Advances in Generator Control and Automatic Synchronization – Eliminating the Need for Standalone Synchronization Systems

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ADVANCES IN GENERATOR CONTROL AND AUTOMATIC SYNCHRONIZATION – ELIMINATING THE NEED FOR STANDALONE SYNCHRONIZATION SYSTEMS

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Abstract—Flexibility in the control of electric power generation within an industrial facility can be improved through the implementation of technology associated with recent advances in electrical system measurement techniques and communications protocols. While generator speed governing and synchronization technology has remained relatively static in recent years, advancements in generator control, including the ability to eliminate the need for standalone bus synchronization systems, are described in this paper. For such advanced systems, time-synchronized measurement and control of generators are required, using technology such as IEEE C37.118 (synchronized phasor measurements). Time-synchronized measurements implemented in each generator governor controller allow precise control of a power system island or group of islands relative to each other or to a master reference. Accordingly, independent, perpetually synchronized power system islands were tested in a laboratory using time-synchronized governor controllers. The results are documented, and conclusions are drawn regarding the feasibility and usefulness of such technology. Additionally, challenges related to control and synchronization difficulties faced at a variety of industrial facilities are discussed, as well as how this new control technology can help overcome such difficulties.

Index Terms—Automatic synchronization, perpetual synchronization, islanding, synchrophasors, governor control.

I. INTRODUCTION

Generation in marine power systems often creates interesting control challenges. The frequency with which units are stopped and started, coupled with changes in the bus topology, makes generation load control and synchronization invaluable to the safe and reliable operations of a vessel. Present technology allows the implementation of schemes that can improve the flexibility with which these generators operate under various system topologies. Systems with this level of flexibility are able to island from the utility and even create islands within the main island while ensuring that each generator is placed in the appropriate control mode and is able to synchronize back to any and all available references.

Generator control has traditionally involved separate hardware from that used for synchronization. Diesel or turbine generator control packages provide standard speed control and load-sharing functionality while a separate synchronization device provides contact or analog outputs to the generator controller package to accomplish generator or bus synchronization. Such synchronization systems require that hard-wired signals from the potential transformer (PT) of every bus needed in the synchronization scheme be wired to the synchronizing device. While this rarely presents a problem in simple applications, such as a single generator being synchronized to a live bus, more complicated scenarios often require sophisticated wiring and selection logic. Consider Fig. 1 as an example of a more sophisticated synchronization scheme.

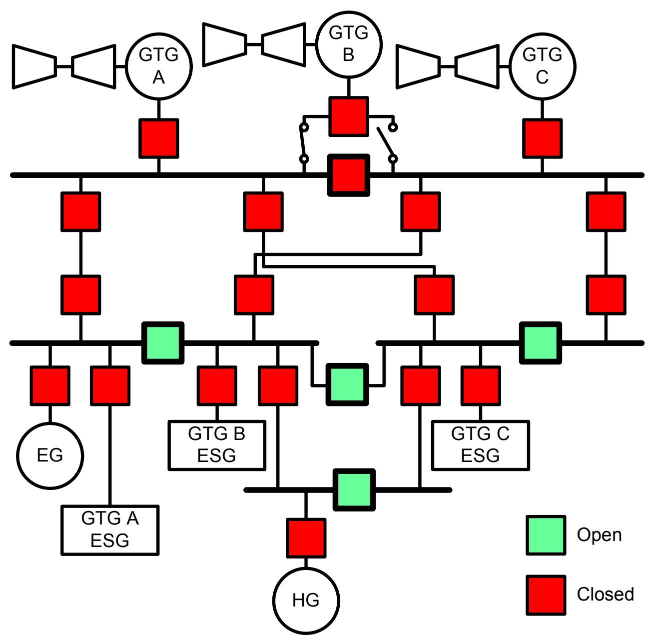

Fig. 1 Simplified Offshore Platform One-Line Diagram

Fig. 1 shows a simplified one-line diagram from a recent greenfield offshore platform project. Three gas turbine generators (GTGs) provide the electric power for the platform, and EG and HG are the emergency and hurricane generators, respectively. In a blackout scenario, the emergency generator is started automatically. The emergency generator is sufficient to power the emergency switchgear (ESG), which allows the starting of the turbines. After the turbines are started, the emergency generator must synchronize to the turbine, so the ESG remains powered while the EG is shut down.

The emergency generator can synchronize to the turbines across a number of breakers, and in an emergency scenario, several options are better than a single option. Wiring PT signals and creating the selection logic for an emergency generator synchronization system that allows synchronization across multiple breakers are not trivial tasks. The same can be said of the hurricane generator synchronization system.

Reducing or eliminating the PT wiring for synchronization schemes would simplify the task of implementing complex automatic synchronization systems. The authors, therefore, are interested in using proven technology to accomplish this task. Additionally, such technology may be able to be leveraged for use in generator control and load-sharing schemes.

In this paper, the authors explore the use of IEEE C37.118 [1] synchronized phasor measurements (synchrophasors) to reduce or eliminate the hard-wired PT signals for synchronization and control purposes. The authors' testing shows that implementing synchrophasor communications within the generator controller allows a single generator, or group of generators, to maintain perpetual synchronization with a reference source. Such flexibility in generator control has never before been possible. Using a synchrophasor communications-based system can eliminate complicated PT wiring and simplify source selection logic.

The goal of this paper is to give a brief background on traditional methods of generator control and synchronization, introduce the concept of using IEEE C37.118 synchrophasors to aid in generator control and synchronization, and offer some examples of challenges encountered in past projects where a synchrophasor-enabled generator controller could have improved the synchronization scheme. The authors have performed testing of the technology using a test bed of laboratory machines; the results of the testing are included.

II. GENERATOR CONTROL – AN INTRODUCTION

The control of generators can be accomplished through two independent methods: an isochronous control scheme, where the controller attempts to maintain the generator at a constant speed reference (i.e., 50 or 60 Hz), or a drooped frequency control scheme, where the frequency of the machine is proportional to its power output. Other modes of control exist, but such modes are hybrid schemes that combine aspects of both droop and isochronous operation.

Fig. 2 shows the response of a 200 W synchronous machine run in isochronous mode to a 10 percent step-load increase. The controller is driving the generator to a 60 Hz set point. The step-load change causes the generator to deviate from 60 Hz temporarily as the controller works to return the unit back to the 60 Hz set point.

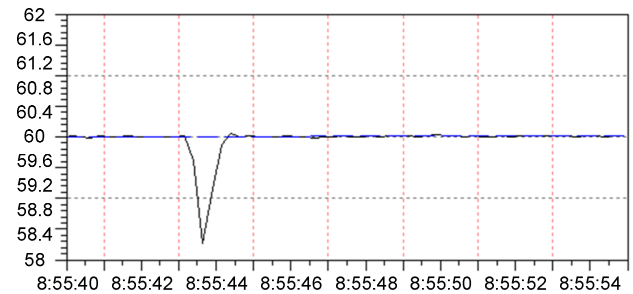

Fig. 2 Isochronous-Run Generator Frequency Response to Load Acceptance

Note that the frequency dips to approximately 58.3 Hz on a 60 Hz system. This may seem like an unusually high frequency deviation relative to the load increase; however, the 200 W machine used in the testing has an extremely small inertia constant, which makes it prone to large frequency deviations under relatively small step-load changes.

Fig. 3 shows the phase angle change to that of a reference phase angle. A 120 Vac wall outlet was wired to the PT input of an intelligent electronic device (IED), and the resulting measured phase angle was used as the reference.

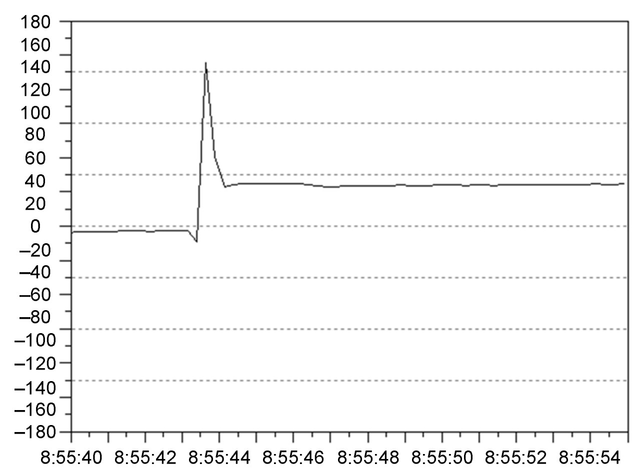

Fig. 3 Isochronous-Run Generator Phase Response to Load Acceptance

Fig. 3 shows a roughly 45-degree separation of the synchronous generator to the wall outlet reference. This scenario is analogous to an industrial facility with a tie to a utility opening the tie breaker under load. As the machines in the facility react to correct the generation-to-load unbalance, the phase angle will shift relative to the utility.

Fig. 4 shows the frequency response of the same 200 W machine to a step-load change while operating in a 5 percent droop control mode.

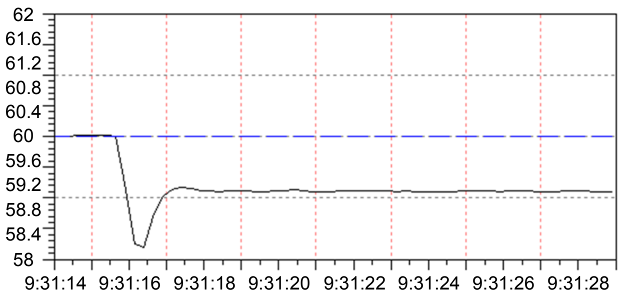

Fig. 4 Droop-Run Generator Frequency Response to Load Acceptance

The deviation in frequency from the 60 Hz nominal is characteristic of a drooped system. The new steady-state frequency of 59.1 Hz indicates that, with a 5 percent droop characteristic, the system underwent a 30 percent step-load change, as shown in (1).

$$\Delta P = \frac{\Delta f}{R} \rightarrow \Delta P = \frac{1.5\%}{5\%} \bullet 100 = 30\% \qquad (1)$$

where:

Δf is the frequency deviation expressed as a percent.

R is the droop regulation expressed as a percent.

ΔP is the net change in power output expressed as a percent of the full load rating.

As a result of the frequency of the machine under test being lower than that of the wall outlet used as a reference, Fig. 5 shows the phase angle of the machine, relative to that of the wall outlet, slipping.

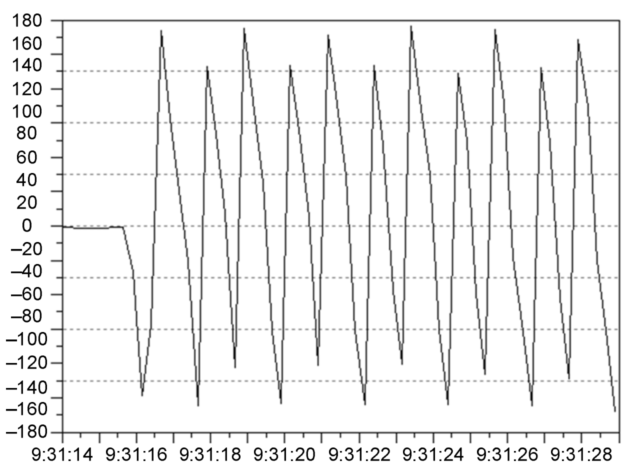

Fig. 5 Droop-Run Generator Phase Angle Response to Load Acceptance

The theory behind the operation of droop mode control is well documented in [2] and [3]; as such, this paper does not delve into the low-level details. However, it is important to note that because of the nature of the droop control scheme, a machine in droop connected to a strong system will follow the system frequency. Therefore, drooped generator control schemes are heavily favored in multimachine systems because the machines will follow the system frequency rather than try to set the system frequency. In addition, each unit in multimachine drooped systems will inherently share load in a stable manner, and the distribution of load amongst the machines can easily be changed by operators.

III. GENERATOR AND ISLAND SYNCHRONIZATION

The automatic synchronization of a generator to a bus and an island to an island involves similar procedures. In each case, voltage magnitudes must be matched and phase angle and slip must be within their respective limits to allow the closing of the synchronization breaker. Reference [4] details the process and requirements of synchronization. The goal is to minimize the amount of transient electrical disturbance on the power system when connecting the two sources together, thereby minimizing the amount of transient torque on the generators and prime movers involved in the synchronization effort. When done properly, the systems mesh together during the closing of the synchronizing breaker and continue running harmoniously thereafter. When done poorly, synchronization can result in large, damaging inrush currents in the stator of the generator and unacceptable mechanical stress on the rotor shaft.

A. Single-Unit Synchronization to a Live Bus

IEEE C50.12 and IEEE C50.13 specify the limits at which round rotor and salient pole machines should be expected to safely synchronize to a live bus [5] [6]. IEEE C50.12 and IEEE C50.13 state that generators that adhere to the standard do not require maintenance or inspection following a synchronization, provided that the synchronization occurs within the following stated limits relative to the bus:

- Phase angle ±10 degrees.
- Slip ±0.067 Hz.
- Voltage 0 to 5 percent.

Reference [7] documents synchronizer permissive settings from operators who are responsible for generator synchronization. The study finds that actual implementations of synchronization settings often differ from the IEEE recommendation.

While the IEEE recommendation states that the slip frequency can be positive or negative, practical implementation has found it desirable to limit the slip from zero to positive in order to reduce the transient torque involved in a slower unit being jolted into place after a connection to a faster system [3].

B. Island-to-Island Synchronization

Synchronizing an island to the grid or an island to another island shares some similarities to synchronizing a single unit to a live bus. IEEE 1547-2005 covers the standard for interconnecting distributed generation (DG) with power systems [8]. While IEEE 1547 does not directly address standards for connecting islanded systems to other islanded systems, it does provide limits for the connection of individual or aggregated resources to a power system. An aggregated DG source could conceivably be interpreted as an island minus any local loading. IEEE 1547 defines the permissible limits as shown in Table I.

TABLE I
IEEE 1547 SYNCHRONIZATION LIMITS

Aggregate Rating of EG (kVA)	**Maximum Frequency Difference (Hz)**	**Maximum Voltage Difference (Percent)**	**Maximum Phase Angle Difference (Degrees)**
S < 500	0.3	10	20
500 < S < 1500	0.2	5	15
S > 1500	0.1	3	10

C. Measured Quantities for Performing Synchronization

IEEE standards suggest that frequency, relative phase angle, and voltage be used for performing synchronization. Other quantities can supplement those listed above, namely, rate of change of frequency and rate of change of voltage. Traditionally, frequency and voltage magnitude and phase measurements are obtained by connecting the source-side PT and the bus-side PT to a single IED. The IED determines the frequency and the voltage magnitude and relative phase difference between the source and the bus. The error between the two signals can be fed into a closed-loop controller for the purposes of automatic synchronization, whereby the controller uses the error signal to adjust the voltage and speed of the generator to within the set constraints.

This method has worked very well for a long time, but as the authors highlight later in this paper, there are some inefficiencies in this method. As demonstrated in Fig. 1, consider a generator that may need to have the flexibility to be synchronized across multiple breakers to multiple buses. The present method of manual or automatic synchronization requires that PT signals from all of the possible buses be wired to a single IED. This has the potential to require relatively long-distance runs of PT cabling and create extremely complicated wiring schemes for PT selection logic. Being able to reduce the amount of PT wiring required for such a scheme and maintain the same level of flexibility would be of great advantage for the user. As such, the subsequent portion of this paper presents the authors' experience using IEEE C37.118 synchrophasor communication to reduce the amount of PT wiring required for complex synchronization schemes.

IV. IEEE C37.118 SYNCHROPHASOR BASICS

Synchrophasors are time-synchronized power system measurements. The concept of synchrophasors is well described in [9] and many other technical papers. Therefore, this paper does not focus on the theory behind synchrophasors but provides basic information regarding their application. For the purpose of generator synchronization, the authors are most interested in voltage magnitude and phase angle measurements, as well as frequency.

Synchrophasors require an accurate time source to be useful. In most cases, the Global Positioning System (GPS) is the time source of preference. Modern GPS clocks boast accuracies to ±100 nanoseconds; such accuracies prove sufficient for synchrophasor measurements. A synchrophasor-capable IED, more commonly known as a phasor measurement unit (PMU), uses this highly accurate time source to create a reference signal by which to reference measured power system quantities. Fig. 6 shows a graphical representation of a voltage measurement referenced to a time signal and the resulting phase angle representation.

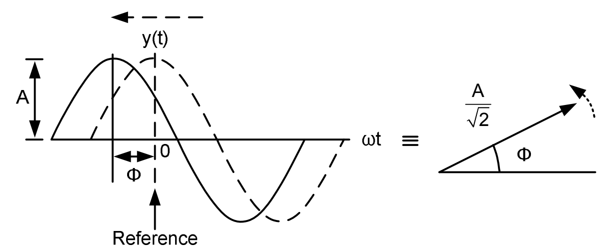

Fig. 6 Time-Referenced Waveform and Phasor Representation

With respect to the topic of generator synchronization, it becomes apparent that if both the generator IED and the bus IED are PMU-enabled devices, comparing the PMU voltage and frequency measurements is similar to using hard-wired PT signals for the same purpose. It follows that PT wiring for synchronization schemes could ostensibly be eliminated within a substation or industrial facility and replaced by PMU communication over a network. However, before the authors advocate a paradigm shift from hard-wired PT signals to digitized PT measurements in synchronizing applications, it is important to look at a few of the complications involved with communications-based synchronizing schemes.

Synchrophasors have a reliance on highly available time distribution. As mentioned previously, GPS is the standard choice when it comes to accurate time distribution. But GPS is not without weaknesses. Because it consists of signals transmitted from a network of satellites, GPS is subject to the same challenges as any other wireless means of communication. Proper GPS antenna placement is required but not always possible for every given installation. GPS antennas work best when they have visibility of the full sky. GPS is also vulnerable to solar flare interruption. The radiation emitted by the flare causes interference with the GPS signal and can ultimately cause the GPS signal to become unavailable for an extended period of time. This problem can be overcome by using specialized network equipment that is capable of maintaining and distributing precise time. Synchronous optical networks (SONETs) are a viable solution for maintaining precise time distribution, regardless of the availability of the GPS signal, but require that each device be part of the SONET ring. Within an industrial facility, such a requirement does not usually present an issue; however, wide-area application may be a different story. While GPS time has proven reliable for use in power system applications

[10], implementation of supplementary time-synchronization capability, specifically through the integration of a SONET network, is certainly advantageous for maintaining high system availability.

The use of synchrophasors for automatic synchronization systems becomes advantageous as the complexity of the scheme increases. For simple applications where a single generator only needs to synchronize to a single specific bus, synchrophasors provide little benefit over the traditional hard-wired PT method. However, as the number of different buses available for synchronization increases or when synchronizing multiple buses together, the complexity of the wiring to accomplish such a task increases and the use of synchrophasors may provide an advantage.

V. ELIMINATING THE NEED FOR STANDALONE SYNCHRONIZATION SCHEMES

Consider the bus architecture presented in Fig. 7, taken from an industrial facility in operation in the Kingdom of Saudi Arabia. Implementing a hard-wired synchronization scheme for synchronizing across the tie breakers becomes a challenging proposition. Such a system requires the synchronization of multiple combinations of buses. In this example bus, A-B, A-C, A-D, B-D, B-C, and C-D are all valid synchronization combinations. Wiring the selection logic for such a system is not a trivial task, because PT signals from all the buses need to be wired to a synchronizing device, across selection switches, in such a way that operators can easily identify which buses they are attempting to synchronize and then control the appropriate generator to drive the two systems together.

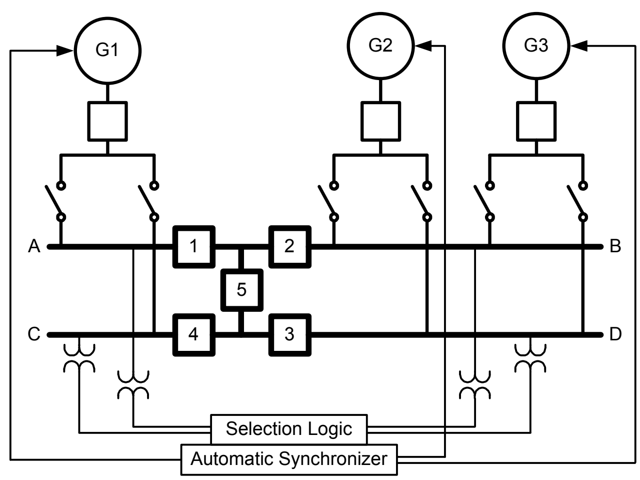

Fig. 7 Example Bus Architecture Using a Hard-Wired Synchronizer

Using synchrophasors to provide the frequency and phase angle information reduces the wiring required for a synchronization scheme. Protective relays or IEDs performing bus-related protection functions can be used to stream synchrophasor measurements directly to the governor controller of the generators, as shown in Fig. 8. Using internal logic, the governor controller can determine the phase angle difference and use this calculation as an additional input to its speed control loop, thereby effectively controlling the relative phase angle difference between it and the selected reference.

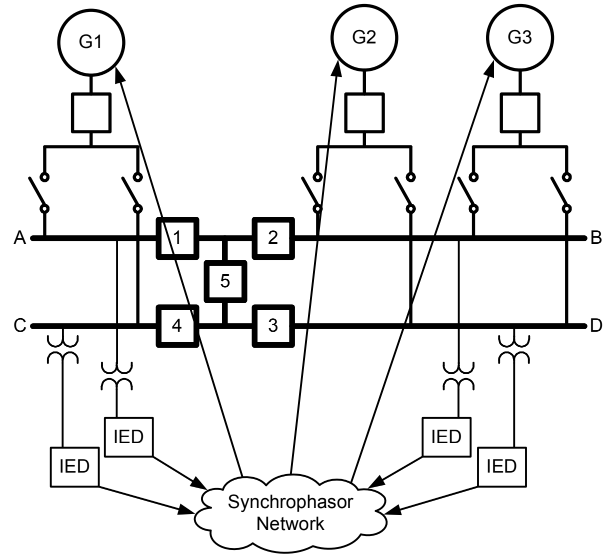

Fig. 8 Example Bus Architecture Using a Synchrophasor Network

The architecture in Fig. 8 makes the following three assumptions:

- The protective relays or IEDs used on the bus are synchrophasor-enabled.
- The governor controller of each unit is synchrophasor-enabled.
- In addition to speed, the governor controller can accommodate and control a second reference, which, in this case, is the phase angle.

Synchrophasor technology is widely available in a variety of protective relays and IEDs from several different manufacturers. Finding an IED capable of acting as a PMU is not a difficult task, nor does it require a large additional investment beyond what would normally be spent for a non-PMU-capable relay. While the major manufacturers of governor controllers currently do not offer PMU functionality, real-time automation controllers are available to supplement or replace legacy governor controllers that lack precise time inputs and the IEEE C37.118 protocol interface.

Putting synchrophasor technology inside of the governor controller eliminates the need for a separate automatic synchronization system. The purpose of the standalone synchronization system is to consolidate the wiring and selection logic to one device, whereby that one device can subsequently issue commands to the necessary generators to bring the systems into synchronism. The synchrophasor network allows each governor controller to have access to all necessary PT signal measurements, thereby making it able to use any of the phase angle measurements as a reference signal in its own control loop.

This paper presents results from testing performed using synchrophasors for synchronization. It should also be noted that the authors are not advocating the removal of the standard synchronism-check (25) element. As in any system,

system transients can occur quickly and unexpectedly. The 25 element provides a level of protection against the unexpected by acting as a permissive to the IED issuing the close command.

VI. PERPETUALLY SYNCHRONIZED ISLANDS

If the governor controller of each generator is PMU-enabled and able to accept PMU data from other PMUs, every generator controller can be aware of its relative phase angle separation from every other generator. If two groups of generators exist on two separate islands but are aware of the phase angle separation between each other, PMU-enabled governor controllers can be used to synchronize the two islands and keep the islands synchronized to each other until the operator decides that the two islands can be reconnected.

Consider the simplified plant one-line diagram from a large industrial facility in Kazakhstan shown in Fig. 9.

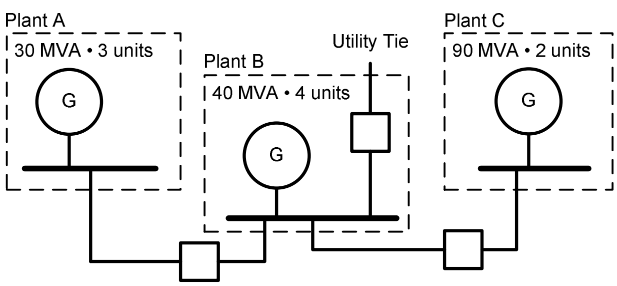

Fig. 9 Simplified Plant One-Line Diagram

Plants A, B, and C are connected by relatively short (< 1 mile) transmission lines. Each plant can operate islanded from the other plants or exist in combined islands. For example, Plants A and B can be connected while Plant C is running isolated. Using streaming frequency and phase angle synchrophasor measurements, the governor controllers of each generator can operate collectively to drive and maintain the phase angle difference between any given island, or combinations of islands, to zero.

Further, if communications between the plants should be jeopardized for any reason and Plants A, B, and C are no longer able to communicate to each other, the inherent mode of operation of synchrophasors still allows the plants to be synchronized together, provided each controller is using GPS time and the time source is healthy. As mentioned earlier, synchrophasor-enabled IEDs generate a reference signal using a highly accurate time source. Each individual IED using GPS as the time source means that each individual IED will generate identical reference signals. Insofar as the generator controllers for Plants A, B, and C are using GPS as a time source, they will generate identical reference signals. The governor controllers can act collectively to drive their respective islands to a zero phase angle difference with their reference, thereby driving each island to a zero phase angle difference with each other.

VII. PUTTING THEORY INTO PRACTICE

Using the phase angle within the governor controller is not a new concept. Synchronization devices presently available allow a user to physically connect PT inputs from the generator and bus PTs to the device. The device measures the relative phase angle error and uses the error to bias the speed control to eliminate the phase angle difference for synchronization. The control block diagram looks similar to Fig. 10.

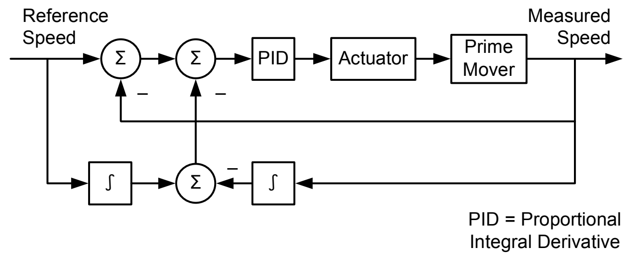

Fig. 10 Speed and Phase Control Block Diagram

While speed is the normal control variable, Fig. 10 shows the addition of phase angle to the control scheme. The advancement in technology presented in this paper makes use of synchrophasor communications and putting this capability into the governor controller itself.

Several scenarios were developed and tested on various generator setups to document the performance of these enhanced synchronization systems. The focus of the testing was to demonstrate the effectiveness of using synchrophasor-enabled governor controllers in complex synchronization applications. Two 200 W synchronous generators driven by dc motor prime movers were evaluated in a laboratory environment.

A. Controlling a Generator to a Stiff Reference

Fig. 11 shows the setup for the simple proof-of-concept test performed. A wall outlet provided a single-phase stiff reference for the test system. The wall outlet signal provided a very constant and slowly fluctuating source for the test generator to follow. A connection from the wall outlet was wired to a single-phase PT on a PMU-enabled IED. The synchrophasor-enabled governor controller retrieved the synchrophasor data from the IED and used the speed and phase angle information as the reference inputs to the control algorithm.

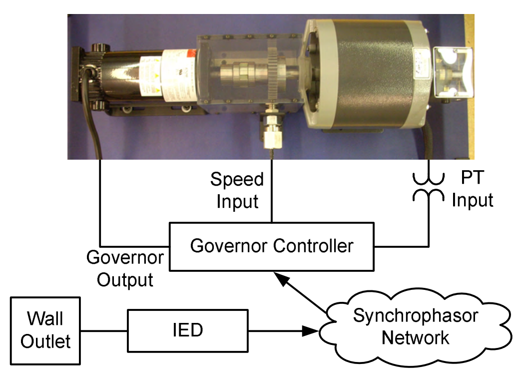

Fig. 11 200 W Machine Simple Test Setup

Using a control scheme similar to Fig. 10, the test setup in Fig. 11 was subjected to step-load acceptance and rejection tests. The results are displayed in Fig. 12 and Fig. 13, respectively. The step-load testing was not meant to highlight how quickly the controller responds but to show results from using the IEEE C37.118 communications protocol in place of traditional hard-wired methods. While the control loop was tuned to perform reasonably quickly, the authors make no claim that the results shown represent an optimally tuned controller.

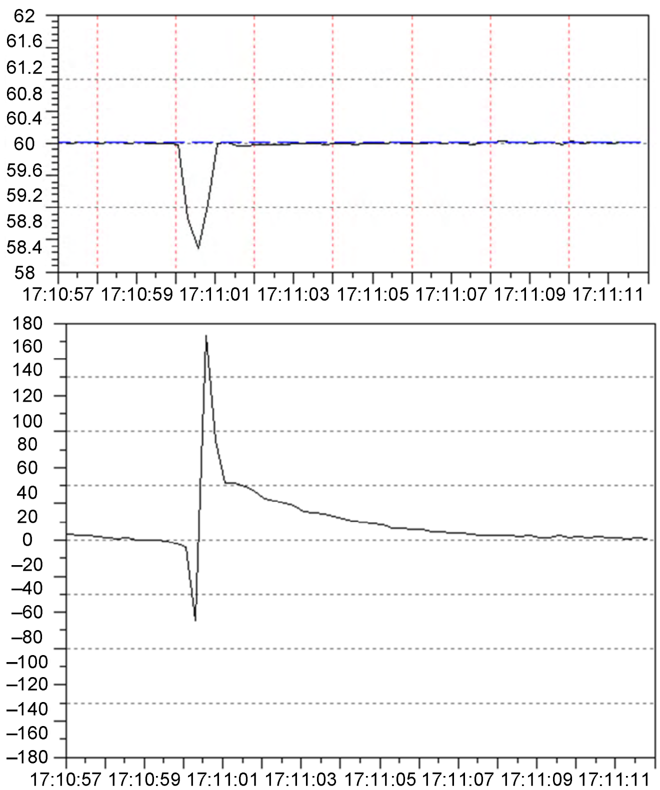

Fig. 12 Frequency and Phase Angle Plots of Step-Load Acceptance Testing With Phase Angle Control

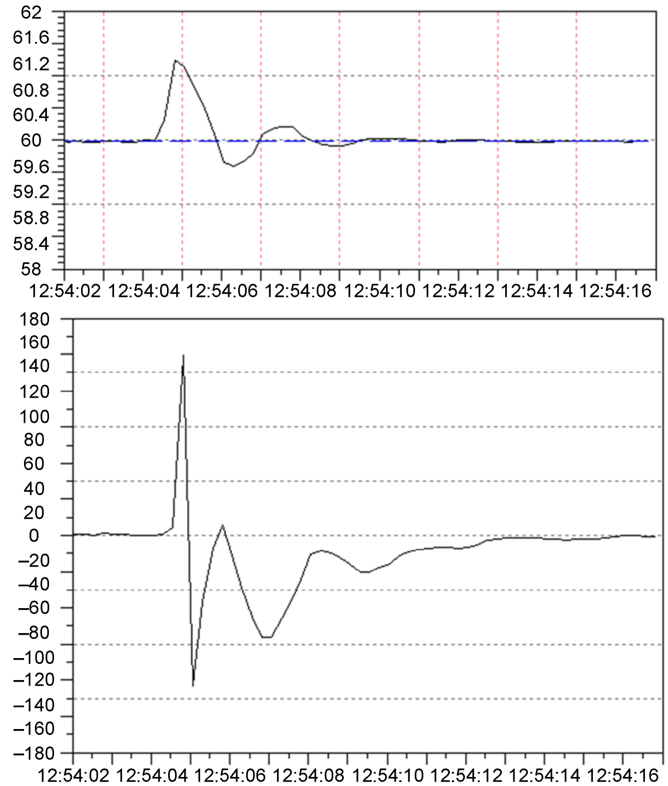

Fig. 13 Frequency and Phase Angle Plots of Step-Load Rejection Testing With Phase Angle Control

The test results from the initial test run illustrate that IEEE C37.118 synchrophasors can act as a capable substitute for hard-wired PT inputs to a generator controller for synchronization purposes. Additional tests are required to validate the use of synchrophasors on more complex generator control and synchronization schemes.

B. Controlling a Generator Relative to Another Generator

Fig. 14 illustrates another test scenario in which two laboratory-scale generators were used and one generator acted as the reference to the other unit.

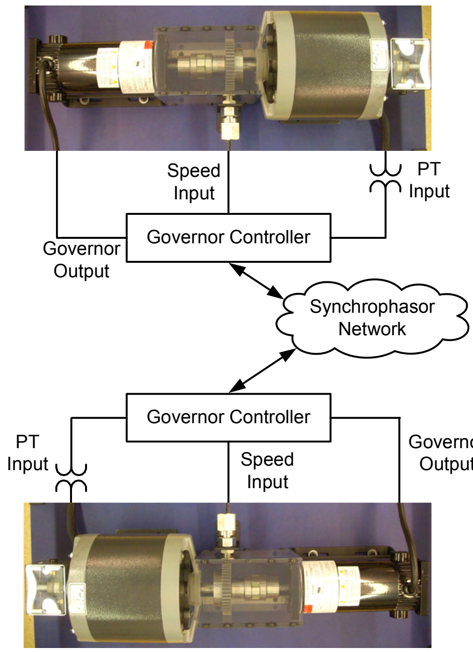

Fig. 14 Two-Generator Laboratory Setup

The ability to control a single unit using another unit as the reference in the laboratory was met with understandable difficulty. The controller was only able to keep the reference machine to within ±30 mHz of the reference set point of 60 Hz. As such, controlling a second generator to match the first proved to be difficult. As the reference unit struggled to match itself to the 60 Hz reference, the second generator had an even more difficult time matching the constantly changing speed of the reference unit. Consequently, controlling the phase angle of the second generator relative to the reference generator was minimally successful.

It is important to note the moment of inertia constant (*H*) of the machines used in the laboratory. Data from the manufacturer indicated that *H* = 0.31 seconds. Traditionally, turbine generators have an *H* of 4 to 10 MW • seconds per MVA [3]. The *H* constant dictates the rate of change of frequency given a torque unbalance, according to (2).

$$\frac{dw}{dt} = \frac{\left(w^2 \bullet Ta\right)}{2 \bullet H \bullet VA} \tag{2}$$

where:

w is the mechanical speed.

Ta is the net accelerating and decelerating torque.

H is the inertia constant.

VA is the VA base.

Because *H* is inversely proportional to the rate of change of speed, the smaller *H* is, the greater the change in speed during a disturbance.

As a result, the above test needs to be validated using large machines in order to fully ascertain the suitability of using a single generator as the reference for the control of another generator.

VIII. CONCLUSION

This paper shows that generator governors can be controlled suitably well using synchrophasor communications. While more testing needs to be done using larger machines, simple laboratory-based experiments have confirmed that controlling a generator to a fixed, stiff reference is achievable.

More testing needs to be done using larger machines to confirm more sophisticated control strategies. The weaknesses of the discussed testing were the use of low-inertia generators and the subsequent difficulty of controlling such light machines.

The results of the testing presented in this paper demonstrate the great potential that synchrophasors have in the future of generation control and synchronizing schemes. Present generation control and synchronization technology has not changed much over the past few years, and synchrophasor technology may bring the next advancements to the industry.

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X. VITAE

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