Distributed Design of Smart Grids for Large-Scalability and Evolution

Tomonori Sadamoto, Takayuki Ishizaki and Jun-ichi Imura

Abstract Due to the massive complexity and organizational differences of future power grids, the notion of *distributed design* becomes more significant in a near future. The distributed design is a new notion of system design in which we individually design local subsystems and independently connect each of them to a pre-existing system. In this article, we discuss challenges and opportunities for solving problems of the distributed design of smart grids so that they are flexible to incorporate regional and organizational differences, resilient to undesirable incidents, and able to facilitate addition and modifications of grid components.

Keywords Distributed design · Controllability · Interoperability
Resiliency · Power system evolution · Plug-and-play capability

1 Introduction

Toward the realization of low-carbon society, activities for the development of smart grids have been growing in the world. Although there is no exact definition of smart grids, anticipated benefits and requirements of smart grids are shown in the report from National Institute of Standards and Technology (NIST) [1]. Following this report, in this article, we focus on the three requirements below.

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1. Smart grids should be flexible to incorporate regional and organizational differences.
2. Smart grids should be operated resiliently to disturbances, attacks, and natural disasters.
3. Smart grids should facilitate addition and modification of system components.

How should we design smart grids satisfying these requirements? One may consider two approaches: *centralized design* and *distributed design*.

The centralized design is a notion of system design in which we design an overall system from the scratch. Examples of the centralized design include stabilizing controller design based on the entire power system model. The centralized design needs both of the full knowledge of the entire system and powerful authority that can construct the entire system from scratch. However, due to the massive complexity and organizational differences of power grids, this approach is impossible.

The distributed design is another notion of system design in which we individually design local subsystems and independently connect each of them to a preexisting system. Examples of the distributed design include local-controllers design based on partial models of a power system, e.g., single-machine-infinite-bus models in which the machine's behavior depending on grid behavior variation is completely neglected. The notion of this distributed design in the control community has been proposed in [2]. We note here that the distributed design is a different notion of traditional distributed control in the literature [3, 4]. In the distributed control, input signals of local controllers are determined individually, but the controllers are designed jointly, with access to the entire system model. On the other hand, in the distributed design of local controllers, not only the controllers' actuation, but also their design is performed individually. Thus, owing to the distributed nature of the design process, this distributed design approach would suit for the construction of large-scale and complex network systems like power grids [5]. Nevertheless, the distributed design theory has not yet been established, and there exist open problems.

This article aims to summarize challenges and opportunities to fulfill the aforementioned three requirements from a viewpoint of the distributed design. This article is organized as follows.

In Sect. 2, we discuss a problem of the distributed design of local controllers to satisfy requirement 1 for a power system with photovoltaic (PV) integration. First, we show a numerical simulation illustrating how the PV integration has an influence on the centralized and distributed design of controllers. The PV penetration causes reduction of system inertia [6, 7], resulting in the enhancement of the system controllability. As a result, in the distributed design case, the transient instability tends to be induced as the inertia reduction because negative effects of the unmodeled dynamics can be more strongly stimulated by the controllers due to higher controllability. Thus, we need a systematic mechanism enabling us the distributed design of local controllers to accomplish a global objective without causing transient instability of power grids. Next, we discuss challenges and opportunities for solving this issue.

In Sect. 3, we consider a problem to make power grids resilient, described as requirement 2. Following [8], in this article, we define resilient systems as systems that can maintain an acceptable level of operation in face of spatially local undesirable incidents. In this section, first, the significance of resilient system design is shown through numerical simulation of wind-integrated power systems. More specifically, we show that faults at wind farms cause serious oscillation in power flow of the entire power system due to a resonance mode of wind farms. Next, we consider a problem of the distributed design of local controllers so that each of them can make the associated local subsystem resilient, and discuss challenges and opportunities to solve the problem.

In Sect. 4, we discuss a problem to satisfy requirement 3. Examples of this power system evolution include penetration of distributed energy resources (DERs), upgrade of power electronics facilities such as transmission lines, and construction of new power plants. The entire power system must adopt such evolution while maintaining transient stability and performance without any additional configuration of the preexisting power system. However, so far, control theory does not have paid much attention to the characteristics of systems' long-term evolution, but studied evolved system. In this section, we focus on evolution aspects of power grids, and briefly discuss challenges and opportunities for such power grid evolution.

Finally, concluding remarks are provided in Sect. 5.

2 Distributed Design of Local Controllers to Incorporate Regional and Organizational Differences

2.1 Motivating Example

In this subsection, we compare the centralized and distributed design of local controllers for two types of power systems having different system inertia caused by different levels of PV penetration [6, 7].

First, we consider a simple power system example composed of five synchronous generators and two loads without any PV farms, as shown in Fig. 1. The synchronous generators are modeled as the combination of electromechanical swing dynamics

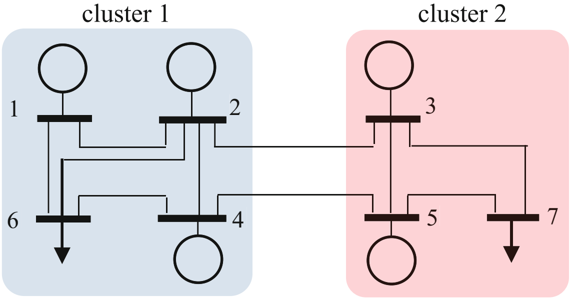


Fig. 1 Power system model composed of five generators and two loads, each of which is denoted by the circles and arrows, respectively

with a second-order governor, and the loads are modeled as dynamical loads whose dynamics are also swing dynamics. For $l \in \{1, 2\}$, we denote the lth cluster dynamics by

$$\begin{aligned} \Sigma_{[1]} &: \begin{cases} \dot{x}_{[1]} = A_{[1]}x_{[1]} + A_{[1,2]}x_{[2]} + B_{[1]}u_{[1]} \\ y_{[1]} = C_{[1]}x_{[1]} \end{cases} \\ \Sigma_{[2]} &: \begin{cases} \dot{x}_{[2]} = A_{[2]}x_{[2]} + A_{[2,1]}x_{[1]} + B_{[2]}u_{[2]} \\ y_{[2]} = C_{[2]}x_{[2]}. \end{cases} \end{aligned} \tag{1}$$

For this power system model, we consider quantifying influence of the lth cluster dynamics on the kth cluster from a viewpoint of controllability. To this end, we define Q_{lk} as the $\mathcal{H}_2$-norm of the system whose input is the lth cluster subsystem and the output is the frequency of all generators and loads inside the kth cluster. Note that the value of Q_{lk} can be regarded as a measure of the controllability of u_l on Σ_k. The values of Q_{lk} for $l = 1$ are

$$Q_{11} = 0.13, \quad Q_{12} = 0.007.$$

By comparing them, we can see that the controllability of $u_{[1]}$ on $\Sigma_{[2]}$ is much lower than that on $\Sigma_{[1]}$. Similarly, we have found that the controllability of $u_{[2]}$ on $\Sigma_{[1]}$ is also much lower than that on $\Sigma_{[2]}$. These results imply that $\Sigma_{[1]}$ and $\Sigma_{[2]}$ are almost decoupled from the viewpoint of the controllability with respect to $u_{[1]}$ and $u_{[2]}$.

We compare the control performance achieved by the following two types of controllers:

- An ensemble of two controllers each of which is designed based on the lth isolated cluster dynamics ($\Sigma_{[l]}$ with $A_{[l,k]} = 0,\ k \neq l$), i.e., $K_{\mathrm{D}} := \{K_{[1]}, K_{[2]}\}$, where

  $$K_{[l]} : \begin{cases} \dot{\xi}_{[l]} = A_{[l]}\xi_{[l]} + B_{[l]}u_{[l]} + H_{[l]}(y_{[l]} - C_{[l]}\xi_{[l]}) \\ u_{[l]} = F_{[l]}\xi_{[l]} \end{cases}, \quad l \in \{1, 2\}. \tag{2}$$

  In (2), $F_{[l]}$ and $H_{[l]}$ are found such that $A_{[l]} + B_{[l]}F_{[l]}$ and $A_{[l]} - H_{[l]}C_{[l]}$ are Hurwitz, respectively.
- A controller based on the entire system model, i.e.,

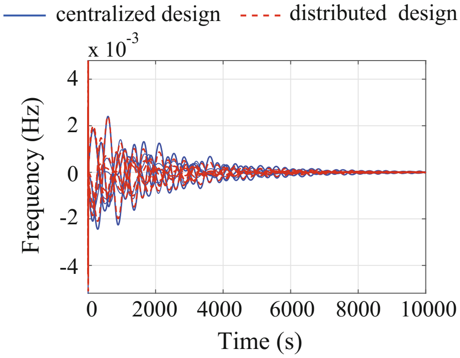
  $$K_{\mathrm{C}} : \begin{cases} \dot{\xi} = A\xi + Bu + H(y - C\xi) \\ u = F\xi, \end{cases} \tag{3}$$

  with $u := [u_{[1]}^{\mathsf{T}}, u_{[2]}^{\mathsf{T}}]^{\mathsf{T}}$, $y := [y_{[1]}^{\mathsf{T}}, y_{[2]}^{\mathsf{T}}]^{\mathsf{T}}$ and

  $$A := \begin{bmatrix} A_{[1]} & A_{[1,2]} \\ A_{[2,1]} & A_{[2]} \end{bmatrix}, B := \begin{bmatrix} B_{[1]} & \\ & B_{[2]} \end{bmatrix}, C := \begin{bmatrix} C_{[1]} & \\ & C_{[2]} \end{bmatrix},$$

  where F and H are found such that $A + BF$ and $A - HC$ are Hurwitz, respectively.

Fig. 2 Trajectories of frequency of all generators and loads



As we have described in Sect. 1, the former partial-model-based controller design is distributed design of local controllers while the latter full-model-based controller design is centralized design of a centralized controller. In Fig. 2, the red dotted lines and blue solid lines show the frequency of all generators and loads in the case where the decentralized controller ensemble K_{D} and the centralized controller K_{C} are used, respectively. We see that K_{D} and K_{C} can achieve comparable damping performance. To quantify this, we define a performance measure

$$J(K) := \sup_{x(0)\in\mathbb{B}} \|\omega(t)\|_{\mathcal{L}_2}, \quad K \in \{K_{\mathrm{D}}, K_{\mathrm{C}}\}, \tag{4}$$

where $\omega \in \mathbb{R}^7$ is the stacked version of the frequency of all generators and loads, and $\mathbb{B}$ is the unit ball such that all state variables excluding angles are confined to zero. The resultant values are

$$J(K_{\mathrm{D}}) = 22.26, \quad J(K_{\mathrm{C}}) = 22.26, \tag{5}$$

which are, in fact, comparable. This fact stems from the aforementioned decoupled property from a viewpoint of controllability.

Next, we investigate what happens when a large amount of PVs are penetrated. We suppose that PV farms, each of which is considered to be an aggregation of PV generators inside each farm, share buses with preexisting generators; see Fig. 3a. In this article, we suppose that the influence of this PV penetration is modeled as the decrement of the value of inertia of generators in order to reflect the fact that the large-scale penetration of PVs can cause the reduction of inertia of the overall power system [6, 7]. In this case, the metric Q_{lk} for $l = 1$ and $k \in \{1, 2\}$ are

$$Q_{11} = 8.8, \quad Q_{12} = 0.4.$$

Next, we design K_{D} in (2) and K_{C} in (3). We plot the resultant frequency trajectories in Fig. 3b. Furthermore, the resultant values of $J(\cdot)$ in (4) are

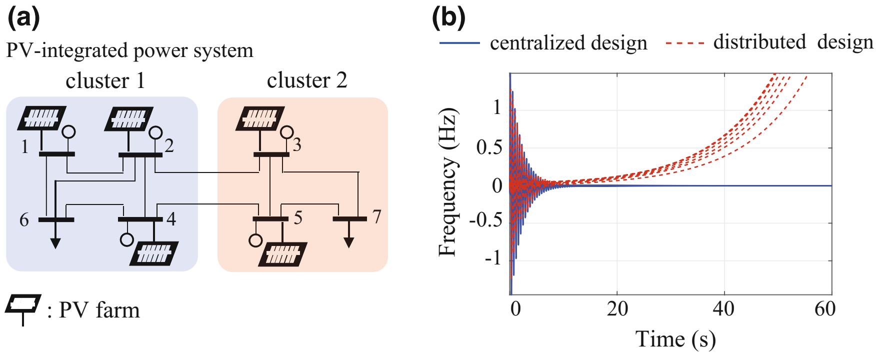


Fig. 3 (Left) Power system with large-scale PV integration. (Right) Trajectories of frequency of all generators and loads

$$J(K_{\mathrm{D}}) = \infty, \quad J(K_{\mathrm{C}}) = 16.62.$$

We can see that the value of $J(K_{\mathrm{C}})$ is smaller than that in (5). This performance improvement stems from the fact that the usual notion of controllability is higher than that in the previous case owing to smaller inertia constants. However, K_{D} destabilizes the system. This discrepancy comes from the fact that the interference between the two clusters, neglected in the design of each decentralized controller, is more strongly induced due to the higher controllability of $u_{[1]}$ on $\Sigma_{[2]}$ and that of $u_{[2]}$ on $\Sigma_{[1]}$.

2.2 *Challenges and Opportunities*

Through the above example, we found that

1. the reduction of the generator inertia enhances system controllability,
2. the centralized design of a centralized controller has the potential to utilize enhanced controllability for control performance improvement, and
3. the distributed design of decentralized controllers may induce instability due to the interference among clusters when the controllability with respect to each cluster is not sufficiently small.

Fact 3 is more significant toward the implementation of smart grids because typical controller design approaches taken in power community are some special cases of this distributed design. An example of such approaches is power system stabilizer (PSS) design [9, 10] based on a single-machine-infinite-bus model, where the behavior of that model is isolated from the other grid dynamics by neglecting the bus voltage variation. However, as we have shown in numerical simulation, such distributed design may pose serious threat to the power system stability in a future smart grid. Therefore, it is crucial to develop a method of distributed design of decentralized controllers so that they can accomplish a global objective such as damping performance of all generators' frequency while guaranteeing the stability of the entire closed-loop system.

Furthermore, it would be meaningful to discuss how to make clusters, i.e., how to partition a system of interest into clusters, for achieving better control performance. To find an optimal (or suboptimal) cluster set, it would be important to consider the controllability as discussed in the motivation example. Furthermore, it would be also significant to clarify what information is needed for finding an optimal (or suboptimal) cluster set.

An open problem related to this optimal clustering is optimal DERs allocation in power grids. The location of DERs has an influence on steady-state power flow of a grid, thereby influencing the grid characteristics such as transient stability and controllability. Thus, in order to solve optimal allocation problems, it would be necessary to reveal the relationship between those dynamical characteristics and power flow.

3 Resilient System Design

3.1 Motivating Example

In this subsection, we numerically investigate how the wind farm dynamics has an impact on the resilience of wind-integrated power systems. We consider an IEEE 68-bus power system with the integration of a single wind farm, as shown in Fig. 4. The generator model is the combination of the standard flux-decay model [9] and an automatic voltage regulator (AVR) with PSS, and the loads are modeled as constant power loads. Following [11], the wind farm can be regarded as an aggregated wind generator whose output power is the total power of wind generators inside the farm. The aggregated model consists of a wind turbine, doubly fed induction generator (DFIG), and an internal controller; see [12] for the modeling details.

Figure 5 shows the trajectories of all generators' frequency when a fault happens at the wind farm. The blue solid and red dotted lines are the cases where the number of wind generators inside the farm is small and large, respectively. We can see from this figure that the entire power system becomes more oscillatory when a larger scale wind farm is penetrated. In other words, a power grid with large-scale wind penetration has less resilience against a fault at the wind farm. This observation was also shown in a slightly different context in [13]. This oscillation induction is due to the fact that the impact caused by the fault is more strongly stimulated by the resonance mode of DFIG, thereby causing the oscillation of power flow of the entire system; see [12] for more detail discussion.

One option to combat this oscillatory behavior is to tune the PI gains of the internal controller in the wind farm. However, such tuning must be done extremely carefully with full knowledge of the entire closed-loop model, because both low and

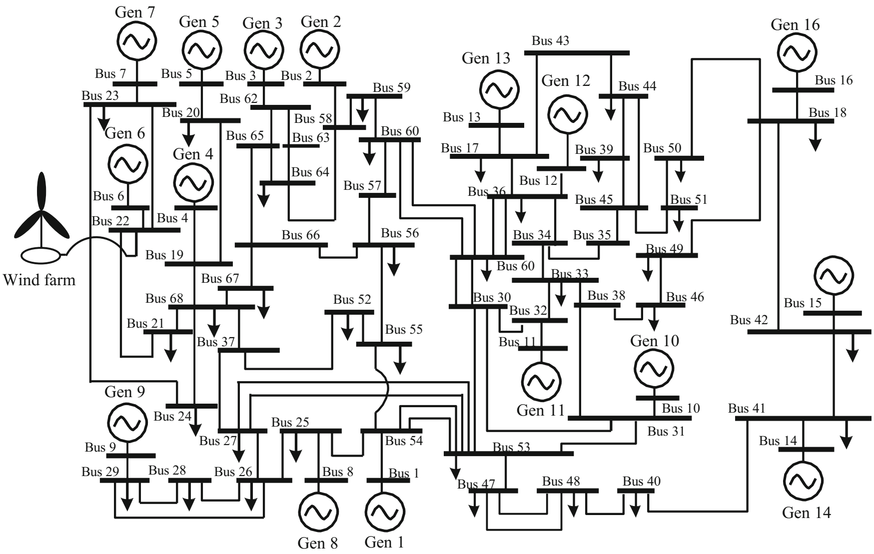


Fig. 4 IEEE 68-bus power system with a single wind farm

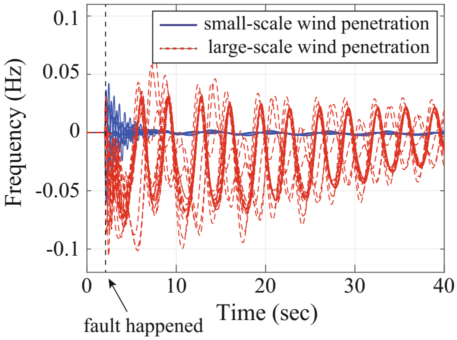


Fig. 5 Trajectories of all generators' frequency when fault happened at wind farm

high values of these gains can jeopardize closed-loop stability. These observations motivate us for building a much more systematic method of the distributed design of controllers by which the resilience of the wind farm can be enhanced in a desired way.

3.2 Challenges and Opportunities

The concept of resilient system design has been introduced in [14]. In [8], the authors have discussed a conceptual property of resilient control systems. As a similar concept to resilience, the authors in [15] have proposed a notion called intelligent balancing authority which is a portfolio of power system equipment responsible for having adequate control to ensure stability and good dynamic response of their own areas. However, it is still an open problem how we design resilient control systems.

Although there is no common definition of resilience, one can define resilient systems as systems that can maintain an acceptable level of operation in the face of spatially local undesirable incidents. As a related work for enhancing resilience in this sense, in [16] the authors have proposed a method called *retrofit control* to improve a performance of spatially local subsystems against local faults. An advantage of this method is that the retrofit controller can be designed based on the model of a local subsystem of interest without any knowledge about the entire system model. Furthermore, retrofit controllers do not have any influence on each other. Indeed, when a fault happens at a certain subsystem, only the corresponding retrofit controller improves damping as soon as it is activated while the other retrofit controllers are inactivated. Therefore, the distributed design of retrofit controllers enjoys a natural decoupling property from one subsystem to another. Future works of this retrofit control include robustness analysis of retrofit controllers against uncertainty of the local subsystem.

4 Challenges and Opportunities for Power Grid Evolution

We deal with power grids' long-term evolution such as the penetration of DERs, as shown in Fig. 6. The entire power system must adopt such evolution while maintaining transient stability and functions of the entire system, without additional configuration of the preexisting power system. So far, control theory does not have paid much attention to the characteristics of systems' long-term evolution. However, in order to establish a mechanism so that power grids can facilitate addition and modification of system components, it would be necessary to develop a theory for explicitly dealing with systems' long-term evolution. We briefly discuss challenges and opportunities for this issue.

So far, power grids have been evolved with the advance of human civilization. However, large-scale blackouts sometimes happen around the world, which shows the vulnerability of power systems. Cascading failure is regarded as one of the main mechanism of large blackouts [17]. Toward the development of power grids that can decrease the risk of cascading failures, in [18], the authors have proposed power grid

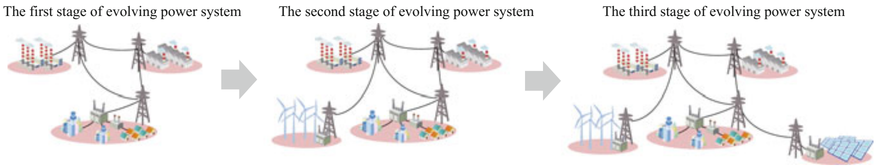


Fig. 6 Illustrative example of power system evolution

evolution models where new power plants and substations are constructed according to a rule reflecting practical power system planning, and have evaluated the probability of cascading failures from a viewpoint of Self-Organized Criticality (SOC) theory in complex network analysis. However, since the proposed models represent the transition of static power systems without any dynamics such as generator dynamics, we cannot evaluate dynamical characteristics such as transient stability. How to describe the long-term transition of dynamical systems is a question that deserves to be further studied.

In order to facilitate the addition of new components, it would be desirable that newly added components have interchangeability or plug-and-play capability [1]. A challenge for the systematic design of interchangeable components is to reveal the class of such components as well as a portfolio to be imposed on the interconnection of the components to preexisting grids. Related works on this topic are as follows. In [19], the authors have proposed a strategy for constructing a large-scale network system while keeping an expanding system stable. It is shown that the entire closed-loop system is stable as long as strictly passive subsystems are interconnected via a passive interconnection. One approach for a broader class of systems can be found in [20]. In this approach, we consider a module consisting of the newly added component satisfying a matching condition and a compensator. It is shown that the evolving network system keeps its stability as long as each module is connected to the associated subsystem such that the local closed-loop system composed of these two systems is stable. These approaches show particular sufficient conditions of components and interconnection rules for guaranteeing the stability of evolving network systems. Further studies to reveal the class of interchangeable components and interconnection rules are necessary.

The evolution of practical power systems is not a self-organized process in a strict sense, but is a process containing feedback mechanism performed by human industrial activities. For example, when a new power plant is constructed today, the amount of power consumption around the new power plant will increase tomorrow, resulting in the need of further evolution of the power system such as upgrade of the transmission line. Such feedback mechanism needs to be introduced to evolution process in order to realize the intelligent power grid's adaptation [18].

5 Conclusion

Smart grid can be regarded as an electric system integrated across electricity generation, transmission, substations, distribution, and consumption, to achieve that the grid is not only clean and stable, but also interoperable, resilient, and changeable. Due to the massive complexity and organizational differences of future power grids, it is impossible to construct such smart grids from the scratch. Instead, an approach what we can take practically is the distributed design of grid components. In view of this, in this article, we have discussed challenges and opportunities for solving the following three problems. First, to make grids flexible to incorporate regional and organizational differences, we have considered a problem of the distributed design of local controllers accomplishing a global objective by cooperating each other. Next, we have considered distributed design of decentralized controllers so that they can individually enhance resilience of associated subsystems. Furthermore, we have discussed long-term grids' evolution caused by addition or modifications of grid components, and have considered the distributed design of components having plug-and-play capability.

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