New Developments in Generator Synchronizing Systems

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***Abstract*—Modern technology, including an advanced automatic synchronizer and systems that use synchrophasors, can significantly improve manual and automatic synchronizing systems. This paper discusses how this technology can simplify synchronizing circuits to reduce cost, improve reliability, and easily accomplish complete integration, automation, and remote control of the system. It also discusses the development and validation of a synchrophasor-based soft synchroscope that is suitable for manually synchronizing a generator to the system and can improve operator performance with better indications than those available from a traditional synchronizing panel. This innovation can revolutionize synchronizing systems by allowing remote synchronizing of islanded systems and enabling a reduction in the number of breakers and VTs required in certain substation topologies.**

I. Introduction

Synchronizing a generator to the power system must be done carefully. The speed (frequency) and voltage of the isolated generator must be closely matched, and the rotor angle must be close to the instantaneous power system phase angle prior to closing the generator breaker to connect the isolated generator to the power system.

Traditionally, generator control systems include a synchronizing panel. The synchronizing panel includes indications of voltage, angle, and slip that show what adjustments the operator needs to make to the governor and exciter and when it is acceptable for the operator to close the breaker. In many cases, the process is automated using an automatic synchronizer with manual control available as a backup.

Options for designing a synchronizing system have been limited in the past because of the inherent limitations of electromechanical synchroscopes and traditional automatic synchronizers. When using these technologies, it was always necessary to have the voltage transformer (VT) signals hard-wired to the generator control room where the generator controls were located. When simply synchronizing a single generator to the bus, this limitation was of little consequence. The synchronizing breakers were located in relatively close proximity to the control room.

Today, with the separation of power generation entities from power transmission entities, there is often a need for separation between the generating plant and the transmission substation. There is often pressure to reduce costs by reducing the number of VTs and circuit breakers in the installation.

In some instances, the generating system is used for reliability islanding of critical loads to prevent disturbances on the power system from affecting critical processes. The synchronizing system must synchronize not just a generator but an islanded system of loads and generation back to the grid. In these cases, the synchronizing breaker will likely be remote from the generator control room.

Today, protective-relay-grade microprocessor devices and synchrophasor-based technology can significantly improve manual and automatic synchronizing systems. This paper discusses how this technology can simplify synchronizing circuits to reduce cost, improve reliability, and easily accomplish complete integration, automation, and remote control of the system. It also describes how enhanced visualization of the synchronizing process using a synchrophasor-based soft synchroscope that provides the operator with better information can make it easier to correctly synchronize the generator every time. Several examples of synchronizing systems that take advantage of these new developments are provided.

II. Fundamentals

A previous paper goes into great detail on the fundamentals of designing generator synchronizing systems [1]. The major points are highlighted here to put the new developments in context.

A. Consequences of Faulty Synchronizing

Poor synchronizing can have the following consequences:

- Damage to the generator and the prime mover because of mechanical stresses caused by the rapid acceleration or deceleration required to bring the rotating masses into synchronism (exactly matched speed and rotor angle) with the power system.
- Damage to the generator and step-up transformer windings caused by high currents.
- Disturbances to the power system such as power oscillations and voltage deviations from nominal.
- The generator prevented from staying online and picking up load when protective relay elements interpret the condition as an abnormal operating condition and trip the generator.

Faulty synchronizing is defined by IEEE C50.12 and IEEE C50.13 as closing the generator breaker outside the following limits [2] [3]:

- Angle: ±10 degrees.
- Voltage: 0 to +5 percent.
- Slip: ±0.067 Hz.

B. Synchronizing System Components

The synchronizing system must perform the following functions:

- Control the governor to match speed.
- Control the exciter to match voltage.
- Close the breaker as close to a 0-degree angle difference as possible.

These functions can be provided by the operator using manual means, automated control systems, or some combination of both. Permissive devices are often included to monitor the process.

C. System Design Considerations

Synchronizing systems must be designed to be robust and fault tolerant. The design should:

- Include redundancy.
- Include multilevel control and supervision.
- Eliminate common-mode failures.

It is important to include redundancy such that no single point of failure makes the generator unavailable. Redundancy typically involves making sure that the manual and automatic synchronizing systems are relatively independent of each other such that either can be used to bring the generator online. Alternatively, automatic systems can be built with redundancy. An example of a redundant automatic synchronizing system is provided in Section IV, Subsection D.

The synchronizing system should include multiple levels of supervision. Typical systems require at least two devices and/or contacts to agree that the synchronism acceptance criteria are met before the generator breaker can be closed. The operator or automatic system attempts to energize the close circuit of the breaker at the precise instant to cause the main contact closure to occur at 0-degree angle difference. This is the first level of supervision. The second level of supervision is typically a synchronism-check relay. In some systems, a third level is included where the operator, the automatic synchronizer, and the synchronism-check relay must all give permission to close the breaker. This scheme takes advantage of the inherent strengths of both human operators and automatic synchronizers.

The synchronizing system must also be designed to eliminate common-mode failures. Proper application of synchronism-check relays that have their VT signal paths independent of the synchronizing panel VT signal paths is one example. This can eliminate the possibility of a failure in the synchronizing switch circuits that switch signals into the synchronizing panel for operator visualization. It can also prevent an automatic synchronizer from causing a faulty synchronization.

III. New Developments

A. Synchrophasors

Wide-area system visibility and high-speed, time-stamped data enable remote system synchronization. Synchrophasors are time-synchronized phasor measurements of a power system relative to a universal time reference such as UTC (Coordinated Universal Time). These measurements reveal the dynamic nature of the power system by displaying high-speed phase angle data across the power system. These real-time data, when converted into information, help the system operator to better protect, control, and monitor the local and wide-area power system.

Many modern digital relays provide streaming synchrophasor data [4]. Today, the precise time reference required to make this phase angle measurement is easily obtained from protective-relay-grade Global Positioning System (GPS) satellite clocks. One popular application of synchrophasor technology is to obtain voltage readings from various devices throughout the power station to be compared for angular difference. A typical phasor measurement unit (PMU) data set includes time-synchronized phasors, analogs, digitals, frequency, rate of change of frequency (DFDT), and status information. These data can be streamed at rates up to 60 messages per second with low latency, providing the needed performance for synchronizing applications [5]. Since PMU functionality in protective relays was first introduced in 2000, synchrophasors have become nearly ubiquitous, and synchrophasor data are available nearly everywhere at no additional expense. Fig. 1 shows the phasor representation of a sine wave referenced to a time signal.

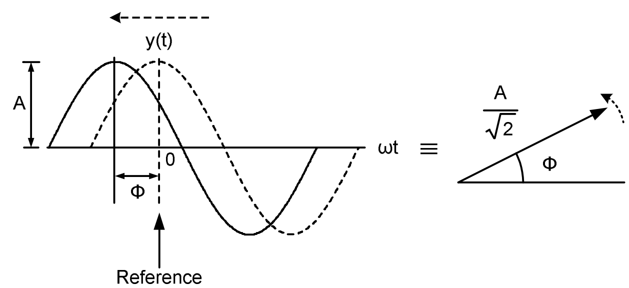

Fig. 1. Sinusoidal waveform translated to phasor representation

The accuracy of synchrophasors is measured using the total vector error (TVE), which is defined by IEEE C37.118 as the measure of error between the theoretical phasor value of the signal being measured and the phasor estimate [6]. The standard describes a need of less than 1 percent TVE for synchrophasor measurement.

Also, IEEE C37.118 states that "…a time error of 1 µs corresponds to a phase error of 0.022 degrees for a 60 Hz system…." This means a phase error of 0.57 degrees causes 1 percent TVE, which also corresponds to a maximum time error of ±26 microseconds for a 60 Hz system. So the time source for synchrophasors should be highly reliable for providing sufficient time accuracy to keep the TVE within the required limits.

With GPS being the major system component, timing is everything for synchrophasors. IEEE C37.118 allows as much as 1,000 nanoseconds of total offset from UTC time for producing valid synchrophasors. Operational testing on some modern clocks shows accuracy within ±100 nanoseconds (average), thus satisfying the IEEE synchrophasor requirement. In all cases, the modern satellite-synchronized clock uses the UTC time determined from GPS time to discipline the clock oscillator to attain accuracies of better than 1 microsecond, referenced to UTC time.

GPS receivers often become unpredictable in less than optimal signal conditions because of poor antenna placement, blocked sky view, and so on. Many of these issues can be addressed by proper antenna placement for good visibility of the sky, allowing good signal reception. But other uncontrollable sources, such as weather, degrade GPS operation. One well-understood interference is caused by solar radio bursts. These bursts are associated with solar flares that can impact GPS signal reception for long times. Also, there are other interference sources, such as electromagnetic pulses, over which we have little or no control. Addressing such issues is important, especially when using synchrophasor phase angle information for critical applications such as generator synchronizing systems. Without a proper reference, the phasor angle information by itself has little significance.

Many modern PMUs switch over to their own internal oscillators when the clock indicates that it has lost satellite synchronization during poor GPS signal conditions. Synchrophasors produced during that time include phase errors because of unsynchronized time sources and can no longer be used.

Thus, for generator synchronizing systems, which typically include devices located in a geographically limited area, it is beneficial to distribute the time reference from a single clock over a terrestrial network such that the PMUs produce relative synchrophasors. Relative synchrophasors are synchronized relative to each other but are not synchronized to the universal time reference. Thus, synchrophasors using a relative local time are suitable for use in a generator synchronizing system. For remote system synchronization, terrestrial distribution of time requires utilization of low-cost, fiber-optic solutions for distributing a synchrophasor-quality time reference. With this kind of implementation, maintaining relative accuracy between the points of measurement enables a system independent of GPS. Reference [7] provides more details about synchronous optical network (SONET) systems that are capable of providing highly reliable relative time, even with the total loss of GPS.

Using a GPS time reference for producing synchrophasor measurements is a proven and accepted industry practice. But considering all the possibilities of interference and the reliability required for synchronization, a good design implementation should include backup plans for a loss of GPS time. These backup plans would use systems that are capable of distributing extremely reliable, high-accuracy time over terrestrial networks.

B. Phasor Data Concentrator (PDC) Synchroscope

To fully eliminate hard-wired voltage and control signal switching circuits and allow complete computer human-machine interface (HMI) integration, a computer-based synchronizing panel using information from sources independent of the automatic synchronizer is required. In applications that require an independent manual synchronizing system, low latency is important. When the operator sees the angle approaching 0 degrees and initiates the close command, the soft synchroscope must not be displaying old information. In the following discussion, the term "soft synchroscope" is used; it is important to understand that a soft synchroscope includes all of the indications found on a complete synchronizing panel.

Delays in real-time computer systems mainly result from polling latency, processing time, and screen update rate. Some latency in the display of information is acceptable in most HMI applications. But the requirements for manual synchronizing are much more stringent. The generator will travel about 2.5 electrical degrees in 100 milliseconds at 0.067 Hz slip.

A dedicated computer running PDC software can receive streaming data from the various microprocessor-based relays applied for protection and control of the synchronizing breakers. The PDC selects the proper signals in its incoming data streams for the incoming and running voltages based upon operator selection of the generator and breaker to be synchronized. No physical signal switching is required. And the synchrophasor voltage measurements from the breaker control relays are independent from the measurements of the automatic synchronizer, which makes the system redundant. The PDC can also scale the voltage signals, if necessary. This might be required if the incoming voltage synchrophasors are from the generator relay connected to the VTs at the generator terminals and the running voltage synchrophasors are coming from a relay on the high-voltage bus VT.

For the manual system, note that the soft synchroscope provides visualization of the critical synchronizing quantities only. The operator still requires direct acting controls for the governor and exciter and for closing the breaker. Initiating a 0-degree close command via an HMI control point will typically include more latency than is acceptable.

The traditional synchronizing panel is not ideal because of the limitations of electromechanical technology. Modern technology is no longer bounded by these limitations. The critical synchronizing quantities are:

- Angle difference.
- Voltage difference.
- Slip (frequency difference).

While the angle difference is directly indicated on the synchroscope, a traditional synchronizing panel typically does not include direct indication of the other two parameters. To determine voltage difference, the operator must read the two voltmeters and mentally subtract the readings. To determine slip, the operator must observe the synchroscope revolutions per minute (rpm). There is no direct indication of voltage difference and slip.

A traditional synchronizing panel can be enhanced by using indications from an advanced synchronism-check relay. The synchronism-check relay can be programmed to close a contact that lights an indicating lamp when the slip is within the acceptance range. Similarly, with programming, some relays can close a contact when the voltage difference is within the acceptance range. These two indications help the operator determine if the close attempt will be successful or blocked by the synchronism-check relay.

Fig. 2 shows an advanced PDC synchroscope that provides direct indication of all significant synchronizing parameters. The voltage difference and slip are directly indicated on separate dials with the acceptance criteria programmed as green zones for easy visualization. The "Instantaneous Voltage Difference" bar at the top of the PDC synchroscope improves on the "two-lamp" function by showing the voltage difference more precisely. Better indication can significantly improve operator performance and consistency of manual synchronization.

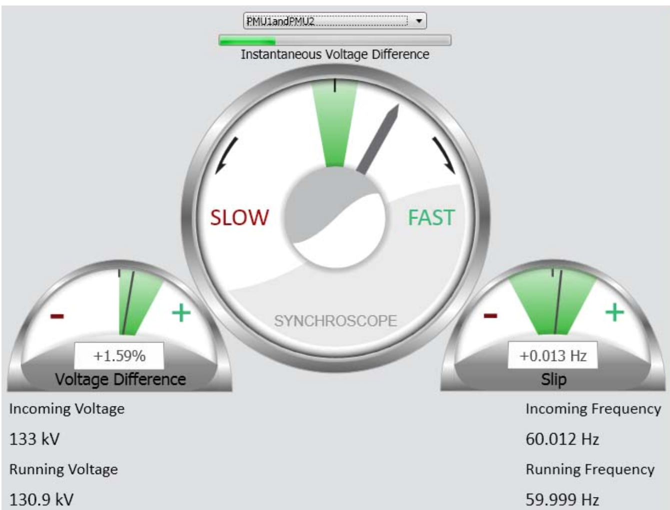

Fig. 2. Advanced PDC synchroscope

Note that today there are commercially available soft synchroscopes that use nonsynchrophasor data for monitoring generator automatic synchronizing. The authors of the paper performed real-time testing of several soft synchroscopes. A simple power system was modeled and simulated in a Real Time Digital Simulator (RTDS®) for establishing a synchronizing scenario. An electromechanical synchroscope was used as a reference for determining the performance of the soft synchroscopes. Today, the electromechanical synchroscope is the state-of-the-art technology available for synchronizing systems because of very low or no latency.

One of the first observations made was that the angular offset measured between the electromechanical synchroscope and soft synchroscopes increases with an increase in slip frequency rates. Each soft synchroscope had its own limitations on performance because of its data polling speed and architectural design. The synchrophasor-based soft synchroscope performance was close to the electromechanical-based synchroscope when compared with the other soft synchroscopes. Table I shows the approximate angle offsets of the soft synchroscopes when compared with the electromechanical synchroscope angle for a given constant slip frequency. SS1 and SS2 are soft synchroscopes designed for monitoring an automatic synchronizer (upper left and lower left soft synchroscopes in Figure 3). SS3 is the PDC synchroscope (upper right soft synchroscope in Figure 3) that is suitable for use with manual synchronizing.

TABLE I
SOFT SYNCHROSCOPE (SS) ERROR VERSUS SLIP RATE

Slip Frequency (Hz)	SS1 Angle Offset	SS2 Angle Offset	SS3 Angle Offset
0.01	5°	5°	1°
0.03	10°	10°	3°
0.05	18°	17°	3°
0.067	15°	12°	3°

The main factors that affected the soft synchroscope performance were:

- Device processing latency.
- Data polling speeds.
- Network latency.
- Screen update rate.
- Configuration of the computer running the soft synchroscope.

Fig. 3 shows a test setup with three soft synchroscopes and two electromechanical synchroscopes. The frame capture is from a test at 0.067 Hz slip frequency at the instant that the electromechanical synchroscope was passing through 12 o'clock. The two electromechanical synchroscopes and the synchrophasor-based soft synchroscope (upper right computer monitor) agree closely at 0-degree phase angle difference. The two soft synchroscopes that are designed to monitor an automatic synchronizer show 12 and 15 degrees of error, but because they are not actually in the control loop (indication to an operator for manual synchronizing), the latency in display is acceptable.

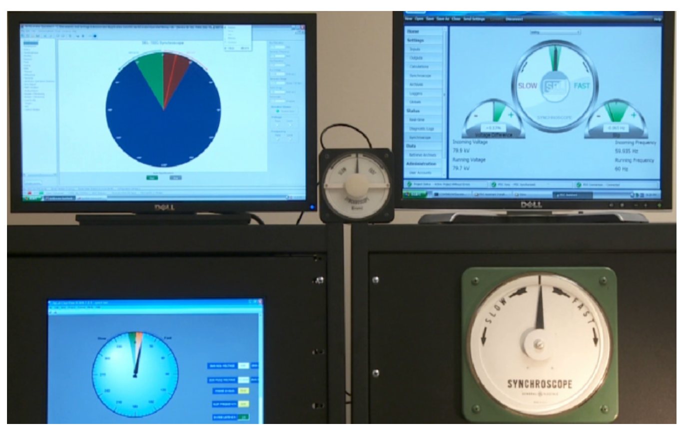

Fig. 3. Synchrophasor-based soft synchroscope test

C. Advanced Automatic Synchronizer

An advanced microprocessor-based automatic synchronizer (A25A in Fig. 4) with six isolated and independent single-phase voltage-sensing inputs and the ability to read an IEEE C37.118 synchrophasor data stream and process it internally to calculate voltage difference, slip, and angle difference between the remote PMU and its own voltage signals in real time is available. The A25A device also has many advanced features to improve synchronizing systems.

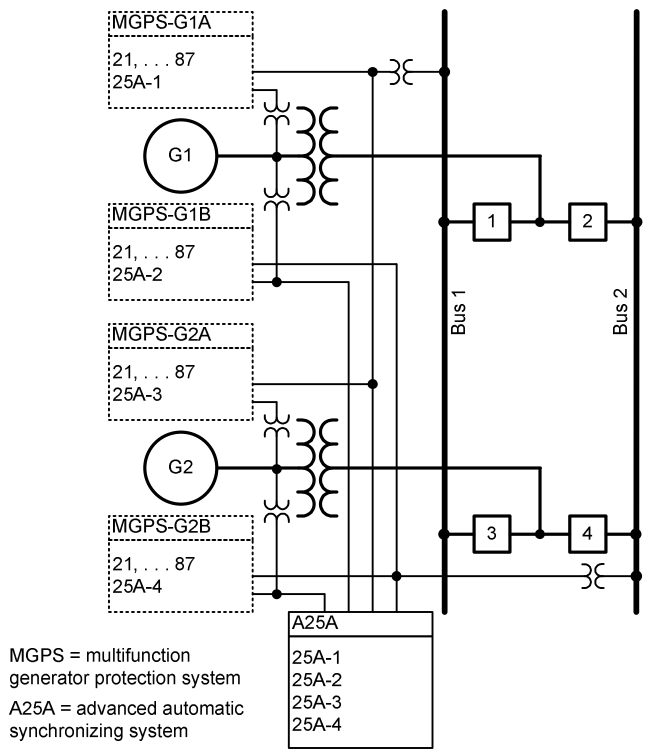

Fig. 4. Example applications using microprocessor-based automatic synchronizer(s) to eliminate VT signal switching

1) Eliminate the Need to Physically Switch VT Signals

The A25A device can eliminate the need to physically switch voltage signals. This can greatly simplify issues with isolation of instrument transformer circuits and hidden failures in complex synchronizing switch circuits. For the example system illustrated in Fig. 4, the two generator VTs and the two bus VTs could be wired to four of the six inputs on A25A. If the generator breakers between the two generators do not share common connections across all synchronizing breakers, each generator may require three VT signals for a total of six. This is just one of many examples.

When the operator selects the generator to synchronize and the breaker to synchronize across, the automatic synchronizer selects the appropriate incoming and running voltages from its six inputs and performs the automatic synchronization process. Further, separate isolated output contacts for the close command can be wired directly into each breaker closing circuit. There is little possibility of hidden failures in the circuitry.

2) Peer-to-Peer Synchrophasors

The A25A device also has the capability to read an IEEE C37.118 synchrophasor data stream and process it internally to calculate voltage difference, slip, and angle difference between the remote PMU and its own voltage signals in real time. The synchrophasor data can be sent from a remote relay by fiber-optic serial or Ethernet communications links, so long VT signal runs can be eliminated. This capability opens up the possibility for designing systems never before possible. The example in Section IV, Subsection E uses this feature.

3) Remote I/O (RIO) Functionality

A standard feature of the A25A device is a high-performance, protective-relay-grade, peer-to-peer communications link [8]. The automatic synchronizer can be connected to a RIO module so that the control signals listed in Table II are available in the control room and the automatic synchronizer is located at the synchronizing breaker.

TABLE II
REMOTE I/O

Control Signals From A25A	Control Signals to A25A
Voltage OK to initiate	Alarm reset
Frequency OK to initiate	Enable dead-bus close
Close fail/lockout	Abort synchronizing process
Raise generator frequency	Initiate synchronizing process
Lower generator frequency	Operator close permissive
Raise generator voltage	–
Lower generator voltage	–

IEC 61850 GOOSE (Generic Object-Oriented Substation Event) messaging over an Ethernet network can also be used with this platform.

4) High-Current Interrupting Contacts

In many cases, the contacts on the automatic synchronizer are damaged from arcing caused by the repeated making and breaking of inductive dc current while pulsing the governor and exciter. If the application requires it, optional high-current interrupting contacts that are rated to interrupt 10 A at 125 V can be included.

High-current interrupting contacts are also advantageous in the breaker close circuit. The closing contact and/or the synchronism-check permissive contact can be damaged if current is still flowing in the breaker close auxiliary relay circuit when the generator slips outside of the acceptance window during a close failure event. High-current interrupting contacts prevent the contact from welding closed and then allowing a faulty synchronization on the next close attempt.

5) Recording and Communication

Additionally, modern equipment includes detailed sequence-of-events and oscillography recording functions that are invaluable for analysis if a faulty synchronization occurs.

The A25A device even has the ability to record generator currents, if they are wired to it, during each synchronization to gauge the smoothness or severity of the operation. This level of information is also invaluable when determining if teardown and inspection are required after a faulty synchronization.

A system that uses synchrophasors can also have the PDC archive the synchrophasor data from the synchronizing process to help with analysis of operator performance, tuning of the automatic synchronizer control parameters, and so on.

The A25A device records the correction pulse duration and the resulting ΔV and ΔF from each correction pulse. When commissioning the system, the seconds-per-hertz and seconds-per-volt response characteristics of the governor and exciter can be calculated and graphed. This information is useful to optimize the proportional pulse slope characteristics of the control.

D. Automatic Synchronizer Built Into a Multifunction Generator Protection Package

Multifunction generator protection systems (MGPSs) now include automatic synchronizer functionality. The two MGPSs on each generator shown in Fig. 4 can be hard-wired to the voltage signals so that each is used for one of the two synchronizing breakers. This can also eliminate the need to physically switch voltage signals. This second architecture for the Fig. 4 application has redundant automatic systems so that if one of the MGPSs is out of service, the generator can always be brought online via the breaker controlled by the remaining MGPS.

E. Fiber-Optic Communications Links

Prior to the availability of a PDC synchroscope, the synchronizing panel needed to be physically close to the breakers and VTs providing the signals. Now, with fiber-optic data links, an operator can monitor and control the generator and breaker from a remote location. Further, high-performance, relay-to-relay logic communication in the A25A device (discussed in Section IV) allows it to be located close to the synchronizing breaker with control signals sent back to the governor and exciter via fiber-optic links.

The ability to build systems for monitoring and control using low-cost, fiber-optic communications links completely revolutionizes the design of generator synchronizing systems. The possibilities for system configurations that were never before possible are now nearly limitless. Section IV describes several configurations.

IV. Examples

The following are several example applications using advanced synchronizing technology. Some of these applications are in service, and some have only been proposed.

A. No Local Synchronizing Breaker

In this application, a combustion turbine generator is located several miles from the substation that ties it to the grid. The installation does not include a local synchronizing breaker. In the past, there would be no way to provide synchronizing panel indications from the VTs located at the substation to the generator control room. The proposed system included an A25A device located at the substation with a RIO located in the control room to adjust the governor and exciter via a fiber-optic link and to take operator control signals for initiate and abort to the A25A. A PDC synchroscope for operator visualization and control and a separate RIO for taking the operator close signal to the remote breaker close coil were included as options.

B. Multiple Synchronizing Points in Reliability Islanding System

In this application, a pharmaceutical facility operates a cogeneration system for process steam and electricity. A major upgrade to the plant electrical distribution system now allows critical load islanding. Fig. 5 shows a simplified one-line diagram of the system. This system has two generator breakers at the Sub 27 bus, three islanding breakers at Sub 75, and one islanding breaker at Sub 66. These various separation points could be selected depending upon the match of generating capacity with facility loads to automatically island portions of the facility in the event of a disturbance on the utility system. The system could also be manually islanded when a disturbance is anticipated, such as during hurricane season.

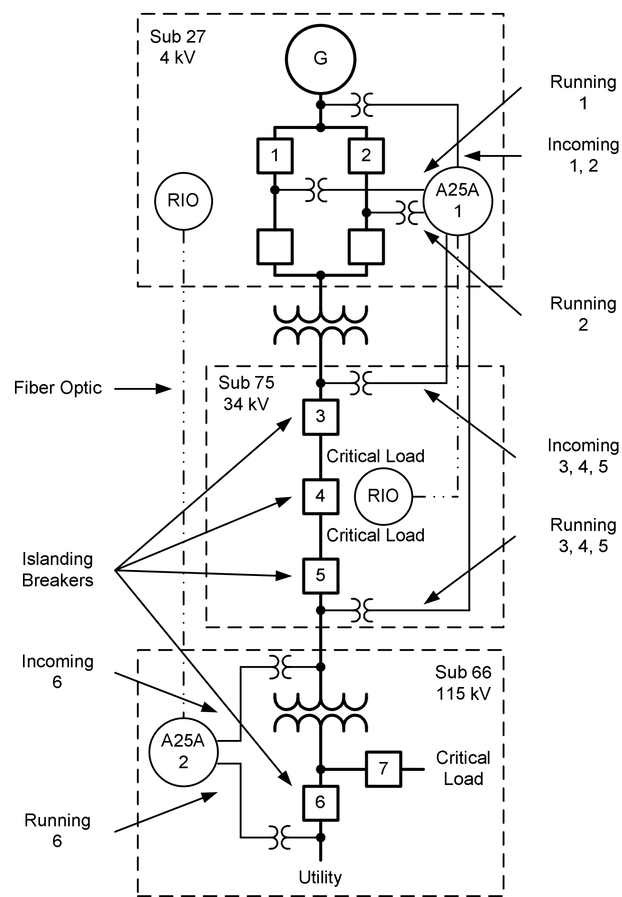

Fig. 5. Reliability islanding and synchronizing system

Sub 75 and Sub 27 are within a few hundred yards of each other, so the synchronizing voltages for Breakers 3, 4, and 5 are wired directly to the A25A 1 device. Closing commands from A25A 1 are sent to Sub 75 using a RIO and fiber-optic link to maintain isolation between the battery systems at the two substations. Sub 66 is about a half mile from Sub 27, so A25A 2 is located there to synchronize across Breaker 6. Raise and lower pulses are sent to Sub 27 using a RIO and fiber-optic link. Automatic synchronizing is the only system allowed at this facility, so no soft synchroscope is installed.

The system is completely controlled via an HMI system in the Sub 27 control room. All of the original synchronizing switch wiring was removed in the upgrade.

C. Elimination of Synchronizing Circuits in a Paper Mill

A paper mill operates a cogeneration system for process steam and electricity. The system includes multiple generators and multiple synchronizing points throughout a complex plant distribution system. All synchronizing circuits go through a single synchronizing cabinet with a complicated arrangement of auxiliary relays and selector switch contacts to set up the various synchronizing scenarios. The plant environment causes corrosion problems for electrical components, so there are frequent failures of components in the synchronizing cabinet. Due to the complexity of the circuitry and the large number of hidden failure points, troubleshooting can be very difficult and time-consuming, resulting in reduced availability of critical generation.

This facility also has a utility tie circuit breaker that is remote from the generator control room. It is sometimes necessary to synchronize the islanded facility back to the utility at that location. Conventional synchronizing technology results in long VT and control circuits running between the electrical substations and poor system reliability.

Modern microprocessor-based equipment can be conformal coated to provide resistance to degradation in harsh industrial environments. Eliminating auxiliary relays and switching contacts and performing all sensing and control signal switching in software can greatly improve the reliability of the synchronizing system.

A system upgrade is planned to install a remote A25A device at the utility tie substation using a RIO to bring control signals back to the control room. In phase two, the existing synchronizing cabinet can be replaced with a number of A25A devices.

D. Redundant Automatic Synchronizing System With Complex Bus and Multiple Synchronizing Scenarios

An alumina processing plant is installing a new gas insulated substation (GIS) in a double-bus/single-breaker arrangement. In a double-bus/single-breaker station, any circuit can be connected to either bus. The two buses are sectionalized, resulting in four bus sections. The GIS connects two additional generators and the two utility tie lines to the existing plant distribution system. Fig. 6 shows a simplified one-line diagram of the system. Load circuits and tie feeders to existing generation buses are not shown. The advanced synchronizing system is designed to synchronize islanded blocks of load and generation across the two bus coupler Breakers 3 and 4, the two bus sectionalizer Breakers 1 and 2, or across the two tie-line Breakers 5 and 6. Generators 5 and 6 have their own system for synchronizing to the bus, so synchronizing Breakers 7 and 8 is not included in the system. Manual synchronizing is not allowed, so the automatic system is designed for redundancy.

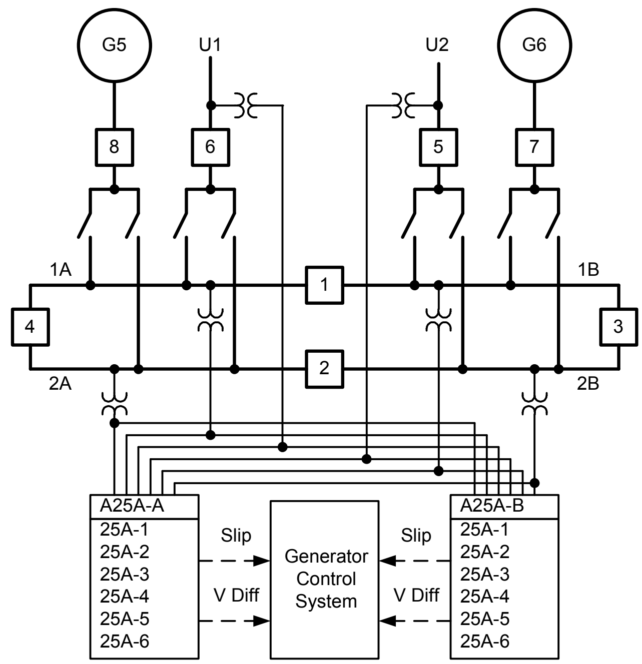

Fig. 6. Complex redundant automatic synchronizing system

Two A25A devices are installed, each connected to all six of the VTs required to synchronize across any of the six breakers. The A25A devices determine the correct incoming and running voltage signals based upon the breaker selected and the station switching topology. The sign of the slip and voltage difference is determined by the synchronizing scenario selected. These values are fed to the generator control system that handles frequency control and load sharing. The control system adjusts the frequency and voltage to minimize error. When the synchronizing acceptance criteria are met, the A25A device calculates the slip-compensated advanced angle and closes the breaker.

E. Elimination of Local Synchronizing Breaker, Remote Synchronizing VT, and Copper VT Circuits Between Plant and Substation

A combined cycle plant is being built as shown in Fig. 7. The generation owner has determined that a local synchronizing breaker will not be installed on the steam turbine generator (STG) to reduce costs. The substation is owned by a separate transmission owner, and the generation owner would prefer to not own any high-voltage equipment in the substation. For this reason, there will be no synchronizing VT located on the high-voltage generator step-up transformer bus between Breakers A and B in the substation yard. A further constraint is that there will be no copper control cables between the two installations, which are located approximately a quarter mile apart. The generation owner is planning on installing PMU-capable relays in the substation for oscillography and synchrophasor disturbance recording.

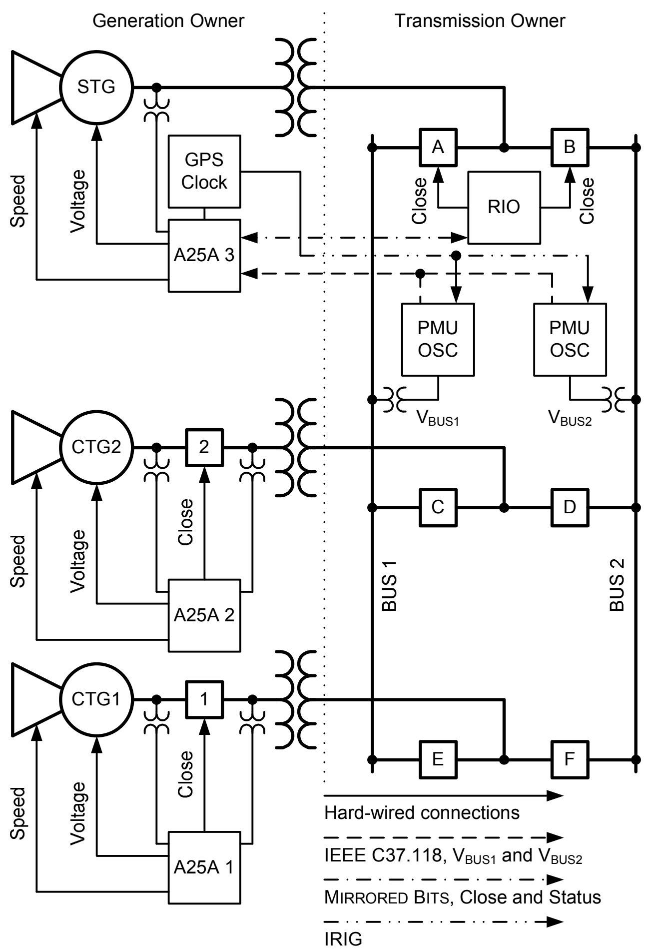

Fig. 7. Peer-to-peer synchrophasor application

The synchronizing system will be a nonredundant, automatic system only. No manual synchronizing system will be installed. Combustion turbine generators (CTG1 and CTG2) will use the A25A device in a conventional design with one A25A per unit.

The STG system will measure the local generator VT for the incoming voltage signal. The running voltage signal will be read from the synchrophasor data from Bus 1 or Bus 2, depending upon which breaker has been chosen for synchronizing. The A25A device and PMU/OSC synchrophasor devices will be synchronized to a common clock located at the generator facility, if possible, such that they will have relative synchrophasors in the event that the GPS system is unavailable.

Close commands for the breakers will be transmitted from the A25A device to the RIO module by relay-to-relay logic communications. Breaker status and local/remote status will be transmitted from the RIO module to the A25A device via the return relay-to-relay logic communications link.

V. Summary and Conclusions

New developments in generator synchronizing systems have opened up a number of possibilities for improving performance, reducing costs, reducing the possibility of hidden failures, and improving reliability. Cost savings can be gained by using advanced technology to reduce the need for costly power system apparatus, such as additional VTs and synchronizing breakers, and replacing wiring with fiber-optic communications links. Advanced technology also makes remote synchronizing of islanded systems possible.

Synchrophasor technology can be used to provide manual synchronizing indications that are independent of an automatic synchronizer. Further, the PDC synchroscope provides superior operator indications. Direct readout of all three synchronizing acceptance indications—voltage difference, frequency difference (slip), and angle difference—makes it easy for operators to synchronize a generator correctly every time.

An A25A device is also available that can use synchrophasor data streaming from a remote synchrophasor-capable relay to calculate voltage difference, frequency difference (slip), and angle difference between its own VT inputs and the remote relay. The automatic synchronizer can send correction pulses to the governor and exciter to match voltage and frequency and then calculate the slip-compensated advanced angle to close the breaker when the angle difference is 0 degrees.

The A25A device also includes six single-phase VT inputs that can be selected internally and many programmable outputs that can eliminate the need to physically switch VT and control signals.

Remote I/O capability is built into the A25A device such that it can be located near the synchronizing breaker and send generator matching pulses back to the control room via a fiber-optic link.

The examples included in this paper show how these advanced features can be used to design synchronizing systems that were never before possible.

VI. References

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VII. Biographies

Michael J. Thompson received his BS, magna cum laude, from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN), where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a principal engineer in the engineering services division at SEL, a senior member of the IEEE, a main committee member of the IEEE PES Power System Relaying Committee, and a registered professional engineer. Michael was a contributor to the reference book *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers, and has a number of patents associated with power system protection and control.

Krishnanjan Gubba Ravikumar received his MSEE degree from Mississippi State University in 2009 and his BS Electrical and Electronics Engineering degree from Anna University, India, in 2007. He focused his graduate studies on power engineering and worked as a research assistant in the Power & Energy Research Lab at Mississippi State University. He was the recipient of the Mississippi State Research Assistant of the Year Award for 2009. He is presently working as a power engineer at Schweitzer Engineering Laboratories, Inc., focusing on the development and operation of synchrophasor-based power systems. His areas of research interest include real-time power system modeling and simulation, substation automation, synchrophasors and their applications, power system stability, and power electronic applications. He is a member of the IEEE and the Eta Kappa Nu Honor Society.

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