{k+1}) \tag{11}$$

where,

$$\Delta = \begin{bmatrix} A_i & -B_iK \\ 0 & A_n - B_nK \end{bmatrix} \tag{12}$$

Equation (11) represents the temporal evolution of system states of the reduced order model and those predicted by the system copy. The state trajectory of system copy with initial state x_0 can be expressed as:

$$x_n(t) = e^{(A_n - B_nK)(t-t_k)}x_0 \text{ for } t \in [t_k, t_{k+1}) \tag{13}$$

Analytical expression for the trajectory of the states of the reduced order linearized power system model is derived as follows. Transforming (12) to Laplace domain we get:

$$\begin{bmatrix} X_i(s) \\ X_n(s) \end{bmatrix} = \mathcal{L}\{e^{\Delta(t-t_k)} \begin{bmatrix} x'_0 \\ x_0 \end{bmatrix}\} = \Xi \begin{bmatrix} x'_0 \\ x_0 \end{bmatrix} \tag{14}$$

where,

$$\Xi = \begin{bmatrix} (sI - A_i)^{-1} & -(sI - A_i)^{-1}B_iK(sI - A_n + B_nK)^{-1} \\ 0 & (sI - (A_n - B_nK))^{-1} \end{bmatrix} \tag{15}$$

Hence, $X_i(s)$ can be written as:

$$\begin{aligned} &X_i(s) = (sI - A_i)^{-1}x'_0 \\ &-(sI - A_i)^{-1}B_iK(sI - A_n + B_nK)^{-1}x_0 \end{aligned} \tag{16}$$

which simplifies to:

$$\begin{aligned} &X_i(s) = (sI - A_i)^{-1}(x'_0 - x_0) \\ &+(sI - A_i)^{-1}[I - B_iK(sI - A_n + B_nK)^{-1}]x_0 \end{aligned} \tag{17}$$

Equation (17) can be further simplified to:

$$\begin{aligned} &X_i(s) = (sI - A_n + B_nK)^{-1}x_0 + (sI - A_i)^{-1}(x'_0 - x_0) \\ &+(sI - A_i)^{-1}(\tilde{A} - \tilde{B}K)(sI - A_n + B_nK)^{-1}x_0 \end{aligned} \tag{18}$$

Notably $\tilde{A}$ and $\tilde{B}$ represent the deviation of the dynamic model embedded in system copy from the linearized system model (corresponding to a particular operating condition). Thus the actual system states are given by:

$$\begin{aligned} &x_i(t) = e^{(A_n - B_nK)(t-t_k)}x_0 + e^{A_i(t-t_k)}(x'_0 - x_0) \\ &+\int_{t_k}^{t} e^{A_i(t-\tau)}(\tilde{A} - \tilde{B}K)e^{(A_n - B_nK)\tau}x_0 d\tau \end{aligned} \tag{19}$$

The error between the reduced order linearized system state trajectory and that estimated by system copy can be expressed as:

$$\begin{aligned} &E(t) := x_i(t) - x_n(t) \\ &= e^{A_i(t-t_k)}(x'_0 - x_0) + \int_{t_k}^{t} e^{A_i(t-\tau)}(\tilde{A} - \tilde{B}K)e^{(A_n - B_nK)\tau}x_0 d\tau \end{aligned} \tag{20}$$

It can be observed that the error term consists of two components. The first term represents the deviation of linearized system state from its asymptotic estimate computed by the observer at $t = t_k$. The second term arises due to the difference between actual power system operating condition and the system copy model. As expected, if both the initial condition error and the model mismatch can be reduced to zero, i.e.

$$x'_0 = x_0; \quad \tilde{A} = 0, \tilde{B} = 0 \tag{21}$$

the error $E(t)$ ceases to exist. However, because of changes in operating conditions in practical systems, (21) does not hold good and there is a finite error.

Assuming stable open-loop system there are constants $k_1 > 0$ and $\alpha_1 > 0$ such that for any vector $c_1 \in \Re^m$:

$$\left\| e^{A_it}c_1 \right\| \leq k_1 e^{-\alpha_1 t} \left\| c_1 \right\| \tag{22}$$

Moreover, the closed-loop nominal system is stable and well-damped with the designed controller implying there exists constants $k_2 > 0$ and $\alpha_2 > 0$ such that for any vector $c_2 \in \Re^m$:

$$\left\| e^{(A_n - B_nK)t}c_2 \right\| \leq k_2 e^{-\alpha_2 t} \left\| c_2 \right\| \tag{23}$$

Using (22) and (23) an estimate of the error $E(t)$ can be derived as follows:

$$\begin{aligned} &\|E(t)\| \leq \left\| e^{A_i(t-t_k)} \right\| \|(x'_0 - x_0)\| \\ &+ \left\| \int_{t_k}^{t} e^{A_i(t-\tau)}(\tilde{A} - \tilde{B}K)e^{(A_n - B_nK)\tau}x_0 d\tau \right\| \\ &\Rightarrow \|E(t)\| \leq k_1 \|(x'_0 - x_0)\| e^{-\alpha_1(t-t_k)} \\ &+k_1k_2 \left\| (\tilde{A} - \tilde{B}K) \right\| \|x_0\| \int_{t_k}^{t} e^{-\alpha_1(t-\tau)}e^{-\alpha_2\tau}d\tau \\ &= k_1 \|(x'_0 - x_0)\| e^{-\alpha_1(t-t_k)} \\ &+k_1k_2 \left\| (\tilde{A} - \tilde{B}K) \right\| \|x_0\| \frac{[e^{-\alpha_2(t-t_k)} - e^{-\alpha_1(t-t_k)}]}{(\alpha_1 - \alpha_2)e^{\alpha_2 t_k}} \end{aligned} \tag{24}$$

It is to be noted that the consecutive asymptotic estimate of reduced order linearized system states reset the system copy over finite intervals of time. Assuming that the eigenvalues

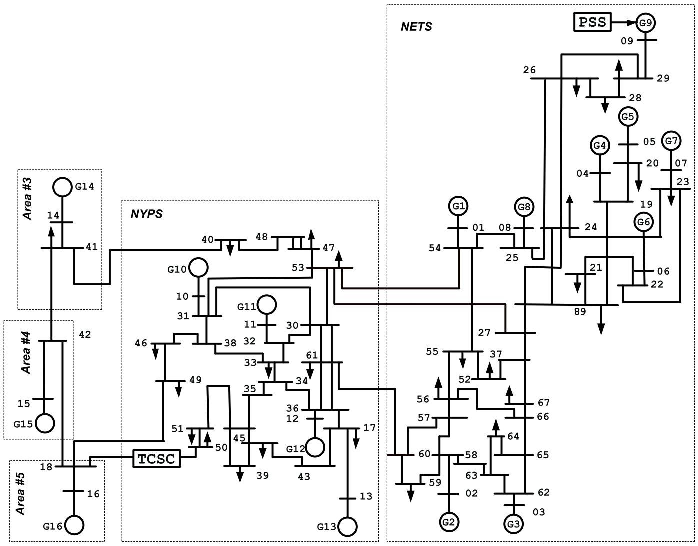

Fig. 2. Test system : 16-machine, 5-area system with a TCSC

of (9) lie inside the unit circle the system (8) is globally, exponentially stable. Hence it follows that the sampling instant error $\|x_i(t_k) - x_n(t_k)\| \rightarrow 0$ as $k \rightarrow \infty$. However, the maximum value of the error during the inter-sample interval, $t \in [t_k, t_{k+1})$ between two consecutive samples is of interest. Suppose the error attain the peak value at some $t_k^* \in [t_k, t_{k+1}]$. Assuming $(x_0' - x_0) = 0$, from (24), it can be seen that the maximum error norm is proportional to the model mismatch:

$$\|E(t^*)\| \propto \left\|\tilde{A} - \tilde{B}K\right\| \tag{25}$$

IV. CASE STUDY

To illustrate the effectiveness of the proposed OSC approach under limited data rate condition, a case study was carried out on a 16-machine, 5-area test system, shown in Fig. 2. A detailed description of the study system including machine, excitation system and network parameters can be found in [21]. A thyristor controlled series capacitor (TCSC) is installed on the tie-line connecting the buses 18 and 50 and is used to damp power oscillations with the real power flow in line 45-35 as feedback signal.

For a conventional feedback (CF) controller, the measured signals from PMUs (y_m) are communicated to the controller at the actuator location. Here such a controller is designed using linear quadratic regulator (LQR) approach [22] based on a 10th order reduced model of the nominal power system.

For the proposed OSC, states of the reduced order system (not the measured outputs) estimated by the observer are communicated over the network. A reduced order system model (system copy) is used to calculate the control input $(\bar{u}(t))$ required by the observer at the PMU location, see Fig. 1. A system copy containing the same reduced order model drives a state feedback controller at the actuator location as described in Section II. In this exercise, balanced truncation approach [23] is used to obtain the reduced order nominal model of the power system. For large scale power systems subspace based techniques for model reduction could be employed.

A low pass filter is used at the output of the system copy to suppress sharp changes in the control signal due to periodic reset with most recent states. A 20 ms latency is considered in the communication channel.

A. Impact of low data rate on CF based WADC

Impact of low data rate on WADC based on CF is illustrated in this subsection. The closed-loop performance was tested for different data rates in the range 1 sample/s (1/s).

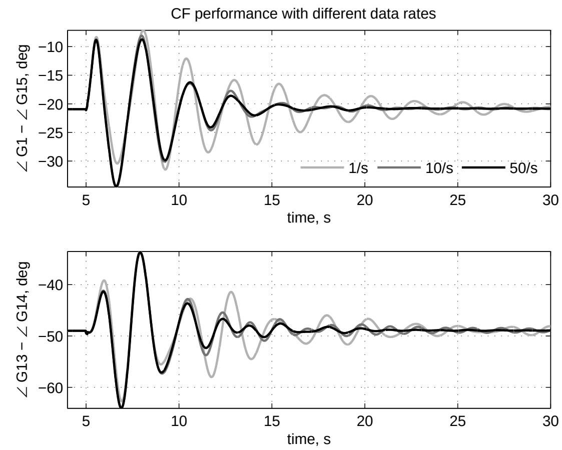

Fig. 3. Comparison of CF based WADC performance for different data rates with a self-clearing fault for 80 ms near bus 60

System responses with CF are compared for data rates of 50, 10 and 1 samples/s following a self-clearing fault for 80 ms near bus 60, see Fig. 3. With 10 samples/s the performance is slightly poorer while it is much worse with 1 sample/s. Here self clearing fault is considered deliberately to rule out any possible performance deterioration due to change in operating condition.

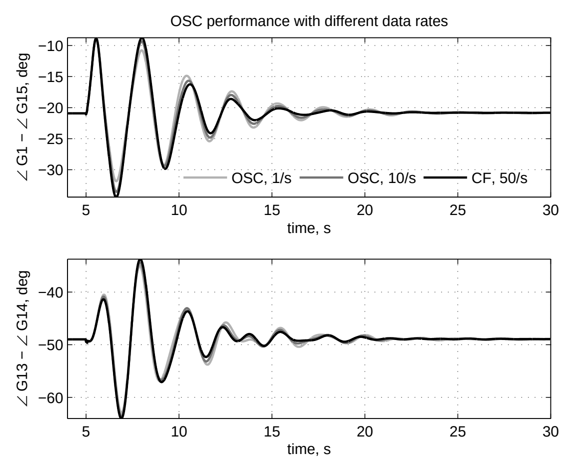

Fig. 4. Comparison of damping performance of CF at nominal data rate (50 samples/s) vs OSC with lower data rate for a self-clearing fault for 80 ms near bus 60

B. Performance of OSC with low data rate

Above case study is repeated with the proposed OSC approach. Fig. 4 compares the damping performance of the

OSC with low data rates against CF using typical PMU rate of 50 samples/s. For a self-clearing fault for 80 ms near bus 60, OSC produces almost identical damping performance as CF. This implies the system copy could approximate the plant dynamics quite closely during intervals of absence of feedback data.

It is to be noted that a system copy having the same order as the linearized plant would exactly replicate the behavior in open-loop condition. However, some deviations are expected in the simulation results due to non-linearities and model reduction effects. Drift in operating condition away from the nominal will result in growing difference between the dynamics estimated by the observer and the system copy leading to deterioration of OSC performance shown in the next subsection.

C. Effect of operating condition on OSC

Performance of the OSC under three different line outage scenarios are compared against the nominal condition. Clearly, there are two factors that are expected to cause a poorer behavior:

- difference between the system copy model (nominal) and the actual operating condition
- controller is design for the nominal condition

Although the impact of these factors can not be decoupled completely, the effect of deviation of system operating condition on OSC can be captured by:

- comparing the OSC performance against CF at nominal data rate (25-60 samples/s) as a benchmark (to take care of the effect of controller)
- illustrating OSC performance with data rates as low as 1 sample every 2 s (this will rely predominantly on the proximity of the system copy model and the actual operating condition)

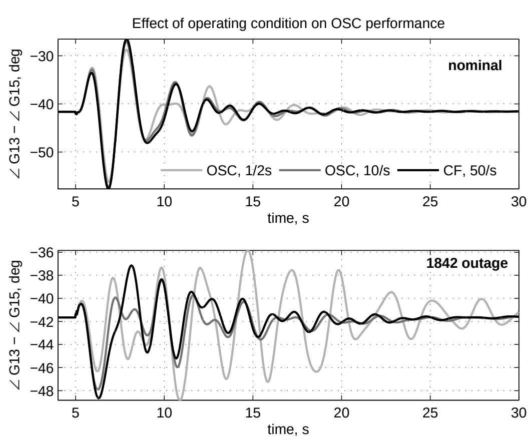

Fig. 5. Effect of change in operating condition on OSC performance

The system performance with CF for different operating conditions are illustrated in Figs. 5 and 6 which reveal the following:

- at nominal condition, OSC with 1 sample every 2 s (1/2 s) behaves marginally differently than CF with 50 samples/s (see Fig. 5) due to system nonlinearities and model reduction effects
- CF with 50 samples/s produces satisfactory damping under different operating conditions indicating a reasonable robustness of the controller (see Figs. 5, 6)
- compared to the CF, considered as benchmark, the performance with OSC becomes poorer with lower data rates due to increasing reliance on accuracy of system copy
- performance with OSC is worst for line 18-42 outage (see Fig. 5) followed by line 40-41 and line 54-53 outages (see Fig. 6)

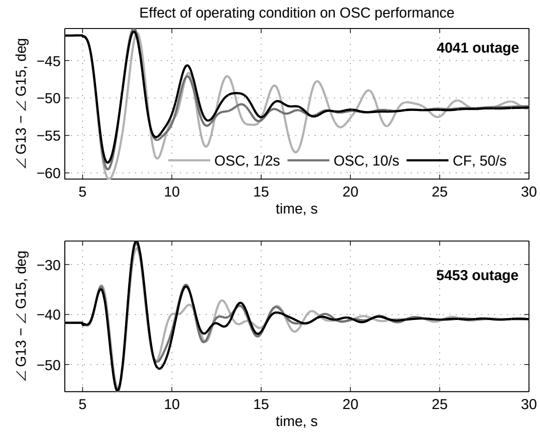

Fig. 6. Effect of change in operating condition on OSC performance

It is not straightforward to justify the trends in simulation with the analysis in Section III primarily, due to the effect of non-linearities. However, the above observations qualitatively agree with the measure of the error bound in (25). The calculated values of error bounds based on the linearized models for different outage conditions is given in Table I. It is important to note that, the objective of this exercise was to illustrate the working principle of the proposed OSC approach in a nonlinear environment and validate whether it behaves as expected from the linear control theory.

TABLE I
MEASURE OF MAXIMUM ERROR BOUND

Outage of line	$\|\tilde{A}-\tilde{B}K\|$
18-42	176
40-41	235
54-53	97
60-61	243

D. OSC vs CF at low data rate

This subsection shows that the performance with OSC, even under off-nominal operating scenarios, is consistently better compared to CF if low data rates are used. Since the performance of CF is poor with 1 sample/s at nominal condition (see Sec IV-A) and more so for outage conditions - a minimum data rate of 2 samples/s was used.

Fig. 7 compares the system responses with CF and OSC for a three phase fault for 80 ms near bus 60 followed by line 60-

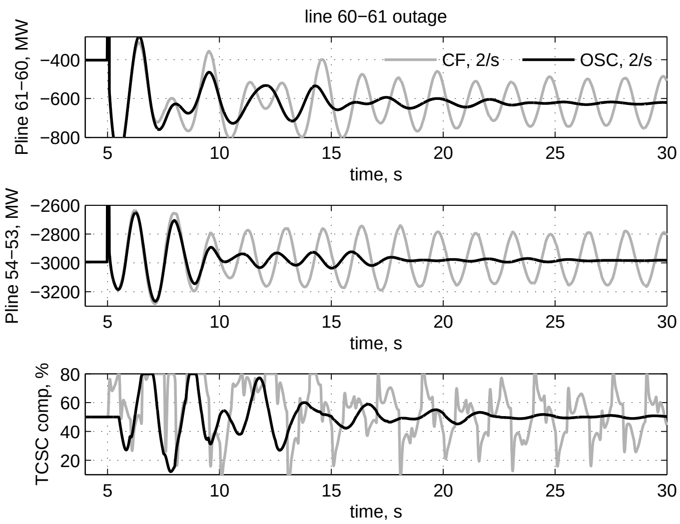

Fig. 7. Comparison of damping performance between OSC and CF at 2 samples/s data rate for line 60-61 outage

61 outage. The effectiveness of OSC is evident in sharp contrast to the adverse impact of low feedback rates on CF. Closer look at the variation of percentage compensation of TCSC (see Fig. 7, lower subplot) reveals that the control effort with OSC is delayed by about 0.5 s (precisely 0.52s) due to the arrival of first sample of non-zero states from the PMU location to the control center. Figs. 8 and 9 show the robustness of the

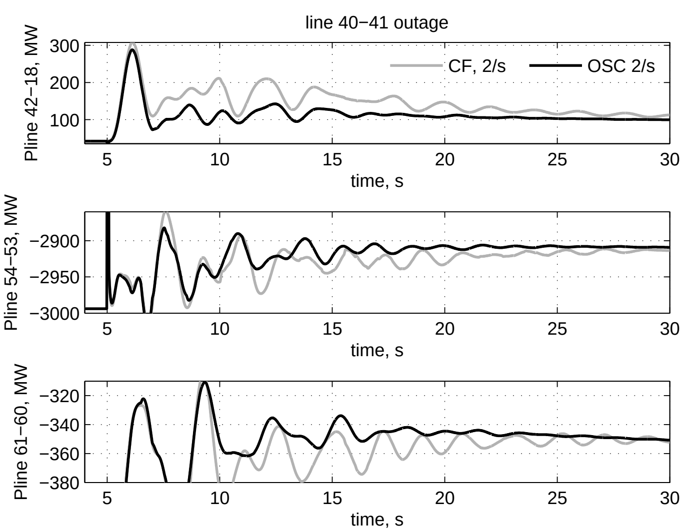

Fig. 8. Comparison of damping performance between OSC and CF at 2 samples/s data rate for line 40-41 outage

proposed technique across different operating conditions (line 40-41 and 18-42 outage). The case studies demonstrate that the proposed OSC approach produces satisfactory closed-loop performance under different operating scenarios. On the other hand WADC based on CF results in unacceptable performance with low data rates. Similar observation holds good for line 54-53 outage illustrated in Fig. 10

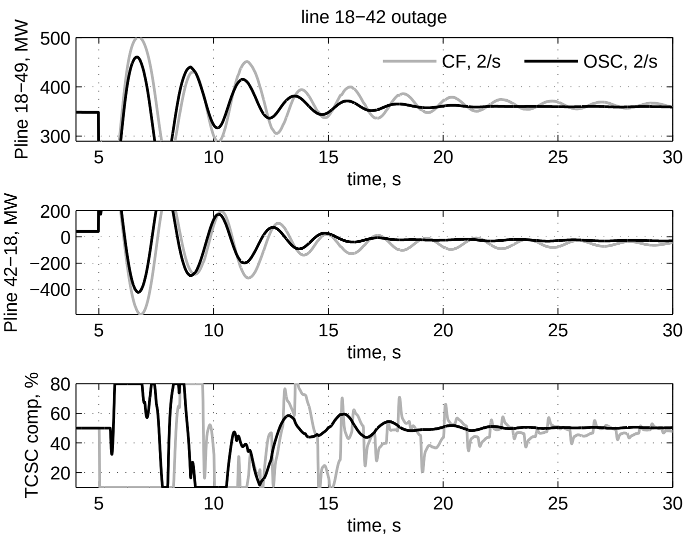

Fig. 9. Comparison of damping performance between OSC and CF at 2 samples/s data rate for line 1842 outage

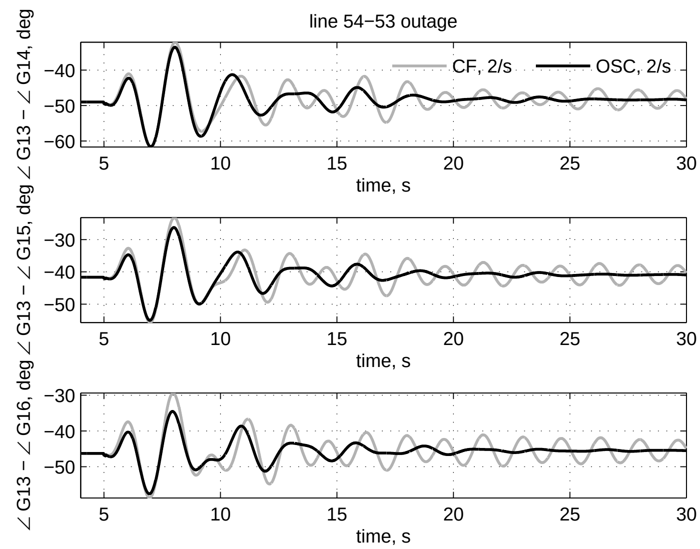

Fig. 10. Comparison of damping performance between OSC and CF at 2 samples/s data rate for line 54-53 outage

E. Performance of OSC at low data rate

With data rates typically in the range of 1-2 samples per second (1-2/s) [5] the OSC approach resulted in satisfactory closed-loop system response even under off-nominal operating scenarios. Fig. 11 compares the performance with CF using typical PMU data rate (50/s) against OSC using a much lower rate (1/s). The system responses are comparable demonstrating the effectiveness of OSC approach under low feedback data rate conditions.

It is to be noted that with still lower data rates (e.g. 1 sample/2 s) OSC produces poorer responses compared to CF with 50 samples/s which is expected beyond a certain point.

V. Conclusion

Data feedback rate below a certain threshold is shown to have adverse effect on wide-area damping control (WADC).

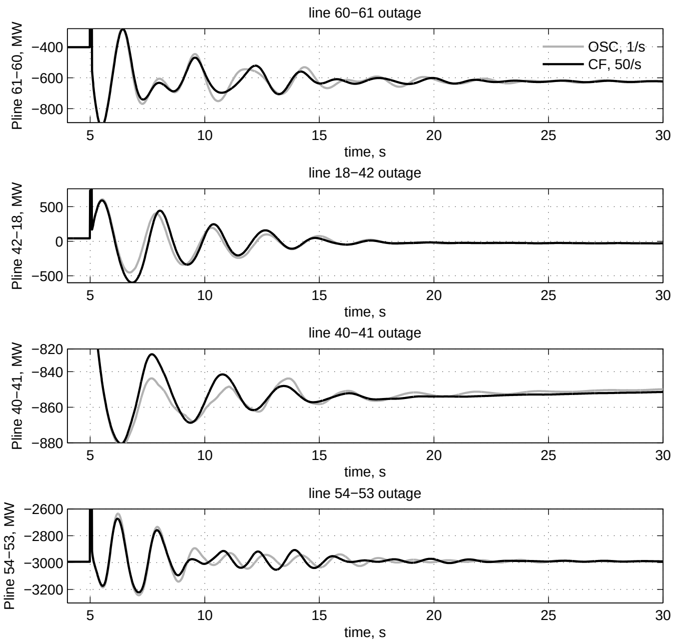

Fig. 11. Comparison of damping performance of OSC at 1 sample/s data rate with CF at nominal (50 samples/s) data rate across different operating conditions

An observer driven system copy (OSC) approach is suggested here to deal with low data rates of the order of 1-2 samples per seconds (1-2/s). The basic idea is to use the knowledge of nominal system dynamics to approximate the actual behavior during intervals when data from phasor measurement units (PMUs) is not available. Each time new data samples arrive, this estimate is updated by the most recent states provided by the observer at the PMU location. Of course the closed-loop performance deteriorates as the operating condition drifts away from the nominal dynamics. Nonetheless, significantly better performance compared to conventional feedback (CF) is obtained under low feedback data rate condition. The deterioration in performance is quantified in terms of the difference between the nominal and off-nominal dynamics.

It should be pointed out that the aim of this paper is not to propose use of low feedback data rate for WADC as output feedback with adequate data rate is always recommended from robust performance point of view. However, under unusual circumstances leading to data rates (detected from time-stamp information at both ends) below a threshold, it is preferable to switch to the proposed OSC, rather than CF and continue to benefit from wide-area information.

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