A Resilient Feedback Linearization Control Scheme for Smart Grids under Cyber-Physical Disturbances

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***Abstract*—A cyber-enabled parametric control scheme is proposed for efficient transient frequency and phase stabilization in the power grid. Different implementations of the proposed control are investigated in this work. First, a centralized control scheme is proposed where the controller relies on timely phasor measurement unit (PMU) information about the grid to employ fast-acting energy storage systems for stabilization. Further, a decentralized controller implementation assumes information about the rest of the grid is not available, and hence acts based on local PMU measurements. For the case of cyber attacks targeting communication channels and resulting in large delays or absence of PMU data, we propose a robust combined control scheme where the controller operates in a centralized mode by default and switches to the decentralized scheme if PMU information is delayed or not available. Numerical results show the effectiveness and robustness of the proposed controller against physical and cyber-physical disturbances in the 39-bus 10-generator New England power system.**

I. Introduction

Smart grid systems combine control, communications and sensor technologies for an enhanced operation of the power system. Articulate sensors such as phasor measurement units (PMUs) are placed at specific locations to collect timely information about the system operation. The cyber communication network then transmits the collected measurements to related controllers, where the controllers analyze the data to determine the sequence of actions that need to be applied to improve the power system operation.

The incorporation of advanced telemetry devices and communication technologies in the cyber-physical smart grid has motivated the development and design of various new and non-traditional controllers. Several wide area monitoring and control systems have evolved as a result. Additionally, controllers can being utilized to enhance the overall resilience of the smart grid to traditional abnormalities and to new vulnerabilities such as cyber attacks.

Recently, Wei *et al.* [1] employed the concept of flocking in multi-agent systems for the design of distributed controllers that address transient stability of synchronous generators against faults. Real-time PMU data of all synchronous generators is employed in [1]–[3] to compute control actions that are actuated via fast-acting energy storage systems. Further, the recent work of Andreasson *et al.* [4]–[6] proposed using a consensus proportional integral (CPI) control scheme to affect the mechanical power of a generator in order to achieve an automatic frequency control strategy; the CPI controller needs to collect the frequency of all system generators in order to find the value of the control output.

From a multi-agent system view, control approaches classify into three schemes based on how much sensor data needs to be collected for the controller input [7]. A centralized control requires complete sensor data of the system to enable efficient control strategies. However, sensor data is conveyed through communication channels as a cyber media; consequently, sensor data is vulnerable to delays and possible cyber attacks. This motivates distributed and decentralized schemes of control. A distributed control relies on data from a subset (neighbours) of the agents in the system to calculate its control action, and a decentralized control follows a worst-case scenario and acts independently based on local measurements only. There are essential tradeoffs between the three schemes in terms of performance, complexity, and robustness.

In this paper we present a low-complexity cyber-enabled parametric controller that easily integrates with generator governor control. The proposed solution utilizes external power sources to achieve transient frequency stability and phase cohesiveness among generators. To achieve stability, sensor measurements are periodically communicated to controllers that then actuate change through fast-acting power injection and absorption entities such as flywheels. The actuation stabilizes the power grid by shaping the dynamics of the closed-loop system to resemble that of a series of stable decoupled linear systems with tunable eigenvalues. Feedback linearization control theory is used to convert the nonlinear power system into an equivalent linear system. Feedback linearization was previously investigated for transient voltage stability in [8] to control the excitation system of the generators in a decentralized approach.

We develop centralized and decentralized versions of the parametric feedback linearization controller. Numerical analysis are conducted to compare the centralized and decentralized schemes using the 39-bus 10-generator New England power system. We also proposes a combined control that switches from the more efficient centralized control into the decentralized control when sensor data is critically delayed or not available during, for example, a denial-of-service (DoS) attack, communication channel congestion or outage. The proposed combined control exhibits a robust and efficient performance of the overall system against severe cyber-physical disturbances.

Contributions of this work include proposing a centralized

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and decentralized feedback linearization control schemes for smart grids to achieve transient frequency stability and phase cohesiveness. Further, a combined control scheme is proposed for robustness against cyber-physical attacks. Moreover, a comparative performance analysis of the control schemes is provided.

The rest of this paper is organized as follows. The problem setting is presented in Section II and the proposed controller is detailed in Section III. Section IV investigates the performance of the proposed controller. Conclusions and final remarks are discussed in Section V.

II. Problem Setup

We model the smart grid as a multi-agent system with N *agents*, where each agent contains a synchronous generator, a PMU that measures the corresponding generator's rotor angle and frequency, and a controller that utilizes the PMU data to control a local fast-acting power injection and absorption energy storage system (ESS) such as a flywheel. In addition, a communication network connects the system's PMUs and controllers. The overall smart grid is a cyber-physical system in which the physical subsystem includes the classical power delivery components as well as the fast-acting ESS, and the cyber subsystem contains the PMU sensors, controllers, and the associated communication network.

In the considered system the dynamics of each agent depend on its own state and the states of the other agents in the multi-agent system. In such setting, a centralized control refers to a scheme where the states of all the agents in the system need to be collected. For a distributed control the controller of a certain agent needs the state of that agent and its neighbors, and a decentralized control scheme requires only the local state of its own agent to be observed. Fig. 1 depicts the centralized and decentralized control schemes [7] cinsidered in this paper.

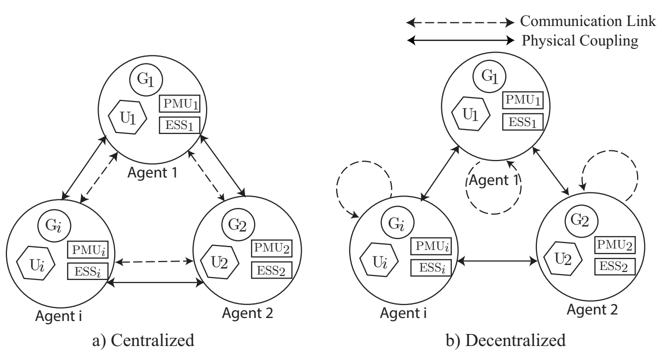

Fig. 1. Centralized Vs. Decentralized Control

We consider the New England 10-generator 39-bus physical power system.We use the swing equation model to describe physical synchronous generator dynamics. The time evolution of the rotor's angle and frequency in the swing equation model enables the study of transient stability. We assume the swing equation parameters remain constant through the system instability duration. We further utilize Kron-reduction to reduce the order of the interconnections in the power system and determine effective mutual physical couplings between the synchronous generators. Kron-reduction is a graph-based technique used in power systems to reduce the order of an complex interconnected system [9] into an equivalent grid between generators.

Let N denote the number of generators in the power system (i.e., N = 10). And let E_i represent the internal voltage of Generator i,every Generator i $\forall i \in \{1, \ldots, N\}$ is described by its rotor angle (δ_i), relative normalized rotor frequency (ω_i), inertia (M_i), damping coefficient (D_i), and electrical and mechanical powers ($P_{e,i}$, $P_{m,i}$) respectively.

We define the relative normalized frequency of Generator i as $\omega_i = \frac{\omega_i^{act} - \omega^{nom}}{\omega^{nom}}$, where ω^{nom} is the nominal angular frequency (in radians per second) of the power system and ω_i^{act} is the actual angular frequency of Generator i. Define $\dot{\delta}_i$ and $\dot{\omega}_i$ to be the derivatives of δ_i and ω_i with respect to time, respectively. Then, the swing equation for Generator i is expressed as [10], [11]

$$\begin{aligned} \dot{\delta}_i &= \omega_i \\ M_i\,\dot{\omega}_i &= -D_i\,\omega_i + (P_{m,i} - P_{e,i}) \ , \end{aligned} \tag{1}$$

where the electrical power of Generator i is defined as [12]

$$\begin{aligned} P_{e,i} = \sum_{k=1}^{N} \ & |E_i|\,|E_k|\,[G_{ik}\cos(\delta_i - \delta_k) + \\ & B_{ik}\sin(\delta_i - \delta_k)] \ , \end{aligned} \tag{2}$$

here $G_{ik} = G_{ki} \geq 0$ and $B_{ik} = B_{ki} > 0$ are the Kron-reduced equivalent conductance and susceptance, respectively, between Generators i and k. Further, we assume that there is no power control in the system. Let $P_{a,i} = P_{m,i} - P_{e,i}$ denote the accelerating power of Generator i, then the swing equation in Eq. (1) is represented as

$$\begin{aligned} \dot{\delta}_i &= \omega_i \\ \dot{\omega}_i &= \frac{1}{M_i}\left[-D_i\,\omega_i + P_{a,i}\right] \ . \end{aligned} \tag{3}$$

We next introduce the proposed cyber-enabled controller that facilitates the overall cyber-physical smart grid system to achieve stability against disturbances.

III. Cyber-Enabled Control for Smart Grid

Synchronous generators typically utilize power control schemes (e.g. exciter and governor controls) to help adjust a generator's internal settings to respond to dynamics in the power grid. However, these local power control systems are often insufficient because of their slow reaction to rapid system-wide changes. Moreover, synchronous generators, without external power control as described in Eq. (3), cannot achieve transient stability alone in the presence of a fault or when a fault is cleared after the critical clearing time either due to a malfunction or cyber attack. We develop a parametric feedback linearization (PFL) controller that utilizes an external power source at Generator i to achieve transient stability. Thus, the swing equation for Generator i after including PFL control input U_i becomes

$$\begin{array}{rcl} \dot{\delta}_i & = & \omega_i \\ \dot{\omega}_i & = & \frac{1}{M_i}\left[-D_i\,\omega_i + P_{a,i} + U_i\right] . \end{array} \quad (4)$$

The proposed controller responds to the dynamics of the power system by absorbing or injecting a specified amount of real power, this is facilitated by the incorporation of a fast-acting ESS at the designated generator. Specifically, a positive U_i value would correspond to the controller of Generator i injecting power into the generator bus, and a negative U_i value indicates that power is being absorbed from the generator bus.

The PFL controller is designed to asymptotically drive the frequency of the system generators into stability following the occurrence of a disturbance; i.e., after the activation of the PFL controller it is required that $\lim_{t\to\infty} \omega_i(t) = 0\ \forall i \in \{1,\ldots,N\}$. Additionally, the PFL controller is to maintain phase cohesiveness between the generators of the power system, the absolute difference between the phases of any two generators should be less than $100°$ [1], [13].

Feedback control depends on measurements from the system to generate the control signal required to drive the overall system (or one of the system variables) into a desirable state. In feedback control the controller compares the measured value with a desired value, and consequently generate a control signal to minimize the difference. Feedback linearization [14, Ch. 13] transforms a nonlinear plant into an equivalent closed-loop linear system. One approach to implement feedback linearization is to introduce a control signal to cancel out the nonlinear terms in the system dynamics, this would result in the closed-loop system exhibiting (full or partial) linear dynamics.

We next detail the design of the proposed centralized and decentralized control schemes.

A. Centralized Control Scheme

A centralized parametric feedback linearization (CPFL) controller relies on receiving timely PMU measurements from all generators in the power system to calculate the control action. Mathematically, the CPFL control for frequency stability and phase cohesion is expressed as

$$U_i = -\left(P_{a,i} + \alpha_i\,\omega_i + \beta_i\,(\delta_i - \delta_i^*)\right) , \quad (5)$$

where $\alpha_i \geq 0$ is called the frequency stability parameter, $\beta_i \geq 0$ is the phase stability parameter, and $\boldsymbol{\delta}^* = [\delta_1^*, \delta_2^*, \ldots, \delta_N^*]^T$ is the desired phase of the system generators. The $\beta_i\,(\delta_i - \delta_i^*)$ term will drive the CPFL controller to settle the phase of the system generators on $\boldsymbol{\delta}^*$. The values of $\boldsymbol{\delta}^*$ are selected such that $|\delta_i^* - \delta_j^*| \leq 100°\ \forall i,j \in \{1,\ldots,N\}$. Consequently, phase cohesiveness is maintained during and after the controller's active time.

The CPFL control will fully cancel the nonlinear terms in the swing equation provided that all PMU measurements are obtained. Consequently, the swing equation of the interconnected power system reduces into a *decoupled* linear equation after implementing the CPFL controller.

We next present the stability analysis of the CPFL control. Substituting the CPFL control in Eq. (5) into the swing equation in Eq. (4) results in

$$\dot{x}_i = A_i\,x_i + b_i\,\delta_i^* , \quad (6)$$

where $x_i = [\delta_i, \omega_i]^T$ is called the state variable of Generator i, $b_i = \left[0, \frac{\beta_i}{M_i}\right]^T$, and $A_i = \begin{bmatrix} 0 & 1 \\ \frac{-\beta_i}{M_i} & \frac{-(D_i+\alpha_i)}{M_i} \end{bmatrix}$. To check the stability of the power system after implementing the proposed CPFL control, the eigenvalues of A_i are calculated and checked to determine if they lie in the left-hand complex plane. The eigenvalues of A_i are calculated as

$$\lambda_{1,2} = \frac{1}{2M_i}\left[-(D_i+\alpha_i) \pm \sqrt{(D_i+\alpha_i)^2 - 4\beta_i M_i}\right] . \quad (7)$$

When evaluated, both eigenvalues are found to lie in the left-hand complex plane. Further, $\mathrm{Re}(\lambda_{1,2}) < 0$; consequently, the power system is globally asymptotically stable under the proposed CPFL controller [14, Theorem 4.5].

B. Decentralized Control Scheme

As previously motivated in Section I, the cyber communication channels relaying PMU measurements from sensors to the controllers are vulnerable to congestion or DoS attacks. A decentralized PFL (DPFL) controller only utilizes the measurements from the PMU situated near the local generator bus. Mathematically, the DPFL control is expressed as

$$U_i = -\left(\alpha_i \omega_i + \beta_i(\delta_i - \delta_i^*)\right) . \quad (8)$$

The DPFL control utilizes local measurements only, and as a result the accelerating power term ($P_{a,i}$) cannot be estimated and consequently cannot be cancelled, resulting in a partially linearized control system.

Next, we present the stability analysis of the DPFL control. Similar to our analysis for the CPFL control, the following is found as we substitute Eq. (8) into Eq. (4)

$$\dot{x}_i = A_i\,x_i + b_i\,\delta_i^* + \left[0, \frac{1}{M_i}\right]^T P_{a,i} . \quad (9)$$

Using the approximations for the relevant terms in $P_{e,i}$ in Eq. (2), it can be shown that $P_{a,i}$ reduces to

$$P_{a,i} \approx P_{m,i} - \delta_i \Delta_i + \Delta_k , \quad (10)$$

where $\Delta_i = \sum_{k\neq i}^{N} |E_i|\,|E_k|B_{ik}$ and $\Delta_k = \sum_{k\neq i}^{N} |E_i|\,|E_k|B_{ik}\delta_k$. Consequently,

$$\dot{x}_i = \hat{A}_i\,x_i + b_i\,\delta_i^* + \left[0, \frac{P_m + \Delta_k}{M_i}\right]^T , \quad (11)$$

where $\hat{A}_i = \begin{bmatrix} 0 & 1 \\ \frac{-(\Delta_i+\beta_i)}{M_i} & \frac{-(D_i+\alpha_i)}{M_i} \end{bmatrix}$. The above equation takes the form of Eq. (6). To check the stability of the power system after implementing the proposed DPFL controller, the eigenvalues of $\hat{A}_i$ are calculated as

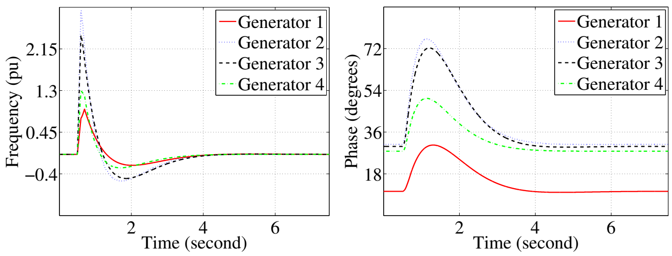

Fig. 2. System performance when CPFL control is activated

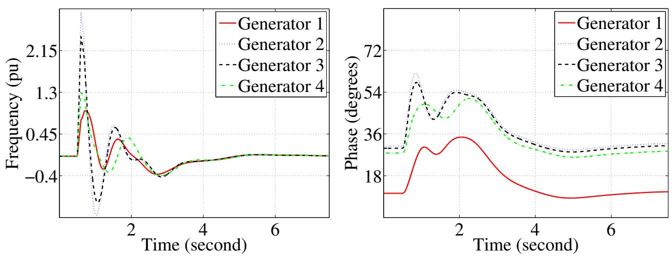

Fig. 3. System performance when DPFL control is activated

$$\lambda_{1,2} = \frac{1}{2M_i}\left[-(D_i+\alpha_i)\pm\sqrt{(D_i+\alpha_i)^2-4M_i\beta_i\Delta_k}\right]. \quad (12)$$

Both eigenvalues are found to lie in the left-hand complex plane. Consequently, the power system is stable under the proposed DPFL controller.

C. Combined Centralized-Decentralized Control Scheme

We propose the combined centralized-decentralized PFL (CDPFL) controller as a mediator solution for the power system when communication latency or DoS attack impacts the cyber-enabled centralized control performance. While cyber-enabled centralized control is efficient and effective, the delay or lack of PMU information hinders it highly ineffective. An intuitive approach is to switch from centralized to decentralized control in the absence of PMU information; hence, we propose the combined mode of our PFL control.

Let $\tau \geq 0$ be the latency between the PMUs and the controller, and let τ^* denote the maximum latency below which the CPFL control can effectively stabilize the system. The proposed CDPFL is then expressed as

$$U_i = \begin{cases} -\left(P_{a,i} + \alpha_i\omega_i + \beta_i(\delta_i - \delta_i^*)\right) & \text{if } \tau < \tau^* \text{ (CPFL)} \\ -\left(\alpha_i\omega_i + \beta_i(\delta_i - \delta_i^*)\right) & \text{if } \tau \geq \tau^* \text{ (DPFL).} \end{cases} \quad (13)$$

It is important to observe that the CDPFL control waits until τ^* before activating the DPFL control, and this results in a considerable deviation in the system state following the disturbance. To address this issue, the parameter α_i can be optimized for a more aggressive control action to stabilize the power system.

Generator	CPFL Control	DPFL Control	CPFL & Governor	DPFL & Governor
1	3.3244	5.5922	3.2769	6.0496
2	3.5231	5.4885	3.4676	6.0210
3	3.4860	5.4782	3.4415	6.0279
4	3.1767	5.4031	3.1156	6.0314
5	3.0014	5.3857	2.9388	6.0270
6	3.2762	5.3972	3.2278	6.0333
7	3.1423	5.3985	3.0783	6.0308
8	2.9837	5.5162	2.9093	6.0451
9	3.1847	5.4103	3.1329	6.0430

TABLE I
STABILITY TIME (SECOND)

Case Study	CPFL Control	DPFL Control	CPFL & Governor	DPFL & Governor
1	3.2332	5.4522	3.1765	6.0343
2	2.8495	3.9111	2.7879	5.1188
3	2.9183	3.9749	2.8588	5.3608
4	2.9552	5.3177	2.8987	6.0039

TABLE II
AVERAGE STABILITY TIME (SECOND)

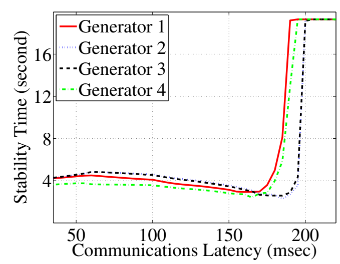

Fig. 4. Performance of the CPFL control versus communication latency

IV. NUMERICAL RESULTS

The different PFL control schemes proposed in this work are numerically evaluated. The CPFL and DPFL controls are first evaluated for different balanced three phases faults with and without the governor control activated at the generators. A robustness analysis of the CDPFL control against cyber-physical disturbances is also conducted.

For the following numerical results, the stability time of a Generator i is the time it takes the controller to keep the frequency stable (i.e., $|\omega_i| \leq 0.02$) permanently. Further, for the purpose of clarity, the following figures show the performance results for the first four synchronous generators; however, similar behaviour is observed for the rest of the generators.

The New England power system is considered. The power system is assumed to be running in normal secure state from $t = 0$ to $t = 0.5$ seconds. However, a balanced three-phase fault occurs at Bus 17 at $t = 0.5$ seconds. Then, Line 17–18 is tripped out to clear the fault at $t = 0.6$ seconds. Finally, the PFL controller is activated on all generators at $t = 0.7$ seconds.

For the balanced three-phase fault detailed above, the frequency and phase of the first four generators in the New England power system are shown in Fig. 2 for the case when the CPFL control is activated. Moreover, Fig. 3 shows the frequency and phase of the system generators under the same

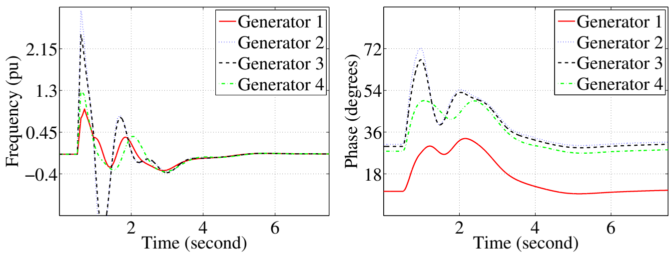

Fig. 5. System performance when CDPFL control is activated during a cyber-physical disturbance

fault scenario with DPFL control activated. Compared to the DPFL controller, these results show that CPFL control scheme achieves more efficient performance.

As a summary of the above numerical results, a detailed record of the stability time of each generator (except Generator 10) in the New England power system is shown in Table I. The stability time is shown for the proposed CPFL and DPFL control with and without the generators' governor activated.

In addition, Table II shows the average stability time of the system generators (except Generator 10) under different cases of faults. In this table, Case Study 1 refers to the previously studied case (i.e., a three-phase fault occurs at Bus 17 at t = 0.5 seconds, Line 17–18 is tripped out at t = 0.6 seconds, and the controller is activated at t = 0.7 seconds). Further, Case Study 2 represents the situation when a fault occurs at Bus 11 then Line 10–11 is tripped out. Moreover, a three-phase fault occurs at Bus 22 and Line 21–22 is tripped out in Case Study 3. Finally, the fault is located in Bus 39 and Line 28–39 is tripped out to clear the fault in Case Study 4.

We further investigate the performance of the CPFL controller versus communication links latency that affect the PMU measurements arrival time at the controllers. Fig. 4 shows that beyond a certain latency value (around 170 msec in this case), the stability time jumps from about 4 seconds to around 18 seconds (the simulation duration). In other words, if the latency is above this value, the CPFL controller cannot stabilize the power system.

Motivated by this analysis we investigate the CDPFL control for the aforementioned system against a cyber-physical disturbance. Similar to Case Study 1, a physical fault occurs in the power system at t = 0.5 seconds, the CPFL control is activated at t = 0.7 seconds, and a worst-case cyber attack (where all communication links to the control center are jammed or under DoS attacks) occurs at t = 0.8 seconds. The CDPFL controller tolerates a wait period of τ^* = 150 msec before switching to DPFL at t = 0.95 seconds. The proposed CDPFL is shown to be able to stabilize the power system under the worst-case DoS scenario as shown in Fig. 5.

V. Conclusions

This paper proposes a frequency and phase stabilizing controller for smart grid systems under severe fault or malfunction of protection devices. The design of the proposed parametric controller is motivated by the feedback linearization control theory, and the controller relies on receiving frequent system state information to actuate fast-acting energy storages to balance the swing equation and drive the power system to stability. The controller is evaluated under centralized and decentralized system designs, and further a combined centralized-decentralized control scheme is proposed to enhance robustness against long communication delays or denial-of-service attacks.

System performance is investigated when the proposed controller is applied to the New England 39-bus 10-generator power system. Further, the performance is studied when both the proposed and governor controls are activated in the power system. Results of this work show the effectiveness of the proposed controller in stabilizing the power grid and making it more resilient to cyber-physical disturbances.

Acknowledgments

This work was supported by the National Science Foundation under grant ECCS-1028246 and the Natural Sciences and Engineering Research Council of Canada.

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