Doctoral Candidacy Written Exam

Research Problems in Distributed Control for Energy Systems

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Candidacy committee

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Abstract and Problem Statement

This document is a tutorial on research problems in distributed control for energy systems. It also includes a critique of two examples papers from the area.

Keywords: distributed control, power systems, wide-area control, distributed power generation, smart power grids, grid disturbance rejection

Original problem statement:

1. *Tutorial on Research Problems in Distributed Control for Energy Systems:*

   Write (in LaTeX) a tutorial introduction to research problems in distributed control for energy systems. There are a number of examples of the need for distributed control for energy systems. There is the notion of the "smart grid" where distributed control strategies may be needed for load balancing and energy management. There are distributed energy generation strategies in a number of areas. For instance, there is a need to control individual photovoltaic modules in a large photovoltaic array. There is a need to manage a large set of wind turbines (a "wind farm"). In many of these problems there is a need for feedback control at both the individual and group level, management of the overall process, and optimization of energy gained. There is often the challenge of how to design the overall system architecture (e.g., flat or vertical hierarchy, and everything in between), and how to minimize the cost of implementation while maximizing energy gains and system reliability.

   Your goal is to identify distributed control research problems. In doing that, although your focus is not on individual level control, you should identify both local control goals (e.g., at the individual photovoltaic module level) and global ones (at the large scale interconnected system level) for each problem you identify, explain how they interact, discuss what disturbances need to be rejected, and provide a list of relevant literature in the area. Goals could include, for example, stabilization, good transient behavior, and optimization.

2. *Paper critiques:*

   You should critique the two papers by Blaabjerg et al. [11] and Tomsovic et al. [83].

You should spend 90% of your effort on (1) and only 10% on (2). You have two weeks (14 days) to complete the exam. Submit a `.pdf` to Professor Passino.

Contents

Part I

Tutorial on Research Problems in Distributed Control for Energy Systems

This tutorial describes distributed control problems in modern and future power generation, transmission, and distribution systems. It will also identify possible applications of the task-processing network (TPN) framework defined in the 2009 doctoral research proposal of Theodore Pavlic. The tutorial is split into two sections. In Section I.1, distributed control challenges are presented in the context of large interconnections of heterogeneous sources and loads. These systems have the most potential for application of the TPN framework. In Section I.2, control challenges for specific generation technologies (e.g., fuel cell, photovoltaic, and wind turbine) are investigated.

1 Grid-level Distributed Control

In this section, distributed control problems for large heterogeneous connections of sources and loads on modern and future power grids are discussed. Section I.1.1 gives a description of the conventional grid, existing resource allocation problems and their solutions, and opportunities for new allocation strategies. Then new problems introduced by distributed generation (DG) are presented in Section I.1.2. Finally, two contrary yet complementary approaches for addressing modern power problems are given in Sections I.1.3 and I.1.4; in particular, the smart grid and the microgrid are introduced. Applications of task-processing networks are given throughout the section.

1.1 The Grid: Background and Challenges

The electrical power grid[1] along with conventional power plants (e.g., fossil fuel, nuclear, and hydroelectric) are reviewed in detail by Bergen and Vittal [9]. Power is provided by large synchronous generators that provide alternating current (AC) sinusoidal voltage signals oscillating at frequency $f_0 \triangleq 60\,\text{Hz}$ with strict regulations on the maximum total harmonic distortion (THD) allowed. To reduce Ohmic transmission power loss, these relatively low voltage signals are transmitted over long distances of conductor only after being *stepped up* to very high voltages. The high voltage signals are then *stepped down* to low voltages for customer use. As a consequence, the current across the long transmission lines is only a small fraction of the corresponding customer load current; hence, transmission losses are reduced. The process of stepping up and down power signals is possible for both direct current (DC) and AC signals, but it is relatively cheap to implement for large AC signals.

Each generator provides three-phase AC power. In the ideal balanced case, a so-called *positive sequence* of equal magnitude sinusoidal signals a, b, and c are generated so that a leads b by 120° and b leads c by 120°. The three-phase generators and three-phase loads are either connected in a $\curlyvee$ (i.e., sharing a common neutral datum) or a Δ configuration (i.e., no common connection point). These line-to-line configurations allow constant instantaneous power to be delivered to loads, which is in contrast with single-phase instantaneous power that oscillates. Additionally, these configurations reduce implementation hardware as return current from one phase can be carried by conductors for the other two phases. The original motivation for three-phase power

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[1] Unless otherwise noted, examples in this document come from the large Eastern interconnection in North America.

was the three-phase synchronous AC machine, which can act like a generator or a motor with no electrical modifications and is substantially simpler to operate and maintain than DC motors and generators. However, as described in later sections of this tutorial, DC power generation, transmission, and distribution are important parts of the evolving power system. The conventional power system allows for use of DC power at customer locations; however, modern and future power system implementations will make use of DC generation, transmission and distribution (T&D) alongside traditional AC generation and T&D.

1.1.1 The Reactive Power Problem

Ohmic losses over long distances in the AC transmission system are minimized by the high voltage transmission system. However, customer loads and the transmission line itself contain loads that store rather than dissipate energy. Even when generated voltage signals are low, empty storage elements (e.g., inductors, capacitors, mechanical inertia) draw large forward currents and energized storage elements provide large reverse currents. As a consequence, the energy stored in these devices is dissipated not across customer loads but across the transmission system itself. Hence, the power delivered to customers is called *active power,* and the power dissipated in the grid due to these reflections is called *reactive power.* It is desirable to design the power grid to reduce the negative effects of reactive power. Reactive power not only fatigues the grid, but it reduces the active power available to all grid customers.

The instantaneous AC power provided to a device (or from a generator) is the product of the voltage across the device and the current through it.[2] For a single phase, under purely active conditions, the current and voltage are proportional to each other. Hence, the instantaneous single-phase power will oscillate at $2f_0$ but will always be non-negative. For any load, the *active power*, denoted by P, is the time average of the instantaneous power, and so purely dissipative loads draw strictly positive active power. However, the effect of reactive storage creates a phase difference between voltage and current. Consequently, the power signal includes both in-phase (or *direct*) and *quadrature* components. The magnitude of the quadrature component, denoted by Q, is the *reactive power.* The total power generated is $\sqrt{P^2+Q^2}$, and so any increase in Q results in a decrease in available P. In particular, it is desirable to maintain a unity *power factor*, which is defined as the ratio $P/\sqrt{P^2+Q^2}$, so that power is not wasted servicing storage elements. Additionally, the inductive reactance on a transmission line between generators on a network creates a delay that reduces stability margins on re-synchronization after a network transient (e.g., a fault from a short circuit). So effective management of reactive elements in a power network is an important design goal.

FACTS Distributed Management of Reactive Power: The *flexible AC transmission system* (FACTS) is a framework developed by the IEEE to assist power systems engineers in the development of technology for the evolving power delivery system [18, 32]. FACTS provides common definitions for distributed technologies used to manage power quality across the power grid. Historically, a static condensor (STATCON) could be added to a point in power system to provide or absorb reactive power to nearby loads [9]. The STATCON is a synchronous machine that spins freely (i.e., with no load), and the inertia in the machine serves as a reactive source or sink to the network. The function of the STATCON is controlled by the excitation signal driving it, and so it can be dynamically adjusted with changing load and generation on the surrounding grid. By managing reactive power close to reactive loads, losses in long distance transmission are avoided.

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[2] The instantaneous power provided to a three-phase device is constant; however, the constant level of power will be reduced if individual phases have strong reactive components.

The FACTS framework represents new technologies have been developed to augment and improve upon the management features provided by STATCONs. Analysis of intelligent FACTS topologies and control policies is an active area of research [17]. Distributed FACTS devices may be either remotely controlled, locally controlled, autonomous, or a combination of these. They be active during everyday operation of a power line or may be engaged only during system events like faults or heavy loads.

Two FACTS technologies that have attracted recent research attention are the static var compensator (SVC) and the static compensator (STATCOM) [5, 59]. The implementation feasibility of these technologies has been aided by advances in power electronics designed for high-speed switching of high-power signals. Like a STATCON, SVCs are distributed throughout a power grid. However, rather than generating reactive power to supply surrounding reactive loads, they themselves at as reactive loads that balance the surrounding customer loads. Hence, stored energy that would otherwise be dissipated in the transmission system is trapped and managed in these complementary storage units. Because the amount of SVC reactance required for a network is unknown and changes over time, SVCs are implemented by switching off banks of inductors and capacitors on and off the power system. Modern power electronics allow this switching to be intelligently controlled by digital signal processors (DSP). However, the technology receiving most attention in distributed management of power flow is the STATCOM, which is a modernization of a STATCON that can be implemented entirely electronically [4, 6, 30, 56, 67, 78, 84].

The basic structure of a STATCOM was developed long before FACTS [16, 54, 64, 65, 73, 76, 92]. In particular, it was recognized that inverter circuits (i.e., circuits that generate AC waveforms from DC signals using high-speed switching and filtering) could actually be used to maximize power flow from a three-phase source into the battery driving the inverter. For this reason, Smollinger and Raddi [76] insisted that these circuits should be called inverters with *reverse energy transfer* rather than be called rectifiers. That is, a traditional rectifier generates a DC signal from an AC signal whereas these circuits generate an AC signal from their DC source so that the interaction with the AC grid maximizes active power flow into the battery. In modern applications, these rectifier–inverter circuits [98] are also known as voltage source converters (VSC) [12, 21], voltage source inverters (VSI) [11, 20, 33, 84], regenerative rectifiers [71], or some derivation of those terms. These new applications do not focus on the VSC as a mechanism to maximize power flow to a DC load. Instead, they focus on using the signals generated by the VSC to replace large STATCON synchronous machines. An electronic VSC can be controlled more quickly than a STATCON and requires less hardware. When connected to a battery, they can provide active power just as a STATCON. When connected to a capacitor or other resonant links [42, 86] they can preform so-called *active filtering* [19, 29] which allows them to act like SVCs. So a STATCOM is a VSC technology that actively manages the nearby power grid like traditional STATCONs and SVCs. At the present time, the VSCs within most STATCOMs are driven by control strategies on top of pulse-width modulation (PWM) [13, 20, 22, 36, 71, 72]. There is presently very little research in developing direct inverter gate control strategies. As reviewed by Blaabjerg et al. [11], some hysteresis band switching controllers have been investigated in the past. Delta modulation [86] for inverter design has been shown in the past, and recently sigma-delta modulation [33–35] has also been shown. More recently, sliding mode [80] techniques have been demonstrated, but variable structure control [85, 96] has largely been ignored despite its obvious application for these switching systems.

FACTS Distributed Management of Power System Stability: Distributed power system stability is discussed by Bergen and Vittal [9]. In the example given, which matches others from the literature [e.g., 48], lightning strikes near a power line and ionizes the nearby air, which creates a plasma conductor between conductors for different phases. The additional energy contributed to the air from the arc between the two conductors prevents the plasma from de-ionizing, and so the short circuit is self sustaining. The power system detects this short circuit and opens nearby circuit breakers (CB) thus removing this region of the power grid from the loads serviced by a nearby fossil-fuel-powered generator. Breaking this connection to the generator not only disconnects it from other generators in which in needs to be synchronized, but it prevents mechanical energy that is stored in rotational inertia from being removed from the machine. As a consequence, the generator begins to rotate faster. If the short circuit resets sufficiently quickly and the CB closes, the generator can re-synchronize to the system; however, if the CB remains open for too long, the local generator control will be unable to stabilize the generator speed and it will not be able to re-synchronize to the power grid. In this condition, the generator will itself be removed from the power grid and manually spun up into synchronization again. Distributed control mechanisms that can improve power system stability margins (e.g., improve how long a generator can "ride through" a fault event) would be a welcome development in power system engineering.

As reviewed by Mithulananthan et al. [59], to define what it means for a CB to reset "sufficiently quickly," a rigorous analysis of an accurate mathematical model of a power system is used. In particular, power systems are modeled by a set of differential and algebraic equations (DAE) that approximate the interconnection of generators and loads in a power system. Typically these models are linearized to form ordinary differential equation (ODE) approximations of the power system around its steady-state operating point, and the stability of the resulting model is analyzed over variations in system parameters (e.g., how long the CB is open). These analyses typically lead to a discovery of Hopf bifurcation points. In the example given by Bergen and Vittal [9] above, power system model has similar dynamics as a pendulum or mass–nonlinear-spring system, and so a heteroclinic orbit surrounds the operating point. System trajectories move away from the operating point and toward the orbit as long as the CB is open. Hence, there is some critical time when the orbit is crossed and the system is unable to return to the operating point after the CB is later closed.

Conventional techniques to improve power system stability margins use lead–lag power system stabilizers (PSS) within the generator control. However, there is presently active research in using FACTS technologies to actively damp power system oscillations introduced by transient events [4, 56, 59]. Although Mithulananthan et al. [59] develop a FACTS stabilizing controller based on Hopf bifurcation analysis, Mak et al. [56] have success using fuzzy controllers to damp otherwise unstable oscillations in a simulated power system. However, it is an open question as to whether FACTS-based stabilization has an attractive cost–benefit ratio compared to conventional generator excitation PSS. Additionally, FACTS technologies are being evaluated as mechanisms for the removal of harmonic distortion and so-called flicker that is added by renewable sources and high-speed power electronics [6, 30, 67].

1.1.2 The Optimal Power Flow Problem

Optimal power flow (OPF) and distributed computation of optimal power allocation is an active area of research [43, 44]. Large scale implementation of distributed algorithms for solving OPF problems will be both complemented and complicated by the development of smart grid technologies like the ones described in Section I.1.3. In particular, large scale optimization algorithms are not possible without a large scale infrastructure. Additionally, deregulation agreements complicate the formation of optimization objectives. Here, the classical OPF problem is described along with suggestions for augmenting the methods for dynamical resource allocation. The ideal-free distribution (IFD) and task-processing network (TPN) extensions to the dispatch problem may be impractical for large scale implementation; however, they may be appropriate for application in microgrid scenarios like the ones described in Section I.1.4.

The Basic Economic Dispatch Problem: The *economic dispatch problem*, as described by Bergen and Vittal [9], is reproduced here. Over a large power grid, any particular generator can supply more or less power to the grid than any of its generator neighbors. So long as the power generated matches the power demanded, a continuum of generation profiles exists. That is, consider a power grid consisting of $m \in \mathbb{N}$ generators and $n \in \mathbb{N}$ loads where P_{G_i} is the power from generator $i \in \{1, 2, \dots, m\}$ and P_{D_j} is the power demanded by load $j \in \{1, 2, \dots, n\}$. Also let $P_{G_i}^{\min}$ and $P_{G_i}^{\max}$ be the minimum and maximum power available from generator $i \in \{1, 2, \dots, m\}$ (i.e., $P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max}$). By the conservation of power, it must be that

$$\sum_{i=1}^{m} P_{G_i} = P_D \triangleq \sum_{i=1}^{n} P_{D_i} \tag{1.1}$$

where P_D is defined to be the total power demanded[3]. For generator $i \in \{1, 2, \dots, m\}$, define function $C_i : \mathbb{R}_{\geq 0} \mapsto \mathbb{R}_{\geq 0}$ so that $C_i(P_{G_i})$ is the cost of generating P_{G_i} power. In the economic dispatch problem, the generated power profile is chosen to minimize the total cost

$$C_T \triangleq \sum_{i=1}^{m} C_i(P_{G_i}). \tag{1.2}$$

As shown by Bergen and Vittal [9] using a Lagrange multiplier method, a necessary condition for the solution of this problem is that Expression (1.1) holds and there exists a constant $\lambda \in \mathbb{R}$ such that

$$\frac{\mathrm{d}C_i(P_{G_i})}{\mathrm{d}P_{G_i}} = \lambda$$

for all $i \in \{1, 2, \dots, m\}$ with $P_{G_i} \in (P_{G_i}^{\min}, P_{G_i}^{\max})$. That is, at the optimal solution, the generators not operating at their limits will all have equal *incremental cost*. Pareto optimal solutions that minimize the cost function in Expression (1.2) only make sense within a single regulated entity. Under deregulation, areas under the control of one organization may not participate in large-scale allocation for cost minimization. In particular, efficient entities that would ramp up production in a Pareto optimal solution may have little incentive to do if the increased production only minimizes a foreign entity's costs. Hence, development of methods that encourage customer-optimal allocations of power under a deregulated generation environment is an interesting research area. However, within a single entity, the economic dispatch problem may accurately model how power could be allocated.

Economic Dispatch as IFD: Although it has not been discussed in the power literature, the economic dispatch problem above is identical to the *ideal free distribution* first described by Fretwell and Lucas [25]. Quijano and Passino [68] develop replicator dynamics that stabilize an ideal free distribution and show how the result can be used to dynamically allocate resources in a temperature control application. A similar application of the IFD to power systems could provide dynamic reallocation of power generation based on changing power demands.

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[3] The problem can be reformulated to handle transmission line losses, but the result is similar, and so the lossless problem is presented here for simplicity.

TPN Alternative to Economic Dispatch: In the economic dispatch problem, the optimal power profile mirrors the intrinsic generation cost profile. That is, the economic allocation ignores any local priorities that are not encapsulated in each generator's cost function. The formulation of the economic dispatch problem given by Bergen and Vittal [9] that accounts for line losses does reformulate the optimal solution based on local and remote line losses. However, there may be other factors that make local generation a priority. For example, in a network of deregulated power generation units, it may not be possible to minimize cost across all units because of their diverse ownership. Additionally, generation to local customer loads may be prioritized over inter-agency load demand. Additionally, as small distributed generators come on and off line, solutions that come from decentralized algorithms may be desirable. Hence, the problem of optimal power dispatch is an opportunity for the application of a task-processing network (TPN). In particular, rather than considering task encounter rates at each agent (e.g., tasks per second), a power system TPN would see demanded load at each agent (e.g., Joules per second). The local agent would be responsible for providing this load, but it would request power generation from its connected cooperators. Those cooperators would then choose a fraction of the requested load to service. Because the TPN framework requires that each task is processed once by a single agent in the network (i.e., tasks cannot be duplicated or dropped as in cooperative packet forwarding networks), the balance between demanded power and generated power will still be met. Large deregulated power systems can relay demanded power from one region across several interconnected generation units until the desired generator very far away, and hence TPNs for power generation may need to be enhanced to allow for relaying of tasks. Again, even if TPN formulation is impractical for large scale implementation, it may be ideal for a microgrid scenario like the ones defined below in Section I.1.4.

1.2 Impact of Distributed Generation on a Fault-Tolerant Grid

All of the conventional power generation and management technologies discussed thus far have been called *distributed.* However, the term *distributed generation* (DG) has emerged to describe atypical power generation by relatively small units [1, 7, 40, 48, 66, 75, 82, 89, 95]. However, the definition of DG is unclear and may be a moving target. Ackermann et al. [1] show nine different ways of defining exactly what DG is (e.g., by location, by technology, by power output, by voltage level, by penetration) and show that several definitions exist within each category. Pepermans et al. [66] review the myriad DG definitions and show that the only common aspect of the definitions involve a connection to the central power grid, but this assertion seems to exclude some of the new microgrid applications described in Section I.1.4. For this purpose of this review, a unit providing DG is loosely defined to be a small power generation unit added to an existing large power system. The DG unit is not centrally controlled and functions to provide power to the local loads around it. Distributed control issues involving specific types of DG units (e.g., photovoltaic, wind turbine, fuel cell) are discussed in Section I.2. Here, the general problem of DG on a fault-tolerant grid is investigated.

Optimal DG Placement: Advocates of DG suggested that it may be used to increase the local capacity of a power system. For example, Wang and Nehrir [89] investigate the optimal placement of a DG unit in a radial feeder (i.e., a leg of the power system that is fed at one end by a generator of the electric utility). In their model, different load profiles combined with power transmission losses along the leg make some generation sites better than others. They then show how a similar procedure predicts the optimal DG placement in more complex power system topologies. However, in one of the many examples given by Barker and de Mello [7] about the dangers of DG, they show that distributed generation can interfere with power quality mechanisms already built into the power system, and that interference leads to a degradation of system performance. In their example, a monitoring system at the head of the radian leg adjusts a transformer tap to raise the voltage level on the feeder as necessary. A nearby DG raises the voltage in the vicinity of the monitoring hardware, and so the appropriate tap change is not made. Hence, any strategy for the optimal placement of DG must also consider the DG effect on management mechanisms as well.

Effect of DG on Transient System Stability: A more significant issue in the placement of DG units within the power system is how DG impairs the system's ability to recover from faults. Kumpulainen and Kauhaniemi [48] describe the same fault condition as given in Section I.1.1.1. That is, a line-to-line short circuit condition is introduced into the power system by a plasma of ionized air between adjacent conductors. The arc is self sustaining, and so the traditional method of clearing the short is to separate the fault from all sources of power and provide enough time for the air to de-ionize. After cleared, the region of the fault can be reconnected to the system. If the load is disconnected from the system for too long, the inertia in nearby generators can lead to instability, and so it is important for fault-protection breakers to open and close automatically and be open for as little time as possible. Nearby DG units complicate this process because they continue to provide fault current even after the main circuit breaker has opened. Hence, the DG can extend the time the breaker stays open and may lead to long outages. Additionally, DG that is separated from faulted loads can itself be made unstable by long outages and then drag the connected power system with it. Kumpulainen and Kauhaniemi provide some simulations demonstrating these negative effects in a radial leg of a power system. However, Slootweg and King [75] show in a more sophisticated simulation that the effect of DG on transient stability is unclear. In each of their simulations, a realistic power system that is commonly used for transient analysis is augmented with a different type of distributed generator at a different location and then is subjected to a fault which does not vary across simulations. The fault leads to automatic opening, correction, and reclosing, and the the transient response of each utility generator is captured. Based on the transient response data, Slootweg and King draw conclusions about the positive and negative effects of DG when compared to a case without DG. For example, it is shown that asynchronous generators (i.e., squirrel cage induction generators) do not have much influence on transient stability because their design naturally reduces generated power when the synchronous frequency of the system increases; the additional load due to the reduction in DG generation retards the rate that the utility's synchronous generators move toward the Hopf bifurcation point. Hence, better analytical techniques need to be introduced to allow for the rigorous investigation of the dynamic behaviors of power systems made up of heterogeneous distributed generation.

Fault Detection and Operation: The continuous operation of a DG unit after a protection breaker has been opened is known as *islanding*. Some of the possible deleterious effects of islanding on transient stability have already been discussed. Islanded generation can also be a safety risk to utility workers who are unaware that the power system is still energized near the fault. Additionally, the accumulated phase and frequency differences between utility generation and DG can lead to conditions that can damage the DG unit, the background power system, or both [7]. Hence, so-called *anti-islanding* strategies that are able to detect and remove the DG after a fault or protection event are under active development [40, 95]. The main challenge to anti-islanding is detecting when an island has been created. Strategies typically use utility voltage and frequency information to estimate the state of the utility connection. To evaluate the various different anti-islanding strategies, the *nondetection zone* (NDZ) metric has been developed [95]. Good anti-islanding schemes will have a small NDZ measure. Alternatively, assuming that a fault will not be removed from a system, Timbus et al. [82] and Blaabjerg et al. [11] have suggested VSC-implementable mechanisms that alter the operation of DG during faults so that service need not be removed entirely. In the transient analysis of Slootweg and King [75], power electronic converters (e.g., grid-connected VSC systems) are shown to have a desirable effect on power system stability due to their ability to so quickly disconnect from the system; however, they are also criticized for causing such a severe drop in voltage leading to other undesirable effects (like the tripping of generators at sites that must remain available during outages). Hence, further analysis may show that the intelligent fault mechanisms suggested by Timbus et al. and Blaabjerg et al. may be able to provide good transient stability performance without leading to negative effects of complete voltage cutout. Thus, development of of control and estimation strategies during fault conditions is an active area of distributed power system research.

1.3 The Smart Grid

The so-called *smart (power) grid* has recently received much attention from media and policy makers, but what defines a smart grid has changed over time and in some cases has become too broad to be useful [e.g., 61]. Early smart grid references [2, 88] envision a collection of intelligent agents managing the power grid that have the ability to self heal after fault events. As described by Amin and Wollenberg [2], local self-interested agents (e.g., software operating at each utility station) would cooperate and compete (just as in a TPN) to achieve global goals. The power grid would normally be controlled by a central authority, but during faults these agents would activate, coordinate as necessary, and bring the grid back into an operational state. No specific technologies are suggested for achieving these goals, but the self-healing mechanisms in an F-15 fighter jet are used as an example. A similar notion of a smart grid is given by Vu et al. [88], who actually refer to a *Self-Managing And Reliable Transmission* (SMART) grid. In their view, the SMART grid will not only respond to faults but use distributed information to predict faults before they occur (i.e., they will measure effective load and source impedances and attempt to avoid maximum power conditions that occur when they cross). Again, no specific technologies are given, but there is an emphasis on the development of monitoring and control for protection. Recent developments in framing the definition of a smart grid have focussed less on automatic control and protection and more on infrastructure development and monitoring. As discussed by Hauser et al. [31] and Tomsovic et al. [83], advanced control techniques are not possible without major infrastructure developments, and that infrastructure will itself motivate new ideas about what is possible in the smart grid.

Demand Response: Most recent definitions of the smart grid [e.g., 23, 27, 38, 61, 69, 79, 87] are not motivated by protection but by efficient management of resources. Some [27, 87] list the escalating price and scarcity of crude oil as driving the need for distributed small-scale generation from renewable sources. To reduce the dependence on fossil-fuel-based generation and to better match the smaller capacity of the distributed renewable sources, there is a common push for so-called *demand response* (DR) mechanisms that increase efficiency and shape power *demand* rather than supply. Development of DR mechanisms rely on a so-called *advanced metering infrastructure* (AMI) that is able to measure and relay information about the the power usage of individual devices. If these measurements were readily available to customers, aggressive pricing schemes could encourage customers to shape their own demand. In such a smart metered grid, some devices (e.g., smart thermostats) could respond automatically in real time to utility power price changes. These distributed decision-making policies will need to be designed carefully to establish both stability of the price of power as well as stable availability of power. Alternatively (or in conjunction with), so-called *advanced meter reading* (AMR) techniques could allow for remote control of loads [69], and so the central utility could have some control over individual customer devices. The complexity of customer power management might drive some customers to join diversified load pools that guarantee a certain amount of service, and the management of the asset portfolio of these pools suggests both optimization and control challenges.

HEV as TPN Agent: The (hybrid) electric vehicle (EV) is a resource driving smart grid development [38, 79, 87]. In particular, mass adoption of EVs will put a major strain on the power grid unless their charge cycles are managed carefully. These vehicles could be charged during off-peak hours (e.g., at night) and actually serve important storage functions when not in use during the day. Power generation from renewable sources like wind turbines (WT) is known to fluctuate rapidly. In the case of wind turbines, not only does power generation increase with wind speed, but it cuts off abruptly above a certain wind speed in order to prevent mechanical damage to the turbine. So a power grid dependent upon WT generation will need to be able to ramp up power from storage to compensate for generation losses. Electric vehicles have batteries that are specially designed for rapid discharge, and future EV will have the bidirectional power ability. Because battery discharge fatigues customer batteries and inconveniences the customer, the power company must compensate the customer when the EV is allowed for use as auxiliary grid storage. Additionally, a customer equipped with local solar or wind power generation may use the EV to improve local power availability during low generation. So the vehicle has the ability to process requests from the power grid, but its priority is servicing its owner. Thus, devices like the EV are modeled well by cooperator agents in a TPN. The economic compensation from the power utility matches the cooperation payment provided by conveyors in a TPN.

1.4 MicroGrids

The smart grids described in Section I.1.3 are all in the context of a large onerous infrastructure that does not presently exist and will be challenging to design and implement itself. Innovation in this new infrastructure will not only be burdened by its structure but also by regulatory mechanisms to ensure safety and quality of service. Hence, Lasseter [50] has proposed the *microgrid*, which provides a convenient place for renewable DG units to be integrated and for diverse innovative technologies to be introduced. Rather than attempting to integrate generators and loads into an existing large power system, microgrid design builds a cluster of small sources, storage systems, and loads that is self sufficient. The microgrid interfaces with the grid, but only for economic benefit. That is, microgrid gateway providers buy and sell energy to and from the large power grid as necessary, but all loads within the microgrid are powered from sources that are also within the microgrid. Only surplus power leaves the microgrid, and power from the large grid is only imported when there are deficits in local sources. From the viewpoint of the utility, the entire microgrid is a single customer.

By design, individual microgrids are less complex than the large utility grid and allow for centralized control of all power units within the grid. Hence, generation, storage, and demand (GSD) strategies that might otherwise be impractical or impossible to implement on the power grid can not only be developed but tested in the laboratory on real hardware [15, 51, 53]. For example, Dimeas and Hatziargyriou [15] develop a microgrid that features distributed software control, management, and ancillary agents that use market operations to make resource allocation decisions within the microgrid. Additionally, this system, which is far from being implementable on the large power grid, is tested experimentally on hardware in a laboratory. Li et al. [53] develop an entirely different microgrid control system and also are able to test its viability in an actual laboratory experiment. Likewise, a TPN for cooperative distribution of power could be built entirely within a microgrid framework, simulated, and then tested within the laboratory and compared to other microgrid designs. Hence, microgrids not only suggest new power system control strategies, but they also provide for their rapid prototyping and implementation. An effective microgrid strategy from the laboratory could be implemented on a larger scale within a small portion of a corporate campus and grown as desired.

2 Source-level Distributed Control

In this section, distributed control challenges are discussed at the level of particular generation technologies. In particular, photovoltaic (PV), wind turbine (WT), and fuel cell (FC) technologies are investigated. To maximize instantaneous power output and minimize overall wear on each generation unit, distributed automated control policies are required. Blaabjerg et al. [10] review the common electronic structures used to gather and distribute power from these three technologies. A challenge common to all three technologies is how to aggregate multiple sources and how to pick the coarseness of the control and power conversion electronics. In particular, when an array of generation units is combined, electronics at each unit can guarantee maximal power out of that particular unit. However, it is costly and sometimes impractical to implement such a fine-grained power conversions strategy. Hence, units can be physically connected and the group is controlled by a single power conversion unit. In these configurations, combined units share some variable (e.g., current, voltage, or synchronous speed) and thus the common variable must be picked to maximize the power out of the aggregate but may sacrifice maximal power out of each individual unit.

As discussed above in Section I.1.1.1 for the case of STATCOMs, modern voltage source converters (VSC) manage banks of DC power to generate flexible three phase power like a power plant. FC and PV technologies naturally generate DC, and so VSCs are typically used to connect these sources to the power grid. Additionally, directly coupling the AC power that is generated directly from WT technologies removes the ability to control active and reactive power injected onto the grid. So unless otherwise noted, it is assumed that distribution of power onto the grid is handled by a VSC. As discussed by Krein et al. [47], the use of a VSC has the added benefit of decoupling generation control from output control, and so designing a control strategy to maximize power output is greatly simplified. Likewise, the development of VSC topologies and control policies that efficiently manage stored power from renewable sources while also maintaining high grid power quality (e.g., low harmonic distortion, unity power factor, low flicker) is an active area of research [3, 8, 10, 11, 14, 28, 37, 47, 57, 58, 78, 81, 90, 91, 94] which overlaps with the STATCOM and VSC development discussed in Section I.1.1.1.

Each power maximization problem is a special case of the problem depicted in Figure 2.1. The open-circuit voltage across the generator is V_s, which is a function of parameter vector $\underline{\lambda}$ (e.g., solar insolation, temperature, wind speed, etc.). The generated current i induces parasitic loading across intrinsic series resistance r_s that is also a function of vector $\underline{\lambda}$. The remaining voltage $(V_s - r_s i)$ is placed across the charging system, which is shown as a variable resistor R_L that is tuned with control u to maximize delivered power. To maximize instantaneous power delivered to R_L, the control policy u must maintain $R_L = r_s$ at all times. A true power control system implements R_L with a current source that maintains a voltage–current ratio of R_L. That current is then moved into a storage device that can be managed by the grid-connected VSC.

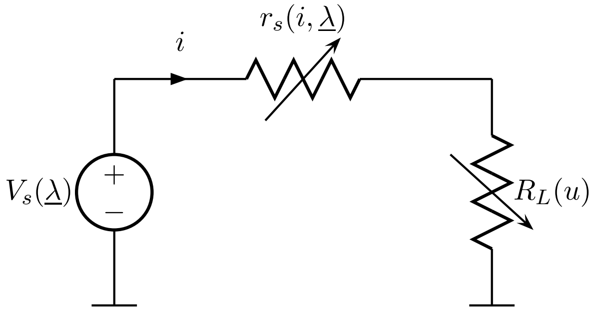

Figure 2.1: The general maximum power problem.

2.1 Fuel Cells

As reviewed by Krein et al. [47], the fuel cell source impedance r_s is primarily a function of FC current i and available fuel flow. Each fuel cell has an open-circuit voltage near $1.2\,\mathrm{V_{DC}}$; however, the source impedance r_s is such that the voltage initially drops quickly as current is increased out of the cell. The voltage eventually plummets, but there is a large region (e.g., 2–6 A) centered around $0.6\,\mathrm{V_{DC}}$ in which the voltage–current ratio is approximately linear with shallow slope (i.e., low resistance). Hence, FC operated in this region can generate significant power. Increasing the fuel flow rate through the cell not only decreases the resistance of the operating region, but it also increases its size (i.e., current range).

Given the fuel flow and a mathematical model of the cell [e.g., 26], the optimal current i^* can be found easily. When fuel cell current and grid output current are coupled, a control system must actively direct current into and out of an adjacent battery to regulate the current out of the FC to the optimal current i^*. Alternatively, flow slowly varying FC loads, the fuel flow rate can be controlled to track power demand. However, in cases with a grid-connected VSC that manages grid current from stored power, maximal power output from the FC can be attained by maximizing fuel flow rate. Because VSC topologies can decouple FC current control and grid current control, sophisticated current tracking technology is not required at the FC level [3, 10, 47, 94].

Practical VSC implementations that store and transmit power from an FC to a power grid require FC stacks of 24–48 $\mathrm{V_{DC}}$. Thus, if the cells in these stacks do not have identical source impedance curves, the aggregate optimal power output will be less than the sum of the optimal power output over all cells. Reviewed literature does not reference how individual fuel flow rate control might be used to improve this situation. That is, it may be possible to adjust fuel flow rates independently in each cell in the stack so that each cell is running closer to its optimal power point. In particular, fuel need not be wasted on greatly reducing the source impedance of a cell that is upstream of another cell with poor source impedance. Developing methods to simultaneously finding and stabilizing the optimal fuel flow rate and corresponding maximum current output during real-time operation may be a valuable research direction. However, if components of FC stacks are relatively homogenous throughout the lifetime of the stack, there may be little to gain from optimizing the fuel flow rate profile.

2.2 Photovoltaic

On the surface, PV power generation is similar to FC power generation. They both produce DC power and require regulating output current for maximum power output. However, whereas FC source impedance is set primarily by the fuel flow rate and output current, PV source impedance r_s varies with output current, solar insolation, and temperature [41, 52, 77, 93]. Solar insolation is subject to seasonal, daily, and even instantaneous variations, and these variations cannot be assumed to be homogeneous across an array. For example, clouds and other obstructions can cause asymmetric shading over a large array [62]. Further, losses generated within the PV cells as well as the power conversion units that are converted into heat may cause additional fluctuations in PV source impedance. Additionally, if the PV current control is not decoupled from the load current (e.g., by a VSC), load variations will also perturb the optimal strategy.

Hence, the major problem in PV power management is so-called *maximum power point tracking* (MPPT), which describes methods that are able to track the maximum output power as it rapidly varies throughout operation of a PV array. Variations on the so-called *perturb and observe* (P&O) method are popular [49, 62, 74]. Without a model of PV dynamics, these methods periodically adjust their operating voltages or currents to test the response of the PV array. Based on the response, the operating point is modified to maximize instantaneous power output. The classical P&O methods could be tricked to move in the wrong direction on the power curve when subjected to shading variations from (e.g., from moving clouds). So other similar methods [49, 55, 93, 97] were developed to be robust to these environmental variations. As all of these methods are special forms of numerical optimization that operate without a model of the PV array, it is necessary that they oscillate around their operating point in order to gain information about the changing power curve. However, some recent methods [52, 70, 77] are informed by models of PV dynamics and attempt to do MPPT more efficiently.

Regardless of MPPT strategy, PV units together into an array is a non-trivial task. As discussed by [10], current can transfer from one PV cell to another if two cells (or series strings of cells) with asymmetric generation are connected in parallel. Placing diodes within each string to prevent reverse current solves this problem, but these diodes dissipate heat for forward current. Hence, modern PV converters are modular and meant to manage a single series string of a PV array. These modulator converters can then be connected to a common AC or DC bus. However, within each series string, the aggregate optimization problem as described in Section I.2.1 as a relatively minor problem for fuel cells is a major concern for PV arrays. The PV cells within any series combination may each have very different maximum power points (MPP) either due to manufacturing to environmental variations. Hence, the series connection of cells may have a different optimal current than each individual cell, and the difference between the aggregate optimal current and the individual currents can vary rapidly over time. Thus, Femia et al. [24] describe a *distributed maximum power point tracking* (MPPT) approach that installs MPPT control mechanisms called *self-controlled PV modules* (SCPVM) at each individual PV unit. Those PV units are then connected to a common DC bus that is grid-connected by a VSC. For reasons described here, it is likely that SCPVM-like solutions will be common in future PV installations, and so single-cell PV controller design is a valuable area of research.

Additional research problems in PV generation include the development of MPPT algorithms with reduced sensor requirements [63]. Likewise, observers for solar array current are also being developed [45, 46]. As SCPVM-like solutions are developed, it seems likely that they will be able to estimate current and future environmental conditions using distributed sensor and computational resources.

2.3 Wind Turbine

A review of WT power generation topologies is given by Baroudi et al. [8]. WT power generation problems are analogous to PV generation problems when electrical variables are recast in a mechanical context. In particular, just as each PV cell has an optimal current that varies with solar insolation, each WT has an optimal rotational speed that varies with wind speed [8, 90].

However, large mechanical WT units have rated torque and speed limits [60, 91]. The WT units can be damaged outside these limits. Hence, efficient WT power generation involves regulating WT speed to generate maximum power while operating within rated limits. The latter goal is often accomplished by using active and passive stall techniques [10, 60]. As wind speed increases toward the ends of operating limits, either mechanical design of the blades or active control of the pitch angle introduces stall that prevents the capture of wind energy but reduces the risk to damage of the WT. Speed control of the WT depends on the particular generator and power electronics. As reviewed by Blaabjerg et al. [11], generators connected without power electronics to the grid must be mechanically designed (e.g., with gear boxes) so that the synchronous frequency of the AC grid matched to the normal wind speed of the area. Not only do these single-frequency configurations generate suboptimal power during wind gusts, but the mechanical stress of operating at the synchronous frequency is detrimental to the WT units. By adding power electronics between the power grid and the WT units, variable frequency control is possible; however, there are additional losses in the power units. As with PV units, variable frequency control allows for MPP tracking. MPP tracking algorithms like the one given by Wang and Chang [90] resemble MPPT algorithms for PV. Additionally, like the cases discussed for FC and PV, different units connected to a single FC farm may have different optimal operating speeds. Hence, Blaabjerg et al. [10] envisions wind farm arrangements like the SCPVM PV array arrangements suggested by Femia et al. [24]. Such arrangements, which come at the cost of increased power electronics, allow for fine grained control of each WT to maximize power output while also improving power quality. Thus a valuable research direction is to develop model-based control of wind turbine speed to track the MPP at an individual WT.

Part II
Critique of two relevant papers

Here, papers by Blaabjerg et al. [11] and Tomsovic et al. [83] are critiqued. The major contribution of both papers is a survey of the state of the art in distributed power system control. However, Blaabjerg et al. [11] address the design of specific local controllers for different types of renewable energy source connected to a distributed power generation system whereas Tomsovic et al. [83] focus supervisory control of large interconnected power systems. When necessary, Tomsovic et al. examine the effects of supervisory control in the context of conventional power generation (i.e., engines with adequate sources of energy that can be governor controlled, like fossil-fuel-based generators), but renewable sources are largely ignored. Hence, the two papers address distributed power generation from opposite ends of a bottom-up–top-down spectrum. The critique in Section II.3 discusses the bottom-up discussion of grid-side renewable energy converters by Blaabjerg et al. [11], and the critique in Section II.4 discusses the top-down discussion of supervisory control and developments in power system middleware by Tomsovic et al. [83]. In both sections, the summary and criticism are separated as subsections.

3 Distributed Power Generation from Renewable Sources

3.1 Summary

The paper by Blaabjerg et al. [11] is largely an overview of synchronous, stationary, and natural reference frame control of grid-side DC–AC inverters connected to renewable energy sources. The authors start by arguing that renewable energy sources will inevitably displace fossil-fuel-based sources. Using this assumption as motivation, they then review the basic structures of the modern systems used to extract energy from fuel cell (FC), photovoltaic (PV), and wind turbine (WT) sources to be used on a connected utility grid. It is shown that in all three cases, a direct-current–alternating-current (DC–AC) connection to the grid is a necessity. Each of the DC–AC methods discussed involve a two-level pulse-width-modulation (PWM) voltage-source inverter circuit. That is, the circuit generates its oscillatory harmonics by switching the polarity of its DC input, and any unwanted higher harmonics are neutralized with resonant (e.g., LCL) filtering. The authors acknowledge that multilevel PWM (e.g., positive, negative, and neutral) and cycloconverter (e.g., matrix converters that periodically switch each output phase connection to different input phase connections so that the fundamental harmonic of the output has the desired main grid frequency) circuits are available, but they claim that they are not validated in distributed generation practice. Hence, the bulk of the paper discusses control structures for grid-side two-level PWM VSI circuits. The design of the PWM inverter circuit is taken for granted.

In the grid-side converter control structures discussed, the PWM inverter generates a sinusoidal voltage much like a synchronous machine (e.g., a fossil-fuel powered synchronous generator). A supervisory controller provides active and reactive power demands to the grid-side converter, and the grid-side converter adjusts the current it provides to the grid in order to meet these requirements. The PWM inverter acts as a current actuator; the inverter output voltage magnitude and phase shift (with respect to the grid signal) control the generated active and reactive power and thus the current (in phases a, b, and c) injected onto the grid. The current feedback controller is expected to have dynamics that are much faster than the outer controllers that adjust power demands. The authors investigate three different structures for controllers that use current feedback to generate the PWM input signals.

In the first controller structure, the *abc* grid currents are transformed into a direct–quadrature (*dq*) reference frame. The *abc* currents are projected onto a rotating reference frame that is synchronous with the lead (a) grid voltage. Hence, the each oscillating current is represented by two DC magnitudes that represent the in-phase (direct) and quadrature components of the current. A proportional–integral (PI) controller regulates each of the *dq* currents to references generated by projecting the supervisory demands onto the *dq* reference frame. The authors show this control policy implemented with an additional feed-forward component to improve the dynamic performance (i.e., to compensate for the transmission line inductance). They also discuss harmonic compensation (HC) in this reference frame. The compensation technique shifts copies of the *abc* currents into new *dq* reference frames that are synchronous with the harmonic frequency to be canceled. Each cancellation block (which consists of high-pass and low-pass filters, an additional PI controller, and two transformation blocks) must be generated for both positive (i.e., phase a leading b leading c) and negative (i.e., phase c leading b leading a) sequences, and so HC with *dq*-based control is deemed to be noticeably complex. The authors also discuss how this control structure is very sensitive to the detected phase angle between the grid voltage and the local oscillator, and so a phase-locked loop (PLL) or arctangent-based method that is robust to harmonic distortion and grid faults is necessary.

In the second controller structure, the *abc* grid currents are transformed into a stationary reference frame with oscillating α and β components that represent the projection of the oscillating waveforms onto stationary axes. In this approach, the supervisory demands are also translated into $\alpha\beta$ references for the $\alpha\beta$ grid currents. Because the reference signal is sinusoidal, a PI controller (i.e., an internal model of a step function) is inappropriate for low steady-state error without a dangerously high proportional gain. Hence, a "proportional–resonant" (PR) controller is used. This controller replaces the PI integrator with an sinusoidal signal with relative degree 1 (i.e., a cosine) synchronous with the grid frequency, and the tendency of the open loop to oscillate allows the controller to track the input with low gain and low steady-state error. Harmonic compensation for PR controller consists of augmenting the controller with additional relative-degree-1 resonators at each frequency to be canceled. In this case, each compensator acts on both the positive and negative sequences, and so the structure is much simpler than the *dq* case.

In the third controller structure, the supervisory demands are translated into *abc* references, and each *abc* current is regulated by a separate controller that may itself be sensitive to errors from the other two phase currents. The authors show how both PI and PR control can be implemented in this natural frame. However, they also introduce the possibility of using nonlinear hysteresis band (HB) and high-speed discrete-time dead-beat (DB) control on each phase. In the case of HB control, the controller generates switching signals for the inverter directly, and so no PWM modulator is needed; however, the HB controller has to be designed to operate at a fixed switching frequency that is a multiple of the grid frequency. The authors claim that the speed of the nonlinear and discrete-time controllers is so fast that harmonic cancellation is unnecessary. They also state that in the natural frame, precise phase angle information is not needed, and so natural-frame methods are the most robust to grid faults that would otherwise corrupt phase angle estimates.

The authors conclude the summary with a discussion of grid fault strategies and methods for estimating the phase angle θ (i.e., for grid synchronization). Focus is placed on the unsymmetrical fault when one or two phases are shorted to ground or to each other. In this case, the system becomes unbalanced and a negative sequence appears in the grid voltages. In the case of synchronous PWM inverters, the negative sequence leads to the generation of strong second harmonics, and so fault and synchronization mechanisms must be robust in the face of these signals. Four fault mechanisms are discussed. In the first, the provided grid current is picked so that no reactive power is added to the grid. In the second, the negative sequence is suppressed so that the system follows the positive sequence only. In the third, the active power generated is held constant. In the fourth, the reactive power generated is held constant. The choice of fault mechanism is picked by the supervisory controller. In the case of grid synchronization, zero-crossing, filtered arctangent, and phase-locked loop (PLL) mechanisms are discussed. State-of-the-art PLL methods are said to be the most robust to grid faults, especially in the case of strong second harmonics produced by negative sequence components in synchronous PWM inverters.

3.2 Criticism

The lead author's presentation of the material shows either some fundamental misunderstanding about how PWM VSI converters are implemented or a cavalier attitude regarding the veracity of the presentation of the material. I focus my attention on the lead author of this paper because other work in its list of references with the same two first authors in opposite order [e.g., 81] do not suffer from the same problems even though the material presented is nearly identical. However, because the intended audience would most likely be familiar with the material, this survey should not mislead researchers referencing it.

Many of the problems of the paper involve both minor and major mistakes in the figures presented. The juxtaposition of Figs. 1(a) and 1(b) is suspicious as their vertical scales are different by an order of magnitude, and their data come from vastly different regions (i.e., Europe and "the world", respectively). The authors are likely making a good-faith presentation of the data, but it appears like they may be over-emphasizing the influence of photovoltaic (PV) generation. Some minor mistakes include the depiction of an LC filter in Fig. 3 as opposed to the proper LCL, gearboxes in Fig. 4 shown in the wrong orientation, and the implication that the phase angle θ is generated from the output of the voltage-controlled oscillator (VCO) in the PLL in Fig. 13. These mistakes would likely not cause any confusion for a technical reader. However, the control structures shown in Figs. 5, 6, and 7 are severely flawed. In the lead of Section IV, the authors briefly describe three different approaches to designing outer and inner control loops for PWM VSI converters. They then refer to the figures as being "general" structures; however, it is unclear how they can be used to implement any of the described approaches. In fact, they appear to be derived from a structure defined by Teodorescu and Blaabjerg [81] for a controller when it has been *disconnected from the grid* (e.g., directly after a fault during intentional islanding), which is certainly inappropriate for this paper. It appears like the authors have slightly modified the grid-disconnected case in an attempt to generalize, but the result shows little congruence with any PWM VSI converter controller structure. The errors in Figs. 5, 6, and 7 are arguably minor because their focus is on the implementation of control in different reference frames. However, none of the figures show the necessary conversion back to the *abc* reference frame. As this conversion is shown in other referenced literature [e.g., 84], it is unclear why it has been omitted here in a discussion of reference frames in particular. Additionally, in the *dq* PI control depiction in Fig. 5, only feed-forward control is shown even though harmonic cancellation is discussed in the accompanying text. The harmonic cancellation is not added until later in the paper in Fig. 9. However, in Fig. 6, harmonic cancellation is shown but is not discussed until much later in the paper. These asymmetries and discontinuities in content may mislead the casual reader.

The major errors in content come in the description of natural frame control. In particular, the authors show confusion about the implementation of dead-beat (DB) control. Early in the description, the authors state that both hysteresis band (HB) control and DB control can generate the switching sequence directly (i.e., without PWM). However, the particular DB control presented is LTI implemented on a digital signal processor (DSP). Hence, as the DB output will be a quantized approximation of an analog signal, and thus will need to be modulated unless the DSP is specially equipped with a PWMDAC. In fact, the authors own DB reference [39] uses a modulator in the description of the DB controller. It is even stranger that the the pole of the DB transfer function is off the z-domain origin. Certainly a DT LTI DB controller should only have a $z = 0$ pole. An additional problem comes in the description of PR control for the natural reference frame. In particular, the authors make a special note that in an isolated neutral case, only two controllers are necessary because $i_a + i_b + i_c = 0$. However, as they implied earlier in the section, this fact is a concern for any natural reference frame controller and should not be highlighted for the PR case only. It is surprising that other continuous-time and variable structure nonlinear controllers are not mentioned. Certainly the field has investigated other PWM VSI structures other than HB and DB control. Because the paper claims that HB and DB are virtuous due to their negligible harmonic distortion, it seems like there should be active investigation into other fast natural frame methods including many that control the inverter gate controls directly.

Additionally, in the section on harmonic cancellation, the authors omit an important discussion on closed-loop system stability. It is unclear that this is the fault of the authors or the field of power system design in general. However, it is clear that the proposed PR harmonic cancellation shown in Fig. 10, the additional uncanceled and undamped open-loop poles will certainly drive the closed-loop system to instability. In fact, this is the reason why PR control uses a resonator with cosine phase (i.e., a transmission zero is necessary to attract the closed loop poles to a region of stability). As discussed by Twining and Holmes [84], stability analysis of dq-based controls are thought to be intractable, and so power system designers use PR control as a benchmark to qualitatively analyze the closed-loop stability of power control systems. The fact that harmonic cancellation in the PR case is not presented without caveat implies that stability in other reference frames may be ignored entirely.

Finally, it is unclear why the section on control strategies under grid faults has been included. It is not a summary of the state of the art in control and grid synchronization of distributed power generation systems. Instead, it reproduces some of the novel strategies suggested by Timbus et al. [82] and also introduces its own fault control strategies. The four authors in the paper by Blaabjerg et al. are included in a different order in the five authors of the paper by Timbus et al. [82], and so it appears like this section on fault control strategies is not meant to be a review but rather an advertisement for other work from the research group. Although there may be value to these contributions, it is disingenuous to present them alongside a so-called *overview* of DPGS.

A summary of reference frame power system control for DC–AC PWM inverters is certainly valuable, and this paper likely is a useful refresher for those not working directly with the design and implementation of PWM VSI sources. No part of the paper is fundamentally flawed; however, the accumulation of its minor errors begs for a revised version to be contributed to the literature. Additionally, the novel content should be removed from the paper so long as it claims to be an overview of existing work in the field.

4 Supervisory Control of Large Power Systems

4.1 Summary

The paper by Tomsovic et al. [83] highlights the complexities in supervisory policy design and implementation for large power systems like the Eastern interconnection in North America. Using these control and communication complexities as motivation, the authors then describe both real and fictitious examples of wide-area control of large power systems. These examples describe abstract policies that are not coupled to particular communications and control mechanisms (e.g., just as PLC is more concrete than SCADA), and so they themselves motivate the generation of a flexible, robust, and fully-featured communication and control infrastructure. The authors provide such an infrastructure and show how it differs from other work in the fields of computer science and power engineering.

Many of the power system challenges given by the authors can be found in popular textbooks [e.g., 9]. They list local goals for power system control including protection of equipment during faults, adjustment of generator power to maintain proper output levels (i.e., power, voltage, and frequency), and damping potentially dangerous low frequency oscillations over the power grid. The authors then list similar goals for wide-area control, but particular focus is given on automatic generation control (AGC) of generator governors. They then briefly summarize some speed and topology challenges to communication schemes over a large power system. All of these control and communication challenges are made more interesting by the fact that the deregulated power grid consists of players with competing interests.

The example applications given by the authors largely come from their own work. In the first example, details are given for a decentralized control of generator governors to adjust frequency based on differences from scheduled generation. Based on regulated power contracts, local areas controlled by different entities deliver power to other parts of the grid. As load increases and generator kinetic energy is drained, the generator frequency in each area is depressed. The proposed controls strategy uses the power deficit in each area to adjust governor controls to maintain a stable system frequency under increasing load schedules. The authors' control is specially designed to handle delays and is shown in simulation to be robust to delays where conventional governor control is not. The second example provides an optimal control framework for finding the optimal switching policy to maintain voltage integrity over a power grid (e.g., switching in reactive components for voltage compensation). The framework is presented without any results; however, it is stated that it is presently being implemented by a third party, and that implementation establishes its feasibility. The third and fourth examples present different frameworks to maintain stability across a power grid. Details are found in the paper's references, which include a pending doctoral dissertation.

The authors then present a brief overview of GridStat, a middleware platform meant to assist in distributing communication and control across a large power system. GridStat includes nodes that publish information to the system as well as subscribers that receive that information. There is also a quality of service (QoS) backplane that processes QoS requirements from different nodes. A high-availability communication system exists within GridStat that is able to account for communication delay. At the time of the publication of the paper, GridStat has been implemented as a prototype with communication latencies of less than 1 ms; however, there are plans for implementation on faster hardware with software featuring hardware-specific optimizations. The faster implementation is predicted to have communication latency of under 1 μs. In both cases, route planning places the most computational burden on the system, but it is expected that route planning can occur rarely and offline. Related work is then summarized in the paper. In each case, the existing systems are shown to be deficient in their ability to transmit data and QoS requirements.

4.2 Criticism

As the survey given by Tomsovic et al. [83] is largely found in readily available power systems texts, it has little value in this paper except for an audience with zero background in the area. The example applications also have questionable value. The first application, which regulates area control error to zero, is shown via simulation to be robust to delay errors. Its development also follows from theory. However, the other three applications seem conjectural from their presentation. The third example, which follows from a doctoral dissertation, claims that simulations show that if it were used in the western blackout of 1996, the instability could *possibly* have been prevented.

Without consulting the referenced text, this statement implies that the strategy only sometimes provided stability in a simulation, and so the value of the strategy is questionable. The authors then give a list of references to their own work on fast-action stability mechanisms, but no results are given. The authors do give a convincing argument that middleware like GridStat is an inevitable necessity. To their credit, the authors do not claim that GridStat should be the ultimate solution to organizing the communication and control of large power systems; instead, they present GridStat as a motivating example.

Hence, a better version of this paper would shorten the classical survey of power system challenges and omit examples from the authors' own work. The need for middleware like GridStat needs little justification, and the bulk that precedes its presentation only confuses the focal point of the paper. The paper has value in inviting specialized infrastructures for power system communication and control; however, it need not also be an advertisement for myriad other work from the authors.

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