Control of Synchronization in Two-Layer Power Grids

Simona Olmi
Istituto dei Sistemi Complessi
CNR - Consiglio Nazionale delle Ricerche
Sesto Fiorentino, Italy
email:simona.olmi@fi.isc.cnr.it
ORCID 0000-0002-8272-3493

Carl H. Totz
Institut für Theoretische Physik
Technische Universität Berlin
Berlin, Germany
email:carl.hendrik@web.de

Eckehard Schöll
Institut für Theoretische Physik
Technische Universität Berlin
Berlin, Germany
Potsdam Institute for Climate Impact Research
Potsdam, Germany
email:schoell@physik.tu-berlin.de
ORCID 0000-0002-7318-2672

***Abstract*—In this work, we suggest to model the dynamics of power grids in terms of a two-layer network, and use the Italian high voltage power grid as a proof-of-principle example. The first layer in our model represents the power grid consisting of generators and consumers, while the second layer represents a dynamic communication network that serves as a controller of the first layer. In particular, the dynamics of the power grid is modelled by the Kuramoto model with inertia, while the communication layer provides a control signal P_i^c for each generator to improve frequency synchronization within the power grid. We propose different realizations of the communication layer topology and different ways to calculate the control signal. Then, we conduct a systematic survey of the two-layer system against a multitude of different realistic perturbation scenarios, such as disconnecting generators, increasing demand of consumers, or generators with stochastic power output. When using a control topology that allows all generators to exchange information, we find that a control scheme aimed to minimize the frequency difference between adjacent nodes operates very efficiently even against the worst scenarios with the strongest perturbations.**
***Keywords*-nonlinear complex networks; power grids; synchronization; stability analysis; control**

I. INTRODUCTION

Global warming, the growing world population and power demand, with a subsequent increase in carbon power emissions, have provoked governments and energy utilities to take solid steps towards the use of renewable energies [1] and their integration within the existing power transmission and distribution systems, thus challenging scientific and technological research towards the goal of increasing the efficiency and flexibility of the power system [2]–[5]. The existing power grid was developed using a centralistic approach, therefore we have a few very high-power ac plants operating at 50 or 60 Hz interconnected by ac or dc transmission systems operating at very high voltages (e.g., 400 kV) and many substations, where the high voltage is transformed to the distribution level (e.g., 20 kV). In order to distribute the power in a capillary way, a huge number of distribution lines is present, supplying the loads directly (in the case of high-power loads) or after voltage transformation in the case of residential or low-power industrial loads (e.g., 400 V in Europe). Recently, renewable energy generators, which produce a few kilowatts in the case of residential photovoltaic systems, up to some megawatts in the case of large photovoltaic and wind generators, have become widely dispersed around the world, thus transforming the present power system into a large-scale distributed generation system incorporating thousands of generators, characterized by different technologies, voltage, current, and power levels, as well as topologies [6] [7]. Hence, their integration with the existing network is fundamentally changing the whole electrical power system [8] [3]: the drawback of renewable energy power plants is that their output is subject to environmental fluctuations outside of human control, i.e., clouds blocking the sun or lack of wind, and these fluctuations emerge on all timescales displaying non-Gaussian behaviour [9] [10]. In addition, these issues are further complicated by the aging infrastructure of the existing power grid, which already cause problems to utilities and customers, providing low power quality at increasing cost. In particular, the power grid infrastructure is very critical and contains a large number of interconnected components: generators, power transformers, and distribution feeders that are geographically spread. Moreover, its increasing complexity and geographical spread, and the side effects caused by the high penetration of renewable, stochastically fluctuating energy generators make it very vulnerable, both from the point of view of required sophisticated security mechanisms [11] and from the point of view of dynamic stability, since renewable sources are usually employed by microgrids in isolated modes to maintain their capability of connecting and disconnecting from the grid [12]. Due to the design of the current power grid as a centralized system where the electric power flows unidirectional through transmission and distribution lines from power plants to the customer, the control is concentrated in central locations and only partially in substations, while remote ends, like loads, are almost or totally passive. Therefore, it is necessary to design new systems that provide more effective and widely distributed intelligent control embedded in local electricity production, two-way electricity and information flows, thus achieving flexible, efficient, economic, and secure power delivery [13]. The new approach, widely known as Smart Grid [14], requires both a complex two-way communication infrastructure, sustaining power flow between intelligent components, and sophisticated computing and information technologies, as well as business applications. The new approach will include grid energy storage, needed for load balancing and for overcoming energy fluctuations caused by the intrinsic nature of renewable energy sources, in addition to preventing widespread power grid cascading failures [15]

[16]. In particular, control is needed in power networks in order to assure stability and to avoid power breakdowns or cascading failures: one of the most important control goals is the preservation of synchronization within the whole power grid. Control mechanisms able to preserve synchronization are ordered by their time scale on which they act: the first second of the disturbance is mainly uncontrolled, and in this case a power plant will unexpectedly shut down with a subsequent shortage of power in the system, energy is drawn from the spinning reserve of the generators. Within the next seconds, the primary control sets on to stabilize the frequency and to prevent a large drop. Finally, to restore the frequency back to its nominal value of 50 (or 60) Hertz, secondary control is necessary. In many recent studies on power system dynamics and stability, the effects of control are completely neglected or only primary control is considered [17]–[22]. This control becomes less feasible if the percentage of renewable power plants increases, due to their reduced inertia [23] [24]. Few studies are devoted to secondary control [25]–[27] and to time-delayed feedback control [28]–[30].

The present extended abstract is organized as follows: In Section II we present the main results, while in Section III a discussion addressing the impact of the proposed research is presented.

II. Proposed Solution

We consider a two-layer network in a full dynamic description. It consists of a power grid layer and a communication layer, which provides the control for the power grid. Each layer is governed by its own dynamics, which is dependent upon the state of the other layer. In particular, the physical topology that relates the interconnection of distributed generators and loads is described by coupled Kuramoto phase oscillators with inertia, closely related to the swing equations [31], while the communication topology, which describes the information flow of the power system control measurements, depends on the information of the neighbors of each node [32]. Starting from the ideal synchronized state, we investigate the effect of multiple different perturbations to which the system is subject, modelling real threats to synchronization of the network, e.g., failure of nodes, increased consumer demand, power plants with stochastically fluctuating output. To describe the fluctuating power output of renewable energy power plants both Gaussian white noise and more realistic intermittent noise have been used (see [33] for more details). For each perturbation, different setups of the communication layer are tested to find an effective control strategy that successfully preserves frequency synchronization against all applied perturbations. As a proof of concept, the Italian high voltage power grid has been considered. In the communication layer we have assumed a selection of different control schemes (control functions f_i^{diff}, f_i^{dir} and f_i^{comb}) and control topologies (adjacency matrices c_{ij}^{loc} and c_{ij}^{ext}). All control schemes take advantage of the second layer by collecting information from adjacent nodes to calculate the control signal. This can be done either in a local setting (c_{ij}^{loc}) where generators possess the same communication links as in the power grid layer, or in an extended control layer topology (c_{ij}^{ext}) where additional communication links between all generators are present. We have tested (i) a control scheme aimed at synchronizing the frequency of the controlled nodes with their neighbors (difference control f^{diff}), (ii) a control scheme aimed at restoring the original synchronization frequency in the neighborhood of the controlled node (direct control f^{dir}), and (iii) a mixed approach combining both (f^{comb}). The only control scheme being able to effectively counteract all of the perturbations is the difference control scheme f^{diff} in the extended control topology, while the direct control has some advantages in the local control topology only. Moreover, the calculation of different topological measures shows that nodes in the power grid layer which are more affected by perturbations are not characterized, in general, by specific topological features. It turns out that the Italian power grid can be divided in two specific parts: the northern, continental part, with a higher average connectivity, which is more resilient to perturbations, and the southern, peninsular part, characterized by a low average connectivity. The elongated structure of the southern part makes it less robust to perturbations.

III. Conclusion

The aim of this work is to investigate the controllability of power networks subject to different kinds of perturbations and to develop novel control concepts considering the communication infrastructure present in the smart grid. Few works have included the communication layer into the synchronization of power networks. Even though the communication infrastructure plays an important role in control and synchronization, preliminary works [34] [35] assume trivial networks, without disconnected nodes, which, however, is of great importance in stabilizing smart grids, due to the necessity of synchronizing grids with isolated generators, microgrids, or even coupled microgrids that can be connected or disconnected to the main grid at any time. Moreover, the inclusion of a communication infrastructure has added new challenges in control and stability [36], where communication constraints emerge, e.g., time-delays, packet losses, sampling and data rate, among others, but, up to now, attention has focussed on sampling problems in order to assure that synchronization is independent on the sampling period [32]. On the other hand, the same two-layer topology, here implemented, has been already investigated in [37] to understand how localized events can present a severe danger to the stability of the whole power grid, by causing a cascade of failures, but without considering the dynamics of the control nodes. Here the focus of our investigation is on the interdependence of the communication network and the power grid: Random failure of a power plant causes the malfunction of connected elements in the communication layer. Communication nodes isolated due to the failure become inert, causing generators connected to them to shut down as well as eventually leading to a far-reaching blackout. In short, our proposed control techniques preserve synchronization for different perturbations [38], thus demonstrating the powerful perspectives of our control approach which considers synchronization of power systems based on the coupled dynamics of the smart grid architecture and the communication infrastructure.

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